CIFE CENTER FOR INTEGRATED FACILITY ENGINEERING

Representation and Reasoning for Integrated Structural Design

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By
Gregory P. Luth
June, 1991

I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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Approved for the University Committee onGraduate Studies:

Dean of Graduate Studies

Dedicated
to the memory
of my father,
Louis H. Luth, Jr.

Abstract

This research effort addresses the general framework required for integration of the activities that constitute structural engineering reasoning during the life cycle of a facility, specifically a high-rise commercial office building. As part of that framework, the global process by which buildings are conceived, design, built, and operated is defined in order to put the structural engineering activities in perspective and to identify the sources of interaction among the domains of design, construction, and facilities management. The reasoning that is performed in the structural engineering domain during the various phases is defined, and a system architecture that accommodates the multiple contexts created by the intersections of phases and domains is proposed.

The framework provides the motivation for using model-based reasoning for integrated structural design. The proposed approach incorporates iterative constraint formulation, propagation, and satisfaction, using first principles rather than heuristic rules. Decisions regarding alternative systems, components, or attributes are based on reducing the Cost/Value of the building as a whole.

Decomposing the structure description into form, function, and behavior objects facilitates both representation and reasoning. Based on the method of decomposition, a constraint classification system that facilitates both the coordination of the design and the integration constructibility issues is developed. The representation of the objects required to fully define form, function, and behavior at a typical floor is developed to demonstrate the potential efficiencies of the representation scheme.

The reasoning necessary to describe the structure function qualitatively in terms of load paths is examined in detail, and a vocabulary of functional elements and attributes capable of representing the structure function explicitly in the facility database is proposed.

Qualitative structure behavior is examined, and the classical approximate techniques that are used to model the structure during the synthesis of lateral systems are addressed. Existing methods of representing the structure form are studied to determine the level and nature of the detail required to support construction and facility management activities - as well as design.

Acknowledgments

This has been my second encounter with academic life at Stanford, the first having concluded in 1976 when I left to embrace the world of structural engineering design. On both occasions, I have been challenged, stimulated, and enriched by the environment and by the people with whom I have had the pleasure of associating. Each of them has contributed to the successful completion of this work. A special note of appreciation is due to Professor Jim Gere and his wife Janice, who graciously opened their home to me on my return to Stanford and helped me readjust to academic life.

I left in 1976 with the intention of returning at a later date when I would have the knowledge and experience necessary to put my research in context. The credit for the knowledge that I had to offer when I left goes to the people who prepared me for my work to begin with, most notably my advisor in 1976, Professor Helmut Krawinkler, as well as Professors Gere and Weaver.

The credit for the experience I have to offer now goes to a group of dedicated professionals with whom I worked over the intervening years, who taught me the meaning of professionalism, and who never failed to unselfishly share with me their accumulated knowledge and wisdom. Two colleagues who contributed immeasurably to my education in practice are Robert L. Koons and Roy P. Keslin. I owe a debt of gratitude also to Bob Fowler and Doug Rutledge who, in spite of their diverse backgrounds, both shared with me a vision of the future in which designers and builders, supported by an automated design system, once again work in concert to achieve great things. Any contribution I am able to make is also the contribution of these four individuals.

In my second incarnation as a student, I had the pleasure of being re-educated by another generation of excellent faculty members at Stanford. Among those who helped me adjust to the current state of technology are Professor Craig Howard, who open my eyes to languages other than FORTRAN, and John Kunz, whose enthusiasm and insights were inspirational and invaluable in helping me to focus my efforts.

I owe a special debt of gratitude to Deepak Jain, a fellow doctoral candidate who humored me when I interrupted his studious pursuit of knowledge with unsolicited and long winded soliloquies about the philosophy of design and the state of the profession. We had a symbiotic relationship in which I passed along what knowledge I could, and Deepak tutored me in the areas of computer science, knowledge based systems, and writing style. Deepak also offered insightful and objective commentary on the evolving framework.

The members of my reading committee guided me and offered encouragement throughout the duration of my candidacy. Professor Ray Levitt introduced me to knowledge-based systems in the first academic quarter after I returned and continued to act as a valuable knowledge resource thereafter. The enthusiasm of Professor Kincho Law, his knowledge of both the potential and the limitations of the technology, and his willingness to look beyond today's technology for the solution to tomorrow's problems were a needed source of both guidance and encouragement to me.

I have known Professor Helmut Krawinkler since my odyssey began in 1974. During that time he has evolved into an eminent engineer and educator, titles that he would not be comfortable with, but which suit him well. He has always accused me of being idealistic, but I have only been following his lead. He has provided me with guidance on technical and professional matters throughout my career. Professor Krawinkler's interests have always focused on the education of his students and the advancement of engineering knowledge; he provides an outstanding example those of us who have had the privilege of knowing him. Without his encouragement I would not have kept the promise I made to myself in 1976 to return and without his help I could not have completed this work. I shall continue to follow his lead, I know of no better role model.

The financial support for the work was provided through the Center for Integrated Facilities Engineering (CIFE) at Stanford, which is continuing the effort to develop better ways to design and build facilities. The Center's support is gratefully acknowledged. I wish to express my appreciation to Paul Teicholz for his continuing work in leading the effort.

The spiritual and emotional support of my family, particularly from my mother and my sister Agnes, contributed immensely to my efforts.

Finally, I wish to thank my wife, Marlene, whose love, patience, encouragement, and faith in me have given my life a richness beyond wealth during our 20 years together, and my daughters, Jenifer and Jessika, who show me how to look at the world around me with the wonder of a child. Marlene, Jessika, and Jenifer cheerfully left the trappings of middle class suburbia and returned with me to the life of a student at Stanford. It is inspiring to watch Jessika and Jenifer grow as they discover the wealth of knowledge in the world that is theirs for the taking and the diversity of culture in the world that is theirs to enjoy.

Contents

List Of Figures

List Of Tables

1
Introduction

1.1 Objectives

The Architecture/Engineering/Construction (AEC) industry in the United States is characterized by numerous small contracting specialists in both design and construction who collaborate on a given project. The distribution of the tasks among many participants who are isolated geographically and have different technical backgrounds results in redundancy, inefficiency, omissions, and errors. Fragmentation in the AEC industry in the U.S. has resulted in a decrease in the competitiveness, quality, and economy in the industry.

The Center for Integrated Facilities Engineering (CIFE) at Stanford University is committed to finding a way to decrease the cost of constructed facilities while increasing their value through integration of the knowledge and the efforts of the participants in the facility life cycle. One proposition is that integration can be aided by means of state of the art computer technologies including artificial intelligence (AI), computer aided design and drafting (CADD), computer aided engineering (CAE), computer aided manufacturing (CAM), and database management systems (DBMS). A method of testing this hypothesis is to develop an integrated software environment in which the essential reasoning underlying the processes and the relationships between the subprocesses are captured. The Integrated Structural Design (ISD) environment described herein is envisioned as one element in such a system.

Continuing advancements in both computing power and software are likely to change our concepts of analytical techniques and data. In addition to the ongoing interest in algorithmic processing of numeric data there is increasing interest in the research community in the semantics, or meaning, of the data and the reasoning process used to manipulate abstract concepts to produce the numeric data. Future software tools are expected to have a firm foundation in the abstract concepts that form the basis for the reasoning in a particular domain. Just as the required form of numerical data is highly dependent on the type and form of algorithmic computations, the required form of the semantic data is dependent on the type and form of the reasoning processes. Therefore, it is essential that the reasoning processes and, to a certain extent, the form of the analytical tools that model those processes, be defined prior to proceeding with development of the databases that include the semantic data.

The focus of the research described in this dissertation is the formal definition of the reasoning concepts that are required to support an Integrated Structural Design (ISD) Knowledge-Based System (KBS) from the perspective of current design practice and in the context of the facility life cycle processes. Accordingly, the specific objectives of this research are as follows:

1) Develop a formal description of the processes involved in the life cycle of a building project and identify the relationships among the various participants;
2) In the context of the processes in (1), define a method of decomposing the reasoning used in structural design into modules that could readily be automated;
3) Survey the state-of-the-art in AI techniques in general, and the application of those techniques in the structural engineering domain to determine which techniques are most applicable to the processes described in (1);
4) Based on the relationships among the various participants in the life cycle processes, propose a conceptual architecture capable of modelling the reasoning involved;
5) Develop a formal approach to the qualitative reasoning used in the conceptual structural design process that is capable of capturing the interrelations of that process with the other processes in the building life cycle;
6) Propose a representation scheme capable of capturing the underlying concepts used in reasoning in structural design.

1.2 Scope

The emphasis in this dissertation is on the qualitative reasoning used in the conceptual design of structures for high rise commercial office buildings. This reasoning involves the interaction of the structural subsystem with the other building subsystems, with construction activities, and with facility management considerations. The scope includes qualitative reasoning about the *function*, *behavior*, and *form* of the structure and extends to the reasoning strategies that are commonly employed in synthesizing structural solutions for this type of facility. On a qualitative level, many of the concepts that must be represented apply equally to structures constructed of materials other than concrete or steel.

The scope, although focusing on a specific type of building, i.e, high rise commercial office buildings, includes the essential characteristics of the reasoning process that would be used for other types of facilities. The concepts of form, function, and behavior, which are taken from model based reasoning approaches [12], apply to all structures as does the constraint classification system presented in Chapter 6. Many of the primitive functional objects that are described in Chapter 8 (i.e., beam, column, vertical, diagonal, horizontal) apply to other types of facilities. Structure behavior, which is governed by constraints arising from first principles, is the same for a specific type of conceptual object, regardless of the type of facility it is used in.

In the context of other types of facilities, the constraints arising from exogenous systems and the manner in which those constraints are used to organize the solution process will be different, but the concept of nested, mutually constrained systems presented in Chapter 4 applies as does the form of the system architecture presented at the end of Chapter 5. The strategic control knowledge used to manipulate the structural design process for high rise office buildings is based on a combination of first principle knowledge and heuristic knowledge that is unique to this type of facility and is not generally applicable to other facility types.

There has been much discussion, both in the literature and in practice, regarding the effect the litigious environment has had on fragmentation in the AEC industry. It is recognized that liability considerations have contributed significantly to fragmentation and cannot be ignored in the final implementation of design systems. Nevertheless the approach in this dissertation is to develop a system that would function well in the absence of liability constraints. This discussion concentrates on the tasks that must be performed by various entities and the communications that must occur between those entities independent of legal relationships among the entities.

1.3 Organization

The objectives of this work and the scope of the research have been discussed in this chapter. The next three chapters establish a framework within which the concept of integrated structural design will be explored. Chapter 2 briefly addresses the historical evolution of the design/construct process to gain some understanding of the nature and origins of the fragmentation in the industry that, together with the need to formalize the qualitative reasoning in the process, provides the motivation for this work. The latter part of the chapter presents some concepts which are used throughout the dissertation.

Chapters 3 and 4 focus on the details of the reasoning involved in the facility life cycle process from program development through facility management in order to develop a design perspective that is consistent with current practice. In Chapter 3 the life cycle reasoning is decomposed into chronological phases and the subgoals during each phase are examined. Chapter 4 examines the domain dependent reasoning activities during each phase, i.e., architectural, structural, mechanical, etc., in order to develop a control strategy.

Chapter 5 describes various approaches to reasoning in an automated environment including rule based, model based, and constraint based reasoning. A brief overview of previously developed knowledge based systems in the domain of structural engineering is presented. The last part of Chapter 5 presents a conceptual architecture for an integrated design environment that reflects the decomposition of the life cycle processes in Chapters 3 and 4.

In Chapter 6, the background presented in Chapters 3, 4, and 5 is used to develop a model based approach to reasoning with constraints in the domain of structural engineering. Model based reasoning offers a method of studying and controlling structure behavior through constraint manipulation and provides the basis for the constraint classification system proposed in Chapter 6. The classification system is keyed to the decomposition of the structure description into conceptual objects representing form, function, and behavior. Constraints on the form, function, and behavior originating in exogenous systems, i.e., architectural, mechanical, construction, are summarized briefly.

Chapter 7 gives an overview of the representation of a typical floor structure for a high rise office building in terms of conceptual objects corresponding to function, form, and behavior for lateral and gravity systems.

Chapter 8 proposes the use of load paths (patterns formed by the structure topology) to describe the structure function, and the load key paradigm as a method of organizing and recording the loads that constrain the structure function. The proposed representation facilitates the automatic formulation of load constraints based on the architectural and M.E.P. system descriptions. The conceptual objects and attributes that are needed to represent the structure function are defined in Chapter 8 by examining the qualitative reasoning required to define the load paths.

Chapter 9 introduces the conceptual objects required to represent the behavior of simple gravity load path elements and introduces classical methods of approximate analysis and design that are used in the synthesis of lateral systems.

Chapter 10 presents brief examples of information about the form[1] of steel and concrete structural systems illustrating the detail that is required to adequately support all the activities in the facility life cycle.

The strategic reasoning that is used in performing the control functions within the structural design process is summarized in Chapter 11.

Chapter 12 discusses the implications of this research for the architecture required for ISD and possible extensions of the research.

The appendices provide related information that may be of interest to some readers. Appendix A contains a more detailed discussion of the exogenous systems and their relationships to the form, function, and behavior of the structure. Appendix B presents the results of a schematic design of a 59 story steel building prepared using the methods described in the body of the dissertation. Appendix C contains a comprehensive tabulation of the gravity function objects required to represent the typical floor presented in Chapter 7 along with the corresponding behavior, form, and lateral function objects. Appendix D contains additional topics in the area of structure function including tabular representation of lateral loads and rules that test for complete load paths in frames that resist lateral loads.

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[1] The term 'form' is used throughout to mean the physical charactersitics of the system in lieu of the term 'structure' to avoid the awkward semantics of the phrase 'structure of the structure.'

2

Preface

2.1 A Historical Perspective

The process of designing and constructing Civil Engineering structures, from dams and power plants to commercial office buildings, has evolved during the past century from simple systems controlled by relatively few individuals to extremely complex systems controlled by numerous individuals working for a variety of contracting entities.

The fragmentation of what ideally should be one continuous process, i.e., conceive/design/build/operate, was a natural result of the evolution. Hardly more than a century ago, buildings were constructed exclusively of brick, stone, or wood; and design and construction occurred simultaneously. The largest buildings were cathedrals that took literally centuries to build. Since that time we have discovered the economies of mass producing steel and cement, designing systems composed of both materials, and prefabricating many elements of the final building. The technologies that led to the industrial revolution also made it possible to construct buildings on a scale never seen previously and society's demand for larger and more complex buildings kept pace with the evolving technology.

In order to accommodate the multiplying demands of increased complexity and decreased time, the AEC industry responded with specialization. A case in point is the evolution of the method of designing and constructing structural steel. Projects that were built around the turn of the century were designed by architects who drew, in great detail, all of the architectural elements, but only the general structural concept. A structural fabricator would then design and build the structural steel system. Today the process involves an architect - who defines the building aesthetics and functional space layout, a structural engineer - who defines the member sizes and layout, a detailer - who refines the information to the level of detail needed for fabrication, a fabricator - who purchases and fabricates the steel, and an erector - who puts the steel in place. Similar delivery methods are used for all other elements of the structural system, as well as for the architectural, mechanical, electrical, and plumbing systems.

Specialization, while it enabled the industry to cope with more complexity, brought with it inefficiencies. The methods of communication among the entities involved have not progressed significantly since the beginning of the last century. Those methods consist primarily of drawings and written specifications distributed via paper copies. The inefficiency of such a system for communicating data regarding the physical structure is obvious. More subtle, but no less important, is the loss of continuity in the conceptual thinking. Early 'master builders' controlled all aspects of the project and were, therefore, able to anticipate downstream requirements and reflect these in the design. Because of specialization, the knowledge needed to implement this anticipation is now distributed among numerous parties. The lack of efficient communication tools and the litigious climate in the U.S. reinforce the isolation and fragmentation in the industry. In order to approach the efficiency of earlier builders, the AEC industry must find a way to formalize and organize the vast amount of knowledge and experience that are required to design and build a modern structure and make that knowledge available in an integrated design environment.

Computer technology, while providing the professions with powerful analytical tools to aid in the technical aspects of the design, has not changed the need for specialization, nor has it changed the methods of communicating the results of the design process. Indeed, programs have been developed to perform even more specialized tasks, reinforcing the trend toward specialization. In structural engineering, algorithmic programs have equipped us to analyze the most complex building structures. However, conceiving the structural system to be analyzed and conceiving the corresponding computer model remain the responsibility of the human engineer, and, unfortunately, even the most powerful analysis tools are useless if the conceptual model is incorrect. Jim Wooten, an engineer with a Midwest fabricator, identified the essence of the challenge that now faces us when he noted facetiously "The computer renders obsolete the necessity of rationalizing and simplifying problems - or even understanding them" [25]. The emphasis on the quantitative aspects of problem solving in the recent past has resulted in a deemphasis of the qualitative reasoning that leads to innovative and responsive structural solutions. Time that could be spent studying the concepts and developing innovative solutions is instead spent processing the mountains of new data generated by our sophisticated analysis tools.

The historical perspective shows that specialization was required in response to the increasing demands made of the AEC industry. It also shows that the specialization served its purpose, but that it increased data communication requirements, while reducing broad based learning and the ability to anticipate downstream requirements. The advent of the computer brought increased emphasis on numerical methods which resulted in less emphasis on the qualitative aspects of problem solving, aspects that characterize anticipation and coordination of the requirements of the various participants in the life cycle processes.

2.2 Motivation

Engineering has always been a combination of art and science. The scientific aspects of structural engineering involve the physical laws that govern both the loads to which the structure responds and the response itself. The art of structural engineering is in the manipulation of the constraints over which the engineer has control within the context of the constraints imposed by physical laws and the project requirements to yield a system that is economical, buildable, *and that behaves in accordance with the intent of the designer.*

Since the advent of computers, much effort has been expended in programming them to solve the mathematical equations resulting from the physical laws that govern the behavior of structural systems. Our ability to analyze complex structures has increased tremendously. Qualitative reasoning that is used to manipulate the constraints, rather than being less important after the development of powerful analytical tools is more important. It is important that our ability to reason conceptually about complex structural systems keep pace with our ability to verify the accuracy of the concepts with the analytical tools. The promise of artificial intelligence and knowledge based systems is that we can start to incorporate the art as well as the science in our design tools. The challenge is that we must find a way to identify, formalize, and automate those parts of the design process that still rely largely on human intuition.

Much of the reasoning in structural engineering involves the visualization of basic concepts like free body diagrams and load paths and requires the manipulation of patterns, activities that are intuitive to humans. It is necessary to distill this reasoning down to its essence, if possible, in order to identify the concepts necessary to model the reasoning in an automated environment. This process is also necessary to identify the semantic data that needs to be included in the database for an automated environment that only *supports* the human reasoning.

While the art of engineering is in the manipulation of the constraints to synthesize an efficient and elegant design solution, the craft is in the communication of the results of those efforts in the form of a graphical representation. A rich vocabulary of graphical objects has evolved over time for this purpose. Communication between machines - and between man and machine - is still of utmost importance to the process. The representation scheme developed for ISD should lend itself well to both purposes.

2.3 Concepts

A number of concepts emerge as fundamental to the reasoning involved in facility life cycle processes. Although some of the terms are borrowed from the field of AI, the concepts expressed in the definitions below are just as useful in describing the life cycle processes as they currently exist.

Attributes: Attributes are data that describe an object. Attributes may be descriptive in nature, as in the case of the depth and weight of a beam, or may express relationships to other objects, as in the 'supported' relation for elements of the load paths discussed in Chapter 8.

Behavior: Behavior is the response of something to specific circumstances. In the context of structural design, behavior refers to the response a structural element or system exhibits while performing its function. Behavior includes the internal stresses and strains for an element, internal forces and deflections for a system, and external reactions deflections for both systems and elements.[1] Behavior is dictated by physical laws depends on the context, i.e., the loads and topology.

Constraint: A constraint restricts a certain attribute of the facility or of a component of the facility to a specific value or range of values. Constraints may express the restriction

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[1] A general approach would recognize other behaviors, among them durability and ductility, although they are not addressed herein.

in terms of relationships between attributes of the same object or between the attributes of different objects. Examples of items restricted by constraints are the space requirements and intended functions of the facility, the ceiling height, the mechanical duct sizes, the structural depth, and the construction sequence for the facility. Constraints do not have to be quantitative in nature, they can also include restrictions on the color, shape, or 'quality' of the features of the facility. Constraints are indispensable in organizing the solution process and in communicating between subprocesses.

Constraint Formulation: There are many potential relationships between the attributes of the elements of a facility that can be expressed as constraints. Constraint formulation is the process of determining which constraints apply in a particular context and defining the appropriate ranges of values for those constraints. The equation expressing the moment at the end of a member as a function of the corresponding rotation is a constraint relating behavior to form constraints (member geometry and material properties) and function constraints (member loads).

Constraint Propagation: Constraint Propagation is the process of communicating a particular constraint to all processes that are affected by the constraint. Constraint propagation may take the form of simply adding the constraint to an object description or it may involve reformulating the constraint in the vocabulary of the particular process that it affects. In the example of the member end rotation, the presence of rotations at one end of the member influences the moments and rotations at the other end of the member. Communicating the value of the rotation and evaluating its effect is a form of constraint propagation. In a different context, constraint propagation involves communicating design decisions as constraints and evaluating the effect of the constraints on the *Cost / Value* ratio.

Constraint Satisfaction: Constraint satisfaction involves selecting components whose attributes satisfy the constraint set once suitable values - or ranges of values - have been chosen for all the constraints. Of all the possible components, those that result in the least *Cost / Value* are selected. In design, constraint formulation, propagation, and satisfaction take place on successively more detailed levels. In the aforementioned structural analysis example, setting a member end moment equal to that dictated by the behavior constraints relating moment and rotation is a form of constraint satisfaction.

Constructibility Constraint: Constructibility constraints arise from the consideration of the resources required to build the facility. These resources may take the form of knowledge (available technology), labor (experience in applying the technology), and material (availability and cost). The availability of these resources is dependent on both time and location. Constructibility constraints determine the most economical material for the facility, the type of structural system (arrangement and geometry) that is most economical given the selected material, and the form of the details that yield the greatest economy for the selected system. In this discussion, it is assumed that the effect of constructibility constraints can be reduced to a variation in cost between the various feasible options.[2] Implicit in this approach is that cost is a measure of constructibility and that all elements of construction cost can be expressed as constructibility constraints.

Cost: Cost includes the cost of design, construction, and operation of the facility. Cost may also include a probabilistic evaluation of the chances of failure as a function of a characteristic of the facility, e.g., the intensity of the design loads. Construction costs, which may include the costs associated with the risk of using untested construction methods or materials (related to Constructibility Constraint above), form the greatest part of short term costs. The costs of operating the facility after construction form, by far, the largest part of the life cycle costs.

Cost / Value Ratio: The *Cost / Value* ratio is the ratio of the estimated cost to the perceived value of the facility. The objective of the design process is to decrease the *Cost / Value* ratio as the design evolves. Quite often the cost and the value include intangible components that cannot be quantified and the assessment of the *Cost / Value* relationship requires qualitative judgements on the part of the owner of the facility.

Entities: Specialization has resulted in the evolution of entities (architect, engineer, contractor, etc.) that each perform a set of related tasks. It is convenient and natural to adopt the concept of entity to describe an agent that performs groups of related tasks in the life cycle processes. However, this does not imply any particular legal status (i.e, separate company) of the agents, nor does it imply that the agents are necessar-

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[2] Objects that cannot be constructed can be assigned an 'infinite' - or very large - cost to avoid the necessity of having to classify them based on heuristic rules that can become obsolete. Items that are unavailable or not constructible now may become constructible or available in the future.

ily human. The concept of entities provides a natural method of decomposing the design problem into weakly linked problems while serving to highlight boundaries that represent potential barriers to communication.

First Principles: First principles are physical laws that govern some aspect of the behavior of an element or define some relationship between attributes. First principles are invariant with the method of reasoning used. The definition is extended in this discussion to include the relationship between the attributes of an object and its cost, even though this is not, in the strictest sense, a first principle. Quite often heuristic knowledge involves the anticipation of certain results that would be obtained if first principles were applied and the heuristic can, therefore, be validated using first principles.

Form: In the context of the structural systems representation presented herein, form is the detailed geometric and material description of the primitive elements composing the structure. As an example, the form description of a steel beam includes its geometric section properties, the ASTM designation of the material, the precise fabricated length, and the precise location and size of all holes, copes, stiffeners, etc. In other words, the form description of the structure contains all the information necessary to order and fabricate a component, information that is currently contained on shop drawings.

Function: The dictionary offers several definitions of function, two of which are used herein:

1) An assigned duty or activity
2) The natural or proper action for which a mechanism is employed, i.e., the purpose for which an object exists is its function.

In the context of life cycle processes, the first definition is used. The life cycle processes are decomposed into domains encompassing groups of related tasks according to their functional classification (architectural, structural, construction, etc.)

In the context of model based reasoning, the second definition is used. The function of the structure is to carry all design loads from their points of origin to the ground. The structure is composed of elements whose function is to carry a specific type of load (or loads) between specific points in space.

Heuristic Knowledge: Heuristic knowledge consists of 'rules of thumb' that are derived from experience. A solution of a circular constraint set can be obtained by assuming values for all but one of the constraints based on heuristic knowledge and allowing the remaining constraint to be dependent. Heuristic knowledge is used to generate candidate solutions to the conceptual design problem.

Load Path: The load path for an element of load consists of the specific functional objects that carry the load, listed in the order in which they carry it, from its point of origin to the ground.

Mutual Constraints: Mutual constraints arise when the values of certain attributes constrain each other. The story height, ceiling height, mechanical depth, and structural depth form a mutually constrained grouping in high rise office buildings. The mutual constraint takes the form of the relation:

$A+B+C=D$ Where:

A is ceiling height
B is mechanical depth
C is structural depth
D is the story height

In general, there is a range of acceptable values for the independent variables that can be expressed with a constraint of the form:

$$W1 < A < W2$$
$$X1 < B < X2$$
$$Y1 < C < Y2$$
$$Z1 < D < Z2$$

The problem statement, in the form of the above constraint set, may be ambiguous since there may be no solution, one solution, or multiple solutions. However, within the solution space, which in building design consists of a finite number of points corresponding to combinations of discrete values satisfying the constraint set, the objective is to find the set of values that results in the minimum *Cost / Value* ratio. This results in three additional constraints that can be written as:

$$\text{Cost} = f(A,B,C,D)$$
$$\text{Value} = g(A,B,C,D)$$
$$\text{MIN}(\text{Cost}/\text{Value})$$

The addition of these constraints normally makes it possible to identify a unique solution from among the potential solutions. Since cost is derived from constructibility constraints and from facility management considerations and the value is derived from owner constraints, this approach explicitly integrates the life cycle process considerations into the design.

In mutually constrained systems, the constraint set is 'circular' and there is no *a priori* order in which to select the variables. While there are optimum values for each of the constraints with respect to the subsystem involved, the optimum *set* of constraints may not involve these local optima. As an example, a beam depth that results in the minimum *Cost / Value* ratio considering the structure in isolation may not result in the minimum *Cost / Value* ratio for the facility as a whole. The mutual constraints are usually general in nature. They describe the relationships among the attributes of classes of objects in a system. Once the optimum values have been determined, those values are used as specific constraints applied to all of the elements in the classes described by the general constraints.

Phase: The dictionary [16] defines a phase as "a distinct stage of development" As the design of a facility evolves over time, the tasks performed by the entities change.[3] The concept of phases is used to describe the chronological sequence of activities during the facility life cycle.

Performance Performance and behavior are usually synonymous. In this dissertation, performance is treated as a behavior goal. Behavior is dictated by physical laws while performance is often dictated by the building code. Constraints from both sources must be satisfied, so only the loads or the member properties can be varied to make performance and behavior coincide.

Process: The dictionary defines a process as "a system of operations in the production of something" or "a series of actions, changes, or functions that bring about an end or a result." For the purposes of this discussion, a process is defined as a set of tasks performed by an entity in order to alter the state of the world through the creation of products. In this dissertation we describe the facility life cycle processes in terms of tasks performed by various entities and products organized by phase.

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[3] On a detailed level, the activities of the entity and the decisions being made are dependent on the phase of the project. However, the classification of those activities (architectural, structural, etc.) does not change.

Structure Topology: Structure topology is the geometric arrangement of functional structural elements (e.g., beams, columns, etc.) in space that forms the system of load paths for the facility.

Value: One component of value that can be compared directly with costs is the monetary benefit derived from the ownership and operation of a facility, whether it is a factory or an office building. However, value can also include intangible benefits that result from the construction of the facility such as the prestige or the social benefits that result from its construction. Value may be reduced by the risks associated with owning the facility. Decisions regarding value are made by the owner of the facility.

3

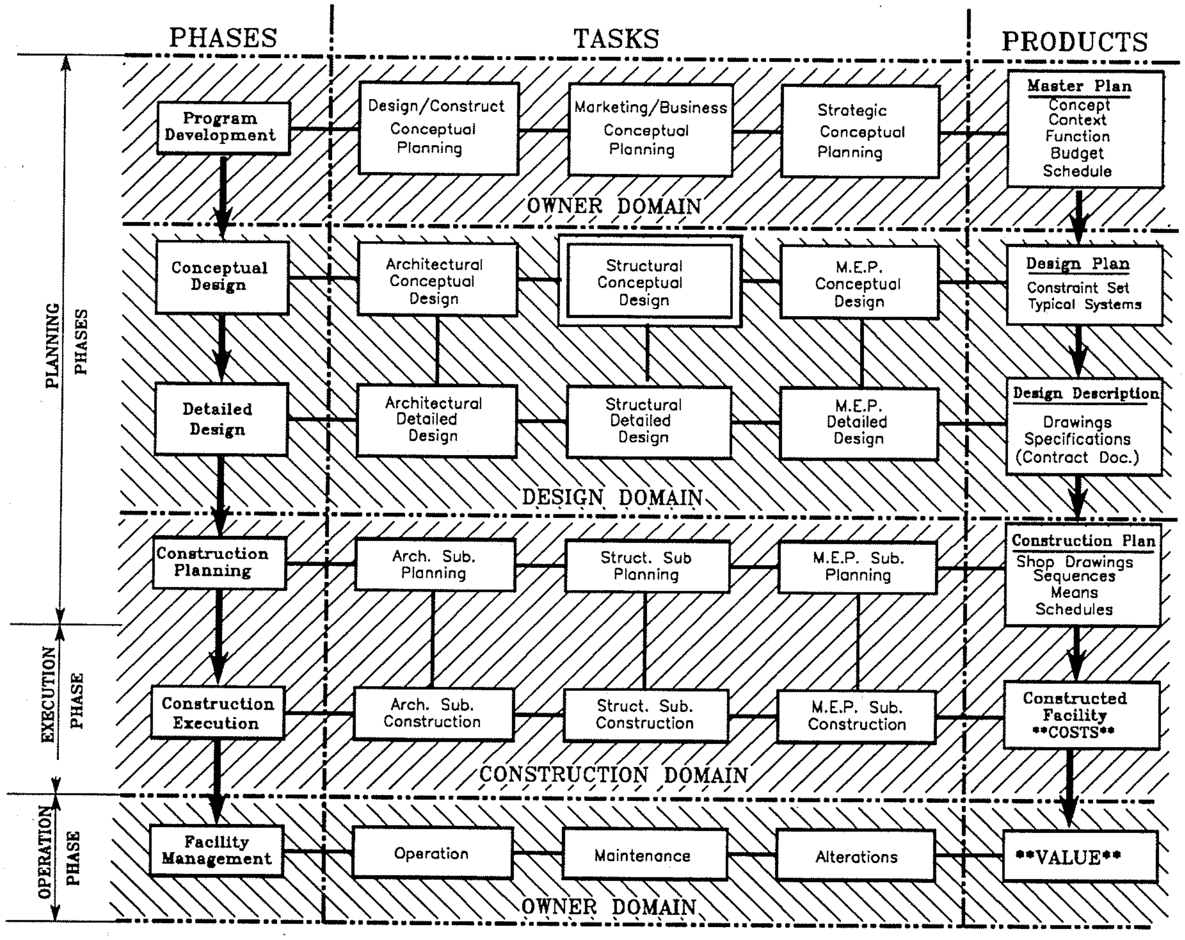
Facility Life Cycle Phases

3.1 Introduction

The reasoning that occurs during a facility life cycle process can be decomposed into weakly linked problem domains such as architectural reasoning, structural reasoning, etc. In general, the detailed reasoning and the decisions that are made within a domain change with time, leading to a chronological sequencing of the process into phases resulting in another set of weakly linked problem domains. The nature of the reasoning is determined by the intersection of the phase and domain boundaries. This chapter examines the phases of the life cycle process while the next chapter examines the reasoning that occurs within the domains. Studying the life cycle phases reveals how the constraint set that describes the facility evolves with time.

The major chronological phases of the facility life cycle, as indicated in Figure 3.1, are *Program Development, Design, Construction*, and *Facility Management*. The processes shown in the figure are arranged in rough chronological sequence with the earliest at the top of the diagram. *Design* is further divided into *Conceptual Design* and *Detailed Design* while *Construction* is divided into *Construction Planning* and *Construction Execution*. The first four phases which can be broadly classified as planning are followed by an execution phase, and, finally, an operation phase as shown on the far left side of Figure 3.1.

During the planning phases constraints are formulated, propagated, and satisfied iteratively until the downstream activities that take place during the construction execution and facility management phases become highly constrained. Conceptually, the constraint set becomes more detailed and comprehensive as the process proceeds from the top to the bottom on Figure 3.1. The project *Costs* (aside from the relatively minor costs of the planning activities themselves) result from the activities in the construction execution phase, while the *Value* of the facility results from the activities in the facility management phase[1]. Since the decisions that are made during the planning process constrain the *Cost*/*Value* ratio, the importance of planning is growing in proportion to the complexity of projects.



→ Indicates direction of increasing time, primary direction of information flow, and increasing completeness of constraint set.

▭ Indicates perspective and focus of this dissertation

Figure 3.1 - Life Cycle Processes

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[1] A majority of the life cycle costs also occur during the facility management phase. However, constraints are formulated during the program development phase in such a way as to assure (as far as possible) that the net result of the facility management phase is value.

The facility life cycle processes are hierarchical in nature since the product of each process forms the initial constraint set for the next process. The processes are also circular in nature since optimizing *Cost/Value* involves anticipating and incorporating downstream considerations. Experience gained from operating facilities becomes part of the initial input to the program development phase and is used to develop high level constraints on the 'Master Plan.' Based on the 'Master Plan', a fairly detailed description of *what* needs to be built is developed in the design phase. Based on the constraints described in the documents produced in the design phase, the construction planning phase further elaborates on *what* is to be built on shop drawings and plans *how* it is to be built, i.e., means, methods, sequences, and schedules.

The constraints that are formulated during the planning phases of the life cycle are abstract since they consist of concepts that *represent* the physical objects that are to be built. The objective of the planning phases of the facility life cycle is to increase the likelihood that the hard constraints being put in place during the construction execution phase are compatible with the function of the facility during the facility management phase. During the design portion of the planning phases, this overall goal of the planning processes is broken down into a series of subgoals.

It should be kept in mind that in modern construction projects, it is quite common for the phases to run in parallel. While this is always true of the *Construction Planning* and *Construction Execution* phases, it may also be true of the *Detailed Design, Construction Planning*, and *Construction Execution* phases, an arrangement known as the 'fast track' approach. The following sections contain a general description of the types of constraints that are formulated during each of the life cycle phases.

3.2 Program Development Phase

Commercial office building projects are initiated when there is a perceived need or opportunity that is normally characterized by economic considerations. The owner undertakes studies to determine whether the Costs of constructing and operating the facility are justified by the potential *Value* of the facility. The subgoal of the program development phase is to define global project objectives and attributes that make those objectives attainable.

It is common to develop the geometry of the floor plates and the massing during this phase. The floor plate areas depend on the functional space requirements at each floor while massing refers to the three dimensional volume that results from the stacking of the floor plates vertically. These attributes, along with general definitions of architectural finish materials are used in the evaluation of costs during this phase. Instead of explicitly addressing mechanical and structural considerations, the average costs and schedules for similar types of buildings in the same geographic area may used in the *Cost* evaluation. Information generated during program development includes the project scope, location, function(s), and construction time frame. The location of the project usually dictates the applicable building code which, in turn, defines many of the hard constraints on the project such as minimum design loads, fire and life safety requirements, energy efficiency requirements, and minimum mechanical, electrical, and plumbing requirements for various occupancies (building functions).

The owner's program may include specific constraints that are more stringent than code requirements. Examples of structural constraints that are sometimes dictated by the owner are heavier design loads to accommodate libraries or filing loads or constraints and the vibration characteristics of the floors.[2] Constraints on the M.E.P. systems that are imposed by the owner may include additional electrical loads to accommodate a higher density of electronic hardware and more cooling or heating capacity than would be required by code. Constraints on the architectural systems that originate with the owner include the type and cost of the materials that will be used for finishes throughout the facility. Owner imposed constraints usually have to do with a desired level of perceived 'quality' or a required utility.

Construction costs associated with various methods and materials, expressed as constructibility constraints, can usually be determined once the geographic location of the project is known. The preferred systems for the superstructure, foundation and mechanical systems can be derived from constructibility constraints. While these data do not dictate a solution, they provide a starting point in synthesizing the potential solutions. In general, it is not possible to predict precisely which systems will be the most economical for a given facility based on heuristic rules since the relative costs of the various possible systems are constantly changing due to market fluctuations and the special conditions inherent in every project may alter the comparison.

The product of the program development phase is a set of constraints that, if satisfied, will result in a project of some specified value. The formal documentation of this constraint

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[2] Building codes typically do not address vibration issues directly.

set is called a *Master Plan.*

3.2.1 Cost/Value Function

Life-cycle costs include both the hard construction costs and the cost of operating the building after construction. The building operation costs are by far the largest component of the facility life cycle costs. Decisions regarding the viability of a design ultimately involve a *Cost / Value* analysis where the costs are as defined above and the value is determined cooperatively by the owner and architect entities.

Ideally, project viability should be based on a *Life Cycle Cost / Value* analysis. However, long term estimates of cost and value involve variables that are beyond the control of the participants in the design/construction process. In order to minimize the risk involved, it is common for decisions on project viability to be made based on the *Short Term Cost / Value* analyses, which involve parameters over which the participants have direct control, and in which the hard construction costs play a pivotal role.

It is important to understand the issue of *Cost / Value,* since this is the basis for decisions made during the design process. Since the objective of the design entities is to describe a system that satisfies the functional constraints of the owner while minimizing *Cost / Value*, it seems obvious that an efficient process would make use of the *Construction Entity* as a resource for cost control during design. In the following discussion of the design process, the term *constructibility* is used to denote parameters that are constrained by the construction process. Most often, the constraint is evaluated in terms of cost.

3.3 Design Phase

The goal of the design phases is to formulate more detailed constraint sets for the major systems such that the Master Plan constraints are satisfied and the corresponding cost is minimized. Since satisfying the Master Plan constraints results in the desired value, minimizing cost at this point minimizes *Cost / Value.*

The design process has been described as a spiral that proceeds from the abstract to the particular over time [21]. In this hierarchical approach decisions regarding the specific values of the constraints are made through iterative cycles of synthesis, analysis, and evaluation. Quite often, heuristic rules are used to synthesize potential solutions, while first principles are used to analyze and evaluate the potential solutions. At each stage of the process the interaction of the constraints is examined to develop the optimum constraint set. Once all the constraints have been formulated, they are explicitly satisfied during detailed design. As with many engineering problems, a significant amount of creative effort is expended in defining the problem, which simplifies the subsequent problem solution.

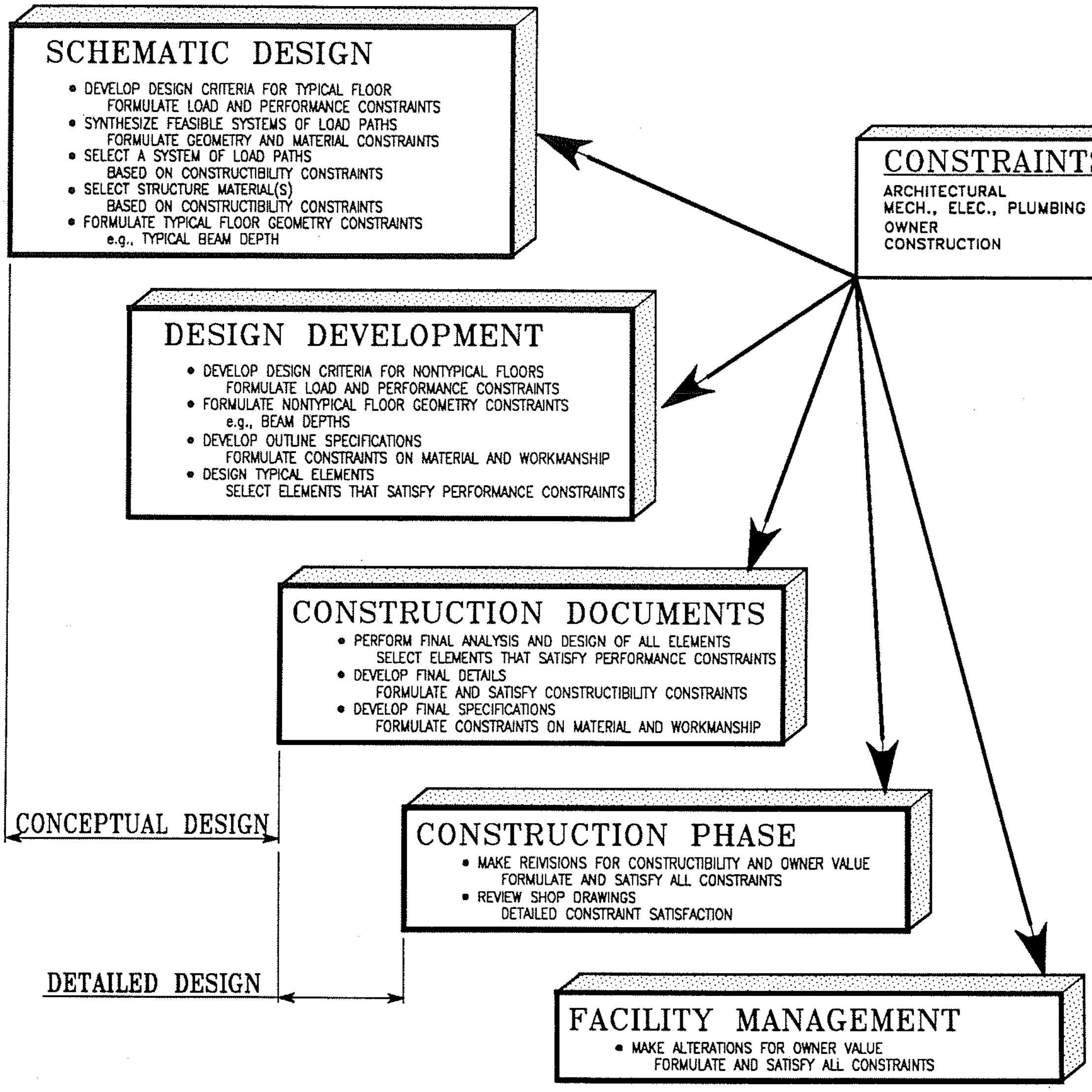

Figure 3.2 Structural Domain Activities by Phase

The design phases shown in Figure 3.1 are conceptual design and detailed design. In practice, conceptual design is usually divided into 'Schematic Design' (SD) and 'Design Development' (DD) while detailed design is termed 'Construction (or Contract) Documents' (CD). Figure 3.2 gives an overview of the chronological breakdown of design activities in the structural engineering domain. The activities for other design entities are similar to these.

3.3.1 Conceptual Design

Conceptual design can be thought of as planning for the design, a two part process that consists of first formulating constraints regarding system parameters at the typical floor and then adapting the typical systems to accommodate the conditions at nontypical floors. Since the building subsystems form a mutually constrained system, the process is iterative and involves formulating soft constraints in the context of the hard constraints. Hard constraints are constraints that cannot be altered such as the code mandated design loads while soft constraints are those that may be modified by the design process such as member arrangement, sizes, and materials.

3.3.1.1 Schematic Design

The goals during the schematic design (SD) phase are to verify the accuracy of the budgets and schedules used in the master plan and to reduce the choices for the major building subsystems to one 'best' choice for each, recognizing the interdependence of these systems. During schematic design, the subsystem studies normally address typical conditions since it is assumed that the most economical systems for the typical conditions are also the most economical systems for the building as a whole. Special features may be studied for the purpose of deciding between two otherwise equally desirable solutions.

In addition to the major entities of architect, structural engineer, and M.E.P. engineer, there may be specialists such as geotechnical engineers and elevator consultants whose task is to define the constraints associated with a specific aspect of the proposed facility. The geotechnical engineer develops site specific soils information and makes recommendations as to feasible types of foundations, seismic characteristics, lateral earth pressures, swelling characteristics, etc. If the site is in an urban area, much of this information can be hypothesized from previous projects in the general vicinity with sufficient accuracy for parametric studies of the building systems.

The architect further refines the floor plans to accommodate support areas such as vertical transportation, amenities, and mechanical systems while manipulating the space, massing, and cladding materials to develop a desirable aesthetic expression for the facility. Quite often, the need for an aesthetically appealing and inviting pedestrian environment as well as requirements for parking and loading docks make the base of the building a highly sensitive and nontypical area.

The mechanical engineer develops a general description of the M.E.P. systems including the approximate space required for the mechanical systems, whether or not there will be a central plant, how many cooling towers will be required, and what type of distribution system will be used. The M.E.P. and architectural systems are mutually constrained because the heating and cooling loads are dependent on architectural attributes such as the building volume and the type of cladding while the M.E.P. space requirements may require modification of those attributes.

The structural engineer develops viable structural solutions reflecting the range of economical materials and systems in the context of the architectural and mechanical solutions. The economy of the structure is directly related to the efficiency of the system of load paths that is developed during this phase. Once the load paths are fixed, the behavior of the structure can be modified only by varying combinations of material and member properties and, within the bounds dictated by codes, it is unlikely that these variations will result in major cost efficiencies. A number of feasible systems of load paths are normally identified and a range of member and material types may be studied for each system.

The relative *Cost/Values* of the various systems are compared using approximate analytical methods to capture the salient qualitative and quantitative differences between schemes while studying a representative sample of feasible alternatives. Utilizing analytical methods that yield reasonably accurate results while maintaining the transparency of the solution facilitates parametric studies to determine the sensitivity of cost to various constraints, e.g., material type, member depths, etc. A large body of knowledge has evolved regarding these methods, which utilize a combination of heuristics and first principles to model the qualitative and quantitative behavior of the structural subsystems.

During the schematic design process some of the architectural features of the building, such as the number, size, and shape of the floors and the size and location of the core, are treated as hard constraints while others such as the structural material, the floor to floor height, the locations of columns, and the locations of mechanical rooms, may be considered soft constraints. Compatible solutions, i.e., sets of values that satisfy the mutual constraints, are generated, evaluated for cost, and presented to the owner for a final decision involving *Cost/Value.*

Constructibility constraints must be considered during the schematic design in order to accurately compare the costs of the candidate solutions. The plan dimensions of the building depend on the site size and shape and constrain construction activities by limiting the space available for support functions (construction trailers, staging, etc.). The viability of excavation influences the architectural solution for below grade space thus affecting the entire architectural solution. The cost and availability of materials for all subsystems is sensitive to local construction practice and expertise. Constructibility constraints that might be considered by the structural engineer during schematic design include the method of erecting the structure, the type of formwork to be used in the case of a concrete building, and the construction sequence for various elements. Constructibility constraints may be used to alter the form of the mutual constraints. An example is the relative cost of routing mechanical ducts through the structural beams versus installing them under the beams.

Since decisions regarding the form of the load paths are made during this phase, any impact the load paths have on the construction cost over and above the direct material costs must be considered. The load paths often have a direct impact on the construction sequence, as in the case of hangers supporting floor areas and, as a result, the 'supports' and 'supported by' relationships that are part of the load path description are important. In some cases detailed knowledge of constructibility constraints is required to accurately capture the difference between systems of load paths. For instance, a structure that consists of many short paths, such as a steel building with closely spaced columns and girders, may require less material but will increase fabrication and erection costs. In such cases, the difference between various schemes cannot be captured by using a constant unit cost based on weight.

By the end of the schematic design phase the building geometry constraints including the floor heights and column locations, and constraints on the system types, material types, element proportions, and element locations for the mechanical and structural subsystems have been formulated.

3.3.1.2 Design Development

Design development (DD) is a continuation of the conceptual design process during which the focus shifts to the non-typical conditions, where the goal is to formulate constraints on element attributes in the context of the systems selected in the schematic design phase. Examples of special conditions that are examined during this phase are the size and load requirements for elevators, the location and weights of major mechanical equipment, and the structural requirements, including vibration and acoustical considerations, for mechanical rooms and penthouses. Transfer girders at discontinuities in the system of load paths, e.g., closely spaced columns that don't extend to the ground or columns that are discontinuous because of setbacks, are addressed during DD. Constructibility issues that may impact the design during this phase include the relationships between the special conditions and the typical building systems. As an example, the top of a concrete office building may have a complex geometric shape that warrants a change in structural materials at that point. The constraints formulated during conceptual design limit the selection of components during detailed design. At the end of the design development phase a relatively complete constraint set has been formulated and the detailed constraint satisfaction through component selection can proceed.

3.3.2 Detailed Design

The goal of the detailed design phase is to develop a detailed physical description of all system components and communicate that description to the construction team. That description forms a set of hard constraints that the construction team must satisfy.

Additional constraints resulting from detailed code safety and serviceability requirements - as well as heuristic serviceability considerations - are formulated during the detailed design phase. Components whose attributes explicitly satisfy all of these constraints, as well as the general constraints on material properties and member geometry that were formulated in the previous phases, are selected. It is during this phase that conventional algorithmic programs can be used to verify the behavior predicted using classical techniques during conceptual design. All design tasks are completed and all member material and sizes that were not defined in SD or DD are specified.

There are a number of constructibility constraints that are addressed during this phase. The availability, cost, and length of time required for delivery for various architectural finish items such as cut stone is important. The same is true for vertical transportation systems such as elevators and escalators and for major pieces of mechanical equipment. Structural issues include the arrangement of reinforcing, the number and locations of size changes in concrete columns, and the maximum dimensions and weights of steel pieces that can be shipped. The sequence of construction is an important constructibility issue, particularly where there is more than one feasible method of constructing the building, as in the case of a core that can be slipformed or conventionally formed. In such cases the constructibility constraints vary between contractors according to their capabilities and the expertise of their available manpower. One strategy is to avoid overconstraining the construction planning by using constructibility constraints to identify the most likely methods of constructing the building and to develop details in such a way that none of the methods are precluded. To the maximum extent possible, the exact details of the means, methods, and sequences of construction are left to the construction planning team so that they can manipulate the constraints to produce the most efficient construction process.

When a complete description of the system components is not provided, as, for instance, in the case of curtain wall assemblies or design-build mechanical systems, then the design team must formulate a comprehensive set of constraints, contained in a performance specification, that will assure that the project objectives are met. Rather than constraining the physical characteristics of such a system directly, a performance specification constrains the function and performance of the system, allowing the construction team to select the most economical method of satisfying those constraints. A performance specification is an example of constraint propagation across both phase and domain boundaries. When items are supplied under a performance specification, the supplier performs the final selection that results in constraint satisfaction. Examples of structural items that are sometimes supplied under a performance specification are precast elements, open web steel joists, and, in many areas of the U.S., connections for structural steel members.

Another objective of the CD phase is the communication of the constraints to the downstream processes of construction and facility management, usually through the use of drawings and written specifications. Design work during the CD phase is tied to a graphical data base, the working drawings, and a textual data base, the specifications. By the end of the construction document phase most of the constraints on the physical attributes of the final building have been formulated and satisfied.

3.4 Construction Phase

In the construction phase the finishing touches are put on the plan. Based on the constraint set produced in the design phases, the construction planning team completes the details of what is to be built and adds the constraints on how and when it is to be built. Then the plan is carried out by the construction execution team.

3.4.1 Construction Planning

There is still some design left to do during the construction phase. Building components that are supplied under a performance specification are typically designed by the supplier in accordance with criteria supplied by the design team. If the specified item is part of a mutually constrained grouping, then the constraint set must also specify the manner in which that item interfaces with other building systems. An example of this is the location of support points for architectural cladding which may have an effect on the design of the structure.

When the structural drawings are issued for construction, the detailed description of the reinforcing bars and structural steel pieces is not complete. The design drawings usually show the number and size of the reinforcing bars and give typical details governing the lengths of the bars. This information must be turned into detailed bar lists that are then used for ordering, fabricating, and placing the bars. A similar approach is used with structural steel, although the degree to which the fabricator is constrained by the design details varies widely according to local design practice. The erector may have a preference as to how to erect the steel that could affect the fabrication details. Ideally, the preferred methods of fabricating and erecting the steel are considered as constructibility constraints before the forms of the connections are finalized. (The loads that the connections must carry and behavior constraints are always generated during the design phase.) The detailing process generates the specific physical description of the individual pieces that enables the fabricator to precut and predrill all of them within very exacting tolerances.

One of the constraints that must be considered by the erector and fabricator is the maximum weight of steel piece that can be lifted by crane. The maximum 'pick' is dependent on the boom length (which depends on the relative locations of the piece being lifted and the crane mast) and the crane capacity. These two variables need to be studied very closely by the contractor to determine the best approach to providing cranes for the construction. The crane must also be used for other activities and it may not be cost effective to use a large crane for everything so the largest size steel piece may have to be revised. The largest pieces in high rise steel office buildings are normally the columns which are usually spliced every two floors. The column lengths can be varied by 50% during the construction phase if the contractor is given the option of decreasing the distance between splices. Consequently, it is usually not necessary to constrain the crane capacity and location during the design phase, leaving these constraints under the control of the construction planning team.

The detailed physical data for the project are documented graphically in the shop drawings and textually in product data which become part of the project 'record documents.' These documents serve a number of purposes, including communication with the workmen that are performing the actual fabrication and erection. The 'record documents' also serve as the owner's permanent database, showing the details of what is actually built and as such serve a quasi-legal purpose in that they are checked for conformance with the design intent.[3] In the process of developing the detailed information the contractor and subcontractors explicitly identify the material, labor, and sequence required for construction. These items form the 'construction plan' shown on the right side of Figure 3.1.

3.4.2 Construction Execution

All elements of the construction plan are carried out during the construction execution phase, a process that is constrained by all of the preceding processes. Even though most of the constraints have been defined, the construction execution activities are not totally constrained since much of the detail about how individual activities are performed is left to the discretion of the field personnel.

At the end of the construction planning phase there are no attributes of the physical components of the facility that have not been completely defined and represented in the design drawings, design specifications, shop drawings, or product data. However, it is still possible for the *physical* structure to deviate from its *symbolic* representation due to unforeseen circumstances that arise during the construction execution phase. As an example, hidden conditions that are discovered during excavation may required modification of the foundations. These are incorporated into the permanent database only if the owner has contracted for 'as built' drawings.

Most of the initial costs of putting a facility in operation occur during the construction phase and , therefore, an accurate assessment of *Cost / Value* must consider the effect of the constraints formulated during the planning phases on the cost of the construction activities.

3.5 Facility Management Phase

The *Owner Entity* undertakes the daily management of the project once the construction of the facility has been completed. Hence the *Owner Entity* ties the entire life cycle process together. The product of the facility management process is *Value*, which is the other major parameter in the objective function. In the facility management phase the activities can be

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[3] Some of these needs can more appropriately be met using an electronic database. There are already many fabrication plants that use automated fabrication equipment and, in these plants, the data on the shop drawings is keyed back into a computer after the requisite approvals, completing a rather tortuous and error-prone process.

divided into operation, maintenance, and alteration. There are costs associated with each of these while the end result of the process is value. The costs associated with operation and maintenance usually involve the architectural and mechanical systems and must be considered upstream in the design of those systems.

During the life of the facility the function, or load carrying capability, of portions of the structure may need to be modified. This is especially common in office buildings where each new tenant has a unique set of requirements. It is quite common for tenants to want libraries or high density filing systems that apply more load than the structure was designed to carry. One of the considerations during the design of the structure is the relative cost of providing enhanced load carrying capability in the original design versus the expected cost of structural modifications during the life of the facility.

3.6 Conclusion

Constructing a system that closely models the phased decision making process used in practice can make it possible to avoid the combinatorial explosion that can occur when numerous feasible alternatives for the building systems are examined. During each phase a limited number of decisions are considered in combination and the search space is pruned before the process progresses to the next phase.

4
Facility Life Cycle Domains

4.1 Introduction

The activities represented by each box in Figure 3.1 have some relationship to the activities represented by each of the other boxes. Because of the numerous potential sources of conflict among competing interests it is crucial to provide some control mechanism in the process. In this chapter we examine the relationships among the various domains in order to gain an understanding of the form of the current control mechanisms.

The domains in Figure 3.1 consist of groups of related tasks which can be examined at three levels of detail: global, regional, and local. The following sections briefly discuss the global level domains of owner, construction, and design; elaborate on the architectural, structural, and M.E.P. activities at the regional level in the design domain; and further elaborate on the activities in structural domain at the local level.

Each of the domain entities involved in the life cycle processes performs tasks during all phases, but the nature of the tasks changes depending on the phase context. At each level of abstraction, the subprocesses are mutually constrained creating the need for communication between subprocesses to facilitate anticipation and coordination. In addition to the communication function, 'control' functions, such as evaluation, arbitration, and decision making must be provided by controllers. In practice, the control functions and the controllers are distributed among multiple levels as shown in Figure 4.1.

Each of the controllers depicted in Figure 4.1 corresponds to a position in the management structure in a typical facility life cycle that is filled by an individual with the appropriate education and experience. In current practice, the controllers are distributed among the various domains. Each of the controllers must possess detailed knowledge about the activities in his/her domain, as well as some knowledge of the activities of the other controllers at the same level and at the levels immediately above and below in the project management hierarchy.

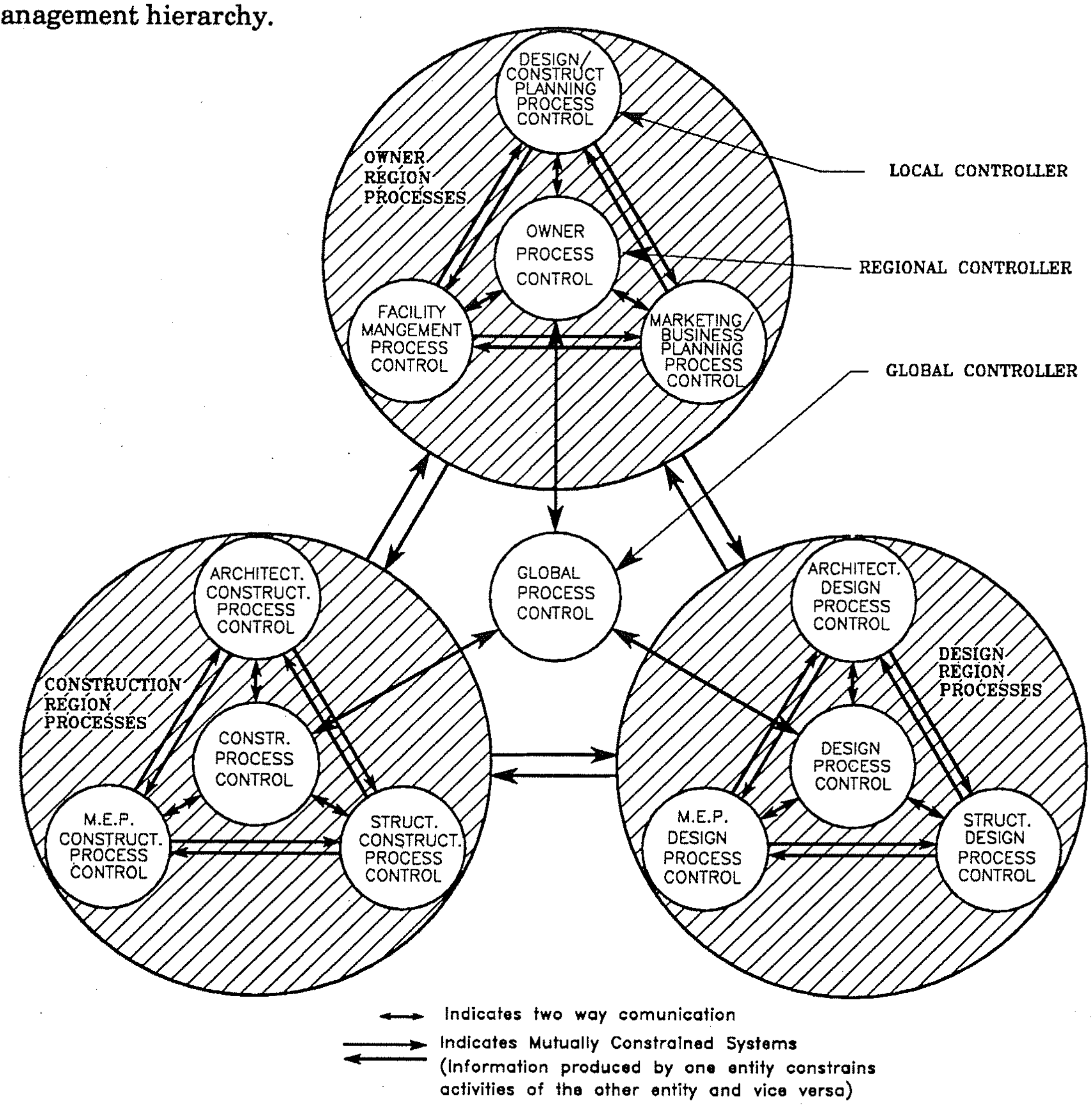

Figure 4.1 Life Cycle Control Hierarchy

The objective of this hierarchical approach is to allow as many decisions as possible to be made on as low a level as possible to minimize the number of entities that have to be involved, while still providing for the integration that is required for some decisions. Hence, a decision as to which of two beams to use, both of which satisfy all applicable constraints, should be made at the local level by the structural controller. On the other hand decisions involving tradeoffs or arbitration between controllers at the same level, such as in the case of structural, mechanical, and architectural mutual constraints must be made at a higher level. If only costs are involved, then the decision could be made at the regional control level, with input from the construction domain. However, if the decision involves value considerations in addition to cost, then it should be made at the global level. The global controller must be equipped with extensive knowledge of all three global regions.

4.2 Global Level Domains

The domains that constitute the global level of the abstraction hierarchy - *Owner*, *Construction*, and *Design* - form a *mutually constrained system* as shown in Figure 4.2. In that figure the pairs of single-headed arrows that connect the domain circles represent bi-directional, or mutual, constraints, which are illustrated in the following discussion. The control at the global level must be provided by an entity with knowledge of all the domains at that level.[1]

At the beginning of the life cycle the *Owner Entity* establishes the broad objectives of the project which include the proposed functional characteristics of the project and the relation of the project to its context. The context includes the location of the project and the surrounding social, political, and physical features of its environment. The product of this process is the *Master Plan* that describes the general project constraints.

The location, size, function, and quality level of the building are constraints *on the design* that are defined in the master plan by the owner entity. However, these are based on assumptions relative to cost that cannot be verified until after the design and construction phases. Costs that are identified during the design phase act as constraints *on the master plan* that may cause the owner to alter the master plan. As a matter of fact, this is the rule rather than the exception, due to the nature of the *mutually constrained system*.

The *Design Entity* undertakes the task of defining the building physical characteristics, both aesthetic and functional, such that the objectives identified in the *Master Plan* are met. The performance of this task usually involves an iterative cooperative effort between owner and designer to refine the definition of those objectives. For each decision that is made

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[1] In practice, this control function is normally provided by a project manager employed by the owner, but may also be provided by an architect or a construction manager.

during the design, a corresponding constraint on the construction tasks is added. However, to minimize the *Cost/Value* ratio the design entity must anticipate the construction cost implications of design decisions and, as a result, *construction* also constrains *design*.[2]

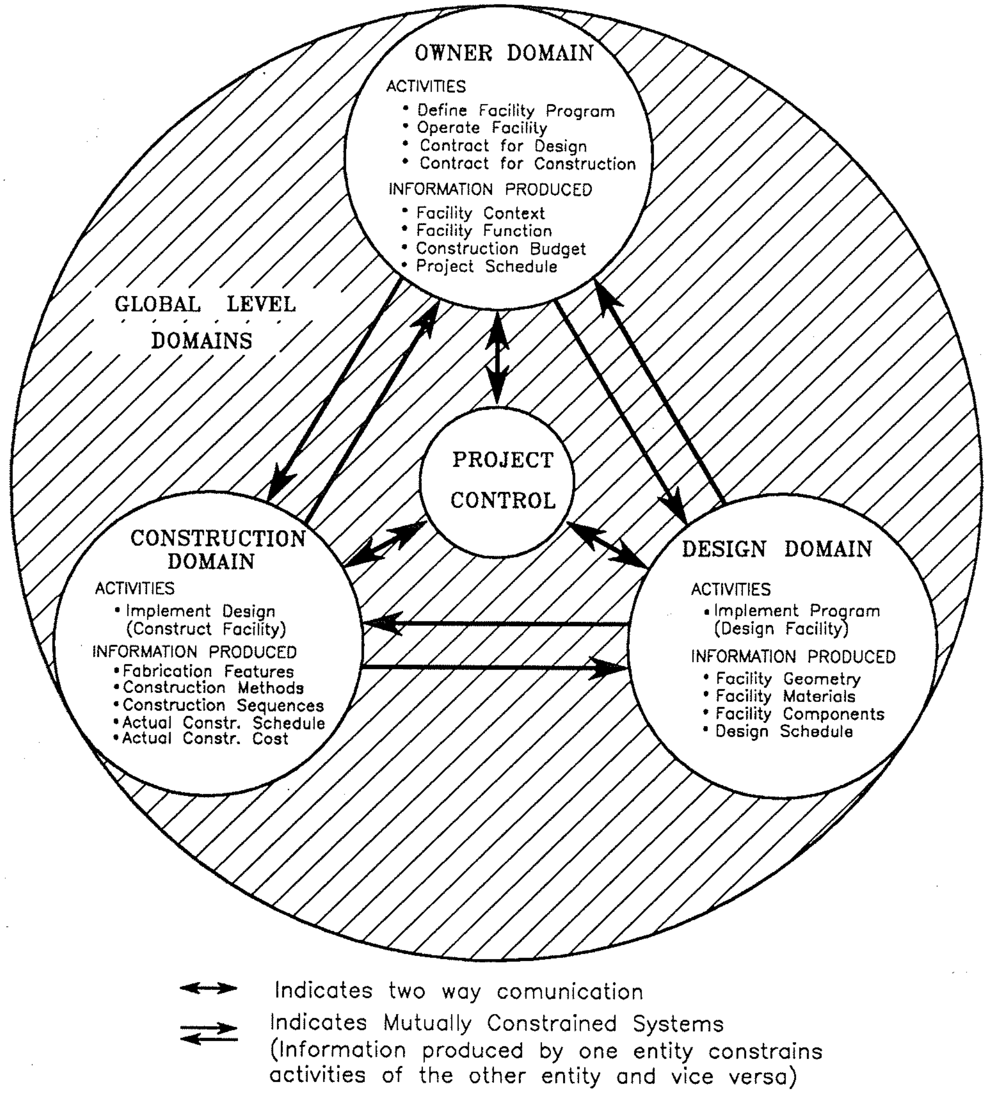

Figure 4.2 Global Level Domains

All constraints between design and construction involve cost and while some of the

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[2] The more fundamental constraint that there be *some* method of constructing the design feature is implicit in this approach if a feature that cannot be constructed is assigned an infinite construction cost.

constraints are straight forward, such as the unit costs of various materials[3], others are circular in nature. An example of a circular constraint is the location, size, and cost of the crane required for the project.

Using the contract documents as input, the *Construction Entity* plans the construction process, a task that involves identifying the activities and resources necessary to construct the physical system and planning the sequence of activities. As part of the planning effort the information shown on the contract documents is elaborated into detailed drawings in which every constraint is defined. A detailed *estimate* of the hard costs is made. The *Owner Entity* may contract for the work at the price represented by this estimate of the hard costs in which case these are *THE* hard costs from the owner's point of view.[4] The *Construction Entity* then undertakes the task of implementing the construction plan.

An example of a mutual constraint between owner and construction entities is the cost or value of time. After the project is in operation, time represents both cost (the cost of operation) and value to the owner, but the net effect of time to the owner is value. Up to a point, time represents cost to the contractor, since the cost of management personnel and other overhead costs accrue with time, and the cost can be reduced by increasing efficiency and reducing the length of the construction schedule. However, at some point the premium for accelerating the construction activities overcomes any savings.[2] Hence, minimizing the *Cost / Value* ratio involves analyzing the owner's and contractor's internal cost constraints to determine the optimum schedule constraint.

4.3 Design Region Domains

Figure 4.3 shows the domains that constitute design at the regional level of abstraction. Note that once again the domains form a *mutually constrained system* and the entity providing the control function must possess fairly detailed knowledge about all the domains that participate at this level and must possess sufficient knowledge of the global level functions to be able to communicate effectively with the global controller.[5] The knowledge

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[3] Again, availability is implicit. A material that is not available has an infinite cost.

[4] The actual hard costs are never known until the end of the construction phase and may differ substantially from the hard bid.

[5] In practice, on commercial building projects, the role of design region controller is almost always filled by the architectural project manager.

must be of sufficient detail and type to allow the design region controller to formulate the design strategy.

The architectural entity turns the abstract constraints contained in the master plan into particular constraints that define the space requirements for the facility as well as the appearance of the building. The architectural attributes of the building result in constraints on the M.E.P. and structural subsystems. In performing the design, the architectural entity must consider constraints arising from the building functions, space requirements, as well as constraints, such as fire separation requirements, arising from local code considerations.

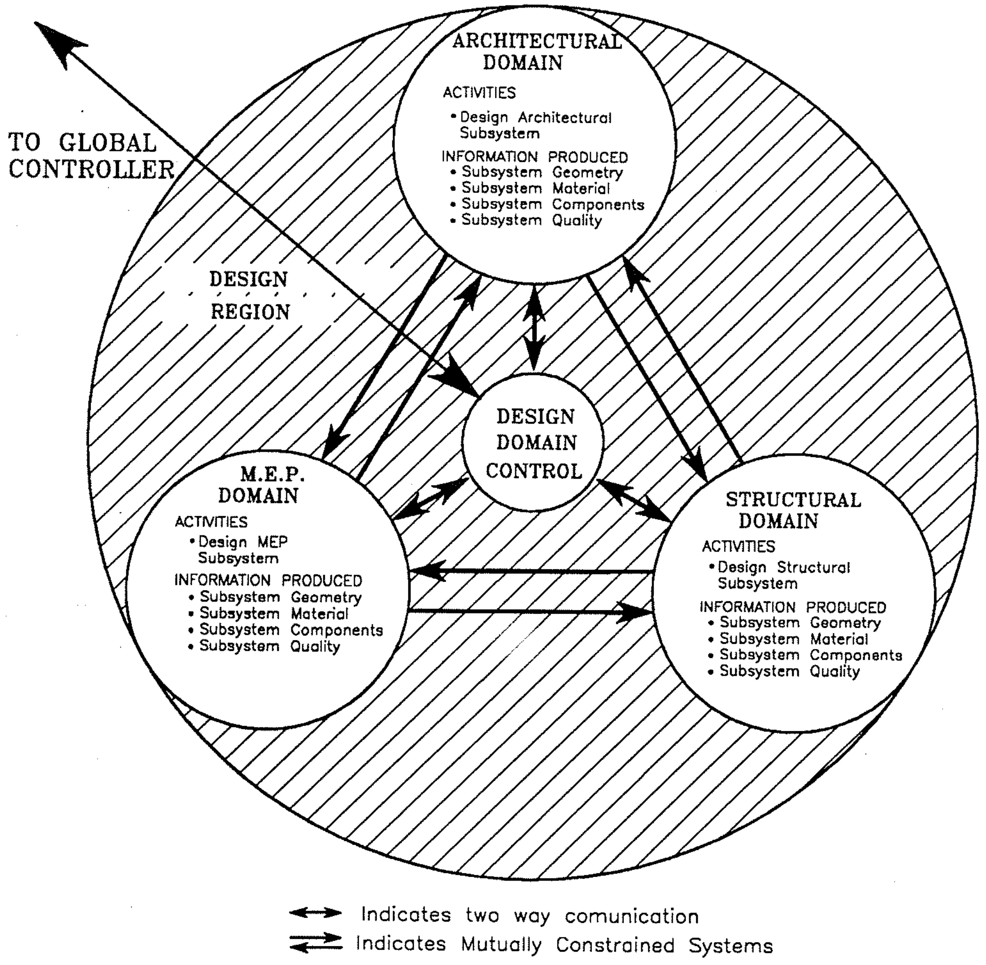

Figure 4.3 Design Region Domains

The product of the architectural design is a set of attributes for the building that define the floor sizes; the number of floors, the area on each floor required for support functions such as vertical circulation, mechanical shafts, and sanitary facilities; and the materials and geometric arrangement of the building elements that are exposed to view such as the cladding and interior partition layout. Certain architectural features form a mutually constrained grouping with the other subsystems. The building columns are significant architectural features that may have an effect on the architectural use of the space. The column locations are also prominent structural features that have a significant impact on the form of the load paths and the cost of the structural subsystem. The total space in the building that must be conditioned and the type of cladding used in the building have important repercussions in the design of the mechanical system while the space required in the architectural plan for the mechanical systems is dependent on these architectural elements.

The architectural features are usually perceived to contribute to the *value* of the building. Some of the features, such as the cladding, also have direct cost implications. Others, such as the locations of the columns and the type of cladding have an indirect influence on cost by virtue of their relationship to the other subsystems.

The primary function of the structure is to *safely* carry loads arising from both the primary and secondary functions of the building spaces and the effects of the environment. Occasionally, the structure may also serve an aesthetic architectural function as well, but in most cases it serves only a support function. As a result, the most apparent structural implications in the design process fall squarely on the *Cost* side of the objective function. In modern high rise buildings 25% or more of the construction cost results from the structural systems. Safety related constraints on the performance of the structure are hard constraints which must always be satisfied, so minimizing *Cost / Value* in the context of these constraints amounts to minimizing *Cost*. The performance of the structure may also have an impact on *Value*, e.g., structures that vibrate, crack, sway in the wind, or appear unreliable may be uncomfortable to occupants, even if they are safe, reducing the perceived *Value* of the space to prospective users. Durability issues can increase the life cycle cost of the structure to the owner. Since serviceability, reliability, and durability constraints are generally not dictated by building codes, minimizing the *Cost / Value* of the structure requires careful consideration of the trade-offs between cost and quality s far as these issues are concerned.

The loads that must be carried arise from physical phenomena such as gravity, wind, earthquakes, temperature, and soil stability. These loads can be broadly classified as vertical (gravity), lateral, and temperature loads. In general, there is a direct relationship between the value of the load that must be carried and the cost of the structure required to carry the load. By developing a suitable strategy for carrying the loads from the point of origin to the ground (i.e. an efficient load path), the structural entity can minimize the cost of the support system. The 'reasoning' in the structural design process occurs in the activities of determining the appropriate loads and synthesizing the systems of load paths in the context of the local construction market, the project schedule, and the architectural concept. The process of analyzing the structure and selecting specific sizes of members *once the load path has been determined* is a highly constrained problem that can often be accomplished utilizing conventional analysis and design programs.

While most of the architectural and mechanical features result in loads that must be carried by the structure, some mechanical and architectural decisions also influence the manner in which the loads should be carried, the locations of columns being one example. When the structure is subjected to loads, it responds in accordance with principles of physics resulting in deflections or vibrations. This behavior of the structure has implications for the architectural and mechanical subsystems. An example of this is the effect of the structural deflections on the cladding of the building or on interior partitions.

Finally, the structure has physical dimensions that are dependent on the loads that must be carried and the geometrical constraints such as column locations that it must satisfy. Since it must fit within the limited space defined by the building envelope, along with the other subsystems, there is an interaction with the geometric properties of the other subsystems.

The function of the M.E.P. entity is to design the infrastructure required to provide life support facilities and amenities in the facility environment. The mechanical systems condition and supply fresh air to the building for occupant comfort and provide a means of exhausting the air that has been 'used up' by the occupants. In case of emergencies, such as fire, the mechanical systems serve the critical life support function of isolating and eliminating harmful contaminants such as smoke. The electrical systems supply the power that is essential to the primary function of the building (i.e. office usage) and to the support systems for that function such as elevators and mechanical equipment. The plumbing systems supply fresh water for sanitary facilities and perform the task of collecting and disposing of both rain water and sanitary waste. In modern high rise buildings, a critical function that is related to plumbing is fire protection which is provided by sprinkler systems located throughout the building.

The total cost associated with the M.E.P. systems is in the same range as the structural costs. However, there is more of a range in evaluating the mechanical systems, since the 'quality' of the environment, or degree of comfort, that is provided can be a variable. An example of this is the choice of whether the mechanical systems should be capable of maintaining an inside temperature of 65 degrees or 75 degrees when the outside temperature exceeds 100 degrees. (By contrast, it is not common to talk of the 'degree' of structural safety as a design variable.)

The factors that influence the design of the mechanical systems include the architectural features, the level of 'quality' desired, and the weather environment. An example of an architectural feature that forms a mutual constraint grouping with the mechanical system is the building cladding. The choice of cladding type has an influence on the heat transmission and therefore constrains the mechanical system. Cladding that has a lower insulating value increases the conditioning load on the mechanical system which, in turn increases the space requirement of that system. The increased space requirement increases the building size, which increases the surface area. Of course, increasing the mechanical system and its space requirements has a direct effect on the structural loads.

Since each of the systems constrains the others, it is necessary to develop a strategy for optimizing the entire constraint set in light of the objective function. This requires that the *Costs* and *Values* associated with the mutual constraints be determined explicitly.

4.4 Local Structural Domain Activities

This section describes the activities that occur during the conceptual design phase at the lowest level of the abstraction hierarchy, from a structural engineering point of view. The discussion is limited to the conceptual design phase because many of the decisions that have an impact on the constructibility of the facility and the interaction of the structure with the other subsystems are made during that phase as part of the formulation of the constraint set that will be used in the detailed design.

The activities that occur at the local structural level of the abstraction hierarchy, shown in Figure 4.4, can be decomposed into groups that define problems that are weakly linked and mutually constrained. Here again a control function is required and the entity providing that function must possess knowledge of each of the problem domains as well as sufficient knowledge of the other design region controllers to be able to communicate. The controller at the local structural level decides on the strategy for developing structural solutions.[6]

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[6] In practice, this role is filled by the structural engineering project manager.

The process of conceptual design is one in which the structural entity ascertains the best 'load path' and establishes the arrangement and sizes of the structural elements that will force the load to follow that particular path. Because of the complexity of the structural systems used in modern buildings, maximum use is made of problem decomposition.

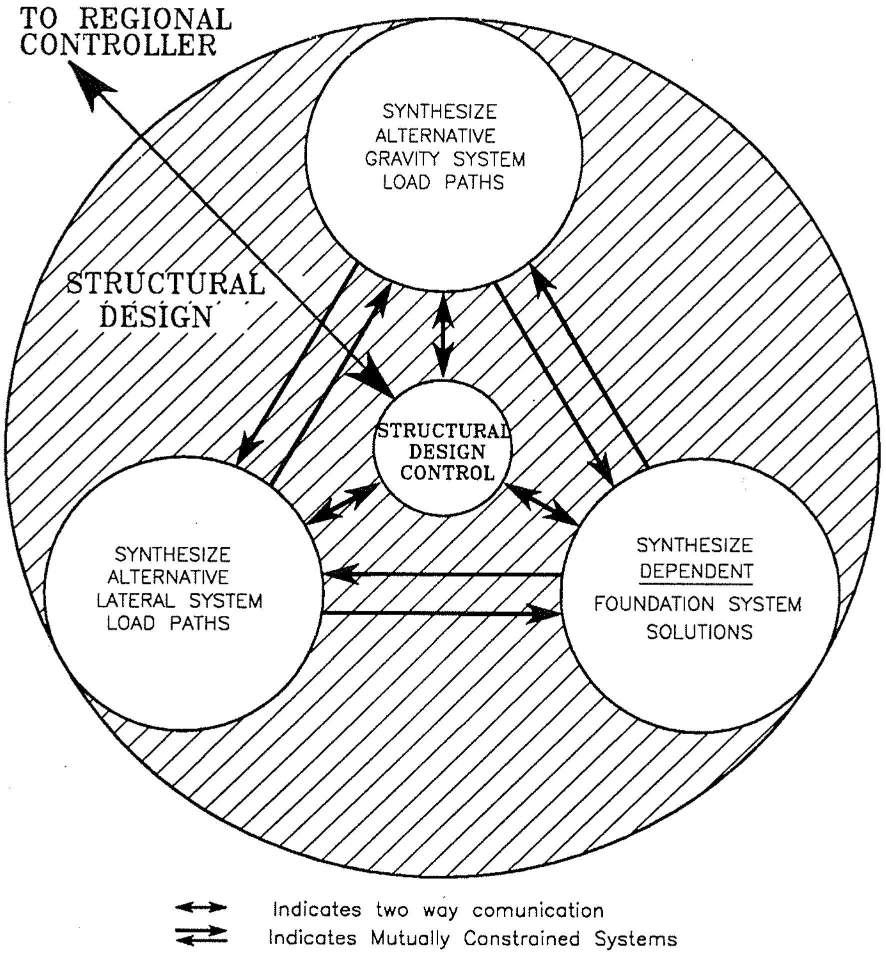

Figure 4.4 Local Structural Conceptual Design Activities

Building structures can usually be decomposed into a lateral system that resists the horizontal loads, a gravity system that resists vertical loads, and a foundation system that transfers the accumulated horizontal and vertical loads to the ground. In addition to elements that transfer the gravity and lateral loads into the ground, the foundation system includes all elements whose primary function is to resist loads arising from earth pressures. The foundation system is dependent on the other two subsystems, since it is the last link in the load paths of both of those systems.

For each of the subsystems, the structural entity determines the appropriate loads that must be resisted, determines the applicable performance constraints (deflection and stress limits), synthesizes one or more feasible systems such that a complete path is provided for all loads, and, using knowledge of first principles, determines constraints on the element properties such that the structure behavior will satisfy performance constraints. Conventional analytical programs cannot be used until after conceptual design when the structure topology and member sizes have been defined. During conceptual design the reasoning about structure behavior takes the form of a combination of qualitative and quantitative reasoning using approximate analytical techniques that capture the essential behavior characteristics of the elements and systems.

The lateral and gravity subsystems are weakly linked due to the fact that some elements of the structure are common to both subsystems. A common approach in synthesizing building structural systems is to start with a system of gravity load paths and then synthesize a lateral system by starting with a subset of the gravity system, e.g., the frames along designated lines or in the core and then developing the balance of the lateral system independent of the gravity system to satisfy performance constraints. After completing the synthesis of the lateral systems, the gravity and lateral solutions must be reconciled to eliminate redundant instances of the common structural elements or to modify the gravity system to include elements that are added for the lateral system. As an example, tubular lateral systems in high rise buildings usually have more columns on the perimeter than would be required for a pure gravity system. The reconciliation task is mediated or directed by the local structural controller. Elements that are common to both the lateral and gravity load paths must also be checked for the combined effect of the loads and the combined systems must be checked for the effects of other physical phenomena arising from environmental factors, e.g., temperature effects, or from consideration of a particular aspect of element behavior in the context of the global systems, e.g., creep in concrete elements. The latter issues are more often resolved during final design, but the controller must be equipped with sufficient knowledge to decide the appropriate time to address them. Constraints on the element properties arising from the performance considerations of either of the subsystems or from the additional factors must be satisfied in the combined system.

A foundation system must be developed for each of the combined systems The foundation system cannot be designed independently since it is strongly linked to both the lateral and gravity systems

The approach taken in the conceptual design of the structural system can be described as 'nested multiple worlds.' For each of the subsystems, multiple solutions are possible. The multiple solutions for gravity and lateral systems are combined and a foundation system is developed for each of the combined systems so that multiple comprehensive design solutions are formed. Each of these comprehensive design solutions represents a different 'world.' Not only do the costs vary between worlds, but the set of constraints relating the structural solution to the architectural and mechanical subsystems may be different for different worlds. In the evaluation of the worlds, the following aspects are considered:

1. The intrinsic cost of the structure which is developed from constructibility input and includes the costs associated with time,
2. The incremental cost of the other building subsystems attributable to the changes in the constraint set required by the scheme, and
3. The incremental changes in value attributable to the changes in the constraint set represented by this scheme

The structural scheme selected is the 'world'[7] that results in the minimum *Cost/Value* ratio for the project as a whole. Wherever possible, actual cost data, rather than heuristics, are used as the basis for the decision. However, even with complete cost data, the decision cannot be made without some assessment of *Value* which requires participation at a higher level, quite often at the global level. The function of the structural entity, then, during the conceptual design is to formulate constraint and cost information regarding the structure to be used in making a decision at a higher level in the life cycle process hierarchy.

In the conceptual structural design process heuristics are used to select the general framework for the solutions within the individual lateral and gravity modules and for breaking ties in the final selection process. At all phases of the conceptual design process engineering principles are used to evaluate behavior and proportion elements, and cost principles are used as an evaluation tool. This rigid adherence to 'first principles' is necessary in order to distinguish between systems within a narrow range of solution costs.

During the schematic phase of the conceptual design, only the typical floor and lateral system are studied. The assumption implicit in this approach is that the most efficient solution for the building as a whole incorporates the most efficient solution for the typical floor. Appendix B contains an example of the results of a schematic design for a 59 story

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[7] The term 'world' is used here to indicate a comprehensive solution, i.e., one in which all subsystems are functional and coordinated, in contrast to a candidate solution which is a *proposed* set of constraints that may not yet be coordinated.

office building.

4.5 Conclusion

The reasoning process used in the design of high rise structures is composed of nested mutually constrained subprocesses. Automated systems that try to model the processes must be capable of addressing the change of focus with time within a particular domain (phase focus) as well as the change in focus between domains (function focus) while providing controllers that communicate, mediate, arbitrate, and make decisions. Based on current practice the control functions should be distributed over multiple levels for efficiency in the decision making process. In the automated system each controller must be equipped with detailed knowledge of its own process, reasonably detailed knowledge of the other controllers at the same level, and sufficient knowledge of the controllers above and below to be able to decide when it is appropriate to pass a decision along to another level.

5

Automated Reasoning Approaches

5.1 Introduction

Artificial Intelligence in general, and knowledge based systems in particular, encompass a wide range of philosophical approaches to modeling human reasoning. In this chapter, a number of these approaches are described and discussed in the context of the structural design process. Each of the approaches offers some advantage in the representation of that process, and there does not appear to be any intrinsic reason why any - or all - of the approaches cannot be combined in a single system.

A few definitions are essential before the discussion commences.

> *Reasoning* - Reasoning is the logical process that is used to derive conclusions or additional facts from the known "facts" [1] in a domain. In AI, a deeper form of reasoning involves the reasoning required to identify which additional facts are required [5].
>
> *Representation* [2] - The dictionary [16] defines representation as "that which symbolizes." The importance of representation in the automated reasoning process is analogous to the importance of words in written and spoken language where a word symbolizes an object or concept. If the vocabulary

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[1] A fact is something known as certain or something asserted as if known. The latter definition is the usage in the context of knowledge based systems where the 'facts' may or may not be known as certain, but are used as if they are.

[2] In AI, the term 'representation' is commonly used to mean the *form* of the representation, i.e., "a set of syntactic and semantic conventions [24]." In this dissertation, the focus is on *what* is being represented rather than *how* it is represented.

doesn't contain a word to represent a concept, that concept cannot be manipulated in a sentence nor communicated to others. Representation is the vocabulary of the language that is used in the reasoning process. Concepts or objects that are not represented cannot be reasoned about.

Knowledge - The dictionary [16] defines knowledge as "that which is known, perceived, discovered, or inferred." In the context of knowledge based systems it is the body of "facts" that are known about the objects and concepts and their interrelationships in a particular domain as well as a set of rules or operators that can be used to generate new facts and a strategy for determining when and how to apply them in problem solving process.

A brief discussion of rule based expert systems, which have been used as the basis for many knowledge based systems is presented first. The subject of model based reasoning is presented in somewhat greater detail because it appears to be closest to the reasoning process actually used in structural engineering design and provides a vehicle for organizing the concepts required for the reasoning and representation. The classification of the elements of representation proposed by Kunz [14] is adopted throughout the balance of this dissertation. The discussion of reasoning with constraints includes a review of MOLGEN, the system developed by Stefik [20] for planning with constraints. This approach is appealing in the context of conceptual design since that phase, in essence, involves planning for the design (as opposed to detailed design which is planning for the construction). The last sections of this chapter contain a review of KBS development in the domain of structural engineering, raise issues that need to be addressed in the development of ISD, and propose an architecture for an integrated design environment.

5.2 Production Rule Systems

Classic expert systems use the IF-THEN rule formalism to represent not only the human reasoning process, but also the characteristics of physical systems. In rule based systems, controllers refer to the current state of the system to determine whether the 'context' within which the rule applies has developed and, if so, the rule is 'fired'. The actual function of the physical system is not explicitly represented in rule based models and behavior is only represented implicitly in the formulation of the rules.

In systems which use the production rule form of representation, a different rule, or clause, is required for each set of circumstances (context) that might produce a different behavior. In order to address the issue of the many possible situations that could effect the way in which a particular piece of knowledge is used, hierarchical reasoning systems were developed. In these systems, the rules have a different effect depending on the context in which they are fired. As the hierarchical systems developed further, the need for different types of knowledge, i.e, strategic or control and domain knowledge, was recognized and incorporated.

Rule based systems rely heavily on expert knowledge and excel at capturing the qualitative heuristic knowledge that is used by experts to direct the search for a solution. However, they are rigid since the rules can only capture the effects of foreseen circumstances, and limited because the number of contexts that can be foreseen and represented in rule form is itself limited.

5.3 Model Based Reasoning

In contrast to the rule based approach, the model based reasoning approach attempts to represent the form [3] and function of a system explicitly and use first principles[4], rather than heuristic rules, to represent behavior whenever possible. This approach results in reasoning systems that are much more flexible in the range of behaviors that they can address. The form of the representation that is appropriate for rule based systems is not necessarily appropriate for all elements of a model based system.

The engineering process involves reasoning about the behavior of physical systems for the purpose of designing those systems to produce a specified behavior under a predetermined set of conditions, or for the purpose of determining the impact of the behavior of one system on another. Model based reasoning has been proposed as a natural paradigm for constructing knowledge based systems that perform engineering reasoning functions [14]. Many of the concepts contained in this discussion are adapted from Kunz in reference [14] to which the reader is referred for a detailed discussion of model based reasoning. In this section, only the main points from that reference, which provide much of the philosophical motivation for the remainder of the dissertation, are presented.

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[3] Kunz [14] uses the term 'structure' where 'form' is used herein. The latter is adopted to avoid the awkward semantics of referring to the 'structure of the structure.'

[4] The term 'first principles' is used to denote physical laws.

5.3.1 Definition of Terms

The dictionary [16] defines a model as "a tentative ideational structure used as a testing device." Models may be physical scale models that faithfully reproduce the relative dimensions of the components of the prototype system in order to facilitate the visualization of the spatial relationships among those components. Other scale models use modified physical properties in order to accurately reproduce some behavior of the prototype that is affected by the scaling process. In all cases, the models facilitate some reasoning process. Kunz [14] uses the following definitions, which are adopted in this discussion:

Diagrammatic Model -- A diagrammatic model is one in which pictures are used to represent the form of the system. Diagrammatic models are extremely important as a tool for visualizing the function of a structural system, i.e, the load paths.[5]

Heuristic Model -- A heuristic model is one in which the behavior of the system is represented symbolically, based on the way an expert describes the system. The 'classic' expert systems utilize heuristic models in which the behavior is represented explicitly but the form and function of the system are not. Heuristic models capture cause and effect relationships but not the underlying principles. As a result heuristic models can only predict results that are foreseen based on past experience. The internal states of the modeled system are not captured in a heuristic model.

Mathematical Model -- "..mathematical models describe the functional behavior of the modeled system using the precise and abstract language of mathematics. .. one of their limitations is that the form of the modeled system is represented only implicitly and explicit knowledge about how to use the model is not represented at all." [14] This definition is extended as follows for our purposes. A mathematical model is composed of algebraic expressions that represent the relationships among the components of a system and the response of those components to specified conditions in order to predict the quantitative value of some aspect of the system's behavior. Only those elements, or attributes of elements, that have a significant effect on the desired response need be modeled.

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[5] Kunz states that the functional characteristics of the system are not usually represented explicitly in the diagrammatic model. However, in the domain of structural engineering, diagrammatic models are the only way of representing function and engineers use them as surrogates for the actual structure, altering the functional description of the structure by manipulating the patterns in the diagrammatic model.

Symbolic Model -- The term symbolic model is used to denote the way people describe the behavior of the system. (This implies a qualitative verbal description as opposed to a quantitative numerical description of behavior.) Model based reasoning uses a *formal symbolic model*, that is one in which both the form and the functional behavior of a system are modeled symbolically. Symbolic models capture the relations between input and output as well as the internal states of the modeled system.

In addition to the above, the following definitions are offered as a preface to the discussion:

Behavior -- From the dictionary [16] : The reactions of systems or components of systems to specified circumstances

Black Box Approach -- An analytical approach in which the user cannot examine intermediate results or alter problem parameters during the solution process.

Conceptual Model -- A model that attempts to represent the general nature of the response of a system to specified circumstances. Conceptual models may be qualitative, quantitative, or both.

Mathematical Structure Model -- A model in which the structure is represented as a series of simultaneous equations relating the displacements at nodes to internal member forces, external loads, and external reactions.

Qualitative Model -- A model that attempts to represent the rough magnitude of the response or the nature of the behavior of the modeled system rather than the precise numerical value of that response.

Quantitative Model -- A model that yields numerical values for the response of the modeled system

Transparent Mathematical Structure Model -- A mathematical model in which the component behavior is represented explicitly as algebraic expressions, but where the intermediate results of the solution process are visible and where the user can vary problem parameters during the solution process.

Transparent Model -- A model in which the user can selectively vary the model parameters during the problem solution, and where intermediate, as well as final, results are available to the user.

5.3.2 Characteristics of Model Based Reasoning Systems

In model based reasoning the form and function of the physical system are represented explicitly and are separated from the representation of control. This produces a layered reasoning system that is intuitively appealing because a knowledge based system attempts to model two conceptual entities, i.e., the human reasoning and the physical system that is the subject of the reasoning. Because of the separation of system and control representation, it is possible to adopt different methods for representing the control reasoning and the reasoning about function and behavior. The control reasoning attempts to model the reactions of the human engineer to the behavior of the structure, which is predicted, or modelled, using first principles.

Kunz [16], proposes a frame based, or object oriented, form of representation as being most appropriate for modeling form and function. The attributes of the objects can be either descriptive, e.g.., weight, or behavioral, e.g., deflection. In the object oriented approach, the 'value' of a slot for a behavior attribute can be a rule, a procedural program for computing the value, or a data item. For instance, the deflection slot in a frame representing a simply supported beam with a uniform load could be the algebraic expression $5wL^4/384EI$.

The control reasoning involves decision making that is based on the observed behavior. This is the part of the reasoning system that models the human thought process and can be represented using IF-THEN rules based on heuristic knowledge.

The concepts that must be included in the representation in a model based reasoning approach to structural design are:

1) *Form* - The representation of form must describe the physical attributes of each individual object. This is the information that is typically communicated among project participants via drawings.

2) *Function* - The function representation must describe qualitatively the purpose of the structure, which is to carry loads from the points of origin to the ground. The global structure function can be described in terms of a spatial arrangement of functional objects to form a system of load paths (referred to herein as the topology) In order to define the topology the representation should explicitly define the support relationships for all components of the structure. The function of each structural component, or conceptual object, must also be represented in the context of the global load paths.

3) *Behavior* - The behavior representation must describe the manifestation of the structure system performing its function, i.e., *how* it performs its function. As the result of carrying loads, structural systems deflect and have internal forces. Behavior must be represented at both the system and the element level.

4) *Reasoning* [6] - Although there is reasoning involved in defining form, function, and behavior, the term is used here to mean the strategic (or control) reasoning involved in manipulating the structure form and function to control its behavior.

Since the form, function, and behavior are modelled explicitly, the model based reasoning approach captures not only inputs and outputs (which are also captured in IF-THEN rules) but also the internal states of the model. This facilitates the reasoning contained in (4) and results in a much more powerful system.

5.3.3 Role of Models in Structural Engineering

The product of the structural engineering process in building design is a set of documents that define a diagrammatic model, enabling the construction team to build a structure that will fulfill its intended function, that of carrying loads, while satisfying performance constraints. The behavior of the structure is usually described in terms of deflections of the system, or elements of the system, and internal stresses of the system components when subjected to the design loads. Constraints on that behavior arise from consideration of the effect the behavior has on human comfort and safety and the interaction with attached architectural elements.

Since building structures are usually 'one of a kind' systems, full scale prototype testing to determine the suitability of the design solution is generally not possible. However, due to the occupant safety considerations it is necessary to develop a reliable way to predict the behavior of the structure. The solution used in practice is to develop two independent models

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[6] Of course the knowledge itself must be represented and when some attributes of an object are expressed in terms of other attributes, the distinction between reasoning and representation becomes blurred. Kunz [13] offers the following thoughts on the subject. "Domain representation can be viewed as the nouns which are to be described in the knowledge based system and their associated adjectives. . . Since reasoning defines the actions which nouns can perform, the reasoning process can be viewed as the verbs which specify the actions performed by particular nouns. The reasoning references and modifies particular adjectives of particular nouns. . . Representation of a domain and reasoning about the domain are related. A useful simple distinction is that representation includes facts which can be asserted directly or retrieved directly from the model. Reasoning is the process of inferring values which are not explicitly represented within the model."

of the system and test them against one another.

The engineer constructs a *conceptual model* of the proposed structural system that satisfies the external geometric constraints using primitive functional elements that form systems of loads paths. Although redundancy in the actual structure results in a structural analysis problem requiring the solution of a large number of simultaneous equations, it is normally possible to make reasonable simplifying assumptions that render the problem tractable using manual calculations. Using the conceptual model and approximate analytical techniques, the engineer hypothesizes a certain behavior, establishes preliminary sizes, and tests the effect of varying the geometry or proportions of the members, thereby quickly generating a preliminary optimal solution to the design problem.

The accuracy of the conceptual model is tested by constructing a *mathematical model* of the preliminary design solution and using it to calculate precise values[7] for the system response. If there are differences between the response of the conceptual model and that of the mathematical model, the differences must be explainable by first principles. It is not unusual for this approach to identify errors in the mathematical model (which, after all, contains its own set of assumptions) as well as in the conceptual model.

A second purpose of the conceptual model is to facilitate the reasoning process during conceptual design when there is insufficient information to construct a precise mathematical model. During this stage of design, the conceptual model is the only vehicle for determining whether or not the proposed design will perform its function and behave satisfactorily. Since the function is defined numerically, the conceptual model must be a quantitative as well as qualitative model in order to serve this purpose as well as to validate the mathematical model.

During the preliminary design process, it is necessary to test the effect of varying the properties of the structural elements. This is accomplished quite easily using the *Quantitative Conceptual Model.* Since the conceptual model, which is based on the fundamental principles of the behavior of the system components (subject to some assumptions), represents the form and function of the system components explicitly and can be modified continuously, it qualifies as a *Transparent Quantitative Conceptual Model.*

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[7] If all goes well these are accurate as well as precise.

5.4 Reasoning With Constraints

In previous chapters the design process has been described as one in which the constraints on the structural system evolve as the system becomes better defined. In this section, several research projects that explicitly addressed the use of constraints in an automated environment are reviewed. The earliest work discussed is Sketchpad [21], which was performed by Sutherland at MIT in 1963 and was the forerunner of many modern CAD programs. While Sutherland's work was performed in what has to be considered the dark ages of hardware technology, Borning's work in Thinglab [3], completed at Stanford in 1979, demonstrated the power of the concept of constraint propagation and satisfaction using a high level language and frame based representation implemented on a 'modern' platform. Both Sutherland and Borning used constraints in numerically intensive graphical manipulations in contrast to Stefik who extended the concepts to qualitative reasoning for the purpose of planning in MOLGEN [20]. In CONMAN [7], Holtz combined qualitative and quantitative reasoning by using constraints to reason about algebraic expressions symbolically. Chan's work [4] explicitly addressed the problems of control in the use of constraints to perform design.

To the extent that all computational systems implement rules or mathematical expressions governing the relationships between objects or concepts, they all represent a form of reasoning with constraints. In structural analysis (FEM) programs the user provides data defining the structure geometry, member and material properties, and loads. The programs assemble the set of simultaneous equations that describe the behavior constraints and solve them by some suitable method, a form of 'constraint satisfaction,' where the constraints take the form of algebraic expressions. However, since the user is not privy to the inner workings of the program and cannot alter or observe the solution process, this method of constraint satisfaction is a 'black box' approach. The results of such analyses do not, in general, inform the user as to the relative contributions of the individual elements to the behavior of the entire system, and ascertaining the impact of varying the properties of single element requires iteration with the entire constraint set, regardless of the actual zone of influence of the property varied.

The contribution of AI research is in the processing of nonnumeric constraints through programming in symbolic languages and in the transparent processing of numeric constraints using object oriented programming techniques.

5.4.1 Sketchpad

Sketchpad [21] was a landmark dissertation documenting a computer graphics program developed at MIT and was, perhaps, the seminal work in the field. It formed the basis for much of the subsequent development in computer-aided drafting (CAD). The program was implemented on an experimental 75 kilobyte mainframe computer (vintage 1956) and utilized a light pen, keyboard, knobs, and toggle switches as the input devices.

The significance of Sketchpad is that it represented graphical objects (points, lines, circles, etc.) and enforced relationships between objects through the use of a representation scheme very similar to what we now think of as 'frames', although the term 'frame' was not used to describe the method of representation. In those days, the programmer worked directly with the storage registers in the computer memory. Sutherland stored the data associated with each object in a block of contiguous registers. The address of the block was the address of the first element in the block while all other addresses were given in relative terms. This allowed all of the data for an object to be manipulated as a single entity. Related data was arranged in a 'ring' structure (termed a hen and chicken structure by Sutherland) where each item of data (chicken) contained a pointer to the next item of data, with the last item pointing back to the first (hen). This is similar to a linked list of records or frames in today's terminology.

Sutherland used the concept of a 'master' object. Any number of copies, or instances, of the master object could be made. The constraints that were intrinsic to the master were intrinsic to the copies. This was a precursor to the now familiar concepts of classes, instances, and inheritance.

The term constraint was used to describe the relationship between objects. A line was an object that had as its ends point one and point two. Points one and two were objects that had X and Y coordinates that controlled their screen location. If the user moved point one on the screen constraint satisfaction was used to assure that the X and Y attributes of the point were changed. All lines that had point one as an endpoint were automatically changed when point one was changed.

Constraint satisfaction was used to assure that all the effects of a change were reflected in the data structure. Constraint sets were classified as linear or circular. Linear constraint sets could be solved by a one pass sweep through the objects in an appropriate sequence. Circular constraint sets had to be solved by a relaxation technique that attempted to reduce the least squares fit approximation of the error on every step. When the error could not be reduced, the constraint set was considered to be mutually exclusive (i.e. there was no solution that satisfied all constraints). In Sutherland's work the term 'constraint propagation' is not used, although it appears that the program did indeed both 'propagate' and 'satisfy' constraints.

The program allowed many different types of numeric constraints to be applied to objects. Sutherland included in his dissertation examples of redundant trusses that were solved using the relaxation method of constraint propagation. In the trusses, the relationships between the axial loads and the member displacements were expressed as constraints. In Sutherland's work the term relaxation refers to the solution of a set of simultaneous equations through successive approximations. The term 'relaxation' was used by later researchers to describe an entirely different process that involved changing the relationship between objects.

5.4.2 Thinglab

Thinglab [3] was a program developed at Stanford University in the late 70's. It picked up where Sketchpad left off - 16 years later! By the late 70's, computer hardware was several orders of magnitude more powerful and software was much more flexible. Thinglab was implemented in a version of Smalltalk, an object oriented programming language developed at the Xerox Palo Alto Research Lab.

Representation concepts like frames and objects were formalized and extended in Smalltalk . The representation built into the language allowed frames to have abstract attributes without values. Such generic objects defined 'classes' and all subsequent objects that were specified to be part of the class 'inherited' the generic attributes (or attribute slots) of the class.

Borning's work adapts the concepts of class and inheritance to the graphical representations examined by Sutherland. Classes are allowed to define constraints between the attributes of objects that are members of the class. Hence, in the class 'squares' all objects are quadrilaterals with all sides of equal length and all angles 90 degrees. Thinglab also allows nonnumeric values for attributes.

As an example of nongraphical constraints, in addition to electrical circuit diagrams, Borning presents the same redundant truss seen earlier in Sutherland's work, this time with a more explicit statement of Hook's law as the governing constraint for all the members. The member force attributes are constrained to be related to its end deflection and area attributes by Hook's law, and are the variable unknowns. The applied forces are the known attributes of the structure. Since the truss is redundant, the values of the attributes, or variables, cannot be determined by simple constraint propagation. Thinglab uses the relaxation method, similar to Sketchpad, to resolve the redundant truss. In one approach, all variables are relaxed. An extension to the concept is suggested whereby the minimum number of independent variables is determined and only these are relaxed. The values of all other variables are expressed as functions of these. In structural analysis problems this scheme is equivalent to defining the number of unknowns to be equal to the degree of redundancy of the structure.

5.4.3 MOLGEN

MOLGEN [20] is a program that uses symbolic logic to plan gene cloning experiments in the domain of molecular biology. It uses the 'divide and conquer' strategy of decomposing the problem into subproblems at successively more detailed levels of abstraction. The subproblems are weakly linked in that each subproblem can be solved independently but has implications on other subproblems. The relationships between subproblems are expressed as constraints.

Molgen utilizes an opportunistic 'least commitment' approach to the planning problem. Solutions to individual subproblems are developed as far as possible using available information. Subproblem solution can be suspended and then restarted when more information becomes available through the process of constraint propagation. Information that is generated in the process of solving subproblems is relayed to other subproblems through constraint propagation. The information is used to formulate constraints, based on scientific principles, in the other subproblems. Specific elements of the plan become increasingly well defined through the addition of the constraints to their definition. When all the constraints relative to an element of the plan are known, that element is 'instantiated' by the inclusion of specific activities in the overall plan.

This process continues until a complete plan has been evolved or until no further refinements are possible. In the latter case, the high level strategy of MOLGEN triggers a decision based on heuristic knowledge rather than first principles to allow the planning process to continue.

Stefik called the approach to constraint based reasoning used in MOLGEN 'constraint posting.' In contrast with the traditional approach of predefining a complete set of hard constraints prior to attempting a solution to the problem, in MOLGEN the constraints are formulated 'on the fly,' in response to the emerging particulars of the solution.

Stefik uses three operations involving constraints:

1. Constraint Formulation
2. Constraint Propagation
3. Constraint Satisfaction

Molgen handles constraint relaxation (changing a previously defined relationship) through a backtracking operation referred to as 'UNDO.' Since the thrust of the research was to use constraint posting to minimize or eliminate backtracking, this feature is not emphasized.

Stefik proposes the following criteria to evaluate the suitability of constraint posting in a particular problem domain:

1. A language of hierarchical objects and relations
2. A language of constraints
3. A set of conditions under which constraints can be formulated and propagated
4. A method of finding solutions that satisfy constraints.

According to Stefik, constraint posting is a knowledge intensive style of problem solving and, as a result, MOLGEN's performance improved whenever it's theory of constraint formulation and propagation, i.e., its domain knowledge, was augmented. The power and flexibility of constraint posting derives from the notion of formulating constraints based on the context of the problem, rather than requiring that all constraints be defined before the solution process is started.

5.4.4 CONMAN

CONMAN [7], which stands for constraint manipulation, is a program that was developed by Holtz at CMU to manipulate constraints contained in structural design specifications. Such constraints are typically represented in the form of algebraic expressions and have been used in decision tables to check the adequacy of designs. In order to use them in a design mode, the constraints must be rewritten such that some structure attribute is expressed as a function of a known code constraint. CONMAN performs symbolic algebraic manipulation of the constraints to automatically rewrite the constraints in the form required. When

CONMAN is used in the design mode it produces expressions that define the upper and lower limits of acceptable values for the unknown attributes. The program was originally implemented in LISP, which Holtz considered far easier than a subsequent reimplementation in PASCAL.

5.4.5 Other Work

Chan [4] extended the constraint based reasoning paradigm to account for performance constraints. In his work, Chan represented the concept of allowable stresses in the form of constraints on the areas of simple truss members. He established further constraints in the form of arbitrary relationships between the areas of the truss elements in order to force a condition of constraint violation that would require modification of the constraint set. The focus of this work was the control required to reason with constraints using a PROLOG implementation. In the implementation, the constraints are hard coded in PROLOG rather than formulated and only the results of the structure behavior are represented, rather than the behavior itself.

5.4.6 Conclusions

Both Sketchpad and Thinglab presented elegant examples of how the process of constraint propagation and satisfaction could be used in an object oriented programming approach to analyze redundant structures through the use of relaxation methods. Both programs explicitly represented and satisfied behavior constraints. In MOLGEN, Stefik proposed a general method of reasoning with constraints that involved formulating constraints on the problem solution from given facts. MOLGEN's reliance on heuristic rules only as a last resort coupled with the concept of constraint posting offers both power and flexibility. Holtz's work is intriguing because of its potential application in deriving limits for attributes that are part of a mutual constraint and its potential in terms of performing the symbolic structural analysis required during the conceptual design.

5.5 Recent Research on KBS for Structural Design

Recent research has concentrated on using knowledge based systems (KBS) to 'reason' about problem solutions within a particular domain. For the most part, these systems have concentrated on integrating selected tasks within one particular domain. Some of the recent research is summarized below.

Among the significant works in the domain of structural engineering are three that were produced at Carnegie-Mellon University: HI-RISE, DESTINY, IBDE. HI-RISE [15] was developed in 1985 to perform preliminary structural design of high rise buildings. In DESTINY [19], Sriram developed a theoretical model of a KBS for performing integrated structural design for arbitrary building types. Work is currently in progress on IBDE [6], an integrated building design environment based on the work in HI-RISE and DESTINY.

INDEX, a KBS that performs both preliminary and detailed design of industrial building structures, was developed at the University of Edinburgh in 1987 [12]. STEELEX, a KBS that performs preliminary and final design on moment frames and designs the connections, was developed at Ohio State [17]. Worcester Polytechnic Institute and Massachusetts Institute of Technology are cooperating in developing a KBS [11] that will perform the preliminary design of high rise buildings using a somewhat richer knowledge base than that used in HI-RISE.

Most of the systems mentioned address the intradisciplinary integration of analysis and design. Some of the systems integrate the conceptual, preliminary, and final design tasks within the structural design discipline. Carnegie-Mellon addresses the horizontal integration between architect and structural engineer in IBDE and provides a construction planning feedback loop.

Three of these systems, HI-RISE, DESTINY, and IBDE, that have the most relevance to this research are addressed in more detail below.

5.5.1 Hi Rise

HI-RISE [15] was one of the first in a series of knowledge based systems developed at the Carnegie-Mellon Engineering Design Research Center in the domain of building design. HI-RISE, and it successors LOW-RISE and ALL-RISE are examples of classic rule based expert systems.

In HI RISE, the geometry (including column and frame locations) and load constraints are provided explicitly as input and are treated as 'hard' constraints. The system uses a set of heuristic rules derived from available literature to arrive at a structure that satisfies the constraints. For the most part behavior and performance constraints are implicit in the heuristic rule set. The system uses classical approximate methods to explicitly satisfy performance constraints related to safety. Performance constraints related to the deflection of the building under lateral loads are not addressed explicitly during the conceptual design.

Cost data are not generated during the conceptual design process and are, therefore, not used as part of the system selection criteria. Heuristic rules are used to determine which subsystems are feasible and to select from the set of predefined subsystems to develop a single unique solution to the structural design problem. In so doing, HI RISE makes implicit decisions about *Cost/Value* while not addressing either part of the objective function explicitly. The approach used in HI-RISE for resolving the beam-duct-ceiling interface is to include a rule that constrains the selection of the structural element to be the one that satisfies design criteria (section properties) and has the minimum depth. This kind of rule may be too rigid.[8]

HI RISE performs constraint propagation and satisfaction, but starts with a relatively complete set of predefined constraints as opposed to using the constraint formulation approach. As an example, the locations of columns and frames, which are primary subjects of the conceptual design process, must be predefined for HI-RISE.

HI RISE was a significant achievement in the application of AI and DBMS in the domain of structural engineering. It was one of the first attempts to model the nonnumeric reasoning process in structural design. The rule based representation used in HI RISE is capable of capturing relationships among design features that cannot be represented as algebraic expressions. This approach makes it possible to automate the heuristic process by which initial solutions to the structural design problems are synthesized.

The disadvantages of HI RISE are that it relies primarily on heuristic rules rather than first principles in the development of the details of the problem solution and it requires that many constraints be predefined rather than formulating them.

5.5.2 DESTINY

DESTINY [19] is a theoretical model of a KBS for performing integrated structural design. It builds on the work of Maher and uses a rule based approach with the same input restrictions as HI-RISE. DESTINY is of interest because of the reasoning modules that are envisioned as necessary and the abstraction of the conceptual objects that were used to represent the structure.

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[8] This rule would cause the system to select a W10x100 in lieu of a W24x55 every time.

The representation scheme proposed in DESTINY is an abstraction hierarchy consisting of eight levels as follows:

1) *TOP* - The top level contains a description of the building in terms of number of stories, building occupancy, design loads, and the building grid. This information is provided as input.
2) *Functional* - This level contains the lateral and gravity load systems, which are linked to the top level by a *part of* relation.
3) *3D-Mat* - This level contains lateral and gravity materials that are linked to level 2 by an *is-alt* relation.
4) *3D* - This level contains geometric descriptions of the lateral and gravity systems. Both systems are described in terms of the number of bays and aisles (where bays are the north-south spaces, while aisles are the east-west spaces). In this way, the building grid is defined as being a number of bays at a uniform grid in each direction. The spacing can be different in the two directions, but the building is divided into a uniform system of identical rectangles. The gravity system is described in the same manner at this level, but contains an additional attribute, which is floor type.
5) *2D* - This level contains a description of the lateral and gravity systems classified according to inside or outside. This classification allows the use of different frame types on interior and exterior bays, in the context of the bay definition contained in (4).
6) *Location* - This level contains information for locating 2D systems in the grid. It is linked to the 2D level by the is-alt relation.
7) *Component* - This level contains component descriptions that are linked to the location level with a component-of relation.
8) *Property-Response* - This level contains the member property and response data and is linked to the component level by the component-of relation.

The above representation scheme emphasizes the form of the structure. Levels 1, and 3 through 7, all contain attributes of the structure describing its form. Part of level 8, properties, is also used for form representation. Function is represented only at a system level, i.e., level 2, while behavior is represented only at the component level, i.e., level 8. The representation of the framing patterns allows only uniform bay spacing in two orthogonal directions.

In the blackboard architecture used for DESTINY, the reasoning process is divided into five knowledge modules as follows:

1) *TACON* This is the task control module and performs the strategic reasoning. The default strategy is to schedule the four *specialist* modules, enumerated below, in sequence.

2) *ALL-RISE* ALL-RISE is the successor to HI-RISE and is extended to accommodate low and mid rise buildings as well as high rise buildings. This module utilizes heuristic rules to synthesize structural systems. The three subtasks that are performed are synthesis, evaluation, and preliminary analysis. Only the first two of these were implemented in DESTINY.

   The synthesis is approached as a problem in constraint based reasoning, in the context of the rule based system. Several methods of constraint classification are proposed. On an abstract level, constraints are classified as either *external*, resulting from external influences, or *internal*, resulting from relationships between components. These two classifications are further grouped according to source as *Designer, Owner/Client, System-based* ('relations imposed by the structural elements and subsystems'), or *Regulatory*. In the actual implementation, the constraints are classified as *Synthesis, Interaction, Causal*, or *Parametric*. Synthesis constraints are constraints that influence the generation of feasible alternatives. Interaction constraints arise from the interaction of structural subsystems among themselves and with other subsystems. Causal constraints represent the equations of equilibrium and compatibility. Parametric constraints are constraints on the attributes of components and include serviceability and strength.

   Only the first two types of constraints, synthesis and interaction, are considered in ALL-RISE.

3) *MASON* *MASON* is envisioned as a pre and post processor for conventional analysis programs. It was not implemented in DESTINY.

4) *DATON* *DATON* sizes, proportions, and details the structural components based on the results generated with MASON. It is envisioned as a standards processor, but was not implemented in DESTINY.

5) *CRITIC* This module checks to see that the design is acceptable and performs the two subtasks: criticize and evaluate. CRITIC was not implemented in DESTINY.

The strategy employed by DESTINY for conceptual design relies on heuristic knowledge.

The function and behavior of the structure are not addressed during the synthesis process. Evidently MASON, DATON, and CRITIC, are envisioned as knowledge modules that perform detailed design. As with HI-RISE, DESTINY examines multiple alternatives for the subsystems and uses heuristics to determine the 'best' combined solution before performing the preliminary analysis and design.

5.5.3 IBDE

Carnegie-Mellon is developing a system, Integrated Building Design Environment (IBDE) [6], that performs all the design and planning functions involved in building structures beginning with the program development and ending with the construction planning. The proposed system utilizes seven knowledge modules that interact in a blackboard architecture. There are also process critics and process activators that are associated with each knowledge module for the purpose of providing and reacting to feedback. An overall design critic is planned that will provide critiques of the design using external knowledge sources. The planned knowledge modules and their proposed functions are summarized below.

> *ARCHPLAN* takes as input a description of the project context, program, and budget and produces an architectural concept describing the building massing, dimensions, core size and location, and the distribution of functions within the building.
>
> *CORE* uses the output from *ARCHPLAN* and produces a core layout including the number and location of elevators.
>
> *STRYPES* takes as input the output from ARCHPLAN and design loads and configures a structural system. It is based on the work done in HI-RISE.
>
> *STANLAY* uses the output from *STRYPES* to generate a complete structural system and performs preliminary analysis.
>
> *SPEX* uses the output from *STANLEY* as input and produces a preliminary design for the structure components.
>
> *FOOTER* uses as input the output from STANLAY and a description of the soil conditions on the site and produces a preliminary foundation design.
>
> *CONSTRUCTION-PLANEX* accepts as input the descriptions generated by the other modules, site information, and resource availability and produces a plan of all construction activities, including a schedule and cost estimate.

In the initial version, IBDE processed the knowledge modules in sequence. Future versions will provide integration of the planning and design activities through the use of the critics. The researchers are using the IBDE system as an experiment to develop theories about the design process rather than attempting to define and model that process *per se*.

5.5.4 Summary

A good part of the effort in current research is directed toward developing the software for implementing the various systems and refining the AI aspects of the KBS. STEELEX was implemented to demonstrate the capabilities of SDL, a programming language developed at Ohio State. INDEX was implemented in PROLOG, as will be the WPI/MIT program. Much of the research effort in IBDE is directed toward the implementation of a data base schema to support the reasoning process.

The systems mentioned place little or no emphasis on the issue of integrating the design and the drawing (communication of the design) functions. STEELEX and IBDE incorporate graphics for user interface only. Since the end users of the information generated by the design process are the construction and owner entities, at this time the constraint propagation must logically end with a transition from electronic communication to human communication.

To date, efforts at acquiring and implementing heuristic knowledge from practice have been limited. The developers of INDEX did attempt to capture the knowledge of practicing professionals and also tested their system on real design problems taken from industry with some success. Almost all of the knowledge used in HI-RISE was derived from textbooks. The developers of CMU's IBDE have purposely taken the approach of developing the system without explicit knowledge of the process currently used for designing buildings preferring to experiment with the system to gain insights into the design process, using it as a "vehicle for discovery and theory formation." [6]

The systems summarized all approach the conceptual design on an abstract level using heuristic rules. Few attempts are made to explicitly represent the function and behavior of the structure during preliminary design. An alternative approach, and one that is closely related to the existing process, is to represent and reason about the function and behavior of the structure based on first principles. This will lead to more general forms of reasoning in which the strategies for controlling behavior can be developed. Model based reasoning, which incorporates the constraint posting method used by Stefik is one approach that could be used to do this.

5.6 Research Issues for ISD

The proposed development of the Integrated Structural Design Environment is based on a philosophy of starting with the process of building design as it now exists in practice. In practice, an expert can produce a conceptual design consisting of several solutions, such as that shown in the example in Appendix B, with estimated behavior and costs in 40 to 80 hours, using a model based approach founded on first principles. It should be possible to define and formalize the qualitative reasoning process used and produce the same results in far less time using AI techniques.

In order to develop such a system it is necessary to formalize the heuristic knowledge of the significant features of the various subsystems and their interrelationships and the heuristic knowledge about strategies that can be used to manipulate the structure attributes. In the following sections some of the issues that will need to be examined in depth are summarized.

5.6.1 Representation Issues

The representation scheme for ISD should explicitly address form, function, behavior, and the constraints that apply to each of those.

The representation must be comprehensive and unambiguous. Humans are adept at overcoming the ambiguities in the language by recognizing subtle changes in context that shade the semantic meanings of the elements of vocabulary. For the computer, it is important to identify precisely the different concepts that are embodied in the knowledge, and to represent those concepts explicitly. The representation must also include concepts that are ingrained or intuitive to humans. All humans experience gravity from the day they're born and know intuitively that objects that are not supported fall. The computer has no such knowledge or intuition unless it is explicitly provided by its human programmer.

Geometric patterns figure prominently in engineering. Most engineers use sketches of geometric patterns as tools to aid in their formulation of an engineering problem, and are considerably less efficient when they do not use those tools. The significance and meaning of the patterns must be discovered and represented in such a way that the knowledge can be used by the computer before developers of automated reasoning systems can successfully reproduce 'reasoning' in the domain of structural engineering.

The form of the representation has an impact on the ease with which facts can be stored and manipulated. In the context of model based reasoning, Kunz [14] suggests that a frame based representation of objects offers advantages. In this approach objects and attributes are stored in a frame that has multiple named slots, or compartments that hold the data, both numeric and symbolic, that describe the object. In an object oriented system, the frame slots can also contain references to procedures that are used to calculate the value of the slot. As an example, an object 'simple-beam' can have attributes w, L, and M; and the value of M can be the procedure $M=wL^2/8$. Relationships between slots can also be expressed as rules. Extensions to the frame based concept include inheritance which defines class-subclass-object relationships. A complete description of these concepts is beyond the scope of this dissertation which focuses on *what* is to be represented rather than *how* it is to be represented. However, in the following discussion and in subsequent chapters, the object oriented paradigm is assumed in the representation schemes presented.

The most fundamental representation issue that must be addressed involves the structure function, that of carrying loads. This is a concept that is second nature to human engineers and underlies all of their reasoning activities. However, seldom is function addressed independently of behavior. Most heuristic rules combine elements of both and design standards focus almost exclusively on behavior, since function cannot exist without behavior.

The premise of this research is that structure function can be explicitly defined and represented independently of behavior, and that this is essential to automating the reasoning process.

As a justification for this statement, consider the conventional method of determining behavior in structural engineering - the use of procedural finite element analysis (FEM) programs. If there is a complete and stable load carrying system, the analysis program can predict the behavior. However, if those conditions do not exist, the behavior is undefined and cannot be predicted by the analysis program. For the purposes of this research, a structure is defined to be functional when its topology forms a complete and stable load carrying system.[9]

The function of the structure can be described in terms of a load path, which is a geometric pattern defined by the structural elements through which a load is transferred

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[9] This conflicts with the common approach in which the structure is considered functional only when there is a complete and stable path *and* all performance constraints are satisfied. Nevertheless, it is felt that the distinction between function, behavior, and performance is necessary to produce a precise and unambiguous vocabulary for use in automating the reasoning.

from the point of origin to the foundation. The geometric patterns are precisely the patterns that appear in the sketches used by engineers to facilitate the reasoning process.

The function representation of the structure should include conceptual objects representing *systems* such as frames and diaphragms as well as conceptual objects representing system *components* such as beams, columns, verticals, and diagonals. Within the context of a system, each component serves a specific function. The same physical object may be a functional component of more than one system and fill different functional roles in each of the systems of which it is a part. In Chapter 8, specific conceptual objects that perform designated functions in the different systems are identified and a representation scheme for both systems and components is developed.

The constraints on the structure function - the loads - must also be represented. The loads for which a structure must be *designed* are related to, and completely defined by, the structure context.[10] The relationships between the context and the value of the loads are well known and documented and therefore the formulation of these constraints in an automated environment should be straightforward. All that is needed is a suitable representation scheme. Automatic formulation of the function constraints is a necessity if a system is to be able to automatically respond to changes in the structure topology or the context.

The representation of structure behavior on a component level includes the forces on the component and the resulting deformations. These are related by behavior constraints which, themselves are derived from physical laws. Deriving the forces from the deformations, or vice versa, is a form of reasoning. This reasoning can be incorporated in the object representation since the values of the force and deflection attributes of the object can contain algebraic procedures expressing the value of an attribute as a function of the values of other attributes. In this approach, the behavior is an attribute of the object.

The behavior representation should include system behavior as well as component behavior. This is particularly important in the treatment of lateral systems, where the element behavior has no meaning outside the context of the system behavior. While the system behavior could be computed and represented with the object oriented paradigm similar to the element behavior, the complexity increases significantly. In this dissertation, system behavior is derived through a reasoning process modelled on the approximate

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[10] This is not to say that the load that the structure may *experience* is completely defined. This is certainly not the case with seismic loads.

classical methods used in practice for conceptual design.

Performance constraints, which limit the behavior to specified values or ranges of values must also be represented on both the system and component levels. An example of a system performance constraint is the permissible story drift under lateral loads.

In addition to representation of function and behavior, the form, i.e., the physical attributes of the structure, must be represented. This is the type of representation that is most familiar, and has received considerable attention in the past. In addition to representing the form of the structure, the constraints on the form, i.e., material and geometric constraints, must be represented. Since many of these constraints are formulated based on the form of the architectural and mechanical systems, the significant features of those systems must also be represented in order to enable constraint formulation. This is only a partial representation of those systems, since only the view that is significant to the structural reasoning is represented.

5.6.2 Reasoning Issues

The reasoning process in ISD occurs on two levels. The abstract level includes the heuristic rules that are used to synthesize potential systems of load paths (structure topology). The heuristic rules for synthesizing structure topology will be similar to those used in the systems discussed previously, although the scope will be expanded to include the reasoning used to synthesize the column locations which are predefined in earlier systems. In addition to that task, the reasoning at this level models the strategic reasoning used in engineering to manipulate the constraint set and/or structure attributes to produce the desired behavior. This strategic reasoning forms the bulk of the control reasoning in ISD. Strategic reasoning is examined in the context of conceptual design example in Chapter 11.

The second type of reasoning is that which is used to derive the structure behavior given the loads and structure topology (load path) and component attributes, or conversely, derive the structure attributes, given the topology and desired behavior.

The two types of reasoning can be summarized as follows:

1) Given *BEHAVIOR* and *FUNCTION*, derive *FORM*, or
2) Given *FORM* and *FUNCTION*, derive *BEHAVIOR*

The reasoning in (1) constitutes a synthesis process that is analogous planning and is difficult to automate because of the role human intuition and inspiration play in that process. The reasoning in (2) constitutes an analysis problem that is straightforward and can be readily automated, provided the physical principles that govern the system are known.

In the design of commercial office buildings, this type of reasoning is most often applied in the context of the lateral systems, since the behavior of those systems tends to be more complex than the behavior of gravity systems. The behavior of a system is a function of the aggregate behavior of the components. Given the member forces, the component behavior can be computed directly as part of the representation. The component forces and behavior can be idealized based on heuristic rules that render the system statically determinate using simplified heuristic models. The system behavior can be related to the component behavior through the use of heuristic rules. In this approach, the classical methods of approximate qualitative and quantitative analysis are explicitl y implemented.

An alternative is to incorporate pre- and post-processors in the system and invoke a standard analysis program to determine behavior, as is envisioned in DESTINY [19]. However, it is inefficient to use such programs during the iterative process of conceptual design, and the precision they offer is of little use during that phase. In addition, the reasoning that is required for preprocessing is that which is required to describe structure function, and the reasoning required to process the results of a rigorous analysis is precisely the reasoning required to implement the classical approximate methods.[11] An additional benefit of implementing the classical methods is that they are transparent, making it possible to test the effects of varying different structure attributes, an essential ingredient in model based reasoning and in conceptual design.

5.6.3 Control Issues

The reasoning process for a global design system should encompass all of the control functions shown in Figure 4.1. This implies that there are at least three levels of control within the entire design system, global, regional, and local. The control functions at the local level include the application of the strategic reasoning discussed in the previous section. Since decisions regarding *Cost / Value* should not be made at the local level, and the local ISD

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[11] Along with these justifications, the following speculation is offered. As hardware becomes more powerful, and software techniques more sophisticated, it is only a matter of time before it becomes eminently feasible using an object oriented approach to develop a 'digital/analog' computer model that reacts instantly, continuously, and accurately to changes in context. When that time arrives, the concept of assembling and solving a massive set of simultaneous equations every time a minor adjustment to the structure is made will seem quaint and primitive.

system is expected to be incorporated in a larger automated environment that includes support for other design entities as well as support for owner and construction functions, the initial implementation should model the control structure at all levels.

5.6.4 Knowledge Acquisition Issues

The ability to perform constraint formulation and propagation is highly dependent on adequate knowledge resources. As a minimum, knowledge is needed in each of the following areas:

1) Factors affecting costs
2) Factors affecting value
3) Constructibility issues that must be addressed during design
4) Mechanical system features that interact with structural features and the cost implications of such interaction
5) Architectural features that interact with structural features and the cost implications of such interaction
6) Heuristic approaches to formulating potential structural systems
7) Methods of performing approximate analyses utilizing a combination of first principles and heuristics

The knowledge can be generally classified as follows.

Specification Knowledge Specification knowledge has to do with regulatory requirements. It is knowledge about the legally required constraints on the design. Specification constraints must always be satisfied. This knowledge is reasonably static and can be maintained separately in a resource library.

The work currently underway in the area of standards processing uses specification knowledge. Decision tables have been used in the past to 'reason' about constraints imposed by specifications. Jain [10] proposes using predicate calculus to process standards. Specification knowledge includes knowledge about when to apply the constraints contained in the specifications as well as knowledge about the constraints, themselves. Reasoning with the first category of knowledge takes the form of constraint formulation while reasoning with the second category takes the form of constraint satisfaction.

First Principle Knowledge This is knowledge about the behavior of the physical systems that are the object of the design. In structural engineering this includes knowledge about the relationships between stress and strain, the principles of static and dynamic equilibrium, and the relationship between forces and deflections.

Heuristic Domain Knowledge Much of the heuristic knowledge used in structural engineering has as its origin the experience gained from the application of first principle knowledge in the domain. This knowledge allows experienced engineers to formulate appropriate solutions for a given problem rapidly without performing all the steps that a novice might perform. Heuristic knowledge is used to simplify complex problems to render them tractable, as in the portal or cantilever methods of analyzing moment frames. Heuristic knowledge is also used in synthesizing floor plans, or potential load paths. Decisions based on heuristic knowledge, which itself is based on first principle knowledge, can be verified using first principles and a conscious effort must be made to utilize the first principles whenever possible.

Market Knowledge Market knowledge is knowledge about the set of potential values for the material or system attributes of the facility and the parameters used in estimating the costs of those materials and systems. This includes manufacturers' data such as the AISC table of steel shapes, manufacturers' catalogues of standard building components, and pricing information relative to material, labor, and prefabricated components. Constructibility knowledge, which includes methods of construction involving different combinations of capital and various kinds of labor, is contained in this category.

This knowledge is used to formulate constraints regarding the set of possible solutions and to evaluate those solutions. Market knowledge can be used to formulate constraints of the form:

Material is one of (steel, reinforced concrete)

Heuristic domain knowledge and first principle knowledge are used to define the structural systems in the context of each potential material and then market knowledge is used to formulate constraints relating the features of each design solution to its cost using the form:

$$\text{Cost} = f(A,B,C)$$

where A, B, C are attributes of the design solution.

Market knowledge must be specific to both the time and the geographic location of the project since costs are subject to fluctuations that depend on local market conditions.

Interaction Knowledge Interaction knowledge is knowledge regarding the interfaces between the attributes of subsystems. Constraints on the structural systems resulting from features of the architectural and mechanical systems are formulated using interaction knowledge.

Meta - or Control - Knowledge Control knowledge is knowledge about the process which is used to develop the solution strategy given the context of the design problem, much of which is derived from heuristics.

Since the subsystems that comprise a modern high rise structure are complex in and of themselves, the nature of the interaction may be subtle. For this reason, maximum use should be made of existing domain expertise in developing interaction and control knowledge.

5.6.5 Communication Issues

The issue of communication - of both data and the meaning of the data (semantics) - is central to the life cycle process. Lack of communication or misinterpretation of communication can have profound effects on the cost and the safety of constructed facilities. For this reason it is essential that automated design systems address external as well as internal communication issues.

The conventional method of communication on projects is by means of graphical representations of the concepts. It should be noted, however, that the form of the diagrammatic and written representation have evolved significantly. This is the result of the need to communicate vast amounts of data, both syntactic and semantic, among the various parties to the design/construction process. [12] As long as people remain in the system a picture will be worth a thousand words. The method of user interface should be graphical and maximum use should be made of the existing graphics vocabulary in developing the graphical representations of the solution.

Ideally, the same graphical representation that is used in the reasoning interface should be used as the means of communication between project participants. The same graphical database should be used to generate video displays for the CAD system, the KBS, and the hard line drawings. This will eliminate inefficient multiple processing of data but will require better integration of the software tools. Object oriented programming again offers a method of accomplishing this. One of the attributes of an object used in the reasoning

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[12] This evolution of the representation was given added impetus by the propensity of the legal profession for insisting on precise and unambiguous contracts. The drawings and specifications form a part of the contract between owner and contractor. Hence the term 'Contract Documents.'

process can be the form of its graphical representation within the standard CAD environment. Eventually, this approach could evolve into a hyper-media data base in which graphical objects are handles for accessing the underlying data, and the form of the graphical object changes as the perspective of the viewer is changed, allowing, for instance, the viewer to see an elevation and then zoom in to look at a connection detail.[13]

Internally, the issue of electronic communication between systems or modules within a system must be addressed. A basic issue is whether all of the system modules will communicate with each other, or if communications will be centralized as in a blackboard system. While communication in some form between all the modules is necessary, it seems logical that the communication should follow the hierarchical lines in order to facilitate control of the process. Allowing all systems to participate in all the decisions of all other systems would lead to chaos and extreme inefficiency. A better approach, and one that has worked well in the human system that we are attempting to model, is to allow the local controllers to synthesize complete solutions and then allow all systems to participate in the mediation of incompatibilities, keeping in mind the overall goal of minimizing *Cost / Value*.

Another issue is the communication and maintenance of the project data for which databases appear to be the natural tool. However, some method of including semantic data as well as physical data will have to be developed. Toward this end, it is essential that the reasoning processes that will use the semantic data be developed simultaneously to assure that the data is stored in appropriate form.

5.7 Proposed System Architecture

In this chapter, general approaches to reasoning have been discussed in the context of Integrated Structural Design, and some specific examples of knowledge based systems in the domain of structural engineering design were examined. The approach that emerges as most suitable for ISD is a combination of constraint posting as in MOLGEN [20] and the model based reasoning method proposed by Kunz [14]. Constraint posting leads to the concepts of constraint *Formulation, Propagation, and Satisfaction*; while the model based approach leads to the concept of representing the structure explicitly in terms of *Form, Function*, and

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[13] This is not the same concept as 'zooming' in current CAD systems, where the graphics data base contains all of the graphical data regardless of whether the current view requires that data. In the system envisioned, the database objects draw themselves in a graphical form that is consistent with the current view - a fundamentally different approach to graphical representation of building data.

Behavior. In subsequent chapters a constraint classification system is developed patterned after the model based reasoning approach, and methods of formulating, propagating, and satisfying constraints are examined in the context of the structural design of buildings.

The system architecture for ISD should be capable of capturing the layered control hierarchy of the design process, which meshes well with the concept of constraint posting used by Stefik in MOLGEN. It should also be capable of capturing the essential characteristics of the design process, that is, the phases and domains. The following proposed system architecture includes the functional description of the software modules that form the KBS and the manner in which they interact and is based on an examination of the reasoning process that is to be modeled. The implementation details are constrained by the capabilities of the software and hardware and the architecture of the final system may vary from the conceptual architecture. Figure 5.1 illustrates a 'two dimensional' view of the conceptual architecture required for ISD.

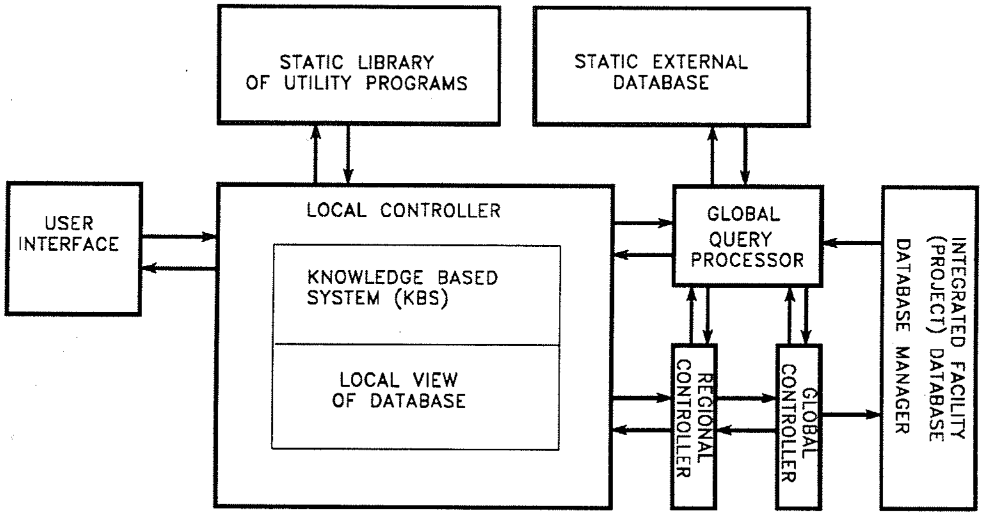

Figure 5.1 Two Dimensional View of Conceptual System Architecture for ISD

The local modules in Figure 5.1 correspond to the domain classification of the life cycle processes. The objectives of the reasoning process within the local modules change depending on the phase of the overall process, i.e., program development, design, construction, facility management. This fact is significant in the development of a KBS in this domain, because the knowledge required and reasoning activities that are performed depend on both the domain and the phase. In order to capture the full range of reasoning that takes place during the life cycle, it is necessary to use an architecture that can accommodate the many different contexts defined by the intersections of phases and domains. As the reasoning progresses, different functional processes (design, construction, facility management) become the focus of the reasoning. However, at all times all functional modules are required. Modules that are outside the primary focus provide support for the primary reasoning, i.e., during the design focus the construction module supports that focus by providing knowledge resources and acting as a critic. The different possible contexts and the 'flow' of the primary focus is shown in Figure 5.2.

As an example of the effect of the different contexts on strategy at the local level, consider the function of the structural reasoning system during schematic design and design development. During schematic design, the objective is to generate feasible worlds by synthesizing and combining multiple potential gravity and lateral systems. Since the set of possible solutions is quite large, the strategy is to examine the potential solutions on an abstract level using approximate methods and focusing on the typical floor and the lateral system. At the end of schematic design, the phase context changes to design development. During the design development phase, the objective is to synthesize structural configurations at the nontypical floors and the strategy is to use the system concepts adopted at the end of schematic design..

DOMAIN / PHASE	OWNER DOMAIN TASKS			DESIGN DOMAIN TASKS			CONSTRUCTION DOMAIN TASKS		
	FACILITY MANAGEMENT	STRATEGIC BUSINESS PLANNING	DESIGN/ CONSTRUCTION PLANNING	ARCHITECTURAL DESIGN	M.E.P. DESIGN	STRUCTURAL DESIGN	CONSTRUCTION PLANNING	CONSTRUCTION CONTROL	CONSTRUCTION EXECUTION
PROGRAM DEVELOPMENT	KNOWLEDGE RESOURCE	PRIMARY REASONING	PRIMARY REASONING	PRIMARY REASONING	KNOWLEDGE RESOURCE	KNOWLEDGE RESOURCE	PRIMARY REASONING	KNOWLEDGE RESOURCE	KNOWLEDGE RESOURCE
CONCEPTUAL DESIGN	KNOWLEDGE RESOURCE	KNOWLEDGE RESOURCE	KNOWLEDGE RESOURCE	PRIMARY REASONING	PRIMARY REASONING	PRIMARY REASONING	KNOWLEDGE RESOURCE	KNOWLEDGE RESOURCE	KNOWLEDGE RESOURCE
DETAILED DESIGN	KNOWLEDGE RESOURCE	KNOWLEDGE RESOURCE	KNOWLEDGE RESOURCE	PRIMARY REASONING	PRIMARY REASONING	PRIMARY REASONING	KNOWLEDGE RESOURCE	KNOWLEDGE RESOURCE	KNOWLEDGE RESOURCE
CONSTRUCTION PLANNING	KNOWLEDGE RESOURCE	KNOWLEDGE RESOURCE	KNOWLEDGE RESOURCE	KNOWLEDGE RESOURCE	KNOWLEDGE RESOURCE	KNOWLEDGE RESOURCE	PRIMARY REASONING	KNOWLEDGE RESOURCE	KNOWLEDGE RESOURCE
CONSTRUCTION EXECUTION	KNOWLEDGE RESOURCE	KNOWLEDGE RESOURCE	KNOWLEDGE RESOURCE	KNOWLEDGE RESOURCE	KNOWLEDGE RESOURCE	KNOWLEDGE RESOURCE	KNOWLEDGE RESOURCE	PRIMARY REASONING	PRIMARY REASONING
FACILITY MANAGEMENT	PRIMARY REASONING	KNOWLEDGE RESOURCE	KNOWLEDGE RESOURCE	KNOWLEDGE RESOURCE	KNOWLEDGE RESOURCE	KNOWLEDGE RESOURCE	KNOWLEDGE RESOURCE	KNOWLEDGE RESOURCE	KNOWLEDGE RESOURCE
PURPOSE	MAINTAIN OPERATE MODIFY	PLAN FINANCIAL RESOURCES	DEFINE PROGRAM ATTRIBUTES	DEFINE ARCHITECTURAL SYSTEM ATTRIBUTES	DEFINE M.E.P. SYSTEM ATTRIBUTES	DEFINE STRUCTURAL SYSTEM ATTRIBUTES	SCHEDULE RESOURCE UTILIZATION	MONITOR RESOURCE UTILIZATION	UTILIZE RESOURCES
	PLAN AND OPERATE			DEFINE PHYSICAL ATTRIBUTES			PLAN AND CONSTRUCT		

Figure 5.2 Life Cycle Reasoning Process Classification

The functional classifications of the processes shown in Figure 5.2 are denoted by descriptive names such as architectural design, structural design, etc. These, in turn, form groups in which the function can be classified on a more abstract level as owner related, design related, or construction related.

Figure 5.3 is a three dimensional view of a conceptual system architecture that corresponds to the different reasoning contexts that occur in the life cycle processes. There are three levels of control illustrated in Figure 5.3 corresponding to the control levels of the life cycle processes from Figure 4.1: global, regional, and local. The controllers correspond to the various domains and are responsible for setting the phase context within their own domain, deciding what strategy to use, and resolving mutual constraints.

The global controller sets the context according to the major phases of Program Development, Design, Construction, or Facility Management and sets the global strategy in addition to its responsibilities for performing the reasoning associated with propagating constraints between regions and making global *Cost / Value* decisions.

Each of the regional controllers is responsible for refining the phase context in its region and setting the regional strategy in addition to propagating constraints between local processes and making regional decisions associated with mutual constraints. An example of refinement to the phase context is the distinction between schematic design and design development.

The local controllers are responsible for setting the local (domain specific) strategy and resolving mutual constraints within the domain, in the context of the phase strategies set at the global and regional levels. The domain specific reasoning is performed by the KBS at the local level. Figure 5.3 illustrates the focus within the ISD KBS in the local structural design module during conceptual schematic design.

In addition to the reasoning and control modules, Figure 5.3 shows the other elements of the system that handle communication, provide resources, and store data. The user interface is shown on the left hand side of the figure as a single element attached to all modules. The interface could just as easily consist of multiple elements attached to the local and regional controllers, or a single element attached to the global controller. Graphics are viewed as indispensable as a means of communication between man and machine. A library of utilities is represented by a large box connected to all modules and is envisioned as the repository for the conventional procedural programs that are currently used by the various project participants. There are two databases associated with the architecture, the *Static External Database* and the *Integrated Facility Database* (IFDB). The static external database contains the standards and product data that are required during the reasoning process, while the IFDB, or project database, contains data specific to the project. The IFDB must be equipped with a database management system for assuring the integrity and consistency of the data. To help in this, the system architecture requires that all manipulations involving project data be communicated through the global controller. A separate query processor, shown attached to all local modules, allows those modules direct 'read only' access to both the IFDB and the static external database. The query processing function is conceptually different than the reasoning associated with the control functions, and it is logical to separate them.

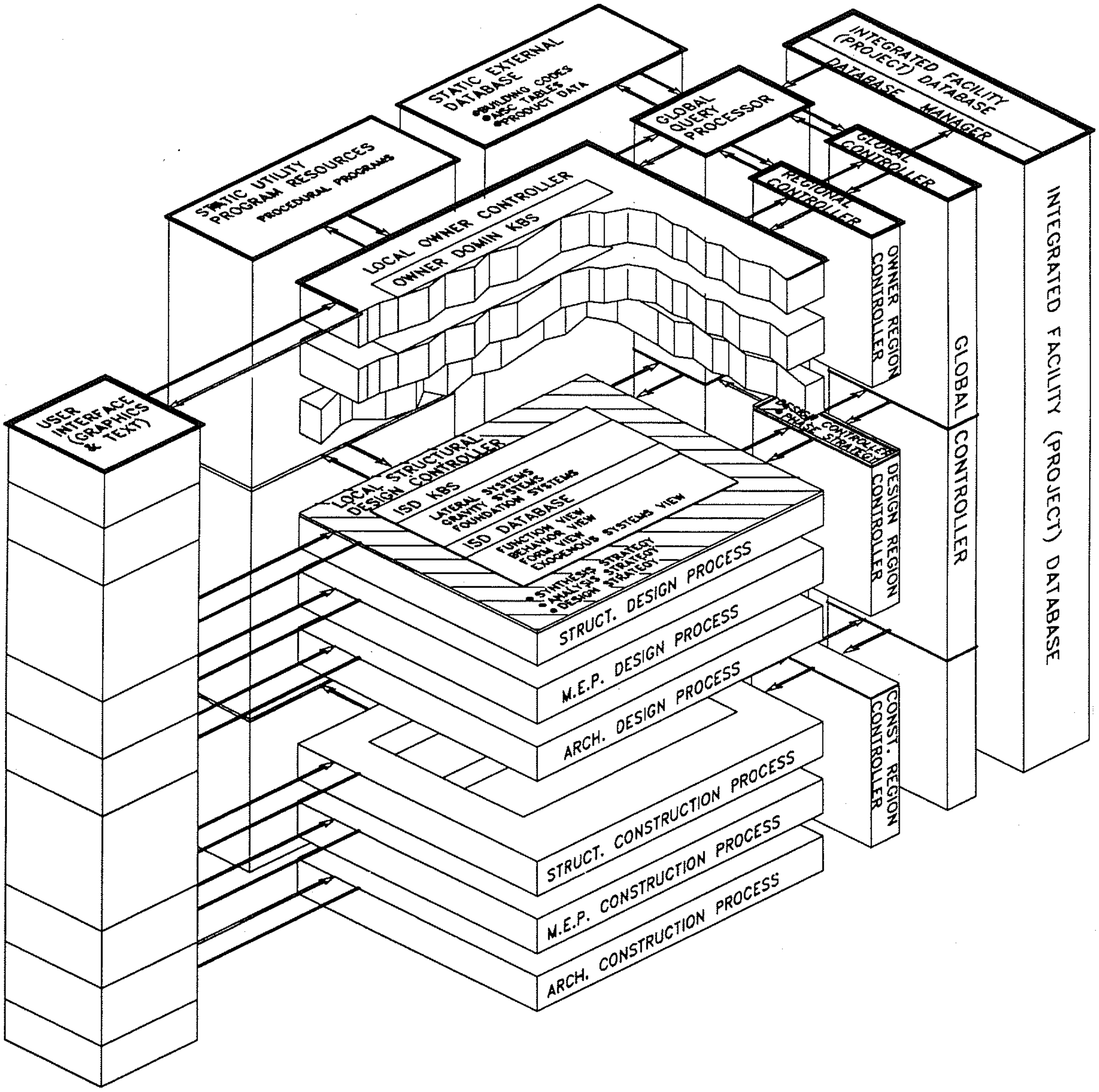

Figure 5.3 Three Dimensional View of Conceptual ISD Architecture

6

Reasoning With Constraints in ISD

6.1 Introduction

In this chapter a method of classifying the constraints that influence the structural design process is proposed. Such a classification is essential to the successful development of the complex integrated reasoning system that is envisioned as the long range goal of this research. The building design process that was described in the previous chapters is examined in light of the classification system and a method of approaching the problem of reasoning with constraints in the context of ISD is described. The latter part of this chapter contains a summary of constraints arising from exogenous systems and how they map onto the structural constraints.

6.2 Constraint Classification in the Structural Engineering Domain

The constraints on the structural system arise from many sources including the architectural systems, the mechanical systems, the construction activities, and the physical laws that governing behavior. However, in order to reason with the constraints, they have to be reformulated in the context of the structural reasoning process as constraints on the *function*, the *form*, or the *behavior* of the structure. In terms of the structural design, each of the constraints that is used in making decisions can be related to *Material, Geometry, Function, Behavior, Performance,* or *Reliability.* Constraints that arise from other subsystems (including constructibility constraints) must be transformed into one of these types of constraints before their impact on the structure can be assessed. In this classification system, the form of the structure is decomposed into *geometry* and *material*, *performance* is related to *behavior*, and *reliability* is related to both *function* and *behavior*.

6.2.1 Function Constraints

The primary - and in many cases the only - function of the structure is to carry loads from their point of origin to the ground. Certain elements of the structure may also perform an architectural function, i.e., the slab in addition to its structural function is the functional object 'floor' from the architectural point of view. When that occurs, there may be constraints on the physical object arising from its function in another domain but only the structural function, i.e., carrying load is discussed here. The constraints that relate to that function are the loads the structure must carry and the place to which it must carry them. In this dissertation, it is implicit that all loads end up at the ground, so the destination is not represented explicitly. The function constraints can be described in terms of forces that have a magnitude, a direction, and a location in space relative to the ground. It is convenient to classify the loads as either area or concentrated loads and according to direction as lateral (in the horizontal direction) or gravity (in the vertical direction) in order to decompose the conceptual design of the structure into subsystems. The form of function constraints can be summarized as:

1) Type of the load (area or concentrated);
2) Direction of the load;
3) Magnitude of the load;
4) Location of the load.

Gravity loads result from the weight of the building systems and occupants and are usually classified as either 'dead loads' which are the loads resulting from the known weight of a component or 'live loads' which are allowances for variable loads (such as those arising from occupants). All elements of the architectural and mechanical systems result in function constraints on the structure in the form of dead loads that arise from the self weight of the system components. In many cases, building codes specify the value of the loads that should be used in the design, based on the architectural function of the supported space. Building codes also give guidelines on the values to be used for the lateral loads that arise from wind or seismic phenomena.

Function constraints result also from soil loads which are lateral loads that depend on the geometry of the below grade structure and the soil properties. Soil pressures can become quite large and in cases where there is a grade change from one side of the building to the other may exceed the wind or seismic loading.

Internal forces can result from physical phenomena such as temperature and foundation movements. In the case of temperature effects and foundation movements the magnitude of the internal forces depends on the behavior of the structure. These loads are not, strictly speaking, function constraints[1] but are, rather attributes of the structure behavior under the effect of natural phenomena which must, nevertheless, be considered in the design.

6.2.2 Behavior Constraints

When structural elements are subjected to loads their behavior is usually characterized in terms of deflections, internal member forces, and stresses. The behavior is dictated by principles of physics some of which are summarized qualitatively below.

1) All of the external forces acting on an object that is in static equilibrium must balance, the classic Newtonian principle of F=ma.

2) The external forces exerted on a part of an object must be in equilibrium with the internal forces on that part. This is the same principle as (1). Not only must the object be in equilibrium, but all its parts must also be in equilibrium. The internal forces result in stresses that are a function of the geometric and material properties of the element and the magnitude of the internal force.

3) All elements deflect when they carry load and for all commonly used structural elements and materials there are well known closed form methods of calculating the deflections of the member given the externally applied loads and the member geometric and material properties.

4) In a system in which the element material remains elastic under applied loads - a common assumption for both conceptual and detailed design - the behavior of an element subjected to a system of multiple loads is equal to the sum of the behaviors of that same element subjected to each load independently, i.e., the principle of

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[1] Carrying these forces cannot be a primary function of the structure since one approach to accommodating the effects is to release the restraints that give rise to the internal forces, eliminating the forces.

superposition. This is a particularly powerful piece of knowledge in the reasoning process used to synthesize structural systems.

5) Members that are connected together at a joint must have compatible deflections at that joint.

The above principles are examples of behavior constraints on the structure. These are hard constraints that are useful in determining the response of the structure while it is performing its function of carrying load. Behavior constraints can be simple relations for linear elastic behavior or complex relations for composite materials or nonlinear behavior. The general form of a behavior constraint contains the following components:

1. The type of force;
2. The type of response(s);
3. The method(s) of computing response(s).

The response of the structural system - as opposed to an element - to applied loads is a function of the aggregation of all the individual element responses. If all the individual element forces are known - *or can be estimated to a reasonable degree of accuracy* - the individual element responses can be calculated. This, combined with knowledge of the relationship between element and system responses, makes qualitative and quantitative reasoning about the behavior of a structural system possible.

6.2.3 Performance Constraints

Performance constraints are limits on the values of the behavior the structure exhibits when subjected to load. Performance constraints enhance the safety and serviceability of the facility. Since behavior and function constraints are 'hard' constraints, the only way to satisfy performance constraints is to vary the structure topology or member material and geometric properties in order to alter the behavior in such a way that performance constraints are satisfied. Therefore, performance constraints are abstract constraints that cannot be satisfied directly but, rather, are satisfied by reformulation and propagation as geometry or material (form) constraints.

Performance constraints can be classified as either 'serviceability' or 'safety' constraints. Serviceability constraints limit the deflection, vibrations, or durability of the structure while safety constraints generally limit the internal stresses in the member. In limit state approaches such as LRFD in steel or ultimate strength design in concrete, rather than limit the stresses, the safety constraints specify a particular relation between the member forces at design load levels and the member's strength capacity for the type of force.

The components of a performance constraint are:

1) The type of behavior to be limited
2) The limiting value.

Most performance constraints that relate to human safety are specified by building codes. Building codes also provide guidelines for some serviceability constraints, although these guidelines are usually less comprehensive. For instance, the codes typically do not give a specific guideline for the amount of deflection the structure can exhibit under the effect of wind loads. Where no guidelines are given in the code, heuristic rules are used to establish the values of the performance constraints.

6.2.4 Reliability Constraints

Reliability, which refers to the probability that the structure behavior will be acceptable from either a safety or a serviceability point of view, is a field that is receiving increasing attention from the engineering community. Reliability constraints can be related to either the structure function, as in the case of redundancies, or to its behavior. An example of the latter is the fact that some engineers consider a tension member more 'reliable' than a compression member. Redundancy, which is a property of the structure related to its function, is sometimes used to qualitatively gauge the reliability of a structure. If there is only a single path for the loads to follow, the structure is 'nonredundant.' If there are multiple load paths such that when an element in one path fails the load can be transferred successfully to an alternate path, the structure is 'redundant.' Redundant structures are considered to be more reliable than nonredundant structures.

Reliability of various structural systems is implicitly considered in the method of determining the seismic design loads. Some aspects of reliability are implicit in the load and resistance factors used in limit state design of steel and concrete. For the most part, though, methods of explicitly incorporating issues of reliability during the design of structures have not been formalized. Heuristic rules based on engineering judgement are still the primary source of reliability input to the design process. As a result, reliability constraints are often described by conventional 'if - then' rules.

Although reliability is related to function, performance, and behavior, it is included as a separate concept as more or less a 'catch-all' constraint category that allows the exercise of engineering judgement, in the form of heuristic rules, that cannot be explicitly justified based on first principles given the current state of knowledge.

6.2.5 Geometric Constraints

Geometric constraints define the location and spatial relationships of the structural elements. Specific limits on member sizes or section properties are also geometric constraints.

The components of a geometric constraint are:

1. Geometric attribute;
2. Discrete value or acceptable range of values.

Geometric constraints result from the fact that the structural system must interact with the other systems in the building. The size and shape of the floor plate [2], the size and shape of the core, and the height of the building are attributes of the architectural solution that produce geometric constraints on the structure. The development of feasible framing patterns within the context of the architectural and mechanical concepts is an objective of the conceptual structural design. Certain of the structural features are also architectural features and therefore have an impact on the architectural as well as structural function of the building. The most prominent among these are the floor slabs and columns. Constraints on the locations and, in the case of the floor slabs, extents of these structural components arise from the impact they have on the other subsystems. Hence if the architectural function requires a column-free space, this becomes a geometric constraint on the location of the columns. It is more convenient to reason about locations where this constraint *doesn't* exist since it is easier to explicitly represent potential column locations that are related to the architectural features than to represent all those locations where there cannot be a column. Geometric constraints can also arise from the spatial relationships between attributes of the subsystem components, as in the example of the mutual constraint amongst the ceiling, duct, and beam.

Some geometric constraints are the result of the structure function since the feasibility of a framing pattern depends on the ability of that pattern to provide a complete load path, i.e., provide structural functionality. Consideration of the performance constraints in the context of behavior constraints results in specific requirements for the member section properties, which are also considered geometric constraints herein. The arrangement of functional

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[2] The word 'plate' is used for the conceptual architectural object, as opposed to 'slab', which denotes a conceptual structural object.

members to form a system of load paths, referred to as the structure topology, is a system of geometry constraints.

Some constructibility constraints are a source of structure geometry constraints. Examples include concrete beams that must be spaced at a particular interval to accommodate a particular arrangement of forms, spacing limits on steel beams that are a function of the cost of fabricating connections, and limits on member sizes based on crane or shipping requirements.

6.2.6 Material Constraints

Material constraints limit the material used in the structure to one of a specified subset of all possible materials. The subset is usually extremely limited based on heuristic knowledge about the type of facility being built. The customary subset of building construction materials used for the structural subsystems, which includes wood, stone, adobe, masonry, concrete, and steel, is limited to the latter three materials for high rise office buildings. Material constraints can result from the architectural form, as, for instance, when the aesthetic expression is exposed concrete. Constraints on the material may also originate within the structural domain as when a specific material strength or stiffness is required in order to satisfy performance constraints.

Material constraints have the following general form:

1. Structural component or feature;
2. Required material or acceptable materials.

The physical arrangement of elements of different materials to form hybrid members is a geometric constraint related to the member internal load paths and behavior, rather than a material constraint, but constraints governing the type of material used for the individual components are material constraints. Examples of hybrid[3] functional elements are reinforced concrete, post-tensioned concrete, composite steel beams.

Many material constraints originate as constructibility constraints. An example of a constructibility constraint that results in a material constraint on the structure is the range of concrete strengths that can be economically and reliably produced in the city where the facility is located. Some care has to be exercised in applying constraints such as this since a material that is available anywhere should be available at the project location *at some cost.*

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[3] The term 'hybrid' is used in lieu of 'composite' because the latter term has evolved to mean specific types of hybrid construction.

Examining all potential materials and trimming the solution space based on *Cost/Value* considerations, should produce the same results as applying heuristic rules, if the heuristic rules are correct.

6.3 Reasoning With Constraints in ISD

The process of structural design involves formulating function, geometry, material, performance, and reliability constraints, considering the project context which includes the project location, the architectural and mechanical system concepts, and local constructibility constraints. These constraints serve a useful purpose in organizing, focusing, and directing the process of synthesizing feasible structural solutions based on heuristic rules. Behavior constraints (first principles), when combined with performance constraints, provide the means for proportioning members and choosing materials, i.e., formulating material and geometric constraints. In this section, we examine how the method of constraint posting, which consists of constraint formulation, propagation, and satisfaction, can be adapted to the structural engineering process.

In the hierarchical planning process described in MOLGEN [20], constraints are formulated and satisfied based on abstract concepts before the planning proceeds to a greater level of detail. At each abstraction level the search space is pruned, minimizing the total number of potential solutions that have to be examined, very similar to the methods used in structural design. In the process of satisfying constraints at a high level of abstraction constraints are created at the next level of abstraction. Constraints that are created in one domain or phase are communicated to the domains and the downstream phases through constraint propagation. At any point in the process only the level of detail required to make the decision at hand is used and only the entities directly affected by the decision are involved, resulting in an efficient process.

In the example of the beam, ceiling, duct problem, the mutual constraint is first examined at an abstract level to determine the sensitivity of the *Cost/Value* function to the various parameters. At the abstract level, a representative 'typical beam' and 'typical duct' are studied in the context of the ceiling height (which is usually fixed because of *Value* considerations) and the floor to floor height (which can be varied). The sensitivity of cost to the three soft constraints, i.e., floor to floor height, beam depth, and duct depth is used to determine specific values for the variables that result in the minimum *Cost/Value*. The parametric study should include all the variables that represent potential design decisions and are involved in the mutual constraint, thus, the above example could also include the slab depth and steel material type as variables. At the next level of detail the specific values for the parameters that yield the minimum *Cost/Value* are used as hard constraints. For instance, if the most economical set of values at the abstract level uses grade 50 steel, a 6-1/4" slab, a beam depth of 18 inches, a duct depth of 16 inches, and a floor to floor height of 12'-6", then these become the values of the corresponding constraints for those attributes at every typical floor and constrain the values of all similar components. Of course, in order for this approach to yield valid results, the relationship between cost and the attributes must be well defined, which requires access to information regarding constructibility constraints. In general, the cost relationship and, therefore, the optimum values for the attributes may vary between potential framing schemes.

Function constraints in the form of loads, geometry constraints regarding the beam lengths, behavior constraints, and performance constraints all have to be considered at the abstract level, but are considered only for the representative beam. Once specific values have been selected for the geometric attributes of the mutually constrained objects, i.e., the depth and material grade in the example, the design is completed in the context of those constraints. The cycle of constraint propagation, formulation, and satisfaction continues during the detailed design wherein the function, geometry, behavior, and performance constraints are used to formulate geometric constraints on the section properties of each beam, given the material and depth constraints formulated at the higher level. If there is more than one beam that satisfies the material, depth, and section property constraints, which is generally the case, then the beam with the minimum cost, usually the lightest beam, is selected to satisfy the constraints.

The decisions that have to do with the selection of the appropriate values to use as hard constraints during detailed design have the greatest potential impact on the cost of the structure and are made during the conceptual design process. During conceptual design these issues are addressed for each of the potential schemes and, as can be seen, by the end of the conceptual design process, the detailed design is highly constrained. As a result, very little can be done during detailed design to alter the *Cost/Value* ratio. Since the detailed design takes the form of constraint satisfaction, it can be accomplished using suitable constraint satisfaction tools such as decision tables.

6.3.1 Constraint Formulation in ISD

Given the general layout of the architectural spaces, the location of the building, and the intended function of the building, many of the geometry and function constraints on the structure can be formulated. There is usually a well defined relationship between architectural features such as elevators, stairs, and wall locations, and structural features such as potential column locations. One or more feasible patterns of structural framing (systems of load paths) can be synthesized by combining conceptual objects based on heuristic rules relating the attributes of the architectural system to the geometric constraints on the structure.

While the process of synthesizing a structural system is organized based on the constraints arising from the architectural system, it must anticipate constructibility constraints. Generic concepts such as slab, beam, girder, and column refer to elements of the load path that can be made of a number of materials or fabricated as an arrangement of subcomponents. Since the most economical systems constructed of concrete have different characteristic dimensions than those constructed of steel, geometric constraints must be formulated based on constructibility knowledge. This implies a two step constraint formulation process consisting of:

1) Proposing several feasible structural systems based on high level heuristics, and,

2) Formulate general constraints on system geometry and materials for each of the proposed systems based on constructibility constraints.

As an example, if one of the structural systems proposed uses pan joists, the second step would generate geometric constraints corresponding to available pan widths and depths and material constraints corresponding to the available classes of concrete. Examples of additional constraints that might be formulated in the construction region based on constructibility knowledge are the costs of various types of forms, concrete, and reinforcing including information relative to the preferred form types (i.e. pan joist, waffle slab, flying forms, etc.). Preferences based on heuristics can be used to direct the solution process when two potential solutions have the same *Cost / Value* ratio.

Performance constraints regarding safety are formulated based on the type of structure and the applicable code. Performance constraints regarding serviceability are formulated based on heuristic knowledge in the context of the specific project. An example of a performance constraint that might vary depending on the context is the allowable deflection of a beam which supports cladding, where the allowable deflection varies according to the material type and the method of supporting the cladding. (The reader is referred to Appendix A for more detail on this issue.)

Behavior constraints on elements should not have to be formulated, since they can be viewed as a property of the element. In an object oriented approach using a frame based representation the attributes of the objects can include member end forces and deflections that are related by behavior constraints. However, the structure topology will determine the effect of the individual element on the system behavior. If the topology is captured automatically by the representation scheme, system behavior constraints can also be expressed as relations between the system attributes.

The behavior of structural elements is dependent on their geometric properties such as area and moment of inertia. In the process of satisfying performance constraints, additional geometric constraints on the element geometric properties can be formulated. This is the type of formulation problem addressed by Holtz in CONMAN [7]. By constructing symbolic structures representing the algebraic relationships between geometry, behavior, and performance and propagating them, Holtz was able to formulate geometric constraints on components such that performance constraints would be satisfied.

6.3.2 Constraint Propagation

Because of the hierarchical nature of the design process and the many different views of the constraint set, constraint propagation involves not only the communication of the constraint to a subprocess but also the reformulation of that constraint in the constraint language of the subprocess. Not all constraints formulated at the global, regional, or local levels are relevant to all of the subprocesses, but the relevant ones must be anticipated and communicated. In this approach each domain must possess some knowledge of the domains with which it interacts. The knowledge required defines the conditions under which there will be interaction, and, therefore, the conditions under which a particular constraint must be propagated. The task of reformulation is assigned to the receiving entity, so each domain must also possess knowledge defining what constraints it might be sent and how to reformulate them into its own constraint language. This knowledge is implemented in the controller functions at the various levels of the hierarchy. The activities that are performed during constraint propagation suggest that constraints that are propagated between domains should be described by a common language.

Masterplan constraints formulated in the owner region are communicated to the design region. These constraints define requirements for the building size, architectural function, quality, special performance and function constraints on the structure, and performance requirements for the MEP systems. The architectural design entity reformulates the constraints as constraints defining particular material and geometric attributes of the building such as floor plate size and shape, number of stories, type of cladding, etc., that are propagated to the structural and MEP entities.

The structural entity reformulates the constraints as geometric, function, or performance constraints that are then used to direct the synthesis of the structural system. Once a decision to synthesize a certain system has been made, that decision must be propagated to the construction region for analysis and synthesis of the appropriate material and geometric constraints.

Within the lateral and gravity system modules of the structural entity, the effects of the behavior constraints must be propagated in order to formulate detailed material and geometric constraints, i.e., section properties. This is the type of constraint propagation that was demonstrated in the simple truss problems of Sketchpad and Thinglab and could be a direct consequence of the representation in an the object oriented approach. This type of propagation is fundamentally different than that referred to in MOLGEN which used constraint propagation as a method of communication between weakly linked problems. The propagation of behavior constraints such as the effect of deflections at one node of a member on the forces at the opposite node is an example of a 'strong' link. Once the independent structural systems have been generated, complete systems must be formed by propagating the respective constraints of the lateral and gravity systems to form the possible worlds. In the example presented in Appendix B, the product of this step is the table of structural quantities for each of the prospective worlds. This is an example of constraint propagation within domain.

Since different structural worlds represent different constraint sets to the other design entities as well as to the construction and owner entities, these constraint sets must be propagated from the structural entity back to the other entities for evaluation. In the example in Appendix B, this step results in the cost premiums noted in the summaries for the different worlds. Finally, the data defining the potential worlds must be communicated back to the global level for a final decision. This decision may be based on qualitative as well as quantitative considerations. For instance, in the design example in Appendix B, although the exterior bracing scheme has the least cost, the owner may decide that the exterior moment frame has the lower *Cost/Value* ratio, based on a qualitative assessment.

6.3.3 Constraint Satisfaction

Constraint satisfaction occurs at all levels and in all domains of the design process. In the hierarchical process, constraints at abstract levels are implicitly satisfied by reformulation and propagation to the detailed levels. In the structural domain, all function and performance constraints are explicitly satisfied when individual components are selected whose attributes satisfy the detailed geometric constraints, i.e., geometric constraints that define required section properties. By applying the behavior constraints in the context of the previously formulated function, geometric, and performance constraints the required values of the element geometric properties are formulated. Constraint satisfaction at the lowest level in the structural design process consists of selecting elements whose properties satisfy those constraints. This is the step that most current design programs perform in conjunction with the analysis.

Constraint satisfaction may be accomplished by selecting appropriate objects from a predetermined set of available products such as the table of standard rolled steel shapes published by the AISC. However, a set of constraints that can be satisfied by a standard steel shape could just as easily be satisfied - in theory - through the use of a custom built object, i.e., a 'built up' steel shape. In some cases, that is the only way a set of constraints can be satisfied. *How* the constraints are satisfied is a strategic decision that must be based on market knowledge, constructibility input, and, in the final analysis, the *Cost/Value* ratio.

6.4 Constraints From Exogenous Systems

This section gives a brief overview of constraints arising from exogenous systems. A more detailed discussion of the exogenous systems themselves is presented in Appendix A.

6.4.1 Global Domain Constraints

Most of the owner originated constraints are filtered through the MEP and Architectural domains so that those that map directly onto the structural domain usually take the form of function and performance constraints, such as specific load carrying capabilities or vibration characteristics. Construction constraints are of two types: constraints regarding the commonly used materials and system geometries in a given market, which are used during system synthesis; and constraints relating the costs and physical features of the systems, which are used in the evaluation of system options.

Tables 6.1 and 6.2 give examples of some of the constraints that originate at the global level in the owner and construction domains. Columns one and two of the tables give the name of the domain features or constraints and the affected structural subsystem. Column three gives the classification of structural constraint that is formulated using the attributes while column four indicates whether the constraint is 'hard' or 'soft' - a heuristic classification that will vary depending on the project context and participants. Column five lists the features that form a mutually constrained grouping with the feature in column one, while the last column gives the phase in which the feature is normally considered. The constraints tabulated for the construction domain are examples of the type that would be used during synthesis. Most constructibility constraints, in the form of cost data, are used in the evaluation of the alternative structural solutions.

6.4.2 Cost Constraints

Most constructibility constraints relate the costs of the various structural solutions to the physical attributes of the solutions. Table 6.3 summarizes the costs that are often used in practice to evaluate the structural concrete solutions for high rise office buildings at the conceptual design phase and indicates whether the costs vary between regions and between contractors within a region. Since all cost data varies with time, it is necessary to examine all systems, both steel and concrete, during conceptual design. Even in the same market, variations in cost as well as changes in contractor expertise over time may alter the cost comparison of different solutions. By utilizing constructibility knowledge, designers can reflect current (or anticipated) market conditions in the conceptual design. This data is required before conceptual design commences in order to start to anticipate constructibility issues.

The objective of estimating during conceptual design is to capture the differences in cost not only between concrete schemes but also between concrete and steel schemes. In order to do this, the data used must be accurate and representative of the final costs of the typical systems, requiring a relatively 'fine-grained' view of the data.

The costs identified in Table 6.3 attempt to capture the difference between single and multiple form uses. Material that must be purchased for a single use can be amortized over multiple elements if the form is used more than once. Depending on the form material, there

Owner Constraint	Structure Feature or Subsystem	Constraint Classification	Constraint Type	Mutual Constraint	Design Phase
Vibration Limit	Gravity System	Performance	Soft	Human Comfort	SD
Acceleration Limit	Lateral System	Performance	Soft	Human Comfort	SD
Design Live Load	Gravity System	Function	Soft	Value Consideration	SD
Modification Flexibility	Gravity System	Function Material	Soft	Operating Costs	DD

Table 6.1 Example Constraints from the Owner Domain

Domain Feature	Structure Feature or Subsystem	Constraint Classification	Constraint Type	Mutual Constraint	Design Phase
Crane Size & Location	Maximum Steel Piece	Geometric	Soft	Column Splice Locations	CD
Available Concrete Strengths	Concrete Strengths	Material	Hard	--	SD
Maximum Shipping Piece	Max. Subassembly Dimension	Geometric	Hard	--	CD
Standard Forms	Joist Spacing, Column Dimensions	Geometric	Hard	--	DD

Table 6.2 Example Constraints from the Construction Domain[1]

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[1] This table shows only constructibility constraints used during synthesis of the structural system. Most constructibility constraints, in the form of cost data, are used in the evaluation of potential solutions rather than in the original synthesis of those solutions.

ITEM	UNIT COST	LOCATION DEPENDENT	CONTRACTOR DEPENDENT
Stick built forms:			
Square Columns 1 use	$/SFF	Yes	Yes
Square Columns 5 uses	$/SFF	Yes	Yes
Round Columns 1 use	$/SFF	Yes	Yes
Round Columns 5 uses	$/SFF	Yes	Yes
Walls 1 use	$/SFF	Yes	Yes
Walls 5 uses	$/SFF	Yes	Yes
Slab and Drop Soffits, 1 use	$/SFS	Yes	Yes
Slab and Drop Soffits, 5 uses	$/SFS	Yes	Yes
Drop Edges	$/SFF	Yes	Yes
Beam Soffits	$/SFF	Yes	Yes
Beam Sides	$/SFF	Yes	Yes
8", 10", 12", 14", 16", 20" Joist Pans	$/SFS	Yes	No
8", 10", 12", 14", 16", 20" Super Pans	$/SFS	Yes	No
Joist and skip joist labor per floor	$/SFS	Yes	Yes
Haunch Soffit	$/SFS	Yes	Yes
Haunch Sides	$/SFF	Yes	Yes
Flying Forms:			
Initial cost	$/SFS	Yes	No
Labor per floor	$/SFS	Yes	Yes
Slip Forms or Climbing Forms:			
Initial cost	$/Each	Yes	No
Labor per floor	$/Each	Yes	Yes
Concrete Materials & Placing:			
NMLWGT 4000 psi	$/CY	Yes	No
NMLWGT 5000 psi	$/CY	Yes	No
NMLWGT 6000 psi	$/CY	Yes	No
NMLWGT 7000 psi	$/CY	Yes	No
NMLWGT 8000 psi	$/CY	Yes	No
LTWGT 4000 psi	$/CY	Yes	No
LTWGT 5000 psi	$/CY	Yes	No
LTWGT 6000 psi	$/CY	Yes	No
Column and wall placement	$/CY	Yes	Yes
Flatwork placement	$/CY	Yes	Yes
Reinforcing Materials Fabrication, & Placing			
A615, Grade 40	$/Ton	Yes	Yes
A615, Grade 60	$/Ton	Yes	Yes
A706, Grade 60	$/Ton	Yes	Yes
A185, WWF	$/Ton	Yes	Yes
A416, Grade 270, PT (Prefab)	$/Ton	Yes	Yes
Fabrication Ties	$/Ton	Yes	Yes
Fabrication Column Offset	$/Ton	Yes	Yes
Fabrication Straight Bars	$/Ton	Yes	Yes
Placing, Slab Reinforcing	$/Ton	Yes	Yes
Placing, Column Reinforcing	$/Ton	Yes	Yes
Placing, Beam Reinforcing	$/Ton	Yes	Yes
Placing, WWF	$/Ton	Yes	Yes
Placing & Stressing PT	$/Ton	Yes	Yes

* SFF - Cost per square foot of face, total form contact area
SFS - Cost per square foot of soffit

Table 6.3 - Concrete Systems Conceptual Cost Data

is a limit on the number of times it can be reused. Table 6.3 is based on an asumption of five reuses.

For pan joist and skip joist systems, enough pans to form an entire floor are either bought or rented. The cost of purchasing or leasing for the duration of construction can be amortized over the number of floors to obtain the cost per square foot of soffit. In addition to the initial cost of the form material, there is a cost associated with the labor of setting and stripping the forms for each floor. Flying forms can be used with most of the framing types, although it is easier with the flat slab and joist systems, since they use a flat soffit form. The 'initial cost ' item under flying forms is intended to include the cost of leasing, purchasing, or building both the strong back (truss) system and the forms. In addition to that cost is a labor cost for setting and stripping each floor.

In a given market the cost/strength curve for concrete is normally fairly flat within the range of strengths that the local suppliers are comfortable with producing, reflecting only the incremental costs of the cement. It is useful to establish this range prior to conceptual design, since it will determine both the size and the cost of the building columns. The concrete material costs are broken into material, which is the cost from the ready mixed supplier, and placement. The intent is to capture the difference between the labor involved in placing concrete in columns versus that involved in placing the concrete in beams and slabs. No cost is included for finishing the slabs, since that cost would be the same for all schemes and, therefore, would not help distinguish between schemes.

Reinforcing materials include conventional reinforcing with yield strengths of 40 and 60 ksi, A706 weldable reinforcing, welded wire fabric (WWF), and post tensioning steel. Fabrication costs are divided into groups representing ranges of costs. Ties which use multiple bends in short, small bars represent high unit fabrication costs. Offset column verticals, which are medium length heavy bars with two bends represent medium fabrication costs. Straight bars which are simply cut to length represent low fabrication costs. A distinction is made between the placement costs for the various types of reinforcing.

As can be seen from Table 6.3, most of the costs associated with concrete construction vary not only with the geographic area, but also between contractors within a geographic area. The most economical system for a given facility may actually vary depending on which contractor is used, since contractors who have more expertise in certain types of construction can usually build those types more economically than a contractor without the expertise. *Unless the contractor is involved during the design phase*, an attempt is usually made to develop generic design solutions that do not depend on particular construction sequences or

ITEM	UNIT COST	LOCATION DEPENDENT	CONTRACTOR DEPENDENT
Noncomposite Metal Deck			
9/16 inch 18, 20, 22 gauge	$/SF	Yes	No
1 inch 18, 20, 22 gauge	$/SF	Yes	No
1-1/2 inch 18, 20, 22 gauge	$/SF	Yes	No
Composite Metal Deck			
2 inch 16, 18, 20 gauge	$/SF	Yes	No
3 inch 16, 18, 20 gauge	$/SF	Yes	No
Shear Studs			
3/4 x 5 inch	$/Each	Yes	No
1/2 x 5 inch	$/Each	Yes	No
Steel Base Cost			
A36	$/100 lb.	Yes	No
A572, Gr 50	$/100 lb.	Yes	No
A53 Grade B Pipe	$/100 lb.	Yes	No
A500 Grade B Tube	$/100 lb.	Yes	No
Size Extras			
W Shapes	$/100 lb.	Yes	No
S Shapes	$/100 lb.	Yes	No
C Shapes	$/100 lb.	Yes	No
L Shapes	$/100 lb.	Yes	No
Length Extras			
< 20 '	$/100 lb.	Yes	No
20' - 30'	$/100 lb.	Yes	No
30' - 40'	$/100 lb.	Yes	No
40' - 50'	$/100 lb.	Yes	No
50' - 65'	$/100 lb.	Yes	No
Miscellaneous Materials			
Paint	$/ton	Yes	Yes
Bolts	$/ton	Yes	Yes
Waste	$/ton	Yes	Yes
Joists	$/ton	Yes	Yes
General Fabrication			
'Easy' lots of repetition	$/ton	Yes	Yes
'Normal' conventional framing	$/ton	Yes	Yes
'Complex' special structures	$/ton	Yes	Yes
Specific Fabrication Items			
Stiffener Pair (Incl Weld)	$/Each	Yes	Yes
Bolts (incl. holes)	$/Each	Yes	Yes
Semiautomatic Weld	$/Foot	Yes	Yes
Manual Weld	$/Foot	Yes	Yes
Cope	$/Each	Yes	Yes
Web Opening (18x36)	$/Each	Yes	Yes
Flange Full Pen Prep	$/Each	Yes	Yes
Camber	$/Each	Yes	Yes
Shop Drawings			
'Easy'	$/ton	Yes	Yes
'Normal'	$/ton	Yes	Yes
'Complex'	$/ton	Yes	Yes

Table 6.4 - Steel Systems Conceptual Cost Data

ITEM	UNIT COST	LOCATION DEPENDENT	CONTRACTOR DEPENDENT
Erection Costs			
'Easy'	$/ton	Yes	Yes
'Normal'	$/ton	Yes	Yes
'Complex'	$/ton	Yes	Yes
1" Full Pen. Weld	$/inch	Yes	Yes
Miscellaneous Costs			
Shoring	$/SF	Yes	Yes
Fireproofing	$/SF	Yes	Yes
Transportation	$/ton	Yes	No
Profit	$/ton	Yes	Yes
Tax	$/ton	Yes	No

Table 6.4 - Steel Systems Conceptual Cost Data (Cont'd)

methods that are not widely understood or used.[4] This is especially true of the more sophisticated technologies such as flying forms, climbing forms, and slip forms. The elements that are constructed using these methods can all be constructed using 'stick built' methods.

Table 6.4 shows the types of steel cost information that are commonly used to perform the evaluation on the structural systems during conceptual design. The fabrication information in the table is patterned after a similar table presented by David Mathews, President of Ace Iron and Steel Corp., Milwaukee, Wisconsin, at a seminar at the University of Wisconsin in October, 1980.

In addition to basic information on steel material costs, Table 6.4 includes detailed constructibility information about related elements, such as metal decking, that are useful in evaluating various possible solutions. Metal deck information is used to evaluate the cost impact of different choices of combinations of beam spacing and concrete weight, e.g., 10 ft. spacing with 3 1/4" lightweight v.s. 8 ft. spacing with 4 1/2" normalweight. The depth and/or gauge of the deck can be varied to accommodate various combinations of span and construction load. The cost of shear studs must be included in the comparison of composite and noncomposite systems and is also useful in analyses relative to future flexibility. The various size and length extras help to define the true variation in cost with bay size and design loads. The miscellaneous materials do not help in distinguishing among the various choices for steel schemes but are necessary for proper comparison of concrete and steel

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[4] This is one of the most serious deterrants to innovation in the design/construction industry.

schemes. The category of fireproofing is needed for comparison of steel schemes and for steel/concrete comparisons. The cost of shoring must be included in evaluating schemes that rely on shoring in the design of the beams.

The categories of 'easy', 'normal', and 'complex' apply to shop drawings, fabrication, and erection and are used as an indication of the relative constructibility of various steel schemes. Simple framing for typical floors qualifies as repetitive and would therefore be classified as 'easy' while simple framing at nontypical floors is 'normal'. Trusses, plate girders, and moment frames are considered 'complex'. An alternative approach to evaluating moment frames is to treat them as 'easy' but add in specific penalties to account for the fabrication and erection of the moment connections. The category of 'Specific Fabrication Items' is provided for this purpose. The cost of a full penetration field weld is proportional to the volume of weld material which, in turn is a function of the thickness of the piece. Based on this assumption, the cost of all full penetration welds can be extrapolated from the cost of the 1" weld. The items in this category also allow evaluation of the additional fabrication costs involved in schemes that utilize beam penetrations for ductwork.

6.4.3 Regional Domain Constraints

At the regional level exogenous constraints take the form of interaction between the structure and the physical features and functions of the architectural and MEP subsystems. Figure 6.1 shows a view of the architectural systems that are of interest at the typical floor. Table 6.5 gives examples of the types of constraints that result from the interaction of the architectural and structural systems.

The architectural design defines the form, function, and aesthetics of a high rise office building. The form of the building includes the arrangement of floor space along the vertical axis of the building and defines the geometric context for all of the building systems. The architectural function is the use (occupancy) that is intended for the floor space and results in function constraints (loads) on the structure. The aesthetic expression of the building includes the visual effects of the geometric arrangement of materials in the building as well as the form. Individual features of the architecture also result in significant constraints on the structure. The since the structure must relate to the architecture, the constraints serve to organize the structural solution, e.g., the location of the core features determine likely column locations. Among these are the elevators and stairs, which are continuous vertical architectural elements, and the cladding system. Fire separation requirements between functional areas, fire ratings, can result in explicit constraints on the material properties of structural elements such as floor slabs.

The mechanical, electrical, and plumbing subsystems serve to temper the building environment and provide power and water to the building occupants. Figure 6.2 and Table 6.6 contain examples of constraints arising from mechanical systems. In modern high rise buildings there is also a fire protection system which, although related to plumbing, is treated as a separate subsystem with its own set of requirements.

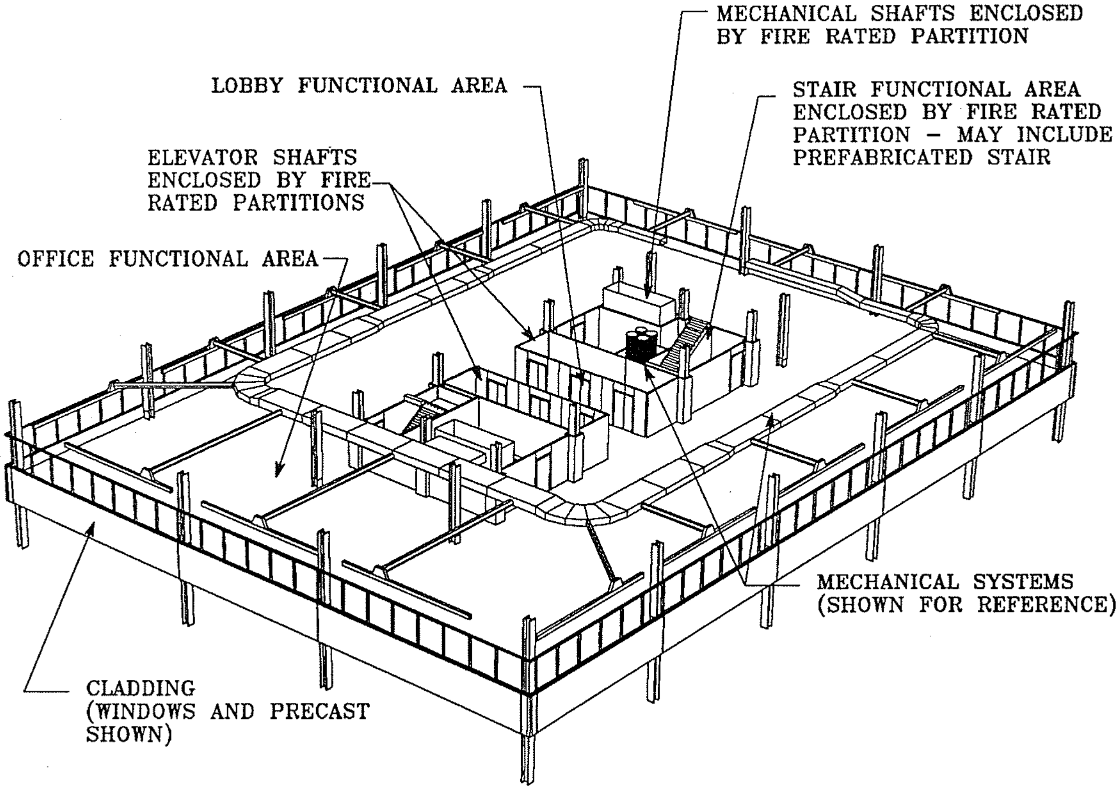

Figure 6.1 Architectural Systems at the Typical Floor

The subsystems are a collection of components with physical attributes such as size and weight. Due to their size attributes, the MEP components compete with the structural and architectural system components for a share of the finite space defined by the building envelope (foundation, roof, and outside walls), giving rise to geometric constraints. The

Subsystem Feature	Structure Feature or Subsystem	Constraint Classification	Constraint Type	Mutual Constraint	Design Phase
No. of Stories	No. of Stories	Geometric	Hard	--	SD
Building Height	Lateral System	Geometric	Soft[1]	Floor Height	SD
Floor Height	Floor Height	Geometric	Soft	Struct. Depth	SD
				Mech. Depth	SD
				Ceiling Height	SD
Plan Dimensions	Slab Dimensions	Geometric	Hard	--	SD
	Lateral System	Function	Hard	--	SD
	Gravity System	Function	Hard	--	SD
Core Dim.	Col. Locations	Geometric	Hard	--	SD
Elevator Loc.	Brace Loc.	Geometric	Soft	--	SD
	Slab Opening	Geometric	Hard	--	SD
Stair Dim.	Slab Openings	Geometric	Hard	--	DD
Stair Type	Gravity System	Function	Soft	--	DD
Elevator Machine Room	Gravity System	Function	Hard	--	DD
		Performance	Hard	--	
Core Partition Type	Gravity System	Function	Soft	--	DD
		Performance	Soft		
Cladding Type	Gravity System	Function	Hard	--	SD
		Performance			
Cladding Support	Gravity System	Function	Soft	Construction Sequence	DD
		Performance			
Typical Flr. Occupancy	Gravity System	Function	Hard	--	SD
Non-Typical Flr. Occupancy	Gravity System	Function	Hard	--	DD
Mech. Room Location	Gravity System	Function	Soft	Mech. System Type	SD
	Lateral System	Performance		Gravity System Type	
		Material		Lateral System Type	
		Geometric			
Planning Module	Column Locations	Geometric	Soft	--	SD

Table 6.5 Examples of Constraints from the Architectural Domain

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[1] This constraint may be hard if the local ordinances limit the building height, in which case it changes the form of the mutual constraints, and, possibly, the preferred system. A good example of this is Washington, D. C., where strict height limits have fostered a propensity for flat plate construction, which yields the absolute minimum floor-to-floor height.

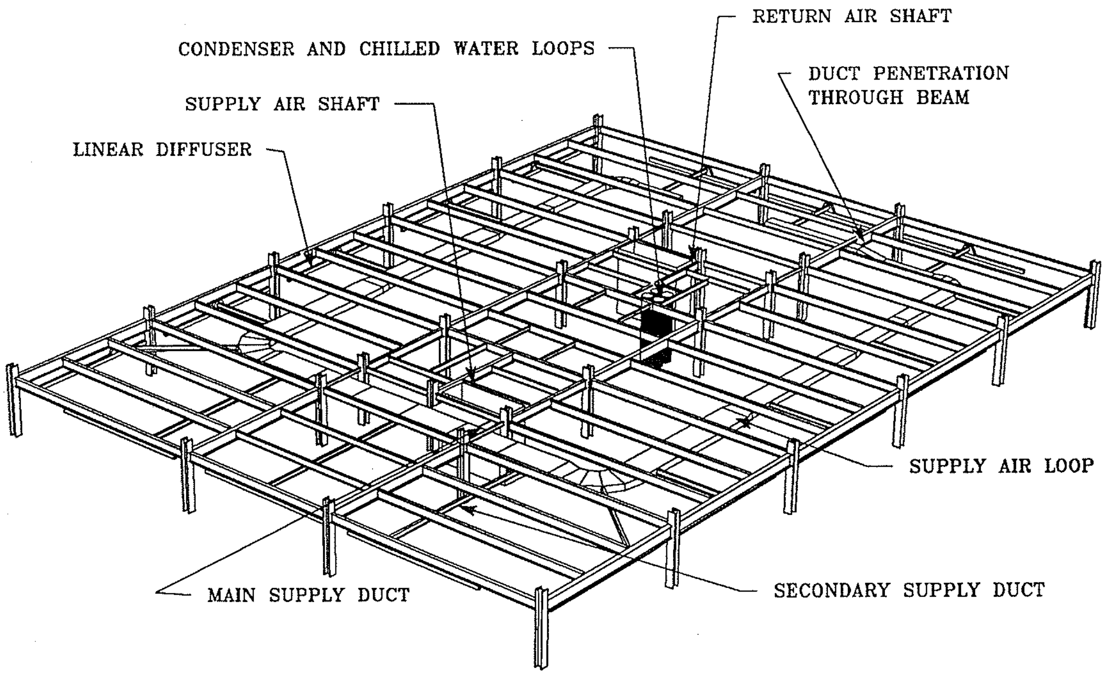

Figure 6.2 Typical Floor Mechanical/Structural Interface

weight attributes of subsystem components become function constraints on the structure. A third type of interaction occurs as the result of the behavioral characteristics of the subsystems within the context of the building occupancy resulting in material, performance, or geometry constraints. For example, noise and vibration resulting from machinery may have to be isolated from adjacent spaces.

6.5 Summary

The decisions that have the greatest potential impact on the cost of the structural solution or on the cost or function of the other building subsystems are made during the conceptual design phase. The conceptual design process is essentially a process of planning for the detailed design phase. An opportunistic planning approach similar to that implemented in MOLGEN appears to be ideally suited to the conceptual design process. The objective of the conceptual design process is to generate a set of constraints that will be used

Subsystem Feature	Structure Feature or Subsystem	Constraint Classification	Constraint Type	Mutual Constraint	Design Phase
Chiller	Gravity system	Function	Hard	--	DD
Cooling Tower	Gravity system	Function	Hard	--	DD
Chilled Water Loop	Gravity system	Function	Hard	--	DD
Air Shafts Size & Location	Slab Openings	Geometric	Soft	Architectural Core Dim.	SD/DD
Main Air Supply duct	Beam Depth	Geometric	Soft	Air Shaft Location Beam Penetration (Constructibility)	SD/DD
Typical Supply Loop	Floor Beam Depth	Geometric	Soft	Ceiling Height Floor Height	SD
Emergency Generator	Gravity system	Function	Hard	--	DD
Transformer Vault	Gravity System	Function Geometric Material	Soft	Fire Rating	DD
Electrical Delivery	Deck Type	Material	Soft	Alternate Delivery Method	SD
Boilers	Gravity system	Function	Hard	--	DD
Water Tanks	Gravity system	Function	Hard	--	DD

Table 6.6 Examples of Constraints from the M.E.P. Domain

in the final design, which is performed after all the constraints have been defined and is essentially a selection process.

Conceptual structural design involves the manipulation of structural subsystems and subsystem components such that the resulting structural system satisfies function, performance, and geometry constraints. The design strategy usually involves examining the effect of modifying some of the geometry constraints in order to determine the sensitivity of the solution to those constraints. Behavior constraints (physical laws governing behavior)e are used to formulate detailed geometric constraints on the attributes of the components for a particular set of function and performance constraints, and to test the effect of altering particular attributes in order to develop an efficient solution. The model based reasoning approach, which stresses first principles in the representation of function and behavior, is ideally suited for this part of the reasoning process. The cost and constraint modification data for each world are used by the architect/owner team to make decisions that involve trade offs between cost and value.

The following steps summarize the conceptual structural design process:

1) Formulate function, performance, material, reliability and geometric constraints based the attributes of the exogenous systems and considering constructibility constraints.

2) Synthesize one or more potential systems of load paths for both gravity and lateral loads. For each potential system of load paths, this involves assembling a structure topology from conceptual objects using the geometric and material constraints; using function, behavior, and performance constraints to formulate material and geometric constraints on both the topology and the components; and selecting members that satisfy the geometric and material constraints.

3) Evaluate the cost of the systems using constructibility constraints and test the sensitivity of the cost to the topology and/or component descriptions. If necessary, iterate steps (2) and (3) to obtain optimum internal constraint set (optimum structure description in the context a fixed set of exogenous constraints.)

4) Evaluate the effect of each soft constraint in the exogenous constraint set on the subsystem cost.

5) Formulate alternative sets of constraints corresponding to exogenous soft constraints and synthesize corresponding structural solutions such that the cost determined in (3) is reduced.

6) Propagate the alternate soft constraint sets to other systems for evaluation.

7) Select all parameters in the mutually constrained subsystems based on an evaluation of the global *Cost / Value* ratio.

Using steps (1) through (7) to create separate worlds for every combination of mutual constraints in a building would result in a combinatorial explosion and is not necessary. It is usually possible to choose appropriate values for systems of mutual constraints by focusing on a very small subset of the total solution. For instance, in the case of the beam-duct-ceiling example, the study could include only one typical beam and the maximum sized duct. The anticipation of constraints that originate in other domains is particularly important in the design of buildings where there are multiple nested mutually constrained systems at successive levels of abstraction.

7

Overview of Structure Representation

7.1 Introduction

The purpose of the structure representation developed herein is to support both the reasoning process and the facility database that is envisioned as one of the ultimate goals of automating the design process. Accordingly, the following specific objectives are proposed for the representation:

1) Accommodate the multiple potential solutions that are examined during conceptual design to allow database support at the earliest stages of the facility life cycle process and to accurately track the early decision making process while avoiding time consuming manual processing of data,

2) Support structural design reasoning to facilitate automatic responses to changes as the structure context evolves during the design, construction, and facility management phases of the life cycle,

3) Provide a means of incorporating constructibility considerations during the design phase,

4) Provide capability for multiple levels of detail to allow extension from simple objects required to support conceptual design to the level of detail in the physical description required to support automated fabrication,

5) Support detailed material lists in a form that is conducive to estimating, procurement, and scheduling during the construction phase,

6) Provide a comprehensive and detailed description of the structure, including information regarding specific design loads and construction details, in support of the facility management activities.

In order to accomplish the first three objectives, the representation scheme must support qualitative and quantitative reasoning by capturing the abstract concepts used in that reasoning, i.e., it must explicitly consider function, behavior, and form. In order to accomplish objectives 4, 5, and 6, a very detailed view of the facility data is required, and an efficient scheme of describing the data is a necessity to prevent the database from becoming unwieldy. In this discussion, form, function, and behavior are treated as independent, and conceptually different, views of the structure, each having its own concepts, objects, and attributes. In the following sections we will show how adopting this approach results in a robust and efficient data structure capable of capturing the semantic and detailed physical data required.

7.2 Motivation for Separation of Function, Form, and Behavior

The motivation for the separation of function, form, and behavior is provided by an examination of the reasoning process that is used in conceptual design. The multiple framing schemes, or systems of load paths, that are studied during that phase are different potential functional views of the structure, and for each of these functional views there are usually multiple choices of material and element types that satisfy the functional requirements. It is advantageous, therefore, to model the functional view of the structure explicitly and independently and then examine each of the options for material and element types in the context of the functional view. Such an approach also facilitates the identification of variations in *Cost/Value* that are attributable directly to the system of load paths rather than to material or element type.

The functional representation of the building, in the form of load paths, must be exhaustive because every structural element in a building serves a *unique* function in the load path that must be represented explicitly. The uniqueness of an element may be determined solely by its location in the structure, e.g., typical floor beams all serve the same function to the extent that they all pick up the same *amount* of load, however, they do not all pick up the *same* load. Only a comprehensive representation of function can adequately capture the effect of changing the function of any element in the building. Since the gravity function representation is comprehensive, the gravity function objects form an ideal key to all structural components in the building.

While the function of the structure remains constant for a given set of load paths, the behavior of the structure varies depending on the loads, the types of elements, and the element materials that are chosen to fill the functional roles in the load paths. As an example, the behavior of a post-tensioned concrete beam differs markedly from that of a reinforced concrete beam, although both can serve the same function in a given system of load paths. Behavior, which for a particular topology depends on both the form and the function constraints, is a distinct view of the structure which can be represented independently.

The representation of behavior requires only a sufficient number of unique objects to define the different possible behaviors. Hence, in a typical office building, while there is a one to one correspondence of typical beams to functional objects, there may only need to be one behavior object since all the typical beams are the same length, carry the same load, and, for design purposes, behave the same way. Different load cases can be addressed by using the concept of classes in the object representation. In this approach, which is covered in more detail in Chapter 9, behavior objects corresponding to construction loads, dead loads, and live loads are instances of a particular class of behavior object.

The need for representing the form of the structure is self evident since this representation includes the physical data that are used by all downstream processes in the life cycle of the facility. Each of the participants in the life cycle process has a particular view of the data and needs particular pieces of information.

The structural engineer is most interested in the specific geometric and material properties of the individual elements and the effect of the loads on the behavior of the elements and system. The architect and M.E.P. engineer need to know that the structure geometry does not conflict with their systems and that the behavior of the structure is consistent with the quality level desired. The construction estimator is primarily concerned with gross quantities and general system types while the construction planner may need to know specific sizes and locations of elements. Most of these issues, which are addressed during the planning phases, can be addressed in a general sense without knowing the precise physical details of the structure.

However, after the planning phases, the level of detail required of the data increases significantly. The fabricator needs to know precisely how long to cut the beams, which depends on whether they are supported on columns or other beams, precisely where to drill each hole and make each cope, and precisely how many nuts, bolts, and washers to deliver to the site. The rebar fabricator needs to know precisely how long each piece of reinforcing is and precisely where to bend it. The foreman needs to know precisely where to place the bar and whether there will be room for the sleeves and inserts he has to install for other trades.

The ability of the data to support automated fabrication and incorporation of constructibility concerns is directly related to the level of detail available. A 'fine grained' view of the data is required to adequately support construction execution activities.

During the facility management phase of the life cycle the most common issues concerning the structure involve questions of geometric conflict, questions regarding the affect of altering or removing structural elements, and questions regarding the capacity of the structure to carry different loads than were originally intended. The first issue is similar to the interaction that occurs between building subsystems during the design phase and is automatically accommodated if the database supports design activities. The second issue involves structure function at the conceptual level and can be accommodated if the representation accurately captures the intended function. The last issue involves structure function at both the conceptual and detailed levels. Quite often it is necessary to know the precise details of the connections as well as the member geometric and material properties to verify the structural capacity.

A representation scheme that is sufficiently detailed to support construction execution activities, and that contains the semantic data necessary to support design activities, will also be sufficient to satisfy facility management requirements.

The representation of the form of the structure must capture all features or dimensions which constrain the architectural and mechanical systems or the downstream processes of construction and facility management. Elements that are represented by the same behavior object may be represented by different form objects. For instance, typical beams may have different lengths and end connections depending on whether they are supported by other beams or columns. One of the objectives of conceptual design is to maximize repetition, which, of course, involves minimizing the number of form objects.

Separating the various views of the structure data makes it possible to develop efficient storage strategies while capturing the qualitative view of the data.

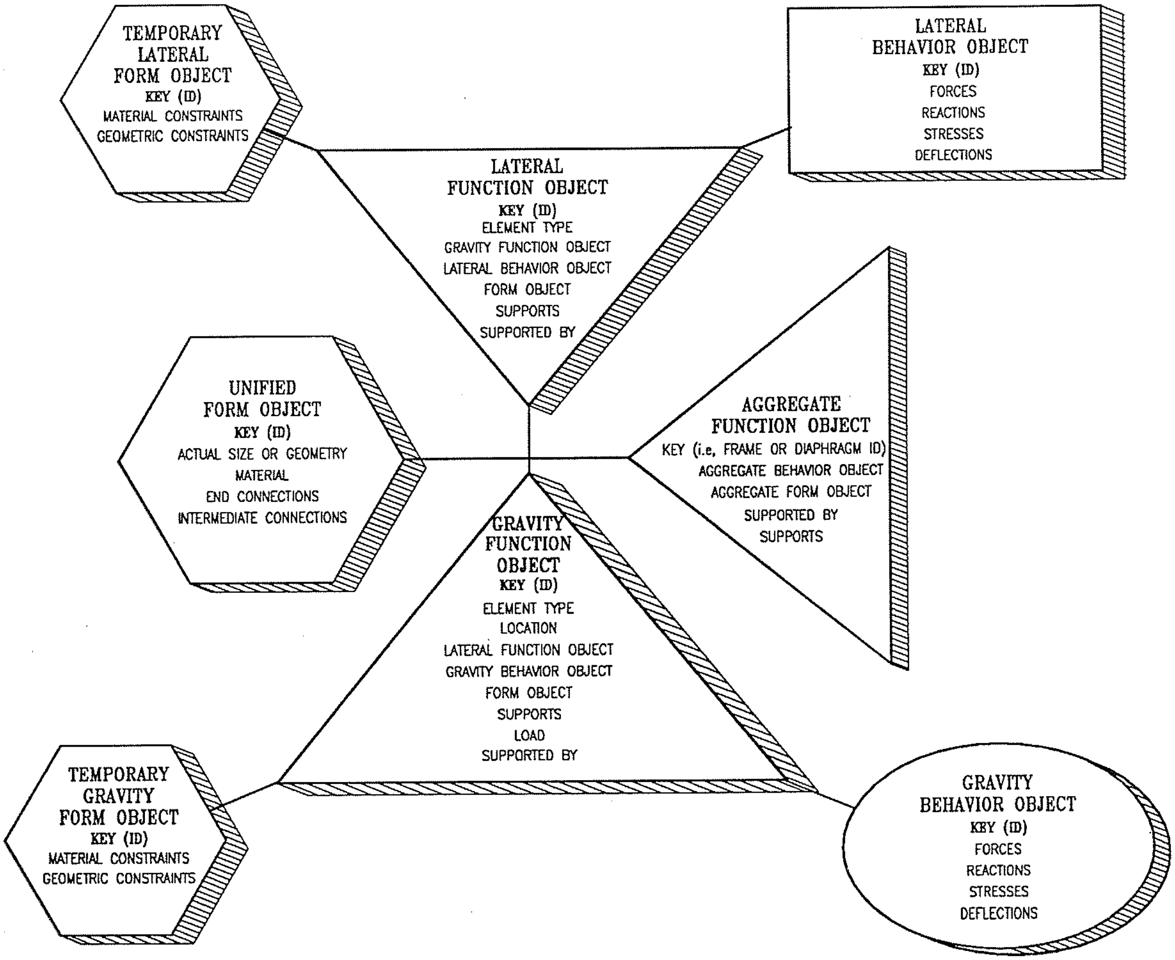

Figure 7.1 Schematic Structure Representation

7.3 Representation Strategy

The foregoing discussion provides the justification for the proposed representation scheme in which each component of the building is represented by a minimum of three objects in the database, one each for form, function, and behavior. While the function objects are unique for each building component, the behavior and form objects may not be unique.

In the proposed representation scheme, shown schematically in Figure 7.1, the gravity function objects are used as the basic building blocks of the structural portion of the facility database.

In Figure 7.1, the gravity function object is represented by the bottom triangle. In order to adequately represent function, the object is described by a type (column, beam, etc.), a location, the names of functional elements it supports, the load(s) it supports, and the names of the functional elements that it is supported by. To fill its role as the directory to the database, the functional object contains references to the appropriate behavior and form objects shown on the lower left and right of the figure.

Every element of a building that serves a lateral load path function either serves a function in the gravity load path, or is a redundant functional element in the gravity load path system. Therefore, the gravity load path representation is comprehensive and can serve as a directory to the existence and location all elements of the lateral load path as well. In the case where the an element fills a functional role in the lateral system, the gravity function object contains a reference to the corresponding lateral function object, indicated by the upper triangle in Figure 7.1.

There are a number of reasons for using a separate lateral load abstraction hierarchy in which the lateral function object provides a directory to the lateral form and behavior objects. Treating the lateral load system as a separate, but related, hierarchy facilitates the reasoning process used in conceptual design in which a similar decomposition is used and results in efficiencies in the representation scheme. Since there are usually far more elements in the gravity system than in the lateral system, there is efficiency in representing only those lateral load objects required to support the reasoning. The individual structural elements often serve completely different functions in the lateral and gravity systems, necessitating distinctly different vocabularies of functional elements for reasoning about the two systems. Using separate lateral load function objects eliminates the need to include the lateral function attributes in the gravity objects.

It is convenient for purposes of conceptual design to use temporary gravity and lateral form objects as indicated on the left of Figure 7.1. Constraints on the individual elements can be formulated separately in the process of synthesizing lateral and gravity systems, provided the constraints are reconciled in the final form object, indicated by the 'unified' form object shown in the figure.

Often structural elements are assembled into systems that themselves exhibit behavior analogous to individual elements and that perform a specific function. In such cases the behavior of individual elements must be considered in the context of the system. Such aggregations are common in lateral systems, e.g., braced frames and moment frames. While it is usually possible to construct a complete system of gravity load paths without considering the aggregate behavior, it is necessary to verify the gravity behavior in the context of the system during final design. Therefore the aggregate object should be recognized as a functional object in the facility database, as shown on the right side of Figure 7.1.

The proposed representation is flexible enough to accommodate the many changes that occur in the life cycle of the facility. If the loads are changed on a particular member, its functional description can be updated and new behavior and form objects created as required. The function representation of the structure establishes the topology that is required under any circumstances. The level of detail added to that description can be varied to accommodate the varying requirements during different phases of the design process by changing the number of form and behavior objects that are used. During those phases, it is likely that the designer will consider only 'typical' elements and will not distinguish between beams that have a different form due to end connections. For purposes of conceptual design and estimating, using the same form and behavior object for all typical beams is a reasonable approximation.

7.4 Example Typical Floor Representation

Figure 7.2 illustrates the application of the proposed representation scheme to a typical floor of a high rise steel office building. The floor plan is similar to that for the architectural systems illustrated in Figure 6.1. Due to space limitations, not all of the objects are shown in the figure, but a comprehensive tabulation of the gravity function objects, along with the corresponding gravity behavior, lateral function, lateral behavior, and form objects is given in Appendix C.

The 120 ft. X 110 ft. floor represented in Figure 7.2 is supported on typical floor beams spaced at 10 ft. and spanning the 40 ft. from the core to the exterior wall parallel to the short dimension of the building. The core is 30 ft. wide and 70 ft. long and is flanked by two girder lines parallel to the long direction of the building. Lateral loads are resisted by an exterior frame utilizing columns spaced at 15 ft. in the long direction and at 20 ft. and 15 ft. in the short direction.[1] There are a total of 46 columns in the plan.

In the last bay on either end of the building, short beams framing into the weak axis of the intermediate columns have been used to provide support for the columns during erection. While the columns can be supported for permanent loads by the slab (as long as appropriate tie bars are provided) they are unstable for erection loads. This is an example of the use of a

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[1] A more efficient lateral load scheme would utilize 10 ft. and 15 ft. column spacings along the short sides of the building.

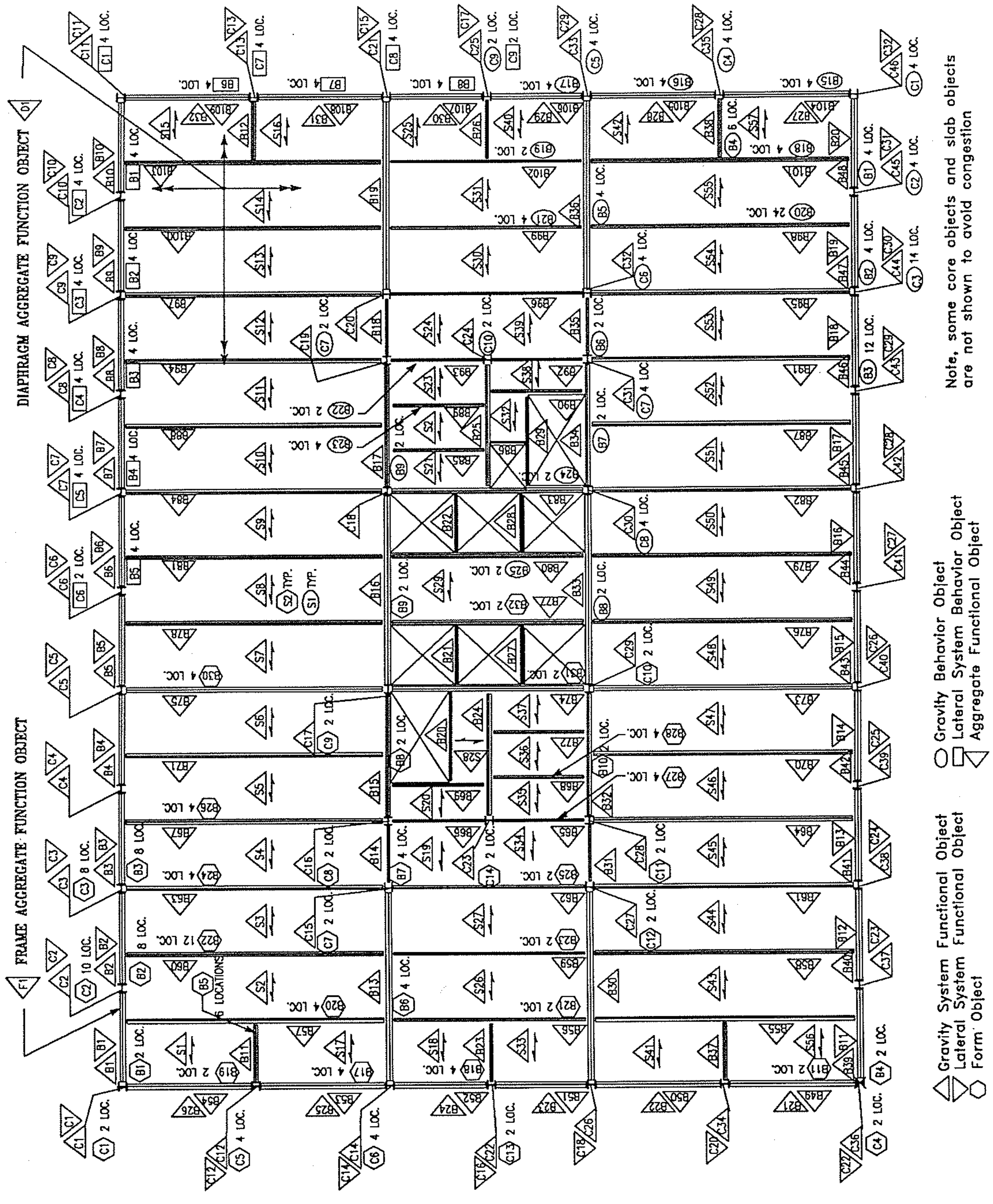

Figure 7.2 - Example Typical Floor Representation Scheme

qualitative constructibility constraint. On the long faces of the building, the edge beams have two independent points of support and can, therefore, cantilever the 5 ft. to provide the necessary column support.

As illustrated in Figure 7.2, the comprehensive representation of functional elements extends to the lowest elements in the hierarchy, the slabs. A separate gravity function object is used for each slab panel, defined as the smallest area bounded on 4 sides by beams. This level of detail is required in order to represent the 'supports' and 'supported by' relationships all the way down to the slabs, which originate the loads that are carried all the way through the load paths.

The slabs in the long bays above and below the core in the figure are supported on the typical floor beams. With the exception of the last beam on each end, the typical beams all carry the same amount of load and, therefore, can be represented by the same behavior object. The behavior of the last beam on each end is assumed to be conceptually different since it supports the stability cross beams.

Although the typical beams can be represented by a single behavior object, close examination reveals that a total of 5 separate form objects are required. The different conditions, indicated by the hexagons in the upper left quadrant of the plan are summarized as follows:

B20	Supported by beams on both ends and supports an intermediate beam;
B22	Supported by beams on both ends;
B24	Supported by a column web on one end and by a column flange on the other end;
B26	Supported by a column web on one end and by a beam on the other end;
B30	Supported by column webs both ends.

In spite of the fine level of detail required to distinguish among the various form objects, there are still only 5 form objects to represent 28 beams. If the same beams are used at more than one level, the efficiency increases, since the same form object can be used for the corresponding beams at the other levels.

The exterior moment frame and the floor diaphragm are aggregate function objects as indicated in the upper left and right corners of the plan. Even though the classification of the components of the frame takes advantage of symmetry about two axes, the representation still requires more lateral behavior objects than gravity behavior objects to represent the exterior beam behavior. This degree of resolution is not require during conceptual design when the beam behavior is approximated using simplified models. However, in a final analysis, the forces in the spandrel beams would vary due to the interaction of frame and column axial effects. Although the exterior beams would probably be considered a class and all designed for the same loads, even in a final design, separate behavior objects would be required to capture the differences in behavior to be able to identify the maximum condition.

In the following summary only the objects that are different are counted. Each object that is counted represents an object - or a relation - in the data base. The efficiency of the scheme depends both on the number of different objects and the amount of data that must be stored for each object. The first table below shows the total number of objects required to represent single floor considering the columns to be one story elements for both form and function. (The columns are always one story elements for function but *may* be two story elements for form.)

One Story Abstraction:

Gravity Function Objects:

Columns	46
Beams	109
Slabs	57
Total GFO	*212*

Gravity Behavior Objects:

Columns	10
Beams	27
Slabs	6
Total GBO	*43*

Lateral Function Objects:

Columns	32
Beams	32
Slabs	46
Total LFO	*110*

Lateral Behavior Objects:

Columns	9
Beams	8
Slabs	11
Total LBO	*28*

Aggregate Function Objects:

Diaphragms	1
Frames	1
Total AFO	*2*

Form Objects:

Columns	14
Beams	33
Slabs	8
Total FO	*55*

Total Objects (1 floor)	*450*

The efficiency of the system becomes apparent when additional floors and the locations of column splices are considered. For each additional floor a complete set of function objects, both lateral and gravity, and a complete set of lateral load behavior objects are required, since the story shears are variable. In the following table it is also assumed that a complete set of form objects would be required at each floor for components of the lateral frame (a conservative assumption). In the gravity system, the column loads vary at each floor requiring a different behavior object, but only a single form object is required for two floors, if two story columns are assumed. No new form or behavior objects are required for the gravity beams that are not part of the lateral system. For every succeeding two floors, the additional objects required are as follows.

Additional Objects for Two More Floors:

Gravity Function Objects:

Columns	92
Beams	218
Slabs	114
Additional GFO (2 floors)	*424*

Gravity Behavior Objects:	
Columns	20
Beams	0
Slabs	0
Additional GBO (2 floors)	*20*
Lateral Function Objects:	
Columns	64
Beams	64
Slabs	92
Additional LFO (2 floors)	*220*
Lateral Behavior Objects:	
Columns	18
Beams	16
Slabs	22
Additional LBO (2 floors)	*56*
Aggregate Function Objects:	
Diaphragms	2
Frames	0
Additional AFO (2 floors)	*2*
Form Objects:	
Columns	14
Beams	16
Slabs	16
Additional FO (2 floors)	*46*
Additional Objects (2 floors)	*768*

7.5 Conclusion

The comprehensive representation presented in the previous section would be sufficiently detailed to support automated fabrication and facility management. It requires only 23 new form objects per floor. Of the 768 new objects for every two floors, 444 are function objects, which can be thought of as 'place holders.' In order to minimize the size of the data base, the function representation should only include the minimum amount of information required to define the structure load paths. In the following chapter, the function of the structure is examined to determine the nature of the attributes that must be stored to accurately represent the structure function.

In addition to the primary structure representation described above, the representation for ISD should include the representation of the function constraints, or loads, in a form that facilitates automatic reformulation of architectural and M.E.P. systems descriptions. Such an approach is essential if the system is to process design changes automatically. One of the most severe limitations of current design tools is that they still rely on the human operator to perform the most mundane and repetitive task, that of compiling design loads and entering them as data. The reason for this is that the task requires qualitative reasoning to transform the exogenous constraints into loads and to recognize the spatial relationships between those loads and the structural system. The reliance on human processing at this critical juncture in the process results in delays and errors, particularly in the context of the confusion that normally surrounds processing of changes in todays accelerated design/construction schedules.

In the proposed representation scheme, the slabs are decomposed into primitive load path elements that are simply supported on each end by beams. To automatically reformulate exogenous constraints the system descriptions must be transformed into loads on individual slab panels. An automated link to the load path description can be achieved by developing a method formulate the line loads on the beams supporting a slab panel subjected to a system of arbitrary loads.

The representation must be able to capture the spatial attributes of the loads, e.g., the difference between a piece of equipment centered over the third beam on the fifth floor and a different piece of equipment situated over the fourth beam on the tenth floor. A less rigorous representation would necessitate human intervention to assess the impact of switching the pieces of equipment. The computer should be capable of handling the mundane chores of data input and reduction such as this, freeing the human engineer for more creative tasks.

8

Structure Function

8.1 Introduction

There are several levels of abstraction in the reasoning process used in the conceptual structural design. The reasoning on the most abstract level is used to synthesize a complete system of load paths or to verify the existence of a complete set of load paths in a proposed structure topology (spatial arrangement of functional elements). This reasoning must be performed prior to the use of conventional analysis programs since those programs cannot yield meaningful results unless there is a complete system of load paths. In automating the conceptual design, the constraint of a complete load path could be implicitly enforced through the definition of the system components, e.g., the definition of a frame only allows frames with complete load paths, but the resulting system can only reason about preconceived load paths. Equipping the software with the fundamental knowledge about primitive functional elements and their use in synthesizing a complete load path could result in more flexible reasoning systems.

In this chapter we formalize a method of reasoning to deduce the existence or non-existence of a complete load path given a structure topology. In the context of reasoning with constraints, the reasoning involves formulating abstract function and geometry constraints and checking for the satisfaction of those constraints. The purpose of developing the rules is to identify the functional elements and the element attributes that must be represented in the facility database to support qualitative reasoning in the domain of structural engineering.

The methodology for developing the representation involves reproducing the reasoning necessary to determine if there exists a complete load path. Objects and attributes that are required for this reasoning are taken to be the minimum necessary for an adequate representation of function. The reasoning process for determining whether there is a complete load path goes on only until *one valid load path is discovered.* As a result, the process does not distinguish different potential load paths in the same structure, and the resulting representation is limited because it does not capture the differences in the load paths that may be due to differences in behavior. However, as a starting point for conceptual design it is sufficient to identify one viable load path and proportion each element along that path to carry its share of the load. The resulting structure is valid and can be refined through the detailed analysis and design that occurs in later phases.

The existence of *a* complete system of load paths is a qualitative characteristic of the structure related to its function.[1] It is useful to extend the representation of the *gravity* function to include not only the existence of support, but also the magnitude of the forces that would be transferred between elements *in the absence of redundancy.* In this approach the *function* representation provides an approximate macroscopic view of *behavior* as well as a detailed view of *function.* The representation of the precise behavior corresponding to the analytical results for the redundant structure is maintained in the behavior representation. It is useful to maintain both views of the gravity system since the 'real' world usually lies somewhere between the two views.[2]

8.2 Building Coordinate System

In the representation of building function it is necessary to define the spatial relationships between functional members as well as between loads and members. In high rise buildings, the global geometric context is the building itself, which on the most abstract level consists of

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[1] Many engineers hold the view that a complete load path description should include both a *qualitative* function description and a *quantitative* behavior description, with the emphasis being on the latter. With such a view, there is no unique functional description of the structure since the functional description would change with each different loading condition. In order to develop a unique functional description the precise value of the forces in the elements is considered to be part of the behavior description herein.

[2] Because of connection flexibility, fit up tolerances, and residual stresses, the *actual* behavior of the structure is rarely - if ever - known. For this reason, it is useful to evaluate the bounds on the behavior as well as the precise analytical prediction of the behavior.

floors arranged vertically in space at predictable locations and supported on vertical elements, columns or walls, that are usually continuous for reasons of economy and reliability. Conceptual design involves manipulating patterns of load paths that converge in one form or another at the columns, thus it is logical to use the column locations to order the geometric reasoning. Since the locations of the columns in the horizontal plane are usually the same for all floors it is common practice to assign named grid lines to the locations and use the grids as a default coordinate system. Both the vertical locations of the floors and the horizontal locations of the column grids in plan are attributes of the building that are defined through the conceptual design process.

In the *Building Coordinate System* (BCS) used in this dissertation vertical coordinates are expressed in terms of levels (L1, L2, etc.) while horizontal coordinates are given in terms of grids (G1, G2, GA, GB, etc.), where the grid or level name is a variable containing the x, y, or z coordinates in space. Both vertical and horizontal coordinates can be given as offsets (L5+5.00, G1+3.00, GA+5.00, etc.) or subdivisions ([L2-L1]/2, [GB-GA/3], etc.), thus enforcing an implicit geometric constraint that the framing elements relate to the floors of which they are a part.

8.3 Function Constraints From Gravity Loads

The function of the structure is to carry loads from their point of origin to the ground. The loads arise from the structure self weight, the weight of the objects that comprise the architectural and mechanical systems, the building occupancy, and environmental factors. One of the keys to automating the conceptual design process is developing a method of representing loads, or function constraints, in an accurate and unambiguous fashion such that they can automatically be incorporated as the design progresses in a manner that facilitates reasoning about multiple structure topologies.

A comprehensive representation of the structure function for use in an automated design environment must facilitate the automatic formulation of the function constraints, in the form of gravity and lateral loads, based on the physical attributes of the other building systems and the environmental context of the building. Figure 8.1 shows functional areas and features at the typical floor of a building. The proposed object representation of gravity loads, or function constraints, is based on the 'load key' paradigm in which the loads based

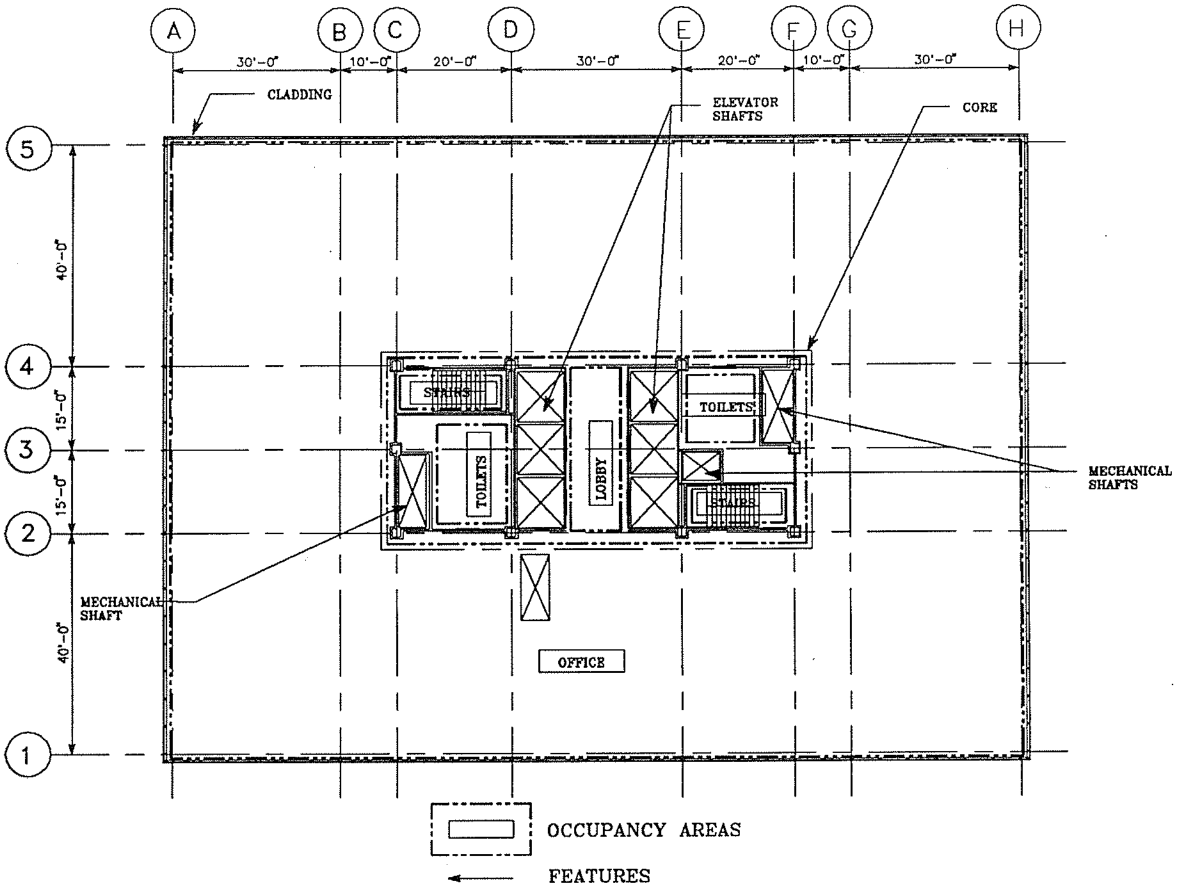

Figure 8.1 Typical Occupancy Areas and Features

on occupancies and code requirements are associated with specific building areas, and all areas are represented explicitly.

With the exception of the structure self weight, gravity loads are related to the form and occupancy of the architectural and mechanical systems. The building code requires specific design live and dead loads for the various areas of the building based on the intended use, or occupancy. These loads are explicitly associated with areas and are expressed as load intensity in pounds per square foot (psf). Examples of code required live loads are 150 psf for mechanical floors, 50 psf for office areas, and 100 psf for exit stairs and lobbies. An example of a code required dead load is the 20 psf allowance for partitions that is usually required for office buildings. The distinguishing feature of these types of loads is that they are anticipatory (i.e. they anticipate future loads) and relate only to the occupancy, or use, of the various areas of the building rather than to physical objects.

In addition to the occupancy loads required by code, the structural design must consider loads arising from specific physical components of the other systems as in the case of loads resulting from architectural cladding which are not included in the partition allowance. Other architectural features that are treated as discrete loads are the core partitions and prefabricated stairs. The magnitude of these loads is computed based on the physical description of the elements which itself is generated in the architectural domain. Mechanical equipment loads are usually not significant in the design of the *typical* floors. They are significant in the design of *mechanical* floors only where the unit intensity of the equipment load exceeds the normal design load for mechanical rooms (usually 150 psf).

The loads resulting from structure self weight can be divided into those resulting from the slab weight and loads resulting from the weight of beam and column elements. The slab loads in steel systems typically range from 30 psf for lightweight concrete slabs on open web steel joists (OWSJ) to 75 psf for normalweight concrete composite slab and beam systems and are usually constant for a given floor. Since the slab loads account for as much as 50% of the total load that must be carried by the structure, a fundamental design decision that must be made before reasoning about the balance of the structure is the type of slab that will be used. Once this decision is made, the only components of the gravity loads that are not known are those arising from individual beam and column elements. For the purpose of conceptual design of steel systems it is common to use an allowance in the range of 10-15 psf for these elements. In concrete systems, the range in slab weights is even wider than for steel systems and can be subject to more variation within a single floor. However, constructibility considerations create a preference for uniform slab depths, in which case the slabs in the concrete system can be treated similar to slabs in steel systems.

Each of the above loads is invariant with the vertical location in the building since, by definition, the gravity loads are the same for all *typical* floors. The loads arising from exogenous systems can be inserted into the project data base at the time the features controlling their values are inserted into the design since the load definitions are not dependent on the structural reasoning process. Figure 8.2 shows a graphical representation, called a load key, of the gravity loads from exogenous systems on the typical floor of a steel office building. Note that in this case there are no specific load constraints arising from the mechanical systems.

Each of the patterns in the diagram is associated with a particular geometric area, just as the anticipatory loads are associated with an area. In order to use this form of representation in automated computing, all areas of the floor must be represented. Hence, the openings in the floor are represented as special areas with a uniform load of zero. With

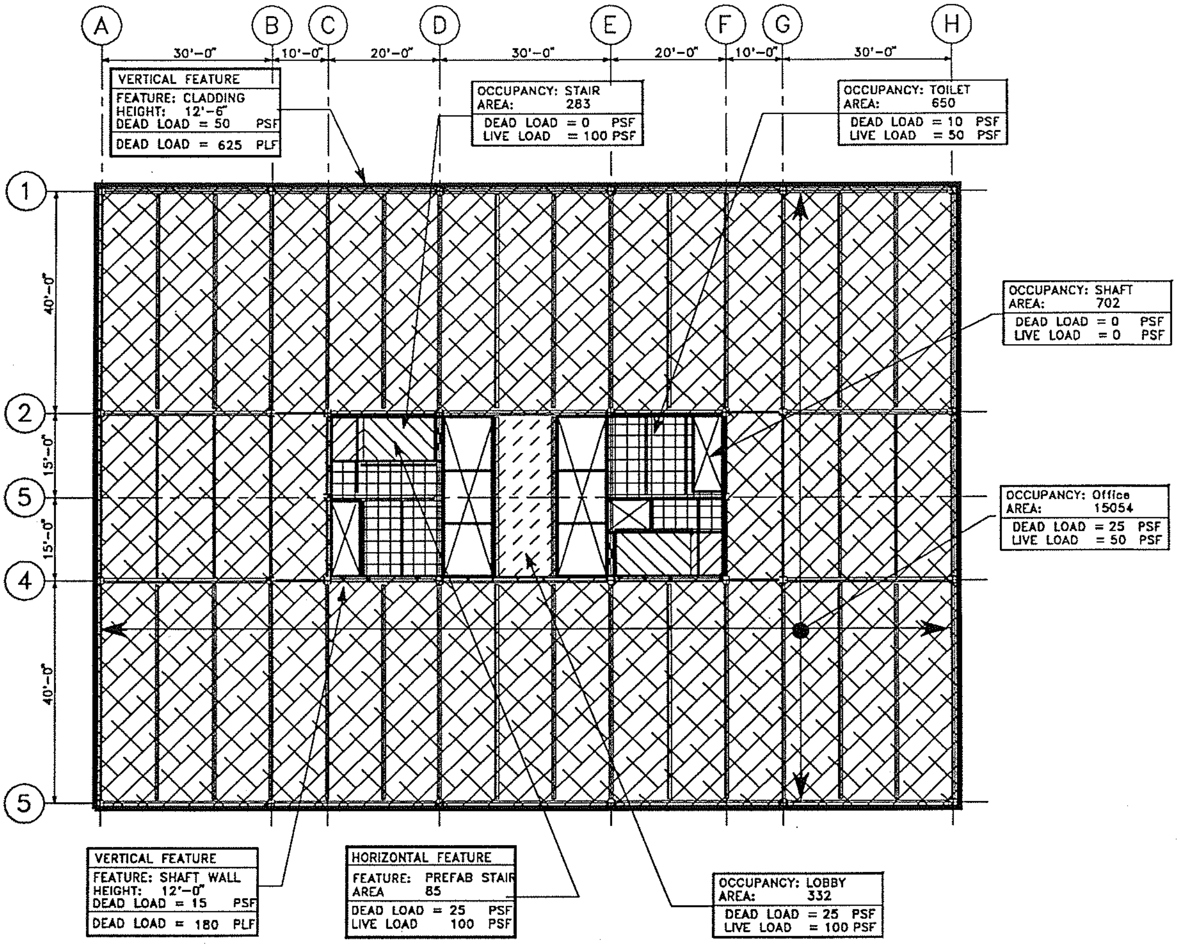

Figure 8.2 Combined Load Key and Framing Plan

this method of representation a constraint that the sum of all areas in the occupancy load diagram must be equal to the total floor area helps assure accurate accounting of all areas.

The features shown in Figure 8.2 are classified as either vertical, which includes the core walls and cladding or horizontal, as in the case of the stairs, and the loads are attributes of the feature. Vertical features project as line loads on the horizontal structural elements while horizontal features result in area loads similar to the occupancy loads. The manner of support is important with both the horizontal and vertical feature loads. The cladding and stairs are both supported at discrete points, while the core walls are supported continuously. The location of the discrete support points for the exterior cladding may be an important consideration during conceptual design, since it can have a significant affect on the sizes of the perimeter beams. Hence, feature load objects must include an attribute defining the method of delivering the load to the structure, i.e., discrete or continuous, and the location of the load.[3] Although none occur at the typical floor shown in Fig. 8.2, mechanical objects such as chillers and cooling towers can be represented as horizontal features similar to the stairs. This information can again be added to the data base at the time the features are inserted. Since they are feature loads, they must include a description of the method of delivery to the structure.

In current practice, all loads resulting from occupancies, self weight, and special features associated with an area are included on a single load key plan which also shows the framing as in Figure 8.2. Such a scheme facilitates communication and reasoning in the human system, but requires that the load key plans be constructed after the conceptual design, when the structural slab properties are known. In an automated environment it is useful to adopt a representational scheme at the earliest point in the design at which the loads are required, i.e. conceptual design, and use that scheme throughout the life cycle of the facility. Hence, it is necessary to adopt a scheme that efficiently accommodates the potential variations in the slab weights between structural solutions during conceptual design. This is accomplished by separating the loads resulting from the functional use of an area and the exogenous systems features from those resulting from the self weight of the structure. For this reason, Figure 8.2 does not include loads that result from structure self weight. For purposes of automation, self-weight is more appropriately a part of the form representation.

The floor slab serves to distribute all loads to the underlying system of beams. The manner in which this is accomplished, described primarily by the direction the slab spans, affects the method of propagating the load constraints. Most slab elements used in high rise buildings are 'one way' elements that transfer loads to the supporting beams perpendicular to their span. In Chapter 7, which summarizes the representation objects, a double headed arrow is used to indicate the slab function objects. A comparison of Figure 7.2 and the load key shown in Figure 8.2 reveals a distinct relationship between the patterns of slab objects created by the beam topology and the patterns of loads. The relationship can be used to organize the representation of the loads, which constrain the functions of the slabs which, in turn, are the originating elements in the load path.

Diagrams such as that shown in Figure 8.2 have been used successfully in practice for

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[3] If the location of the load from a prefabricated component has an impact on the design of the structure, the location must be constrained in the performance specification.

coordination and quality control as well as for communication with the downstream process of facility management. They lend themselves readily to manipulation in a graphical environment and to representation in a form that facilitates computational methods. The juxtaposition of load and framing patterns facilitates the qualitative reasoning process used by engineers during the design.

The important concepts involved in the representation of the gravity loads are summarized below:

1) *Occupancy Loads* are anticipatory design live and dead loads which are prescribed according to the uses of the architectural spaces in the building. These loads are usually described in terms of an intensity, in psf, and area over which that intensity is applied. The default values of anticipatory loads are controlled by building code requirements, but may be overridden by specific owner constraints.

2) *Feature Loads* are dead loads arising from the weight of the physical objects comprising architectural and mechanical subsystems. Important attributes of feature loads include the manner in which the load is applied to the structure, i.e. continuous or discrete, and the location at which it is applied.

3) *Horizontal Feature Loads* include loads from prefabricated stairs and loads from mechanical equipment. These loads are related to the area of the projection of the feature on a horizontal plane and may be applied continuously or at discrete points.

4) *Vertical Feature Loads* include loads from exterior cladding systems and loads from interior partitions (usually in the core). These loads are related to the area of the projection of the feature on a vertical plane, and result in line loads on the horizontal structural framing. These loads may be supported continuously, as in the case of core partitions, or at discrete points, as in the case of the exterior cladding.

5) Anticipatory and feature loads are controlled by systems exogenous to the structural design reasoning process and the reformulation of the exogenous systems descriptions into structural function constraints can proceed external to the structural design process.

6) The load key is a convenient graphical representation of these loads in which the extent of the load is denoted by geometric patterns on a floor plan. In the load keys, all areas of the floor are represented, with the openings being represented as special load areas with an intensity of zero.

7) The load characteristics of the structural slab must be formulated within the structural reasoning process, since they may vary according to the structural scheme used. The most convenient way to do this is to calculate self weight as part of the form representation.

The information shown graphically in the load key diagrams can be represented as a system of objects and attributes to facilitate processing in an automated environment. The process of reasoning about the relationships between the load objects and the structure topology may involve searching through arbitrary geometric patterns. In order to minimize the amount of search that is necessary, a suitable strategy for representing the geometric information is required. One approach is to consider 'typical' and 'nontypical' loading conditions, in which a particular loading condition applies to all areas subject to listed exceptions and additions. In this approach all loading areas are described by their plan coordinates with the 'typical' loading having coordinates corresponding to the overall plan and exceptions having coordinates that fall within that plan. In essence, the nontypical areas are cut out of the typical area or added to the loads in the typical area. Figure 8.3 shows frames that represent the various typical and nontypical occupancy loading conditions

OCCUPANCY LOAD : TYPICAL FLOOR	
TYPE	OFFICES
LIVE LOAD	50 PSF
PARTITION LOAD	20 PSF
CEILING	5 PSF
FINISH	0 PSF
EXTENT(S)	GA,G1;GH,G5
EXCEPTIONS	TYPICAL CORE
ADDITIONS	CLADDING

OCCUPANCY LOAD : TYPICAL CORE	
TYPE	TOILETS
LIVE LOAD	50 PSF
CEILING LOAD	5
FLOOR FINISH	0
EXTENT(S)	GC, G2; GF, G4
EXCEPTIONS	EXIT STAIRS, ELEVATOR CHASES, MECHANICAL CHASE, ELEVATOR LOBBY
ADDITIONS	CORE SHAFT WALLS CORE PARTITIONS

OCCUPANCY LOAD : EXIT STAIRS	
TYPE	EXIT FACILITIES
LIVE LOAD	100 PSF
DEAD LOAD	0
EXTENT(S)	GC, G3+7.00; GD, G4 GE, G2; G2+8.00, GF
EXCEPTIONS	PREFAB STAIRS
ADDITIONS	PREFAB STAIRS CORE PARTITIONS

OCCUPANCY LOAD: MECHANICAL CHASE	
TYPE	OPENING
LIVE LOAD	0
DEAD LOAD	0
EXTENT(S)	(G2, GC; G3, GC+8.00) (G2+8.00, GE; G3, GE+8.00) (G3, GE+12.00; G4,GF),
EXCEPTIONS	NONE
ADDITIONS	NONE

ALL DIMENSIONS ARE IN BUILDING COORDINATE SYSTEM

Figure 8.3 Typical Floor Occupancy Load Objects

shown graphically in Figure 8.2. The frame attributes are those that would be required for a simple rectangular floor plan. More complex floor plans could be handled by expanding the typical area to encompass all areas of the floor and then including special zero load rectangular areas to form cutouts around the periphery of that area. In Figure 8.3 the *typical floor* occupancy load is applied over the entire floor plate with the exception of the core. Feature loads that are added to the typical load in this area include the cladding. The typical core load is chosen to accommodate the design loads in the irregular space that is left after all defined functional areas are carved out of the core. The locations and sizes of the defined functional areas in the core can all be described by a pair of xy coordinates, contained in the 'extents' slot, that are the lower left and upper right coordinates of the area in plan. Feature loads due to core partitions are listed as an addition to the core loads, while the feature loads due to the stairs are listed as additions in the stair areas. Where there is more than one rectangular area for a given function, as is the case with all of the special areas in the core except the lobby, the extents of each area are provided as lists in the frame slot.

A constraint implied in this formulation is that the area of a load object may only overlap another area whose coordinates appear in the objects list of exceptions. Conversely, at least one of the coordinates of an exception must lie within the area of the load object. For rectangular geometry parallel to the XY axes these constraints can be expressed in rule form as follows:

```
If AREA1 X1 is greater than AREA2 X1 and less than AREA2 X2
and AREA1 Y1 is greater than AREA2 Y1 and less than AREA2 Y2
or AREA1 X2 is greater than AREA2 X1 and less than AREA2 X2
and AREA1 Y2 is greater than AREA2 Y1 and less than AREA2 Y2
then AREA1 is an EXCEPTION to AREA2
```

The above constraint is sufficient for rectangular parallel geometry and provides for nested and overlapping areas. However, for arbitrary or rectangular non-parallel geometry, the constraint would be considerably more complex, since all corner nodes would have to be checked. In the latter case, the simple coordinate representation of areas used in the frames would not be adequate to describe the areas.

Because the load definition starts with the floor extents and then lists exceptions within those extents, the loads associated with all floor areas are explicitly defined. The coordinate definition and names of the load areas correspond exactly with the architectural definition of the spaces. The associated loads shown with each area are the default loads prescribed in the 1988 UBC [7], with the addition of a 5 psf allowance in those areas scheduled to receive ceilings (office, core, lobby). In some office buildings, there may be additional loads from floor finishes in specific areas such as tile in the toilets or lobbies that would need to be included at the time those areas are defined by the architect.

Figure 8.4 gives examples of the frames required to define the feature loads at the typical floor. Since features are defined to be physical objects, the dead loads associated with them are dependent on the attributes of those objects and there are no additions or exceptions. Additional attributes defining the method of support of the feature, either continuous or discrete, and the locations of the supports are required. The additional attribute of total load is included to accommodate mechanical equipment for which total operating weights are usually listed in manufacturer's data along with the equipment dimensions. Note that the area occupied by the prefab stairs is not the same as the area of the exit stairs in this case, since the stair landing at the floor is included with the structural slab.

HFEATURE LOAD : PREFAB STAIRS	
TYPE	STEEL STAIR
DEAD LOAD	25 PSF
LIVE LOAD	100 PSF
EXTENT(S)	(G3+7.00, GC+4.00; G4, GD) (G2, GE; G2+8.00, GE+16.00)
SUPPORT TYPE	DISCRETE, CORNERS
TOTAL LOAD	3010 LB

VFEATURE LOAD : CLADDING	
TYPE	PRECAST,GLASS
HEIGHT	6.5 FT,6 FT
DEAD LOAD	75 PSF, 15 PSF
LINE LOAD	642.5 PLF
SUPPORT TYPE	DISCRETE, @5 FT
LOCATION(S)	(GA, G1; GA, G5; GH, G5; GH, G1; GA, G1)

ALL DIMENSIONS ARE IN BUILDING COORDINATE SYSTEM

Figure 8.4 Typical Floor Feature Loads

Different representations are required for vertical and horizontal features. Horizontal features are similar to occupancy loads in that they can be described by an area and load intensity. The vertical features include the cladding and the core walls and differ from the horizontal features in that the loads that result from the object weights are a function of the floor to floor height and wall composition. In the proposed representation the cladding is composed of two material types, glass and precast, each of which has a vertical dimension such that the sum of the vertical dimensions is equal to the floor to floor height (12'-6" for this example). This allows the variation in floor to floor to be related to one of the materials, the precast, for instance. However, since the composition does not vary along the length of the wall in this example, only one object is required to describe the load. If each of the materials were represented independently, then the fact that the precast supports the glass would have to be represented, since the line load that the structure sees is the combined load from the glass and the precast, but is specifically applied through the precast connections.

The locations of feature loads are defined by means of a list of coordinates. In the case of vertical features the coordinates are given in sets of four corresponding to the x and y coordinates of each end of the line load resulting from the vertical feature. In the case of walls, such as the cladding vertical feature, the location slot contains a list of all the locations of the particular feature. Such lists can be generated transparently during the graphical input of the architectural plans.

The data regarding the weights of various materials should be available in the data base while the dimensions of the objects are set by design. Rather than a specific value, as shown in the figure, the load slots should contain the methods for computing the loads based on the other object attributes.

Information such as that contained in the frames shown in Figures 8.3 and 8.4 can define the function constraints that are required in order to proceed with the conceptual design of the gravity framing systems at the typical floor. The information pertaining to the exogenous systems remains constant for a given cycle of conceptual design while the information pertaining to the slab weights and span direction will change depending on the structural system under consideration. The proposed method of representation can be readily implemented by automating the acquisition and storage of the information required for the load object slots during the initial creation of the graphics data base for the exogenous systems.

8.4 Gravity System Load Paths

The gravity aspect of the structure function implies a geometric path from a point in space, the point of origin of the loads, to another point in space, the point at which the loads are delivered to the ground. The load path is the hierarchical description of the functional elements that participate in carrying the load between the beginning and the end of the path. The slab, which is the first element in the load path, is a continuum that is supported by a network of discrete horizontal and vertical members, each of which is an element in the load path However, in the approach described here the slab is treated as if it consisted of individual one way panels, the boundaries of which are defined by the underlying framing. The location of the slab element in the context of the load definition objects determines the nature of the slab design superimposed loads that, combined with its self weight, are supported by the framing members.

The following discussion focuses on the discrete elements of the load path. Figure 8.5 shows a graphical representation of the load paths for a two story two bay frame. For clarity, the slab elements are not shown. In general, the manner in which the slab distributes the load to the supporting beams is dependent on first principles governing redundant systems. However, for the purposes of this discussion, we will make the assumption that the slab is hinged at all beam lines producing a series of simple span elements that are all statically determinate, i.e. the reactions at the beams can be determined by the application of the equations of static equilibrium.[4] Conceptually, the function of the slab is to transform the area loads described in the load objects into line loads at the beam locations.

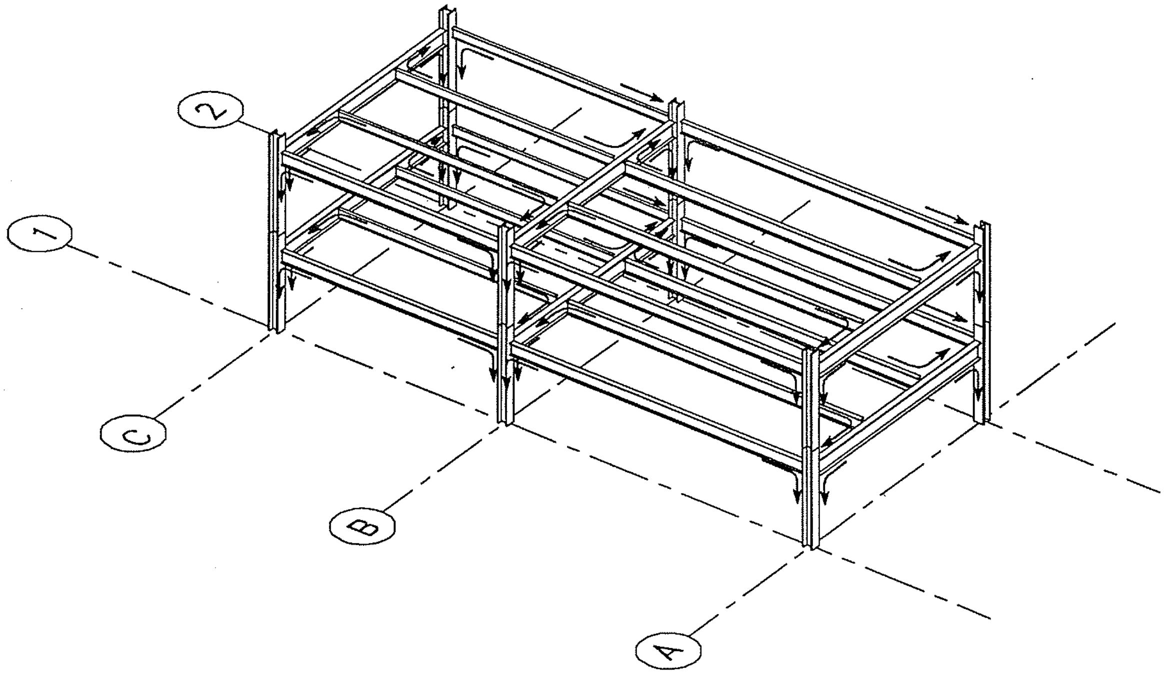

Figure 8.5 Perspective of Gravity Load Paths

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[4] This assumption is consistent with standard conceptual design practice and is accurate for composite slabs on beams, since the reinforcement provided in the top of the slab is typically not sufficient to develop the redundant negative bending moment.

The load is transferred through the system of discrete horizontal and vertical members, as indicated by the arrows in Figure 8.5. The horizontal elements support the slab and transform the applied line loads to loads at other horizontal or vertical elements at remote points in the horizontal plane. Eventually, all loads are collected at discrete locations in space and transferred vertically down to the bottom of the structure. At the ground, the load is distributed through foundations (not shown in Figure 8.5). The basic gravity load support system consists of the following element types:

1) *Slabs* are continuums that support all applied loads at the floors and transform them to line loads along the supporting beams. For conceptual design, the continuum can be treated as a series of discrete, simply supported one-way panels whose primary mode of behavior is flexure.

2) *Beams* are discrete horizontal elements that collect distributed line and point loads and transform them into point loads at remote points in the horizontal plane. Since this transforms the location of the forces perpendicular to the line of action of the forces, it requires the presence of moments for equilibrium and flexure is the primary mode of behavior of beams. Secondary beams support slabs while primary beams support other beams.[5]

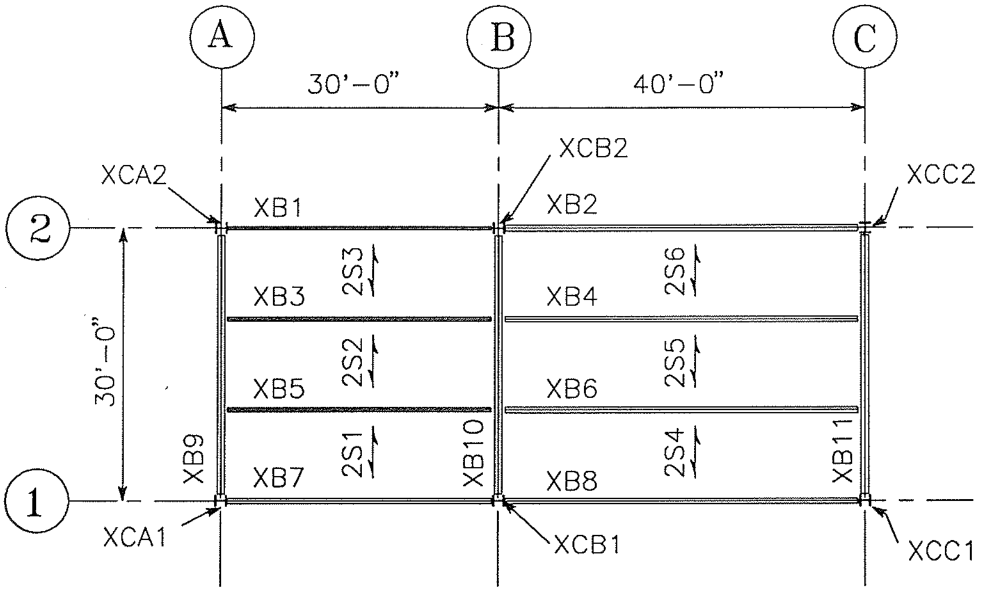
3) *Columns* are discrete vertical elements that change the location of the line of action of the applied load in the vertical plane. Since this transforms the location of the force parallel to the line of action and in the direction of the line of action it does not require the presence of moments and axial compression is the primary mode of behavior of gravity columns. (In this discussion, hangers, which transform the load along the line of action but in a direction that is opposite the line of action, are not addressed.)

4) *Foundations* transform the accumulated loads from the columns into a form suitable for transferring those loads to the ground.

The above definitions are generic since they are related only to the functions of the elements. Figure 8.6 is a plan of the structure shown in Figure 8.5 in which the lines represent the horizontal elements of the load paths. The numbering system shown in the plan accommodates multiple instances of this particular system of load paths in order to

---

[5] It is common to use the term 'beam' to indicate a beam that supports slabs, and 'girder' to indicate beams that support other beams. In this discussion the term 'beam' is used to denote the concept of functional entity, i.e., a horizontal flexural member in the gravity load path, which is the same for both primary and secondary members.



XC – Indicates column number
XB – Indicates beam number
XS – Indicates slab number
where "x" is floor number

Figure 8.6 Load Path Object Names

facilitate the processing of typical floors in an office building, e.g., 1CB1 is the first floor column at the intersection of line B and line 1.

Figure 8.7 is a semantic net representing the load paths for the three dimensional structure of Figure 8.5 using the object names from Figure 8.6. In the network, the ellipses represent instances of column and beam elements, while the arrows represent 'supported by' relationships among those elements with the arrow pointing to the supporting member. The presence of an arrow between two members indicates that there is a connection between the members. In steel systems, the links are physical entities consisting of plates, welds, bolts, etc. In concrete systems, the links represent the intersection of two elements, and therefore, the intersection of the formwork for constructing those elements.

A comprehensive representation scheme must recognize the links as functional elements in their own right, but including them at the highest level of abstraction is inconsistent with the need for efficiency (since there are two connections per beam), leads to inconsistencies between the function representation of steel and concrete systems, and does not contribute to the qualitative reasoning process during conceptual design. For this reason, although it is intuitively appealing to include the connections as separate functional objects at the highest level, they are instead associated with the element form representation, in the same way that subcomponents of built-up members would be.[6]

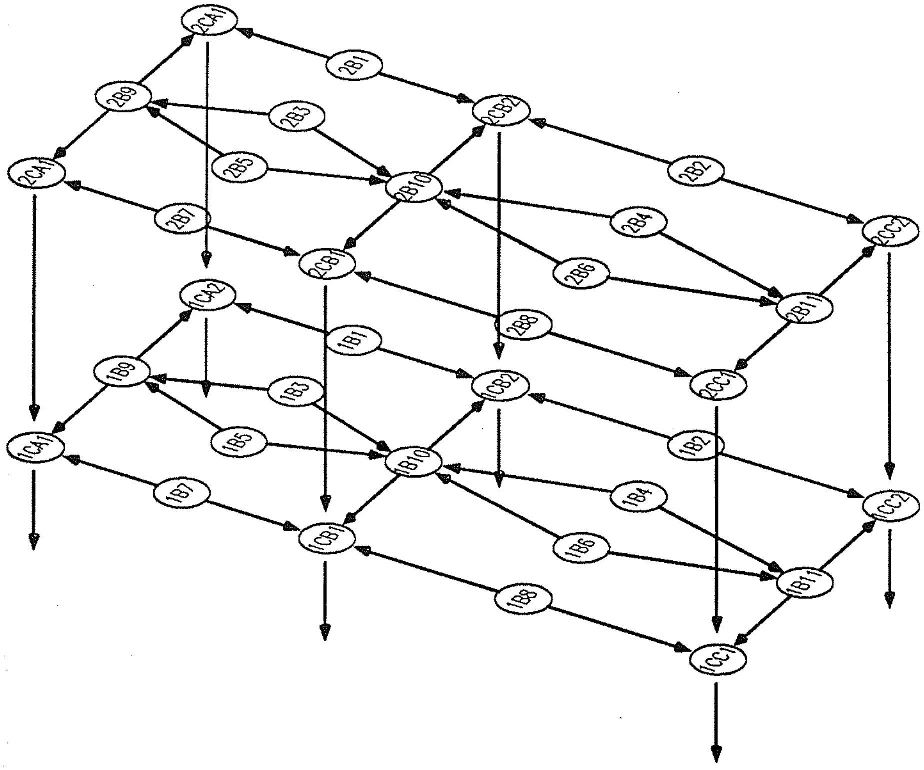


Figure 8.7 Load Path Semantic Net

In the general case, the magnitude of the load that is transferred through a link is a function of the behavior of the supported element as well as the load on the supported element. In simple systems, i.e., systems in which there are no member end moments, the reactions at the ends of horizontal members are independent of element behavior and can be calculated directly for each individual member based on the structure topology and the

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[6] This goes against the argument that the connections are every bit as important as the other elements of the load path. Nonetheless, their presence is implicit in the discrete nature of the load path elements they link, so including them at the highest level of abstraction adds nothing to our knowledge or understanding of the structure.

applied loads. The system of element forces that results from applying this assumption forms one boundary of the envelope of gravity design forces. It is common to use these forces in the conceptual design of individual elements for gravity loads.[7]

The process of conceptual structural design involves synthesizing one or more sets of load paths such that all slabs are supported by elements that are themselves supported. This recursive definition results in a hierarchical tree in which any element of the tree is supported only if the chain of 'supported/supporting' elements, i.e. the load path, is unbroken between that element and the root node, and the root node is itself supported.

In planar systems subjected to gravity load a vertical reaction and a moment are required for a member to be considered supported. In simply supported systems, two vertical reactions, assumed to be at the ends of the supported member, provide the required support.

The conditions for determining member support in simply supported gravity systems can be expressed in the form of a rule as follows:

```
If end I of an element, E1, is supported by element, E2,
and E1 end J is supported by element , E3,
and E2 and E3 are supported,
then E1 is supported
else E1 is not supported
```

There is also a geometric constraint in that supported members must be adjacent to supporting members as defined in the next section.

In continuous gravity systems the members are connected in such a way that moments can be induced their ends and the reactions of a member are no longer independent of its behavior. In the general case a topology that results in a complete load path in the absence of continuity will also yield a complete load path when continuity is considered, in which case the continuity is a constraint on the behavior rather than the function. Nevertheless, it is necessary to address the issue of continuity in the function representation in order to handle systems of load paths where the continuity is a requirement for a complete load path, as it is in cantilevered beams.

Moment continuity between members requires a specific relationship between the members. For the purposes of this discussion, beam elements can only be continuous with other beam elements that are adjacent and collinear, as illustrated in Figure 8.8, or with

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[7] In steel systems, where the elements are assumed to be simply supported - unless special connection details are added to force them to behave as continuous - this assumption may be accurate for detailed design as well.

column elements. Members at a level are defined to be adjacent if they have the same theoretical end point, where end points are defined to be the coordinates of the projection of the intersection of the axes of the supporting and supported members on a horizontal plane. (The adjacency relationship is also useful in formulating constraints on the member connections of both concrete and steel systems as shown in the figure.) Cast-in-place concrete systems are inherently continuous, as long as the appropriate continuity reinforcing is present, whereas special details are required to render steel systems continuous.

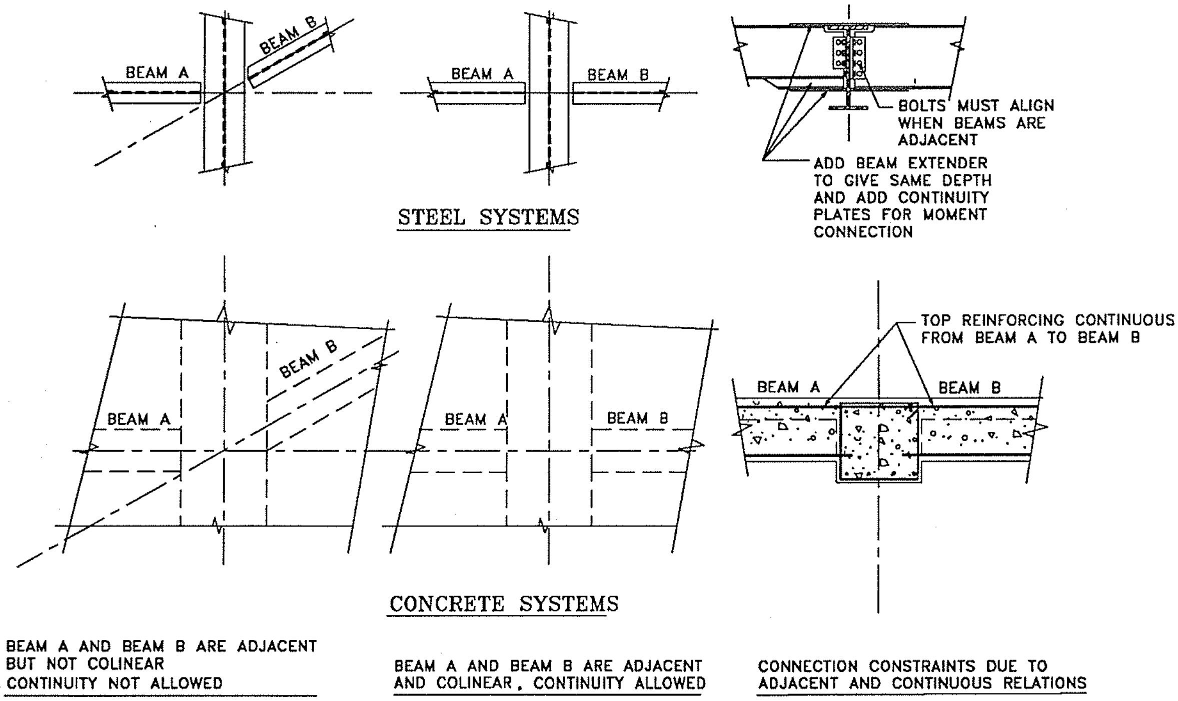

Figure 8.8 Adjacency and Continuity of Structural Elements

In the case of cantilevers, the element is supported if there is a non-NIL vertical support at either end and there is continuity at either end. The vertical support and the continuity do not have to occur at the same end. An additional test for support of cantilevered elements can be expressed in rule form as:

```
If end I or end J of element E1 is supported by an element, E2,
and end I or end J is continuous with an element, E3 (which can be E2),
and E2 and E3 are supported
then E1 is supported
else E1 is not supported
```

It is possible to represent a gravity load path as a series of functional objects with attributes SUPPORTS, SUPPORTED BY, and SUPPORTED. The function objects required to define a portion of the load path for slab 2S4 in Figure 8.6 are shown in Figure 8.9. The first attribute slot defines the element location, which consists x, y, and Z coordinates of the two end points given in the building coordinate system (BCS). The next set of attributes contain the names of the corresponding gravity behavior, lateral function, and form objects (GBO, LFO, FO). The SUPPORTS attribute contains a list of the loads supported in the case of slabs and a list of elements supported in the case of beams and columns. Beam and slab objects have SUPPORTED BY, REACTION, and CONTINUOUS WITH attributes at the left and right ends (or I and J ends). Columns have attributes SUPPORTED BY and AXIAL LOAD at the bottom end only, which is consistent with the definition of column behavior (axial compression). In the calculation of the reactions, each function object, including slab objects, must refer to its form object to determine its self weight for the purpose of calculating its reactions. All objects have the boolean attribute SUPPORTED which is used to flag the condition where an object has local support but where there is a break somewhere downstream in the load path (which results in a value of FALSE).

The types of function objects represented in Figure 8.9 are sufficient to define a complete gravity load path. The value of the SUPPORTED slot in an object can be determined by testing both the I and J ends of a horizontal member or the bottom end of a vertical member for non-NIL SUPPORTS that themselves have a value of TRUE in their supported slots. A system of load paths is complete if all of the slabs are carried by elements with a value of TRUE in their SUPPORTED slots. When the load paths for a floor are complete, the sum of all the column axial loads is equal to the sum of all function loads, feature loads, and member self weights at that floor.

This method of representation facilitates the determination of the effects of altering the structure topology by propagating the new support relationships. As an example, if column 1CB1 is removed from the system in Figure 8.7, column 2CB1 and beams 1B10, 1B7, and 1B8 have a NIL support and their supported slot value is changed to FALSE. Because the value of the supported slot for 2CB1 is FALSE, beams 2B7, 2B8, and 2B10 have their supported slot values changed to FALSE and so on until all beams and columns directly or indirectly affected by the change have been processed. Changes in SUPPORTED values are propagated up the tree through the lists of elements contained in the SUPPORTS slots. Reasoning about the completeness of the load path or the effects of changes in the support relationships can be carried out using only qualitative reasoning.

GFO SLAB :	2S4
LOCATION	L2, GB, G1+10.00'; L2, GC, G1+20.00'
GBO	B SLAB 1
FO	F SLAB 2
LFO	NIL
SUPPORTS	OCC. LOAD:TYPICAL FLOOR
SUPPORTED BY L	2B8
REACTION L END	0.375 (DL,KLF),0.250 (LL,KLF)
CONTINUOUS WITH L	NIL
SUPPORTED BY R	2B6
REACTION R END	0.375 (DL,KLF),0.250 (LL,KLF)
CONTINUOUS WITH R	NIL
SUPPORTED	TRUE

GFO BEAM :	2B6
LOCATION L END	L2, GB, G1+10.00 L2, GC, G1+10.00
GBO	B BEAM 4
FO	F BEAM 4
LFO	NIL
SUPPORTS	S4R,S5L
SUPPORTED BY L	2B10
REACTION L END	15.0 (DL,KIPS),10.0 (LL,KIPS)
CONTINUOUS WITH L	NIL
SUPPORTED BY R	2B11
REACTION R END	15.7 (DL,KIPS),10.0 (LL,KIPS)
CONTINUOUS WITH R	NIL
SUPPORTED	TRUE

GFO BEAM : 2B10	
LOCATION L END	L2, GB, G1 L2, GB, G2
GBO	B BEAM 6
FO	F BEAM 7
LFO	NIL
SUPPORTS	2B3R,2B4L,2B5R,2B6L
SUPPORTED BY L	2CB2
REACTION L END	28.4 (DL,KIPS),17.5 (LL,KIPS)
CONTINUOUS WITH L	NIL
SUPPORTED BY R	2CB2
REACTION R END	28.4 (DL,KIPS),17.5 (LL,KIPS)
CONTINUOUS WITH R	NIL
SUPPORTED	TRUE

GFO COLUMN: 1CB2	
LOCATION	L0, GB, G2 L0, GB, G2
GBO	B COLUMN 2
FO	F COLUMN 5
LFO	NIL
SUPPORTS	1B1,1B2,1B10,CB1
CONTINUOUS WITH T	NIL
CONTINUOUS WITH B	NIL
AXIAL LOAD	85.8 (DL,KIPS),52.5 (LL,KIPS)
SUPPORTED BY BOTT	F2
SUPPORTED	TRUE

GFO COLUMN: 2CB2	
LOCATION	L1, GB, G2 L2, GB, G2
GBO	B COLUMN 5
FO	F COLUMN 5
LFO	NIL
SUPPORTS	2B1,2B2,2B10
AXIAL LOAD	42.9 (DL,KIPS),26.3 (LL,KIPS)
SUPPORTED BY BOTT	1CB1
CONTINUOUS WITH T	NIL
CONTINUOUS WITH B	NIL
SUPPORTED	TRUE

GFO FOUNDATION: F2	
LOCATION	L0, GB, G2
GBO	B FOUNDATION 2
FO	F FOUNDATION 2
LFO	NIL
SUPPORTS	1CB1
	85.8 (DL,KIPS),52.5 (LL,KIPS)
SUPPORTED BY	GROUND
SUPPORTED	TRUE

GFO - GRAVITY FUNCTION OBJECT

GBO - GRAVITY BEHAVIOR OBJECT

LFO - LATERAL FUNCTION OBJECT

FO - FORM OBJECT

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Figure 8.9 Example Gravity Function Objects

The representation for the loads presented previously, combined with the representation for the load paths, creates a powerful tool for use in reasoning about structures. For a given pattern of functional elements, the loads on the slabs can be automatically determined based on the relationships between the geometry of loaded areas and the structure topology. Changes to the loading patterns result in changes to the slab loads that can be automatically propagated to the elements supporting the slab and so on until all element forces affected by the change in loading have been processed. The effects of changes in loading are propagated down the tree through the element identifiers contained in the SUPPORTED BY slots.

The member locations and member support relationships contained in the frame representation of the load paths are defined during the conceptual design process. The support relationships between the slabs and the secondary beams can be determined automatically based on the relationship between the beam and slab location and the slab span characteristics.

The existence of a complete load path is a necessary, but not sufficient, requirement for a safe and functional design. The individual elements forming the load path must still be proportioned to satisfy performance constraints.

8.5 Function Constraints from Lateral Loads

Wind and seismic phenomena result in lateral loads on the structure, the magnitudes of which depend on the geographic location of the facility and the surrounding topography.

Building codes give guidelines for wind loads in various regions as a function of the wind speed for some design recurrence interval, 50 years being the most common, and height above the ground. Most codes also allow the use of wind tunnel testing for generating the requisite design information which is usually given in terms of a pressure and area and can be represented similar to occupancy loads, with the area occurring in a vertical plane. The data required to define the wind load areas for conceptual design can be generated automatically, provided the code provisions are available in a suitable electronic format. The wind loads are invariant once the envelope of the building has been established and can therefore be considered constant during a given cycle of conceptual design.

The seismic loads on the structure are depend on the geographic location, the type of structural system, the dynamic characteristics of the building, and the magnitude and distribution of mass within the building. Both the mass and the dynamic characteristics of the building may vary between the various structural systems that are considered during conceptual design, and when this occurs new seismic loads must be determined. The proposed representation for function constraints based on the load key and discretized slabs facilitates the automatic computation of both the magnitude and location of the floor masses.

Y_WIND_FLOOR_N	
FLOOR_ABOVE	Y_WIND_ROOF
FORCE_CENTER	x_{CN}
STORY_FORCE	F_N
STORY_SHEAR	V_N
CENTER_OF_SHEAR	x_{VCN}
STORY_OT_MOMENT	M_N

Figure 8.10 Typical Lateral Load Object

Unlike gravity systems, lateral load systems are always cantilevered, since they are supported only at the ground. In one fashion or another, the lateral loads are delivered to floor slabs that perform a function similar to the beams in the gravity load path system, i.e., that of collecting the distributed loads and delivering them to a primary resisting element. Since the locations of the floor slabs are invariant for a given cycle of conceptual design, it is convenient to represent the lateral loads in terms of not only the applied area loads but also the internal 'forces' in the cantilever, i.e., the total shear and overturning moment at each floor, to facilitate the reasoning process. It is common to represent this information in tabular form as shown in Appendix D. The table representation of lateral loads can be readily converted to an object representation as shown in Figure 8.10. Since many of the force quantities in a load object are calculated in terms of the force quantities at the floor above, the object references that floor, and the set of objects describing a complete lateral load case form a linked list.

8.6 Lateral System Load Paths

As with the gravity loads, the function of the structure is to carry the lateral loads from the point of origin to the ground, and the load path can be described as a series of elements and the value of the force they carry. However, unlike gravity load paths in which each floor can be treated independently for the purpose of conceptual design lateral load paths must consider the three dimensional behavior of the structure. This results in a two level hierarchical definition of the lateral load paths. At the global level, the load paths consist of frames, diaphragms, and collectors, while at the local level the load path description includes the elements of individual frames.

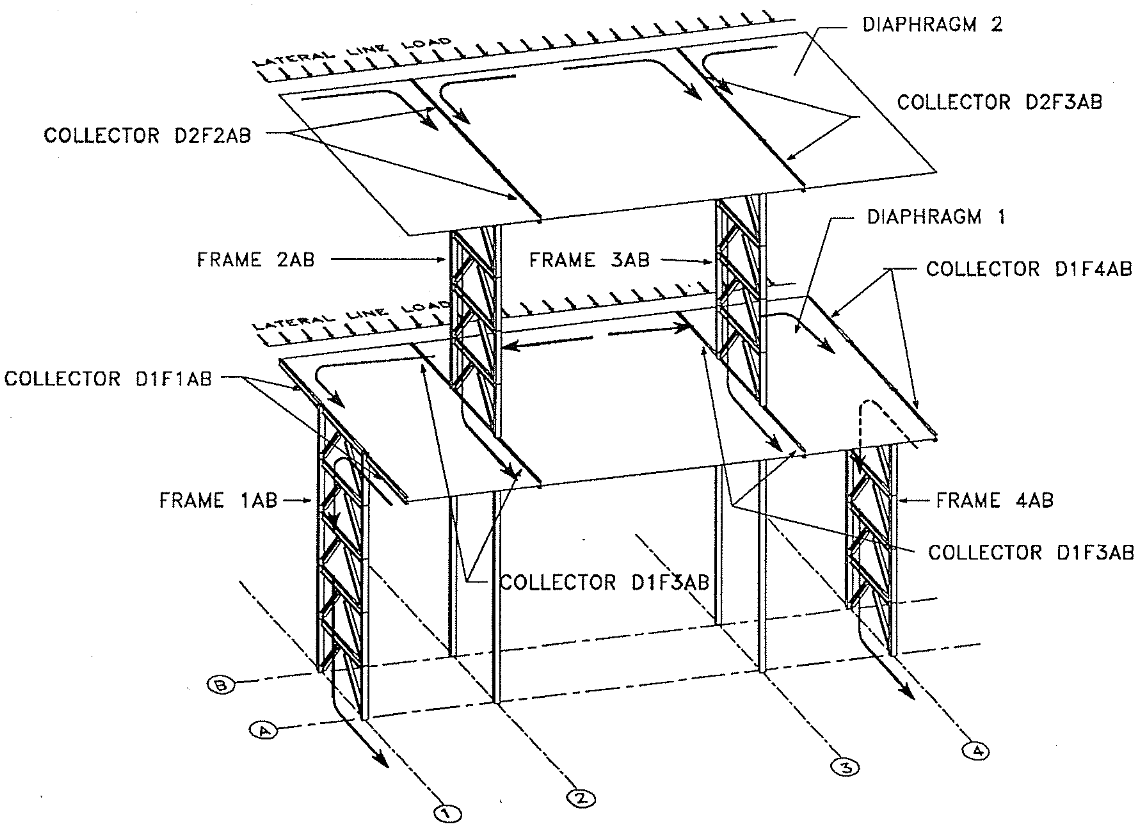


Figure 8.11 Global Lateral Load Path (One Direction)

8.6.1 Global Lateral Load Paths

Figure 8.11 is a graphical representation of the global lateral load paths in one direction. The dimensions of the lateral load resisting 'elements' must be scaled up relative to the length of the load path which, in turn, is of the same order as the height of the building. As a result of these scaling requirements, lateral load resisting 'elements are usually systems of beams, columns, and diagonals that are arranged and connected in such a way that the behavior of the system, or frame, is analogous to the behavior of an individual element. (Individual shear walls are an exception to this, since they are themselves elements.) Each frame in the building behaves similar to a beam cantilevered off its support and will be treated as a single element in the following discussion.

In the initial discussion of global load paths, only plane frame systems, in which frames have a lateral stiffness in one direction, are considered. In order to simplify the representation, only orthogonal systems are considered in the examples, although the representation developed can accommodate arbitrary geometry. The essential characteristics of the lateral load paths can be more clearly identified and examined in the context of these simplifying assumptions.

The cladding performs a function in the lateral load path for wind loads similar to that of the slab in gravity systems, namely that of transforming the distributed loads on the building faces to line loads at the locations of the slabs. Seismic loads are delivered to the slabs as a system of inertial forces applied both at the edge of the slab and distributed over its area. For both seismic and wind loads the slab functions as a horizontal beam element to transform the line of action of the applied forces horizontally in space to discrete points at its connection to the frames. Slabs that perform this function are called diaphragms and it is convenient to adopt this terminology to differentiate between the functional object, *diaphragm*, in the lateral load path, and the functional object, *slab*, in the gravity load path.

Diaphragm 2 in the figure transforms the load to discrete forces at frames 2AB and 3AB. The function of the frames is to transform the line of action of the forces in a vertical plane analogous to the columns in the gravity load paths. Frames may transfer the load vertically to the ground, as in the case of frames 1AB and 4AB in the figure, or to a diaphragm, as in the case of 2AB and 3AB. In the latter case, the collectors, which serve as the connecting elements between the diaphragms and the frames, are critical links in the load path.

In the process of transferring horizontal shear vertically, i.e., in a direction perpendicular to the line of action, internal overturning moments are developed and must be resisted over the height of the frames. In order for a frame to be supported, the total external overturning moment required for equilibrium must be resisted by supporting elements, usually at the base of the frame. In frames 2AB and 3AB this resistance is provided by a couple in the form of axial loads in the supporting columns, which will be called 'verticals' to distinguish the lateral load path functional element from its gravity load path counterpart. Without the ability to resist moment, the frames cannot carry any shear, so the verticals that resist overturning are also critical elements in the load path.

The essential elements of a global lateral load path and their functions are summarized as follows:

1) *Diaphragms* function as horizontal beams to transform the distributed horizontal loads into discrete forces along lines at specific locations in a horizontal plane. The primary modes of behavior of diaphragms are shear and bending.

2) *Collectors* collect the diaphragm forces along lines and transform them into concentrated horizontal forces at the frames. Collectors are the connecting elements between diaphragms and frames and are usually axially loaded tension *and* compression elements.

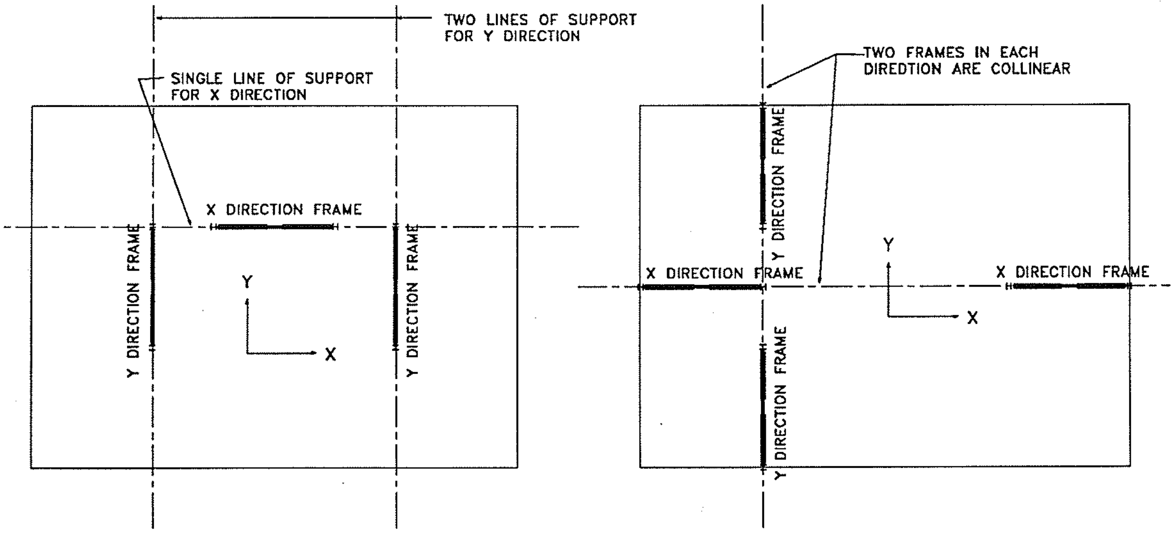
3) *Frames* transform the line of action of the forces in a vertical plane from the top of the frame to the bottom of the frame. As the result of this function, frame behavior is characterized by flexure and shear, where these refer to the behavior of the system as opposed to the components of the system.

4) provide resistance to overturning moments in the form of couples formed by axial loads. *Verticals* can exist as global entities, as in the case of the supporting columns for frames 2AB and 3AB in Figure 8.11, or as local entities that are components of a frame. The identifier *'vertical'* is used herein to distinguish this functional entity from its gravity load path counterpart, *column*.

5) *Foundations* are the terminal elements providing the link to the ground. In the case of lateral loads, particularly those due to wind, the foundations must resist both positive and negative vertical loads resulting from the overturning moments.

A fundamental decision has to be made as to the boundaries of the frames for the purposes of the global load path representation. One approach is to treat the portions of the frames that are bounded by diaphragms as individual elements in the load path that may themselves consist of segments, as is the case for the frames shown in Figure 8.11. A second approach treats the frame as a continuous element that may be connected to multiple diaphragms along its vertical axis. The latter approach, in which the frames are analogous to the primary beams that support one or more secondary beams in the gravity load paths is adopted in this discussion because it is more consistent with the concepts used in the gravity load paths and is consistent with the approach used in practice. In this case pertinent data regarding the frame consists of its location and resistance direction in plan and the starting and ending diaphragms. In Figure 8.11 frames 1AB and 4AB start at the ground and end at Diaphragm 1 while frames 2AB and 3AB start at Diaphragm 1 and end at Diaphragm 2.

In order for a system of lateral load paths to be complete, all diaphragms must be supported against movements in two orthogonal directions and against rotations about a vertical axis. These conditions are satisfied if there are three frames, none of which are collinear, and two of which are not parallel. An example of a valid diaphragm support condition is shown in Figure 8.12 (a). The diaphragm in Figure 8.12 (b) is unsupported because the for frames are arranged in pairs of collinear frames that intersect at a single point resulting in no torsional support. Although it is common for frames to be orthogonal in building structures, it is not a requirement. However, in the following treatment, the assumption of orthogonality will be enforced and frames will have stiffness in either the X or Y directions.



DIAPHRAGM SUPPORTED FOR BOTH X AND Y DIRECTIONS

DIAPHRAGM UNSUPPORTED FOR BOTH X AND Y DIRECTIONS

<u>Figure 8.12 Examples of Diaphragm Support</u>

A frame can only be considered a point of support if it is, itself, supported for both shear and moment and has a complete internal load path. If a frame starts at the ground, then support for both moment and shear must be provided by the foundation as in Figure 8.13 (A). When the frame starts above the ground level, but is supported at its end by two columns, as is the case in Figure 8.13 (B), then the shear is transferred to the diaphragm at the bottom

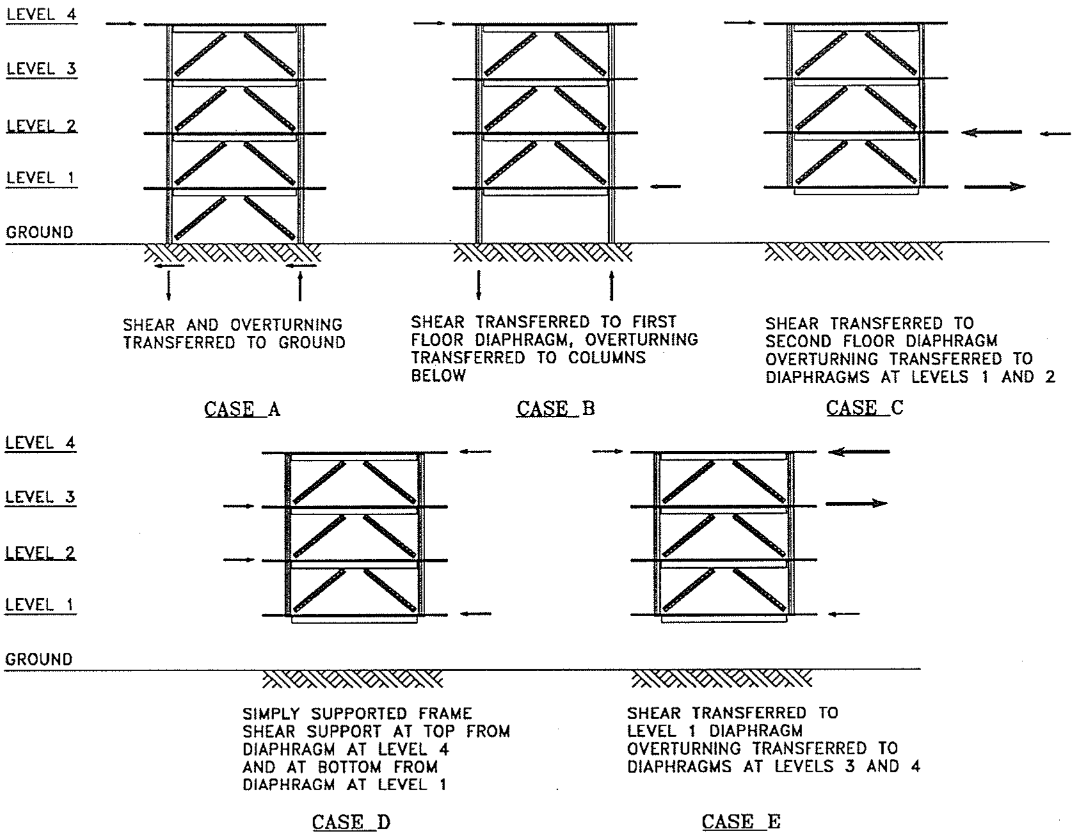


Figure 8.13 Examples of Frame Support

of the frame and the moment is resisted by axial forces in the columns. In this case, the frame is supported if the bottom diaphragm is supported and the columns are supported. A third possibility, applicable to lateral loads only, is that the frame starts at a diaphragm but is not supported on columns. In this case, shown in Figure 8.13 (C), the moment is transferred by means of a horizontal couple at the two bottom diaphragms, while the shear is transferred by means of a reaction at the second diaphragm from the bottom. In this special case, the supporting diaphragms must themselves be connected to each other by frames independently of the supported frame in order to create a complete load path. In case (D), support is provide by means of reactions at the top and bottom of the frame. This is the frame equivalent of a simply supported beam, and is useful in describing the support of 'nested' frames such as occur in the 'super frame' concept shown in Figure 8.14. Case (E) in Figure 8.13 is similar to case C, except the moment support is provided at the top of the frame instead of the bottom.

While the conditions shown in Figure 8.13 (C) and (E) do not satisfy the requirements for a complete gravity load path, they do satisfy lateral load path requirements. Although it is uncommon to use these types of load paths in practice, except in the case of very tall buildings, they should be recognized as potential paths. They are useful in the conceptual design of lateral systems that utilize the outrigger concept as shown in Figure 8.14.[8]

Cases (C) and (E) of Figure 8.13 illustrate the fact that any two diaphragms along the length of the frame could provide the moment support. For the purposes of reasoning about load paths, some distinction must be made between normal three dimensional frame interaction and moment supports provided by diaphragms, since conditions such as the latter result in very high collector forces as well as high shears in the frames between the two diaphragms. During conceptual design, a load path is constructed with the supports for each element defined, and the types of support conditions are then used to formulate constraints on the behavior of the elements, that, when propagated, result in constraints on the frame component attributes. When the path requires that moment support be provided by diaphragms, then a special condition exists which should be explicitly represented.

Figure 8.14 shows two examples of complex frame support systems that the representation of the lateral load path should be capable of describing. The distinguishing characteristic of the 'super frame' system shown on the left side of the figure is that only the diaphragms that occur at the same elevations as the primary frame panel points are supported by the primary frame. (A primary frame panel point is a locations where a multi-story diagonal intersects a horizontal and a vertical, i.e., levels 4, 8, 12, 16, and 20, in Figure 8.14.) Intermediate diaphragms must be supported by a secondary frame that has panel points at all levels. The secondary frame spans between the primary frame panel points. Although this system could be represented as a simple system of redundant frames, it is useful to identify it as a distinctive type of load path for conceptual design purposes.

The super frame system is useful to illustrate a second function of the diaphragms, that of providing stability support for the gravity columns. Without the secondary frame in the 'super frame' scheme, the effective lengths of the gravity columns would be equal to the distance between the primary frame panel points and would have to carry the lateral loads from the intermediate diaphragms in bending. In all buildings, the connections between the diaphragms and the columns they support must have sufficient strength to resist stability

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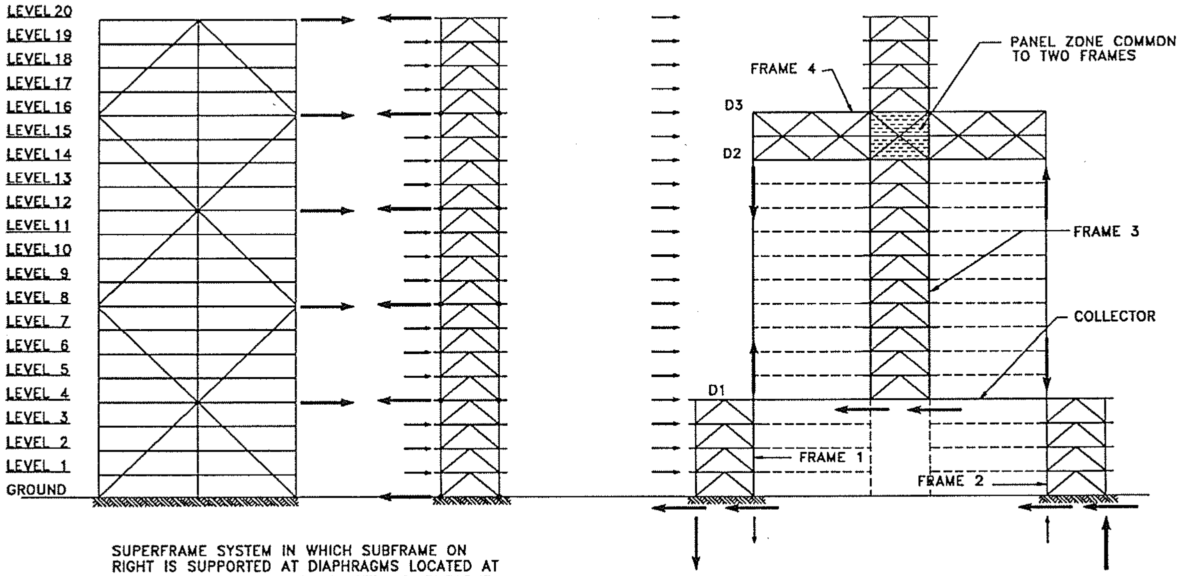
[8] It is also possible to inadvertently develop frame forces consistent with these types of load paths in three dimensional FEM analyses where frames that have significantly different rigidities are connected by 'rigid' diaphragms.

loads. This constraint must be explicitly addressed at columns along the edges of the slab at the outside of the building and at core openings. (The intermediate columns along the long faces of the building in Figure 7.2 are examples of places where this constraint would affect the form of the slabs.)



SUPERFRAME SYSTEM IN WHICH SUBFRAME ON RIGHT IS SUPPORTED AT DIAPHRAGMS LOCATED AT PANEL POINTS OF FRAME ON LEFT. DIAPHRAGMS BETWEEN SUPERFRAME PANEL POINTS ARE SUPPORTED ON DIAPHRAGMS WHICH ARE SUPPORTED ON SUBFRAME

EXAMPLE OF COMPLEX FRAME SUPPORT PROVIDED BY DIAPHRAGMS AND WIND COLUMNS IN OUTRIGGER SYSTEM

Figure 8.14 Examples of Complex Frame Support Systems

The 'outrigger' system shown on the right of Figure 8.14 utilizes combinations of all the frame support conditions that were shown in Figure 8.13. The dashed lines indicate structural elements that are not part of the lateral load path but do provide support for the columns that are primary elements. The columns under the center frame are shown dashed to focus attention on the load paths created by the outrigger. In actual buildings, the outrigger system is used in combination with the primary columns to reduce the overturning moment in the core.

In the outrigger system, Frame 3 is supported for moment by two diaphragms along its length, D2 and D3, and, in turn, provides the shear support for those diaphragms. The independent support of the diaphragms providing moment resistance is supplied by frame 4, which is provided with moment resistance by columns that extend to the ground. This example leads to a constraint on the independent frames that support the two diaphragms, Frame 4 in the figure. The moment in those frames must be supported by elements, such as the columns, that are supported vertically. Frame 3 is supported for shear by the bottom diaphragm, D1, which is supported by frames 1 and 2. .

It is not necessary for all of these frames to be collinear in order for the 'outrigger' system to function. The frame and collector forces can all be computed independently based on equilibrium constraints. For the special case where the frames are collinear, as in the conventional outrigger system, the forces in the zone of overlap can be obtained by superimposing the independent frame forces and the outrigger chord forces are equal to the sum of the collector forces from the individual frames. Frames 3 and 4 are an example of this special condition. Another example of this type of load path is the belt truss system in which the independent supporting frame is located on the perimeter of the building.

As with the gravity systems, the completeness of the lateral load path can be determined by using qualitative reasoning and working through the path from the bottom to the top of the structure propagating SUPPORTED relations up the tree. There are always at least two lateral load conditions, one in each of two orthogonal directions, each of which has a distinct lateral load path. Since the locations and rigidities of the frames are constraints on the lateral load paths that are formulated during the conceptual design, it is common to make the assumption of independence in the two directions and then use this to formulate constraints that, when satisfied, will result in the validity of the assumption for symmetrical loadings.[9] However, the representation of the lateral load path should be general enough to accommodate systems for which this assumption is not valid.

The verticals and foundations in the lateral load paths always serve the same function, i.e. that of supporting other independent elements, the only difference being that the foundations are terminal elements while the verticals must themselves be supported by other verticals or foundations. The existence of collectors is implicit in the attachment relationships between diaphragms and frames, just as connections are implicit in the gravity load path. However, their is no library of 'standard' collectors, so they must appear explicitly in the function representation.

The reasoning required to determine the supporting relationships between diaphragms and frames can be complex since the relationship can be applied in either direction, i.e., a frame can either support - or be supported by - a diaphragm. When a frame supports a

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[9] Loads that are not symmetrical with respect to the lateral system result in torsion. Under these conditions, in the general case, the two directions cannot be independent. A counter example occurs when a diaphragm such as that shown on the right side of Figure 8.12, is subjected to an unsymmetrical loading perpendicular to the single frame.

diaphragm, the force quantity from the diaphragm perspective takes the form of shear. Frames, though, can be supported for either moment or shear by the diaphragms and diaphragms that support a frame for moment may themselves be supported by the diaphragm for shear.

In the face of these daunting complications, it is necessary to develop a systematic, hierarchical approach to the reasoning that will render the problem tractable. The set of rules below tests for the existence of one complete set of lateral load paths, i.e. one that provides support for all diaphragms. Testing for the existence of a complete set of load paths is useful, since failure to satisfy this constraint results in ill-conditioning problems that make it impossible to perform conventional analysis on the structural system.

In order to initiate the reasoning process, the data required include the existence and locations of foundations, columns, frames, including valid frame load points, and diaphragms. From this data, the attachment and support relations can be derived.

Rules for Existence of Complete System of Global Lateral Load Paths:

1) If the elevation of a valid frame load point corresponds to the elevation of a diaphragm, then there is a collector connecting the frame and the diaphragm, the diaphragm is attached to the frame, and the frame is attached to the diaphragm
2) A frame starts at its lowest valid load point that corresponds to either the foundation elevation or a diaphragm attachment
3) A frame ends at its highest valid load point that corresponds to a diaphragm attachment
4) If a frame is supported for moment and shear, then it is supported else it is NOT supported
5) If there exists another frame that has the same start, end, and diaphragm attachments as the current frame, is parallel to the current frame, and is supported, then the current frame has the same support type and supporting elements as that frame
6) If a frame, F1, starts at a foundation, then it is supported for shear by the foundation

   ELSE

   If there exists a diaphragm to which the frame is attached that is supported in the direction of F1, then F1 is supported for shear by the lowest such diaphragm

   ELSE

   The frame is NOT supported for shear
7) If a frame, F1, starts at a foundation, then it is supported for moment by the foundation

   ELSE

   If there are supported columns located at the ends of F1 at the start elevation of F1, then F1 is supported for moment by the columns

   ELSE

   If there exist two diaphragms, D1 and D2, that are attached to F1 and are also attached to a frame, F2, which is NOT perpendicular to F1 and which is supported for moment, or there are two diaphragms that are supported and attached to F1, then F1 is supported for moment by diaphragms consisting of the lowest such diaphragm, D1, and the highest such diaphragm, D2

   ELSE

   F1 is NOT supported for moment
8) If a supported frame is attached to a diaphragm and the diaphragm does not support the frame for shear, then the frame supports the diaphragm
9) If a diaphragm is supported by at least three frames, none of which are collinear, and one of which is not parallel to the other two, then the diaphragm unsupported direction is none, the diaphragm is supported for moment, and the diaphragm is supported

- a) If a diaphragm is not attached to any frames or all of the frames to which it is attached are unsupported, then its unsupported direction is all and it is unsupported for moment
- b) If all the frames supporting a diaphragm are parallel then the diaphragm is unsupported in the direction perpendicular to the frames
- c) If a diaphragm is not supported by a supported frame that has a direction cosine in the X direction, then the diaphragm is unsupported in direction X
- d) If a diaphragm is not supported by a supported frame that has a direction cosine in the Y direction, then the diaphragm is unsupported in direction Y
- e) If a diaphragm is supported by at least two frames which are not perpendicular and are not collinear, then the diaphragm is supported for moment

10) If all diaphragms are supported, then a complete system of lateral load paths exist

In the above set of rules, the simple relationships involving frames and diaphragm attachments are addressed in rules 1 - 3, which can be categorized as load path topology rules. Rules 4 through 7 use constraints to determine whether frames are supported and the nature of the support.

Rule 5 is a 'common sense' rule that states that similar frames are intended to have similar supports and is required due to the redundancy of normal lateral systems. As an example, if there were two frames similar to Frame 3 in Figure 8.14, rules 6 and 7 would correctly identify the support relationships for the first frame, but erroneously identify a different system of supports for the second frame. When the results of the first support relationships are propagated, the diaphragm support conditions are changed, since the diaphragms at the top and bottom of Frame 4 become supported in the direction parallel to Frame 3. When a second frame, identical to frame 3 in its attachments is processed, it would be assigned moment supports consisting of the start diaphragm and the diaphragm at the bottom of Frame 4. It is more likely that the intent of the design would be for the second frame to serve a function similar to the first frame, and a second supporting frame is required for moment support of the diaphragm, hence the assignments in rule 5.

In determining the moment and shear support relationships for the frames, a preference is established, which, when applied, will result in a single unique method of support for each frame. The order of preference for deciding among multiple possible methods of support is based on the intuitive philosophy that the most efficient, and, therefore, the most likely load path, based on the 'least work' principle, is the most direct load path. Hence, the method of moment support chosen is the one that occurs closest to terminal nodes, the foundations, and which involves the least amount of interaction between frames and diaphragms. Shear support for a frame can only be provided by the foundations or a diaphragm. When it is provided by a diaphragm, the lowest diaphragm that satisfies the support constraint is chosen.

The order of preference for frame moment supports are:

1) Foundations
2) Verticals
3) Diaphragms

When the moment support is provided by diaphragms, then only two diaphragms are used for this purpose. The first is the lowest diaphragm that satisfies the constraint of independent support while the second is the highest diaphragm that satisfies that constraint. An alternate approach would be to use the two lowest diaphragms that satisfy the support constraints. Since the actual support conditions are dependent on the system behavior, the desired supports are determined based on heuristic knowledge and architectural system attributes during conceptual design and are then used to formulate constraints on the behavior.

Rules 8 and 9 determine the diaphragm support conditions. Subsets of rule 9 are included to identify qualitative attributes which further define the nature of the diaphragm support, or lack thereof, such as the direction in which the diaphragm is unsupported.

Rule 10 contains the governing constraint for the existence of a complete system of lateral load paths. If a complete system of lateral load paths exists, then it is possible to analyze the structure for any set of lateral loads, otherwise, the results of such analyses would not be valid. As with the gravity load paths, the simple existence of a lateral load path is a necessary but not sufficient condition for an acceptable structural design. The system behavior and geometric properties must still be such that performance constraints are satisfied.

The rules presented above simply test for the existence of a potential system of lateral load paths, which may not be the only possible system. For instance, if the rules were applied to the super frame system in Fig. 8.14, they would predict that both the shallow and deep frames would be supported for moment by the foundations and all diaphragms at the location of a panel point on either frame would be supported by that frame. The fact that the shallow frame is supported on the deep frame at primary panel points can be deduced based on qualitative reason about behavior. Although the rules would predict the load path for the single outrigger system contained in Fig. 8.14, they would not capture the design intent in a system that has multiple outriggers along the vertical axis, since only the first moment support is considered. In actual lateral load systems, there may be multiple moment supports consisting of foundations or columns and one or more outrigger levels, or multiple shear supports as in the super frame system.

Fortunately, during the synthesis of lateral load systems, it is not necessary to deduce the behavior based on an arbitrary system description, since the objective is to derive the system description to produce a desired behavior - which is actually a much easier task using qualitative reasoning. The objective during conceptual design is to determine what type of systems are possible, evaluate the relative feasibility of the systems, and synthesize one or more possible systems of load paths.

The order of preference for determining moment support suggested above is an example of a heuristic that might be used to rank the feasibility of various potential systems. Usually the simplest systems, which generally have the shortest aggregate load paths, are the most economical. Complex systems such as the outrigger system on the right side of Figure 8.14 are used only as a last resort when the frames that are permissible do not have adequate dimensions. The outrigger and frames in Figure 8.14 are analogous to moment frame system on a grand scale in which the vertical and horizontal beams are trusses. Such systems are used to increase the effective width of the lateral system to decrease the effects of column shortening in narrow core frames.

The system of load paths synthesized during conceptual design, which will be complete if the frame and diaphragm support constraints are satisfied, can be analyzed using conventional programs to determine the precise behavior. The results of this step will validate the conceptual design if qualitative and approximate quantitative reasoning have been used to correctly proportion the elements and systems.

8.6.2 Frame Lateral Load Paths

In order for the global lateral load path system to be complete, the frames that provide the support for the diaphragms must themselves have complete internal load paths. The frames consist of components whose behavior and connectivity results in the transfer of the lateral shear in the vertical plane. Depending on the frame type, different conceptual entities are used to accomplish this. In steel systems, valid frame types are braced frames, eccentrically braced frames, and moment frames, while in concrete systems valid frame types are walls and moment frames. While there have been examples of braced concrete frames and steel walls in practice, these are considered unusual systems and are not addressed here.

In order to identify those attributes of frames which are necessary to the reasoning process the load paths in each type of frame will be examined in turn. The function of the frames is to transform the line of action of a lateral shear force in a vertical plane. As a result, in order for the frame lateral load path to be complete, it must be capable of resisting the direct shear as well as the moment that is incidental to the transformation.

In the following discussion, the term *frame* is used to indicate a functional 'element' in the global system of load paths. The functional role of *frame* may be filled by a wall or a system of primitive elements that approximates the behavior of a wall.[10]

8.6.2.1 Concrete Walls

The simplest type of *frame* is a concrete wall, which is a continuous element that is capable of resisting both moments and shears. Walls are, precisely, vertical beams (for lateral loads, beam-columns for gravity loads) which can be loaded at any point along their length. By definition, walls have a complete load path, and no further reasoning is required.

8.6.2.2 Braced Frames

Pure braced frames are frames in which all of the forces are carried axially by the frame components with no incidental moments. In order to carry lateral loads while conforming to this definition two constraints must be satisfied:

1) The frame must have components whose axes have a nonzero cosine in both the horizontal and vertical planes *at all elevations* in the frame, i.e., there must be diagonal elements at all elevations.
2) The frame can only be loaded horizontally at points of intersection of members that have a nonzero horizontal cosine and are supported in the horizontal direction.

A typical multi-story braced frame consists of three basic component types:

1) *Diagonals* are the primary functional elements of the braced frame and are required for a complete braced frame load path. Diagonals transform the line of action of the horizontal force in the vertical plane by carrying forces which have both horizontal and vertical components. The frame shear at a level is equal to the sum of the horizontal components in the diagonals at that level. The primary mode of behavior of diagonals is axial tension and compression.
2) *Verticals* are elements that carry the vertical force components that

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[10] It is apparent that a less ambiguous term is needed for the functional object.

are incidental to the diagonal function. *Verticals* are essential for a complete load path. Under lateral loads only, the algebraic sum of the forces in the verticals is zero and the sum of the couples produced by the verticals at a level is equal to the frame overturning moment at that level. The primary mode of behavior of *verticals* is axial tension and compression.

3) *Horizontals* are elements that transform the point of application of the horizontal force in a horizontal plane. Some frame topologies do not require horizontals which are required only when the force cannot be transferred directly between diagonals.[11] The primary mode of behavior of *horizontals* is axial tension and compression.

A complete frame load path exists is supported at each end and is stable. This condition is satisfied if the element is supported perpendicular to its axis at each end and parallel to its axis on one end. Supporting elements must themselves be supported at both ends. If one end of a horizontal or vertical element is supported, the far end is also supported for the functional load carrying aspects of the element, i.e., vertical and horizontal loads. The supports for the ends of a diagonal are independent for both direction components, i.e., if one end is supported, the opposite end is not necessarily supported. Components whose ends have the same coordinates are connected to each other and only other components that are connected to a component can provide support for it.

Frames which would have a complete internal load path if they started at a foundation, will also have a complete load path for any of the other possible support conditions. Because of this, it is possible to reason about the completeness of the frame load path independent of the support conditions by treating the frame as if it were supported by a foundation. The ends of all elements which start at a foundation are supported. As with gravity load paths and global lateral load paths, the completeness of the load path can be determined using qualitative reasoning and propagating support conditions up the structure.

Braced frames can be divided into segments which are logically complete. For the purpose of this discussion, segments are assumed to be portions of the frame which are bounded by horizontal elements and may or may not contain a complete internal load path.[12]

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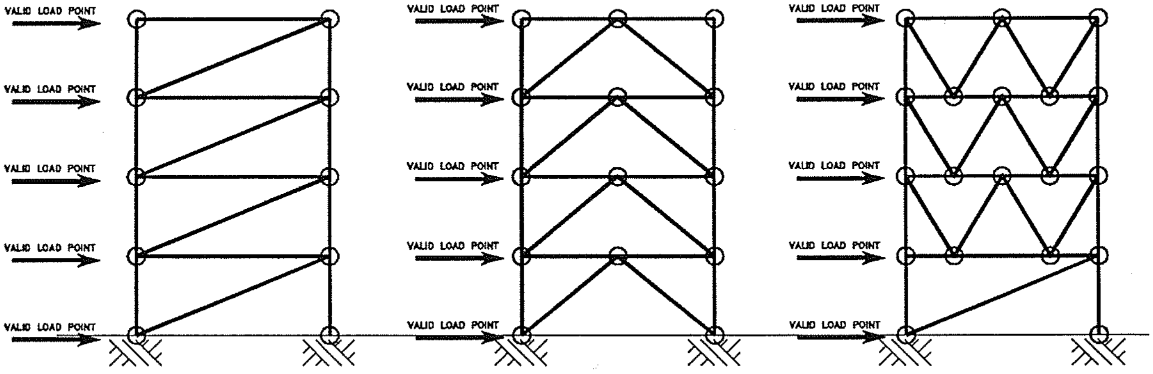
[11] The most efficient frame load path is one in which the diagonals are the only elements that participate in the frame function, since that produces the shortest path.

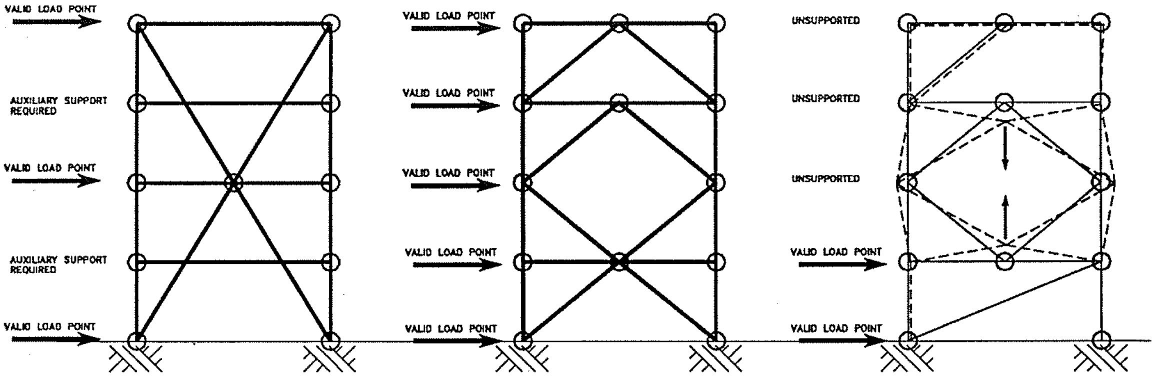
[12] An attempt was made to define a segment as a separate entity that had a complete internal load path and was, therefore, bounded by levels that were valid load points, but was abandoned when it led to unnecessary complications in the representation of the 'super frame' system.

In the current approach, each level of the frame is treated as a logical segment which can either be a valid load point or a level requiring auxiliary support. Special rules are required to address frames which have a complete load path, but in which individual segments do not have a complete load path.

Although it is possible to have a complete internal load path without having verticals at every segment, this discussion is limited to frames which have at least two verticals which must occur at the frame edges. A frame may have more than two verticals, but the existence of *boundary* verticals is used as a hard constraint.



A) Simple Diagonal B) Chevron Bracing C) Multiple "V" Bracing



D) "Superdiagonal" E) Complex Combinations F) Unsupported Conditions

Figure 8.15 Examples of Braced Frame Load Paths

Examples of braced frame load paths are shown in Figure 8.15. Example rules for determining the existence of a complete frame load path are given in Appendix D. Such rules should be able to identify the existence of a complete load path in cases (a) through (e). The qualitative reasoning on which the rules are based is summarized here.

The underlying rule for all cases is that all elements must have at least three supports consisting of combinations of horizontals and verticals at the ends. Special rules are used for verticals and horizontals, since only one of the supports can be in the direction of the member. Case (a) is a simple diagonal system for which the load path can be easily identified.

The rules for determining support for chevron braces involve reasoning about the existence of vertical support at the center node which is fairly straightforward due to the method of propagating the support, i.e., upwards, since the bottom ends of the diagonals are always supported.

For 'V' braces, it is necessary to reason about the existence of vertical support which is horizontally remote from the brace ends by tracing the vertical load path through the diagonals back to a supported column and simultaneously reasoning about the horizontal attachments between diagonals. (The resulting rules could be used equally as well for reasoning about complete load paths in gravity trusses.)

Rules that can correctly address 'V' braces, can be used to distinguish between the complete 'complex' load path in (e) while identifying the incomplete 'complex' path in (f). The rules should identify the complete load path in the 'super frame' scheme in (d) while at the same time identifying the existence of the need for auxiliary support requirements for unsupported levels. This requires reasoning about supports which are 'remote' both horizontally and vertically.

Figure 8.16 gives examples of the objects that are necessary to represent the qualitative aspects of the global and local frame lateral load paths for the two level structure of Figure 8.11. The attributes accommodate the multiple supports that could be reasoned about during conceptual design.

The lateral load path contains a hierarchy of Aggregate Lateral Function Objects (ALFO) which include the diaphragms at the global level and the frame segments at the local level. The behavior of the system can be represented at the aggregate as well as at the component level. The form representation that is of interest at the aggregate level, i.e., the geometric arrangement of functional elements or subsystems, is already contained in the function representation, so form objects are required only at the lowest component level.

ALFO DIAPHRAGM: D1	
LOCATION	GA-30.00, G1; GB+30.00, G4
AGFO	AGGREGATE SLAB 1
ALBO	D1
CONSTRAINTS	FLOOR 1 LATERAL LOADS
ATTACHED TO	F2AB, F3AB, F1AB, F4AB
COLLECTORS	D1F2AB, D1F3AB, 1F1AB, D1F4AB
SUPPORTED BY	F1AB, F4AB
SUPPORTS	F2AB, F3AB
UNSUPPORTED DIRECTION	X
SUPPORTED MOMENT	TRUE
SUPPORTED	FALSE

LFO VERTICAL : 1VA3	
LOCATION	GA, G3
GFO	1CA3
LBO	V1
TFO	V1
STARTS : ENDS	L0, L1
SUPPORTS	F3AB
SUPPORTED BY	FDA3
SUPPORTED	TRUE

LFO FOUNDATION : FDA3	
LOCATION	GA, G3
GFO	FDA3
LBO	FDA3
TFO	FDA3
SUPPORTS	1VA3

ALFO SEGMENT : F3S1	
ALBO	B_F3S1
HEIGHT	.2x(L2-L1)
WIDTH	(B-A)
DIAGONALS_LOC	(F3S1D1,0,W/2),(F3S1D2,W,W/2)
VERTICALS_LOC	(V1,0),(V2,W)
HORIZONTALS_LOC	(H1,HEIGHT)
SUPPORT_TYPE	SUPPORTED

ALFO FRAME : F3AB	
LOCATION	GA, G3; GB, G3
AGFO	F3AB
ALBO	F3AB
BOTTOM : TOP	L1, L2
ATTACHMENTS	D1, D2
SUPPORT TYPE V	SINGLE
SUPPORT TYPE M	SINGLE
SUPPORTED BY V	D1
SUPPORTED BY M	1V3A, 1V3B
SUPPORTED	TRUE
SEGMENTS	F3S1, 0.2x(L2-L1); F3S2, 0.4x(L2-L1); F3S3, 0.6x(L2-L1); F3S4, 0.8x(L2-L1); F3S5, L2;
VALID LOAD PTS	0 0.2x(L2-L1); 0.4x(L2-L1); 0.6x(L2-L1); 0.8x(L2-L1); L2;
AUX SUPPORT REQUD	NONE
UNSUPP. SEGMENTS	NONE
FLP COMPLETE	TRUE
SUPPORTS	D2

LFO COLLECTOR : D1F1AB	
LOCATION	GA-30.00, G1 GA+30.00, G1
GFO	1B1
LBO	D1F1AB
TFO	D1F1AB
SUPPORTS	D1
SUPPORTED BY V	F1AB

LFO VERTICAL : F1S1V1	
GFO	2CA3
LBO	F1S1V1
TFO	F1S1V1
CONNECTED TO	F3S1H1,F3S1D1,F3S2V1,F3S2D1
SUPPORTED BY X I	D1
SUPPORTED BY Y I	1VA3
CONTINUOUS WITH I	NIL
SUPPORTED BY X J	F3S1H1
SUPPORTED BY Y J	SELF
CONTINUOUS WITH J	NIL
SUPPORTED	TRUE

ALFO - AGGREGATE LATERAL FUNCTION OBJECT
AGFO - AGGREGATE GRAVITY FUNCTION OBJECT
ALBO - AGGREGATE LATERAL BEHAVIOR OBJECT
LFO - LATERAL FUNCTION OBJECT
LBO - LATERAL BEHAVIOR OBJECT
TFO - TEMPORARY FORM OBJECT

DIMENSIONS ARE IN BUILDING COORDINATE SYSTEM
OR FRAME COORDINATE SYSTEM

Figure 8.16 Example Lateral Function Objects

An individual braced frame can be represented as a collection of segments where each segment has an attribute describing its support type (supported, or auxiliary support required) A segment can be represented as a collection of diagonal, vertical, and horizontal components. Components of the braced frame are represented with a type, a coordinate location, and a list of supporting components for each direction at each end. The attribute 'continuous with' is included to accommodate topologies in which member continuity is a constraint on one or more elements in order to produce a complete frame load path. Examples of the latter are the diagonal elements in the 'super frame' scheme in Fig. 8.15 (D). (This condition is addressed by rules 9(d) and 10(c) in Appendix D.) Individual elements also contain slots that reference the corresponding gravity function object (GFO) and the lateral behavior object (LBO).

The geometry of the segments within the frame representation is given in Frame Coordinates (which use the segment width and height and are analogous to Building Coordinates) to facilitate propagation of changes in the global or frame geometry. In high rise office buildings, braced frames typically have elements that begin and end at floors, and the vertical coordinates of the end nodes do not vary. This condition is presumed in the representation and used to reduce the number of descriptors that must be stored for each element. The Y coordinates of the I and J nodes for all verticals and diagonals at level i are equal to the Y coordinates of level i-1 and level i, respectively, while the Y coordinates of the I and J ends of the horizontals are equal to the Y coordinate of level i. Hence the locations of all the elements in a frame can be represented by specifying the level at which the element occurs and the X location within that level of the end coordinates. If the component type is vertical, only one coordinate is required to describe its location within the level. Horizontals and diagonals each require two coordinates.

8.6.2.3 Moment Frames

Moment frames are frames in which the wind shear is carried by vertical elements in flexure, *vertical beams*, to distinguish them from the gravity load functional element *column* and the braced frame axial load member *vertical*. The *vertical beams* in a moment frame transform an horizontal shear at one level into a horizontal shear at the level below, as shown on the right in Figure 8.17. Since the shear force is transformed perpendicular to its line of action, a moment is produced.

In order for there to be a complete load path the *vertical beams*, must be supported in the horizontal direction and be continuous with a *horizontal beam*. The *horizontal beams* in moment frames serve the function of resisting the moment that is incidental to the vertical beam function. In the process of accomplishing this, the horizontal beams transform the moment, which originates as a couple consisting of horizontal forces, into a couple consisting of vertical forces. In order for a horizontal beam must itself have support against rotation. The rotational restraint is usually provided by a couple consisting of vertical shears on the ends of the beam. The right side of Figure 8.17 shows a system consisting of a *vertical beam* that resists a horizontal shear, V_h, and the *horizontal beams* that provide rotational restraint.

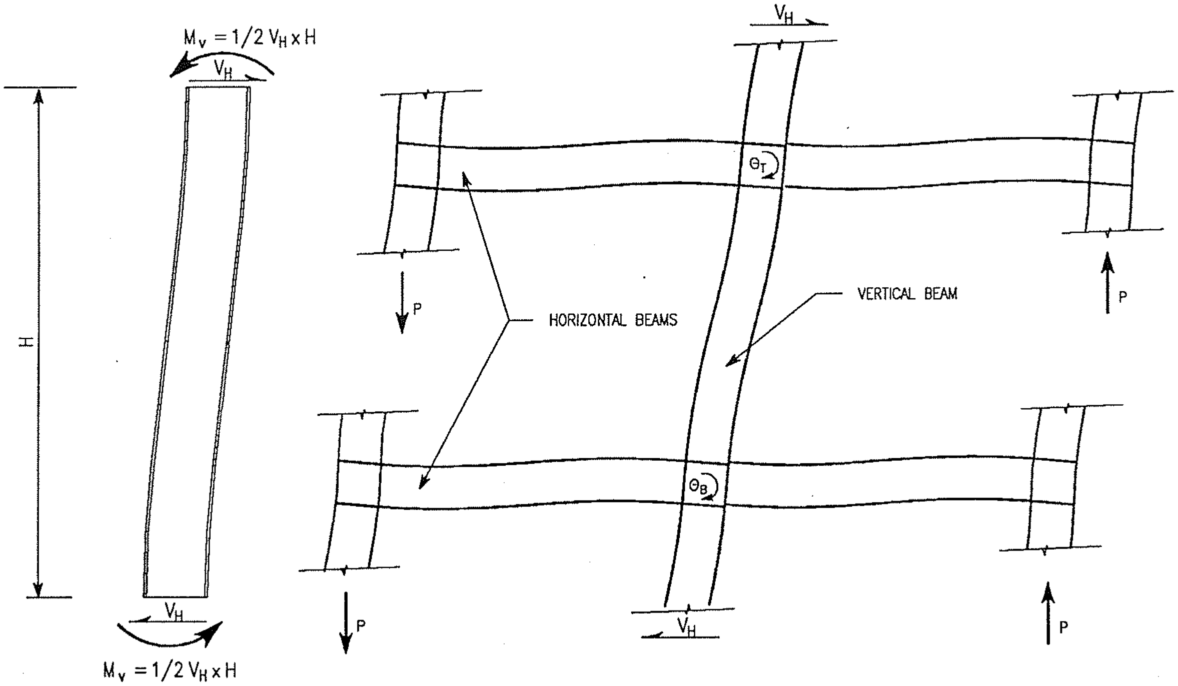


Figure 8.17 Moment Frame Elements

In moment frames, both the vertical beams and horizontal beams serve a dual function. The verticals, in addition to transforming the line of action of the horizontal shear in a vertical plane, provide the vertical support required for the horizontal beams and transmit the resulting force axially to the vertical elements at the level below. This aspect of the function of the moment frame vertical beams is identical to the function of the verticals in a braced frame. The horizontal beams, in addition to resisting the moments in the vertical beams, distribute the total horizontal force among multiple vertical beams at a level.

The functional elements of moment frames are summarized as follows:

1) *Vertical beams* are the primary functional elements that transform the line of action of the horizontal forces in a vertical plane through flexure. Vertical beams serve a secondary function of resisting the vertical forces at the ends of the *horizontal beams* and transmitting these forces along their lines of action to the verticals at the level below.

2) *Horizontal beams* provide support for the moments in the *vertical beams* by transforming the moment into a couple consisting of vertical forces at the beam ends. Horizontal beams serve a secondary function in distributing the horizontal force among the available vertical beams at a level.

For a complete load path, the moment frame must have at least one vertical beam at every level that is 'continuous with' a horizontal beam that is, itself, prevented from rotating. Figure 8.18 shows examples of complete frame load paths in moment frames. In the figure the solid triangles at the ends of the horizontal beams indicate moment connections while open circles indicate 'pinned' connections.

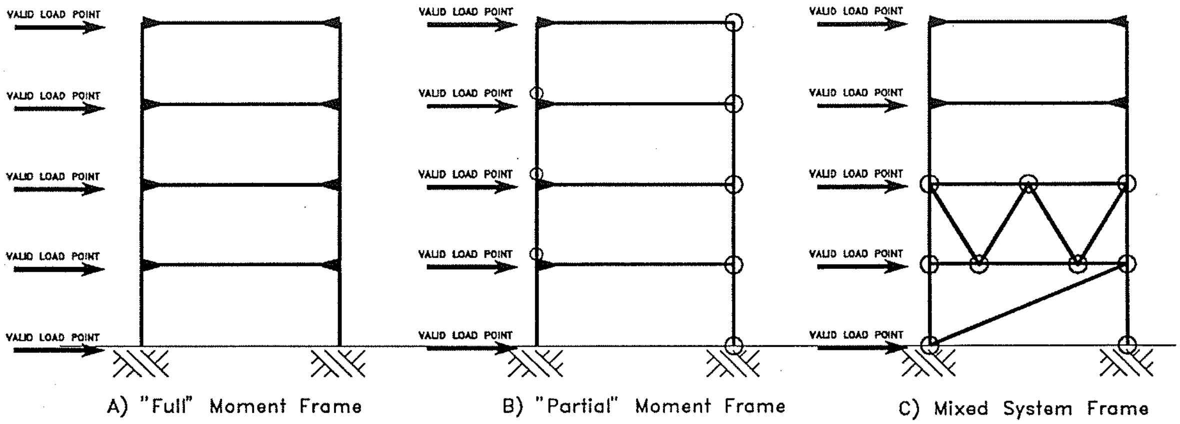


Figure 8.18 Valid Moment Frame and Mixed Systems Load Paths

Cases (A) and (B) in Fig. 8.18 represent the two possible extremes in moment frames, which are the maximum and minimum continuity requirements for a complete lateral load path. In case (A) all of the verticals are continuous with the verticals above and below as well as with all the beams to which they are connected. In case (B), each vertical on the left hand side of the frame is continuous with only one beam, i.e., all verticals are pinned at the I end and all beams are pinned at the J end. The verticals on the right hand side of case (B) are identical to their braced frame counterparts. From case (B) it is obvious that the test for a complete load path involves testing for the existence of at least one vertical that is supported in the vertical direction and is continuous with a beam element that is supported vertically at the opposite end. Such a condition at any level results in the level being supported.

No modifications are required to the representation in Fig. 8.16 to accommodate moment frames. The attribute of 'continuous with' contained in the component function object in Figure 8.16 can be used to represent the moment connections in the moment frame. In this case the values contained in the slot are the identifiers of the horizontals and/or verticals that are continuous with the component.

Note that the condition of continuity results in additional constraints on the connections between the components. The only difference in the representation components of braced and moment frames is in the value of the 'continuous with' attributes. Vertical and horizontal beams are, therefore, special cases of the general horizontal and vertical elements contained in the braced frame.[13]

8.6.2.4 Eccentrically Braced Frames

In eccentrically braced frames, the resistance to horizontal forces is provided by diagonal elements, as in the braced frame. However, as shown in Figure 8.19, in the eccentrically braced frame the vertical component of the brace force is resisted by a beam element working in flexure and shear instead of by another diagonal or a vertical. The horizontal components in eccentrically braced frames serve a dual function consisting of distributing the horizontal force to the resisting components, in this case diagonals, and resisting the vertical components of the brace forces. The functions of the verticals and diagonals are the same as for braced frames.

In the object representation, the value of the 'continuous with' slot is the identifier of the adjacent horizontal for the continuous horizontal components. Hence, no modifications to the initial representation scheme are required to accommodate eccentrically braced frames.

Treating the horizontals as discrete components between points of attachment to other frame components was convenient in the discussion of braced frame behavior, since such a

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[13] The philosophical approach is that moment continuity is a special condition requiring a one piece element or special constraints on the member connections.

treatment is necessary to the representation of pure axially loaded elements. However, the common condition in building structures is for the horizontal to be continuous between vertical elements simplifying the job of erecting the steel. Continuous horizontals are a necessity in high seismic regions where there must be a complete gravity load path in the absence of the diagonals. Under these conditions all levels of a frame such as that in Figure 8.15 (F) would be supported. Such an approach to the representation, while it is appealing because of its close similarity to the physical structure, lacks the ability to accurately capture the design intent, since it can no longer capture incomplete paths in frames that were intended to *function* as braced frames. The proposed representation accurately captures that intent while at the same time accommodating the eccentrically braced frame by adding constraints to the simple case.

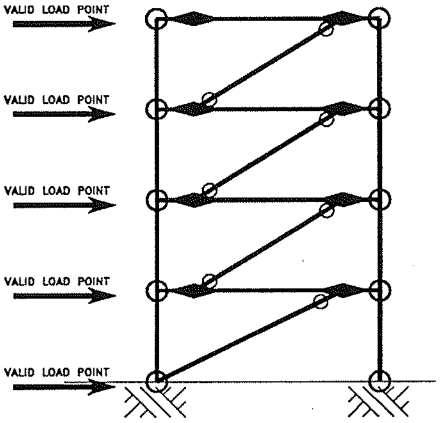


Figure 8.19 Eccentrically Braced Frame Load Path

Seldom do *all* the components have moment discontinuity at a braced frame joint. The proposed representation allows the selection of moment continuity to be made at the designer's discretion as part of the reasoning process rather than enforcing an arbitrary default of continuous horizontals or verticals. If the horizontals are continuous with each other, then there is certainly a preference for the horizontal to be the continuous element. On the other hand, there are cases where the diagonal element must be continuous, or where the diagonal is much more heavily loaded than the horizontal, as in the 'super frame', and in these cases it may make more sense for the diagonal to be the continuous element. Since the proposed representation allows for any of these conditions, it is preferable to one in which continuity is decided *a priori* by the form of the representation.

8.6.2.5 Three Dimensional Frames

In the plane frames discussed above, the overturning moment is resisted by axial loads in the vertical elements in the plane of the frame. In practice it is common to arrange the frames in two orthogonal directions in such a way that the boundary vertical of one frame is coincident with the boundary vertical of a frame in the orthogonal direction, resulting in a three dimensional frame, which may be stiffer for overturning moments. However, there is no conceptual difference in the completeness of the *building* load paths whether such a frame is treated as a three dimensional frame or an arrangement of plane frames.

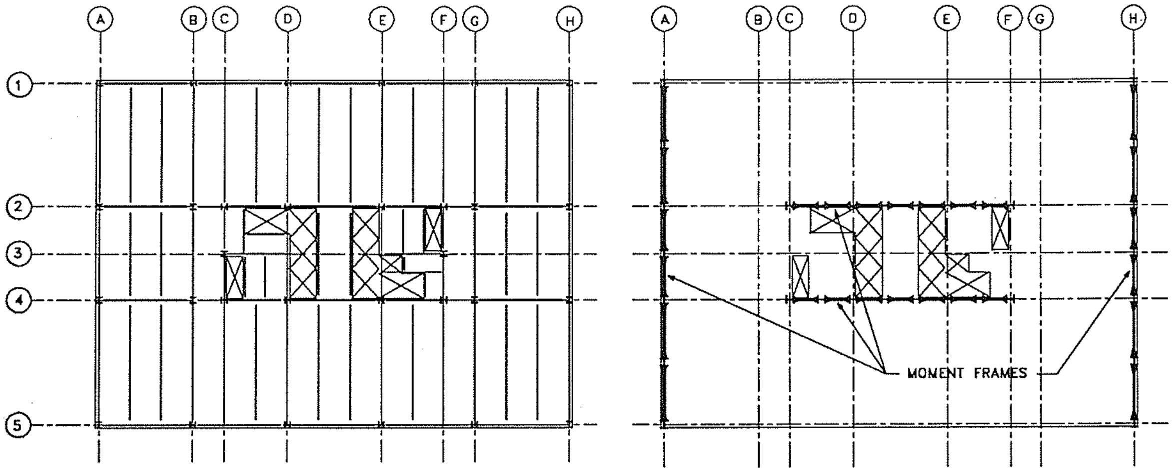
There are no significant differences between a three dimensional structure and the corresponding planar structure in the ability of the system of frames to carry horizontal shear loads. Those loads are carried in the *webs* of the system, i.e., the portions of the frames that are parallel to the shear, which are present in either approach. If the arrangement of plane frames results in an incomplete *building* load path system, the *building* load path will be incomplete if the frames are treated as three dimensional systems.

There are differences in the *behavior* of planar and three dimensional systems, specifically differences in the behavior under the action of overturning moments and torsion. Because of the constraint on the deformations of the boundary verticals, frames that are connected to form a three dimensional system are inherently stiffer for overturning. When the frames form a closed polygon, the torsional stiffness is much higher because the flexibility due to axial deformations of the verticals is reduced.

8.7 Building Load Paths

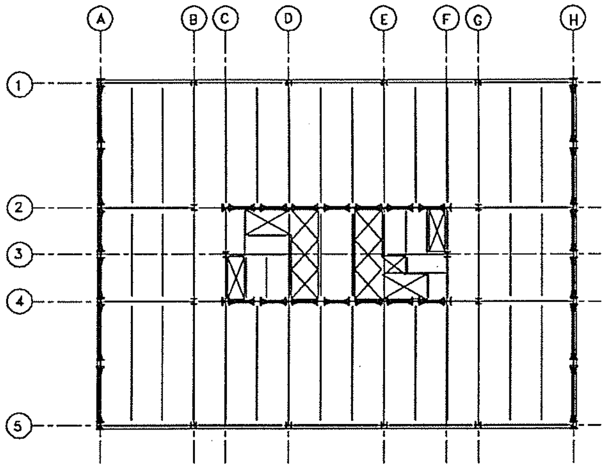
Isolating the representation of lateral load paths from gravity load paths is to facilitate the reasoning process involved in the conceptual design of the two systems. However, both a complete system of gravity load paths and a complete system of lateral load paths are required before the building load path system is complete. Valid combinations of lateral and gravity load paths form complete load path 'worlds' with each different set of building load paths representing a different potential 'world'. Figure 8.21 illustrates one combination of lateral and gravity load paths for a building. In the general case, there will be a set of lateral load paths corresponding to each feasible lateral system for the building.

When gravity and lateral load path systems are combined some reconciliation needs to be performed to assure that the resulting 'world' is internally consistent. This manipulation of



A) PLAN – GRAVITY LOAD PATHS

B) PLAN – LATERAL LOAD PATHS



D) PLAN – COMBINED LOAD PATHS

Figure 8.20 Building Load Paths

the design solution can be accomplished using only qualitative reasoning and working with the abstract representation of the structure function. In order to combine and reconcile a system of gravity load paths and lateral load paths, coincident members must be cross referenced, members that are present in the lateral system must be added to the gravity system, and the affected portions of the gravity load path must be reconstructed. In Figure 8.20, the lateral load paths use moment frames on lines A, H, 2, and 4. Along each of these lines, the vertical elements of the lateral load paths are spaced closer than in the gravity load path system. The building load paths are reconciled by adding columns in the gravity load paths at the additional locations and cross referencing all gravity load path elements to the corresponding lateral load path element. This process is performed for each valid combination.

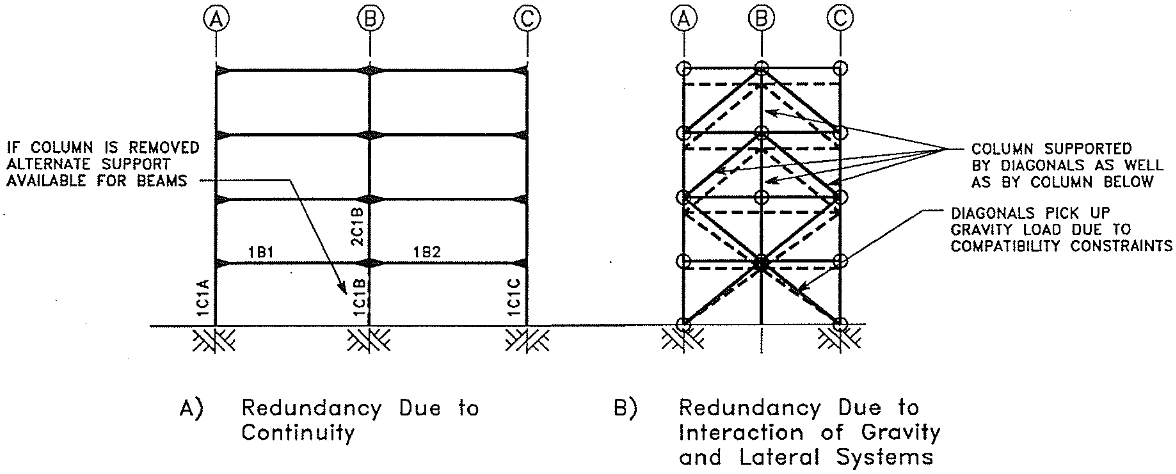


Figure 8.21 Redundant Gravity Load Paths

8.8 Redundant Load Paths

By definition, redundant structures are structures in which there are multiple *potential* load paths. When redundancies occur in a structure, the amount of load that travels along each path is a function of the stiffness of that path, and is considered herein to be a characteristic of the structure *behavior* as opposed to the structure *function.* In the treatment of structure function it is only necessary to establish the existence of one potential load path. The proposed rules and representation make this possible. However, they also make it possible to detect redundancy by checking for a complete load path when a member is removed from the structure.

Figure 8.21 illustrates two examples of redundant gravity load paths. In case (A), the beams are continuous with the columns, as would be the case when a moment frame is used as part of the lateral system. Even with the simple rules proposed earlier, the presence of a complete load path would be detected in the event that column 1C1B is removed, since all the beams would still be supported by virtue of the presence of a valid cantilever condition at all beams at all levels. (See section 8.4.) The rule set can be made more powerful by the addition of rules that would detect that beams 1B1 and 1B2 are adjacent and collinear, establish a continuous relationship between those beams, and establish a support relationship between 2C1B and the beams 1B1 and 1B2.

Case (B) is an example of redundancy that results from the interaction of the gravity and lateral load paths. When the columns of the gravity load path deform under the effects of axial loads, the ends of the horizontals and diagonals that are part of the lateral system are constrained to deflect the same amount. In symmetrical systems this results in the diagonals carrying a portion of the gravity load. In unsymmetrical systems, the structure response may consist of only a vertical deflections at the columns and a sidesway deflection with no resultant axial loads in the braces or it may be a combination of axial brace loads and sidesway. Whether or not the corresponding reduction in the column loads is accounted for in the design depends on code restrictions. For instance, in seismic areas there must be a complete gravity load path independent of the diagonals. However, the presence of the diagonals must be recognized when the systems are combined and appropriate gravity load path objects created and support relationships identified. In Figure 8.20 (B), each of the columns on line B is supported by the diagonals as well as the column below. The rules that would determine whether the diagonals in the gravity load path are a support for vertical loads would be similar to the rules used in the lateral load path.

8.9 Summary and Conclusions

The definition of structure function and the formalization of a method of representing the structure function are key steps toward developing systems that can perform qualitative reasoning using first principles rather than heuristic rules. The same steps are required in the development of a facility database that captures the intent of the design as well as its physical description. In either case, defining the detailed qualitative reasoning that is used in the conceptual design process aids in the identification of the objects and attributes necessary to define the structure function.

A substantial amount of reasoning about relatively complex systems can be accomplished using a very limited vocabulary of primitive functional elements. In this chapter we have introduced *slabs*, *beams*, and *columns* for describing gravity load paths, and *vertical beams*, *horizontal beams*, *diagonals*, *frames*, and *diaphragms* for describing lateral load paths. Most of these terms are familiar to structural engineers, as they should be, since our intent is not to develop a new vocabulary, but to define the qualitative reasoning that gave rise to the existing vocabulary. In the discussion of lateral systems, we have enforced a distinction between the elements of moment frame load paths and their gravity load counterparts that does not exist in the current vocabulary. Practicing engineers do not need to make such a distinction - and may even find it confusing - because they intuitively combine function, form, and behavior for both gravity and lateral loads in their normal thought process. Nevertheless, at least as a starting point in developing 'intelligent' design assistants, such a distinction is useful.

Developing an automated approach to reformulating exogenous constraints and project context information into function constraints is the key to providing more powerful design tools. In the past, much attention has been focused on developing tools that would utilize the power of the computer to solve problems that could not have been solved precisely by manual methods. However, the key to increasing productivity and efficiency is to develop tools that can perform the mundane tasks that are still performed by people. The load key paradigm that was presented in the first part of this chapter is one approach that would enable an automated the link between design disciplines.

The real benefits of automating the link between system descriptions and structural design comes during the construction and facility management phases. Such a step would expedite the processing of changes during construction minimizing costly delays and the errors that always creep in when designers work under duress. The benefits continue to accrue during the facility management phase, when the same capability can enable the facilities manager to quickly access information relative to the structural capacity the building.

Connections are among the most critical functional elements in the structure; the worst building disasters have been the result of inadequate attention to connection details. Connections are mentioned here one more time for emphasis. Because connections are ubiquitous, they are sometimes overlooked. The proposed representation approach, which seems to relegate the connections to a secondary position as attributes of the function objects, is not intended to denigrate the importance of these links in the load path.

The approach to connection representation is a pragmatic recognition of the subordinate role the connections play. Connections link elements of the load path and are constrained by the physical and behavior attributes of those elements. In steel systems the connections themselves are elements in the load path whose function is to transfer load from a supported element to the supporting element. A large library of parametric descriptions of complete functional objects already exists for steel connections and is the source of numerous constructibility constraints. In order to minimize the number of objects, the connections are represented as an attribute of the form object rather than as a separate functional object. While it is possible to foresee circumstances in future applications where the connection behavior, i.e. flexibility, would need to be explicitly represented, that is beyond the scope of this discussion and the proposed representation contains no behavior objects for connections.

9

Structure Behavior

9.1 Introduction

In the previous chapter, the reasoning on the highest level of abstraction, that of structure function, was explored. In this chapter we explore the next level of abstraction, in which the reasoning process makes use of established patterns of behavior that relate to objects and specific frame geometries. It is possible to use 'heuristic rules' and an established vocabulary of system geometries and component properties to synthesize systems which will behave in a predictable manner. The 'heuristic rules' are derived from knowledge of the anticipated behavior based on first principles combined with prior experience and are used to formulate constraints on the attributes of the structure subsystems and subsystem components. In this way knowledge about load paths and system behavior is used to force the structure into the desired mode of behavior.

While the reasoning at the highest level is concerned with *what* the structure must do, the reasoning at this level answers the question: given a topology and a set of function constraints, *how* should the structure behave and what component attributes are required to produce this behavior? This reasoning involves formulating specific performance constraints limiting the behavior attributes of the structure, and then propagating these constraints by using behavior constraints which relate the structure behavior to the topology and component attributes. The constraints are satisfied implicitly through the formulation of explicit geometric and material constraints on the structural components.

The reasoning at the lowest level of abstraction involves deducing the detailed mode of behavior given a system of loads, a structure topology, and the component material and geometry constraints. This analysis can be accomplished using algorithmic programs that excel at assembling and solving the system of simultaneous equations that describe the structure behavior constraints and determine the quantitative description of the behavior in terms of element forces and system deflections. If the resulting behavior does not satisfy performance constraints, the principles used at the second level of reasoning are invoked to strategically identify and modify those properties that will have the greatest effect on the desired behavior.

Reasoning about behavior involves formulating and satisfying behavior constraints which are derived from the physical laws governing element behavior. Many of the element behavior constraints can be propagated directly within the object representation by expressing the behavior attributes as relations between the element loads and deflections.

9.2 Gravity Load Path Element Behavior

In general the behaviors that are of interest in the representation of the gravity load path objects are the internal moments and shears, external reactions, and deflections. The internal forces and deflections are used in proportioning structural members, whereas the external reactions are used as function constraints on the supporting members in the load path. During conceptual design, performance constraints on the stress levels and deflections are used to formulate constraints on the geometric and material properties of the form object. Although the actual behavior of the structural elements consists of a complete three dimensional system of axial loads, end moments, and shears, it is common to focus on the characteristic force components in two dimensions for the purpose of preliminary sizing, hence the behavior objects representing the characteristics of interest can be rather simple. In gravity systems it is usually possible to isolate the behavior on a floor by floor basis and idealize the two dimensional behavior of individual functional elements in the context of the floor load paths.

For a class of functional objects, such as typical floor beams, the representation must be able to accommodate multiple behaviors, i.e., different load cases. For steel beams the loads of interest include construction loads, superimposed dead loads, and superimposed live loads, while for concrete beams the loads of interest are total dead loads and total live loads. The representation should be flexible enough to support the different methods of calculating stresses or ultimate strengths for different types of materials and systems. The behavior representation of concrete beams should include the effects of creep and shrinkage.

One of the purposes of the behavior representation is to minimize the number of different objects that need to be explicitly addressed while capturing the governing load case for a class of functional objects. The proposed function representation scheme facilitates the identification of the loads that are applied to each slab in the facility, making it possible to explicitly define the loads in every element of the load path (in the absence of redundancies). However only the governing loading conditions for each class of functional objects need be stored in the facility database. The behavior object is the repository of the governing loading and the behavior associated with that loading. This requires that the controlling loads be represented explicitly, with a reference to the particular function object from which the loads originated. The concepts of classes and subclasses are useful in constructing the required behavior objects, as shown in Figure 9.1. This philosophical approach will also accommodate redundant systems, except that the member loads and forces must be derived considering the redundant behavior.

GBO SIMPLE BEAM : TYPICAL FLOOR BEAM	
Vlt MAX	Maximum shear left end
Vrt MAX	Maximum shear right end
Mspan MAX	Maximum span moment
C.L. Defl. MAX	Maximum construction load deflection
D. L. Defl. MAX	Maximum dead load deflection
L. L. Defl. MAX	Maximum live load deflection
Creep Defl. MAX.	maximum creep deflection

GBO SIMPLE BEAM : TYPICAL FLOOR BEAM : CONSTRUCTION LOADS	
Vlt MAX	Maximum shear left end
Vrt MAX	Maximum shear right end
Mspan MAX	Maximum span moment
C.L. Defl. MAX	Maximum construction load deflection
ωCL	Uniform construction load
PCL	Concentrated construction loads
SOURCE	GFO BEAM : (e.g., B1)

Figure 9.1 Typical Floor Beam Behavior Objects

In Figure 9.1, the object on the left belongs to the general class 'simple beams,' defines a subclass 'typical beams,' and acts as the repository for the maximum force and deflection quantities for the beams that belong to that subclass. The object on the right is in the subclass of 'typical beams' called 'construction loads', acts as the repository and for the controlling construction load case, and contains a reference to the particular function object that generates the controlling construction load. Each functional object that belongs to the class 'typical beams' is a potential source of the maximum construction load, and each must be considered in the process of defining the maximum condition. The loads that go into the slots ωCL and PCL can be derived from the SUPPORTS attribute of the SOURCE function object.

The behavior objects form a hierarchical tree that mirrors the function representation wherein the slab behavior objects are the ultimate source of the loads. Since all loaded areas of the building are explicitly represented, any changes in the function constraints that are directly related to the slab representation can be automatically carried through the system.

In addition to computing its own reactions from the tributary superimposed loads, each behavior object must calculate its reactions due to its own weight, based on the attributes of its corresponding form object, thus explicitly incorporating the structure self weight as part of the representation. In an object oriented approach the slots defining particular behavior attributes contain a method for calculating that attribute as a function of the attributes of the corresponding form object. Objects similar to those shown in Figure 9.1 are used to define behavior for the typical beam under live and dead loads while similar sets of behavior objects are used to represent classes of columns and slabs, axial deflections and force components for the columns.

Although many of the beams and columns that are of interest during conceptual design can be treated as pinned members for the purpose of gravity design, the general representation should be able to accommodate end moments and rotations for both beams and columns in order to capture the effects of gravity loads on members that are part of redundant frames, as in the case of wind beams. The presence of end moments is indicated in the function representation by a non-NIL value as the CONTINUOUS WITH attribute at a member end. In such a case the relationship between the end deflection components and the end reaction are the familiar elements of the member stiffness matrix. The beam behavior objects can be generalized to 2D and 3D beams by the addition of attributes corresponding to the force and deflection components of interest, as shown in Figure 9.2.

For a given functional element, only the significant behavior modes need be represented, e.g., the out of plane bending components are rarely of interest when addressing gravity floor beams. The addition of force components on the ends of members results in additional constraints being applied to the connection requirements and corresponding attributes must be added to the form objects to assure that the final form object is consistent with the design assumptions.

GBO 2D BEAM : N-S EDGE BEAMS : LEVEL 3 BEAMS	
M LEFT	Maximum moment left end
V LEFT	Maximum shear left end
M RIGHT	Maximum moment right end
V RIGHT	Maximum shear right end
Mspan MAX	Maximum span moment
C.L. Δ MAX	Maximum construction load deflection
D. L. Δ MAX	Maximum dead load deflection
L. L. Δ MAX	Maximum live load deflection
Creep Defl. MAX.	Maximum creep deflection

GBO 2D BEAM : N-S EDGE BEAMS : LEVEL 3 BEAMS : LIVE LOADS	
T LEFT	Maximum LL rotation left end
Δ LEFT	Maximum LL rotation left end
M LEFT	Maximum LL moment left end
V LEFT	Maximum LL shear left end
T RIGHT	Maximum LL rotation right end
Δ RIGHT	Maximum LL rotation right end
M RIGHT	Maximum LL moment right end
V RIGHT	Maximum LL shear right end
Mspan MAX	Maximum LL span moment
L. L. Δ MAX	Maximum live load deflection
ω_{CL}	Uniform construction load
P_{CL}	Concentrated construction loads
SOURCE	GFO BEAM : (e.g., B1

Figure 9.2 Example 2D Beam Behavior Objects

The deflection and rotation components at the continuous ends of an element are constrained to be identical to the corresponding attributes of the object to which that element is connected. This raises the intriguing possibility of performing structural analysis as an iterative process of constraint satisfaction, similar to that performed by Sutherland [21] and Borning [3]. Such an analytical technique would offer far more transparency than is available with current computer-based analytical tools.

9.3 Lateral Load Systems

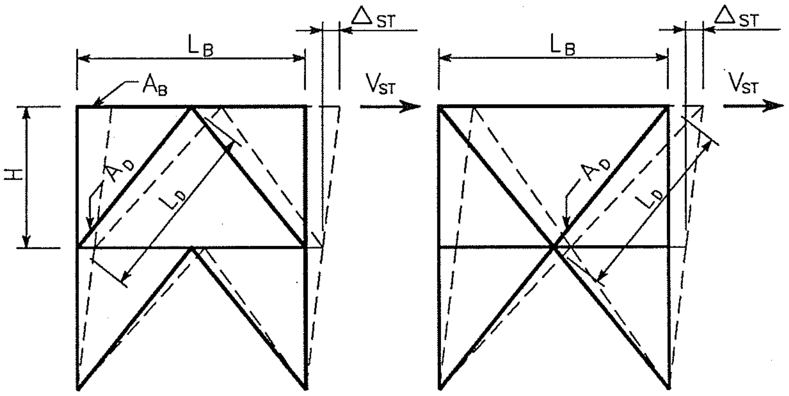
In lateral systems the behavior of the elements and subsystems is strongly linked to the global lateral load behavior. In the case of lateral systems, it is always necessary to examine the elements by starting with the global context. The global topology and loading environment, along with the behavior of an individual subsystem, determines the loads that the subsystem will carry. The aggregate behaviors of the components of the subsystem determine the response of that subsystem to a particular set of loads. The following sections discuss the behavior first of components and then of subsystems and the manner in which those behaviors can be controlled to produce a desired behavior at the global level.

9.3.1 Lateral Load Path Component Behavior

Lateral load component behavior consists of axial loads and deflections for *diagonals*, *horizontals*, and *verticals*, and flexural moments and rotations for *vertical beams* and *horizontal beams*. However, for the purposes of conceptual design it is useful to further idealize the behavior into the effects of the individual components on the lateral deflections at a given level of a frame. In this approach, the idealized component forces and deflections are expressed in terms of the frame story shears.

Figure 9.3 shows the idealized behavior for a single bay of chevron bracing and for an 'X' braced system. In the idealized frame, the components are assumed to be pin ended so the beam cannot resist vertical loads from the diagonals. Under these conditions, the frame is statically determinate, the vertical components in the diagonals are equal, and for the special case of symmetrically placed diagonals indicated in Figure 9.3, the horizontal loads in the braces are also equal. The deflections in the frame due to the diagonal and horizontal component deformations can be derived either by geometric construction or by virtual work. The resulting expressions relating the lateral frame deflection at the story level to the component properties are given in the figure.

The qualitative difference between the chevron braces on the left side of the figure and the 'X' braces on the right is the manner in which the load is transferred between diagonal components that are stacked vertically. In the chevron brace, the load travels through a horizontal component between the diagonals while in the 'X' brace the load is transferred directly between the diagonals. As the result of shortening the load path, the 'X' braced frame exhibits less interstory deflection, as indicated by the expression for its deflection.



$$\Delta_{ST} = \frac{2 V_{ST} L_D^3}{A_D E L_B^2} + \frac{V_{ST} L_B}{4 A_B E}$$

CHEVRON BRACE

$$\Delta_{ST} = \frac{2 V_{ST} L_D^3}{A_D E L_B^2}$$

TWO STORY X BRACE

Figure 9.3 Braced Frame Component Behavior

The lateral deflections due to the diagonal and horizontal deformations are cumulative up the building and can be computed independently on a story by story basis since a unit deflection at any given story translates to the same deflection at the top of the building. This type of deflection is analogous to the shearing deformations in a beam and will be referred to as the shearing deformation of the frame. This corresponds directly to the function of the diagonal which is to transfer the horizontal loads in a vertical plane.

The verticals in the frame perform a distinctly different function and, therefore, have a distinctly different effect on the frame behavior. The expressions for the story deflections in Figure 9.3 do not contain any contributions from the columns which are addressed in the latter part of this section. Throughout this section, the philosophy is to decompose the frame behavior into shearing and bending components. The effect of shearing deformations is cumulative but spatially independent, i.e., a unit shearing deformation of one level produces a unit displacement at all levels above.

The other method of performing the shear transfer function in lateral load resisting frames is to use a system of *vertical beams* and *horizontal beams*. In this case, the *vertical beam* carries the *shear directly*, which produces flexural behavior in the component and a bending moment that is resisted by the *horizontal beams*. The behavior can be idealized using a suitable simplifying assumption, such as the 'portal' assumption,[1] which is the basis for the subassembly depicted in Figure 9.4. In the subassembly, the frame shearing deflection, i.e., the story deflection, results from the local distortions of the subassembly components. In this approach the individual components consist of the verticals above and below the joint, the horizontals on either side of the joint, and the joint itself, called the 'panel zone.'

The total story deflection of the subassembly in Figure 9.4 consists of contributions due to flexure in the vertical beams and beams, shearing deformations of the vertical beams and beams, shearing deformations in the panel zone, and, in the case of rectangular concrete beams, flexure in the panel zone. The expressions on the right of the figure for the contributions of a individual components to the story deflection can be derived each component by assuming all other components are rigid and then calculating the resulting deflection. The advantage of this type of approach is that the effects of individual attributes on behavior can be estimated directly, facilitating the identification of an economical combination of attributes.

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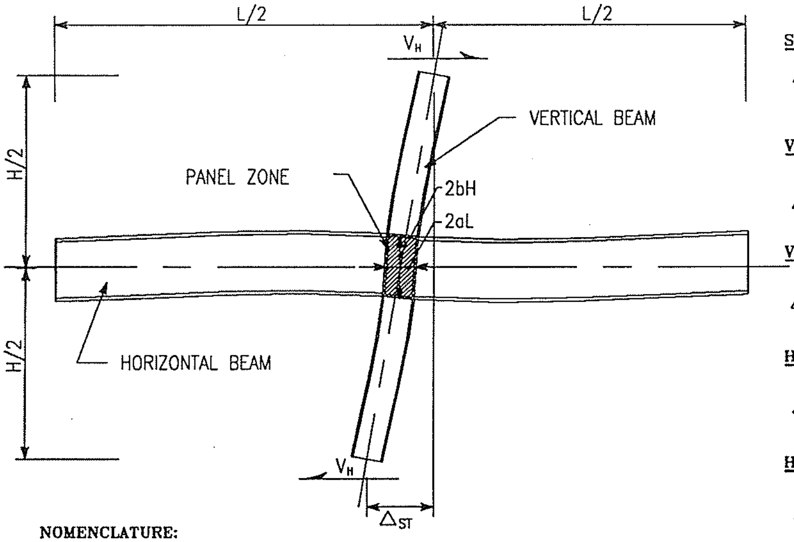
[1] In tall slender structures, the 'cantilever' method of approximation may be more appropriate due to the effect of axial deformations in the vertical elements. Even this is not a 'hard' heuristic, since the ratios of the areas of corner to interior verticals and the presence of verticals on the orthogonal faces in 'tubular' structures all influence the definition of 'suitable', so engineering judgement is required.



STORY DEFLECTION

$$\Delta_{ST} = \Delta_{VF} + \Delta_{W} + \Delta_{HF} + \Delta_{HV} + \Delta_{PV} + \Delta_{PF}$$

VERTICAL FLEXURE

$$\Delta_{VF} = \frac{V_H H^3}{12\, E I_V} \left[8\,(0.5-b)^3\right]$$

VERTICAL SHEARING

$$\Delta_{W} = \frac{V_H H}{A_V G} \left[2\,(0.5-b)\right]$$

HORIZONTAL FLEXURE

$$\Delta_{HF} = \frac{V_H H^2 L}{12\, E I_H} \left[8\,(0.5-a)^3\right]$$

HORIZONTAL SHEARING

$$\Delta_{HV} = \frac{V_H H^2}{L A_H G} \left[2\,(0.5-a)\right]$$

PANEL ZONE SHEARING

$$\Delta_{PV} = \frac{V_H H}{L t G} \left[\frac{(0.5-a-b)^2}{a\, b}\right]$$

PANEL ZONE FLEXURE (CONCRETE ONLY)

$$\Delta_{PF} = \frac{V_H H^3}{12 E I_c} \left[6b\,(0.5-b)^2 + 3\left(\frac{L}{H}\right)\left(\frac{I_c}{I_B}\right) a(0.5-a)\right]$$

NOMENCLATURE:

E	YOUNG'S MODULUS	H	STORY HEIGHT
G	SHEAR MODULUS	L	BAY WIDTH
I_V	MOMENT OF INERTIA OF VERTICAL	a	HOR. PANEL ZONE DIM.
A_V	SHEAR AREA OF VERTICAL	b	VERT. PANEL ZONE DIM.
I_H	MOMENT OF INERTIA OF HORIZONTAL	t	PANEL ZONE THICKNESS
A_H	SHEAR AREA OF HORIZONTAL	V_H	HORIZ. SHEAR IN VERTICAL

Figure 9.4 Moment Frame Component Behavior

The approximate equations for component behavior demonstrate some of the qualitative aspects of that behavior that are significant in the conceptual design process. The expression for flexure in the vertical beam can be derived using the equations for the deflection of a cantilever with a length of 0.5H-bH. The quantity bH is the distance from the theoretical centerline to the top or bottom edge of the panel zone (2bH is the total depth of the panel zone, while 2aL is the total width of the panel zone). In the equation, the effect of the finite joint size is isolated as a modifier on the basic expression for the deflection of the component when joint sizes are ignored making it easier to identify the effects of the joint size. The joint size quite often has a significant affect on the behavior of concrete frames, whereas in steel frames, the effect is usually not as significant and is offset to a greater degree by the effects of panel zone shear. This type of information is quite often expressed as heuristic knowledge, but is more appropriately derived based on first principles when possible. It is common to neglect the shearing deformations in assessing the behavior of the assembly due to the heuristic knowledge that shearing deformations are *usually* not significant compared with the magnitude of the bending deflections. However, the application of such a heuristic requires engineering judgement, since sometimes the shearing deformations are significant. Assessing the behavior directly as in the equations in Figure 9.4 makes the application of the heuristic unnecessary.

The above approach is not mathematically rigorous nor precise from an engineering mechanics perspective, e.g., the effects of column axial deformations alter the moments and inflection points of the horizontal beams. The derivation of equations such as those in Figure 9.4 is based on assumptions involving engineering judgements and the application of the equations also requires engineering judgement.[2] Nonetheless, such an approach is extremely useful in evaluating the lateral system behavior in a qualitative and approximate quantitative sense in order to synthesize a system that can then be analyzed precisely using conventional algorithmic programs.

The above treatment of braced and moment frames did not include the effects of the axial loads and deformations in the verticals. In braced frames the sum of the couples produced by the vertical axial forces is equal to the overturning moment. In moment frames the moment carried by vertical axial effects is reduced by the moment carried by direct bending in the verticals, but the latter effect is not significant for high rise buildings. For such buildings moment frame behavior can be assumed to be the same as braced frame behavior as far as the vertical axial effects are concerned. Due to the axial forces, the verticals on the tension side of the frame stretch while those on the compression side shorten, resulting in an increment of rotation being added to the frame. The rotation from horizontal at any level is equal to the algebraic difference in the lengths of the tension and compression verticals divided by the frame width. Rotations at any level have the effect of producing horizontal displacements at all floors above the magnitude of which are proportional to the distance from the rotated floor. Hence, the effect of vertical axial deformations is not spatially independent.

The frame behavior that results from vertical axial deformations is directly analogous to the flexural deformations that occur in a cantilevered beam. Once all of the sizes and forces are known for all of the frame vertical components, the effects can be calculated directly at any level in the frame by summing the axial deformations of all the vertical components below that level. However, during the synthesis of the frame topology it is convenient to make use of the cantilever analogy, shown in Figure 9.4, to evaluate the aggregate behavior

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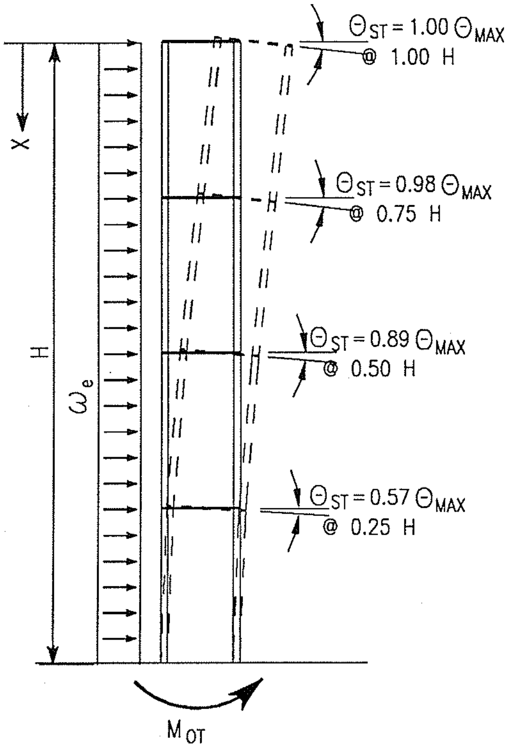
[2] For example, deciding on the appropriate value to use for the moment of inertia of concrete beams, which may be cracked for some portion of their length, is not a simple matter.

of the verticals. In that analogy, the frame is treated as a cantilevered beam with a variable moment of inertia that is equal to the sum of the vertical areas times the square of their distances from the center of area of all the verticals at any level. The rotation of the cantilever can be compared directly to the allowable drift index, e.g., h/400, which is also a rotation. The allowable frame shearing deflection at a level can be determined by multiplying the difference between the allowable drift index and the cantilever rotation at that level, by the story height.



EQUIVALENT UNIFORM LOAD

$$\omega_e = \frac{2\,M_{OT}}{H^2}$$

EQUIVALENT CANTILEVER INERTIA

$$I_e = \sum A_C d^2$$

where d is the distance of individual columns from the center of area of all columns and A is the area of the individual column

SLOPE AT POINT "X"

$$\Theta_X = \int_x^H \frac{(1)\omega_e x^2}{2EI_e}\,dx = \left.\frac{\omega_e x^3}{6EI_e}\right|_x^H$$

SLOPE AT POINTS ALONG CANTILEVER

Average $\Theta_{ave} = \frac{\Delta}{H} = \frac{\omega_e H^3}{8\,I_e}$

@ h = H : $\Theta = 1.00\frac{\omega_e H^3}{6EI_e} = 1.33\ \Theta_{ave}$

@ h = 0.75 H : $\Theta = [1.00-(0.25)^3]\frac{\omega_e H^3}{6EI_e} = 0.98\frac{\omega_e H^3}{6EI_e}$

@ h = 0.50 H : $\Theta = [1.00-(0.50)^3]\frac{\omega_e H^3}{6EI_e} = 0.88\frac{\omega_e H^3}{6EI_e}$

@ h = 0.25 H : $\Theta = [1.00-(0.75)^3]\frac{\omega_e H^3}{6EI_e} = 0.57\frac{\omega_e H^3}{6EI_e}$

Figure 9.5 Vertical Component Axial Behavior

Figure 9.5 illustrates the fact that with a uniform cross section and uniform load, a majority of the rotation from flexure occurs in the first 25% of the length of the cantilever. Lateral loads on buildings are typically trapezoidal or triangular, and the effective moments of inertia of frames are usually variable. However, acceptable results for the first cycle of synthesis in conceptual design can be obtained by evaluating the required effective moment of inertia at 1/3 of the height and assuming a linear variation around that point using strength sizes at the roof and by approximating the lateral load as a uniform load which produces the same base overturning moment as the actual lateral loads. Sizes that are generated by this method can then be used to generate actual deformations in the context of the frame behavior representation. It is useful to maintain the transparency of the solution by representing the effects of the vertical deformations explicitly in the frame representation because it is easily accomplished[3] and makes it possible to see the effect of varying the area of a given vertical immediately.

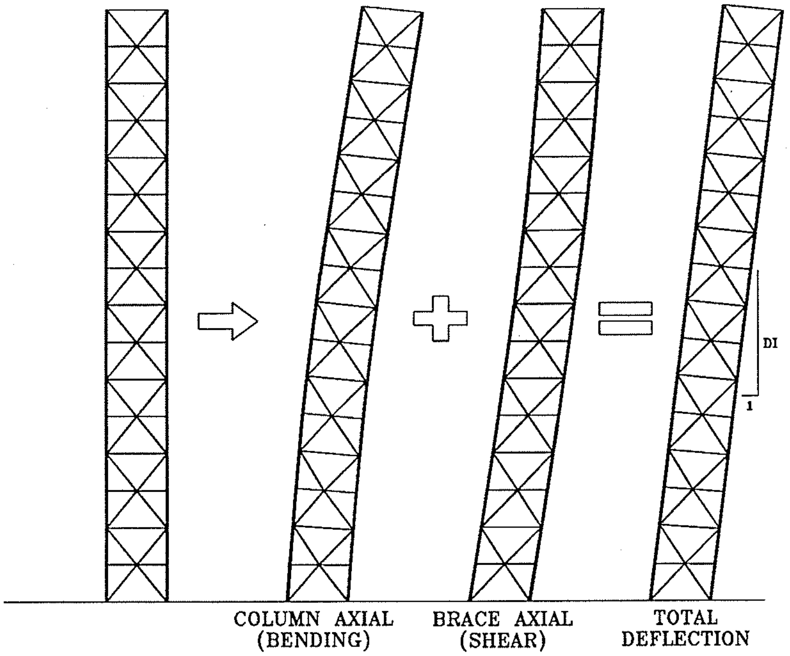


Figure 9.6 Lateral Subsystem Synthesis

9.3.2 Lateral Load Path Subsystem Behavior

Using the concepts discussed in the previous section, it is possible to develop a methodical approach to synthesizing lateral subsystems for a structure. The general approach is to vary the component properties in such a way that the combined effects of the frame shear and bending deflections results in the desired mode of behavior for drift control. The lower bound on a component size is the size required for strength, while, for steel, the upper limit on the size is the maximum available rolled shape, unless built up members are a feasible alternative.

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[3] As an example, both the moment frame and braced frame solutions of the building example in Appendix B were developed using spread sheets in which the axial deformations of the verticals were calculated and summed explicitly leading to an extremely transparent analytical technique.

The general methodology consists of the following steps, given a frame location and desired topology and general building parameters such as number of stories, story height, and plan dimensions:

1. Determine lateral loads, including story shears and overturning moments for the building.
2. Select an appropriate value for the maximum permissible drift based on serviceability considerations related to the other subsystem characteristics.
3. Decide on the amount of load to be carried by individual frames. A standard approach is to use symmetry, if possible, to simplify this step. A possible strategy is to allocate the total lateral loads to the individual frames in proportion to the amount of dead load restoring moment that they can mobilize.
4. Estimate the frame component forces and determine minimum sizes for strength requirements.
5. Calculate the frame overturning moments based on the load allocation.
6. Calculate an equivalent uniform load that would produce the same base overturning moment on the frame.
7. Calculate an equivalent frame I at 1/3 of the height using the column areas from 4.
8. Calculate the frame deflection due to axial deformations of the vertical components using the cantilever analogy.

   If cantilever deflection exceeds 75% of the allowable total drift at the top of the building, the areas of the vertical elements must be increased using a suitable strategy[4] and doing the following:

   a. Select the desired amount of drift at the top due to cantilever action.
   b. Calculate required frame equivalent moment of inertia to produce the desired deflection.

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[4] Possible strategies include increasing all verticals, increasing only corner verticals, or mobilizing 'flange' verticals by enforcing tubular action.

   c. Calculate minimum vertical area at 1/3 height to produce required equivalent frame inertia. use linear variation of areas around the 1/3 point converging on areas required for strength considerations at the roof.

9. Calculate the allowable drift at each floor due to shearing deflections of the frame. This is equal to the difference between the idealized cantilever slope and the maximum permissible slope or drift.
10. At each floor select component properties that result in satisfying the constraint on the allowable frame shearing deflection at that floor. Where there are multiple components that contribute to the shearing deformation as in the case of braced frames with horizontals and moment frames, use iterative procedure to identify the optimum combination of discrete sizes.
11. Iterate steps 4 through 10 to determine optimum ratio of bending drift to shearing drift.

A sample spread sheet calculation for *vertical beam* and *horizontal beam* sizes is contained in Table 9.1. The building used for the data in Table 9.1 is 30 stories tall and uses the plan configuration of the building in Figure 7.2. Wind loads on the long faces of the building for the wind zone and exposure indicated result in a base shear of 1,338,480 lb. and an overturning moment of 306,519,525 ft-lbs.

One half of the load is distributed to each end frame based on an assumption of symmetry and each interior vertical carries 101 kips of horizontal shear based on the portal assumption. The minimum vertical size for strength at the 7th floor is a W14x342. (This is conservative, but a smaller size results in a deflection in the vertical alone that exceeds the total allowable for the frame.) The verticals are spaced at 15 ft., 35 ft., and 55 ft., from the center of the narrow faces on each end of the building, resulting in an effective frame inertia of 6277 ft^4 and a calculated cantilever deflection of 0.207 ft, or H/1600.

The maximum slope of the cantilever is 133% of the average slope, or H/1370. The slope at the 7th floor, which is approximately 25% up the cantilever, is 57% of the maximum, H/2300 (0.00042). For an allowable total drift of H/400 (0.0025), the allowable frame shearing deformation at the 7th floor is: 0.0025 - 0.00042 = 0.0021 h, or 0.31 inches per floor.

The selection table at the bottom of Table 9.1 gives the results of four combinations of vertical and horizontal sizes that satisfy the deflection constraint. The size selection is based on the simple strategy of starting with the minimum vertical size, in this case a W14x342,

Building Data:

Width	110 ft.
Length	150 ft.
No. Stories	30
Story Height	12.5 ft.
Height	375 ft.

Wind Load Data:

Wind Speed	70 mph
Exposure B	
qs	13
Cq	1.3
E	29000 ksi

Building Wind Loads (Units : Pounds, Feet))

Interval (in feet)		Ce	p wind	Interval Force	Interval Shear	Interval O.T.Moment
300	375	1.8	30	342225	342225	
200	300	1.6	27	405600	747825	12833437
150	200	1.4	23	177450	925275	37391250
100	150	1.3	21	164775	1090050	106786875
60	100	1.2	20	121680	1211730	161289375
40	60	1.0	16	50700	1262430	215817225
20	40	0.8	13	40560	1302990	253690125
0	20	0.7	11	35490	1338480	279749925
						306519525

Preliminary Design - Beams and Columns Level 7 Short Direction (Units : Kips, Feet)

Average Trib. Column Area = **300** ft^2 Typical Axial Load Per Floor = **36.25** kips
P Wind @ 7th Corner = **778** kips Typical = **315** kips Axial Design Load at 7th Floor = **1511** kips
Frame Shear at 7th Floor = 1/2 Building Shear @ 60 -100 (From Symmetry) = **605** kips
Interior Column (Portal) Shear = **100** kips Beam and Column Wind Moments = **631** ft - kips
P - Delta Allowance =(Sum Vh/(Sum P*Delta/H))*Mwind = (Sum Vh/(DI* Sum P))*Mwind = **85** ft-kips
Column and Beam Design Moments = **716** ft-kips
Minimum Beam Size for Strength = **W30x99** I beam = **3990** in^4
Minimum Column Size for Strength (Using Bx Method for Moment) = **W14x342** (Use for Corners also)
Icolumn = **4900** in^4 Acolumn = **101** in^2
Equivalent Uniform Wind Load, One Frame, We = **2.18** klf (pwind eq.= **29** psf)
Frame Inertia With Strength Columns = 2*Ac*(15^2+35^2+55^2) = **6277** ft^4
Frame Bending Deflection With Strength Columns = (We*H^4)/(8*E*I) = **0.207** ft. = **H/1800**
Maximum Cantilever Slope = 1.33* Average = **H/1370**
Cantilever Slope at 7th Floor (25% of Height) = 0.57 Max = h/2400 = **0.00042** h
Allowable Total Story Drift = h/400 = **0.0025** h
Allowable Frame Shearing drift = 0.0025 H - 0.00042 H = 0.0021 H = **0.31** in.

Vertical/Horizontal Selection Table (20 ft. Bays) (Units : Kips, Inches)

L max = 240 in. h = 150 in. Vh = 100 kips

	Vert. Size	**A_V Vert.**	**I Vert.**	**Δ vf**	**Δ vv**	**Δ. Vert**	**Max Δ Hor.**	**Min I Hor.**
1st Iter.	W14x342	19	4900	0.200	0.062	0.262	0.050	36825
2nd Iter.	W14x500	28	8210	0.119	0.044	0.163	0.149	12371
3rd Iter.	W14x730	39	14300	0.068	0.031	0.100	0.212	8684
4th Iter.	W36x300	29	20300	0.048	0.041	0.090	0.222	8300

	Hor. Size	**A_V Hor.**	**I Hor.**	**Δ. hf**	**Δ. hv**	**Δ. Hor.**	**Δ. Tot.**	**Weight**
1st Iter.	W40x480	53	39500	0.040	0.014	0.054	0.316	13488
2nd Iter.	W36x210	28	12100	0.119	0.027	0.146	0.308	10450
3rd Iter.	W36x150	22	9040	0.173	0.034	0.208	0.307	12125
4th Iter.	W36x150	22	9040	0.173	0.034	0.208	0.297	6750

Table 9.1 Sample Conceptual Lateral Design

incrementing the vertical size, calculating the constraint on the horizontal properties to satisfy the deflection constraint, selecting a horizontal that satisfies the property constraint, and iterating until the optimum point has been passed. If architectural considerations constrain the selection to W14 sections (to minimize the width of the vertical architectural element), the minimum weight combination for the example is a W14x500 column with a W36x210 beam, giving a subassembly weight of 10450 lb. An alternate constraint set that would be generated for evaluation would relax the depth constraint to allow a W36 vertical, in which case the vertical is a W36x300 and the horizontal is a W36x150, resulting in a subassembly weight of 6750 lb., a material savings of 35%.

In this example, a reliability constraint that could be applicable, particularly in high seismic areas, is that the plastic moment capacity of the columns framing into a joint exceed that of the beams at the joint, a constraint that is satisfied by the lightest combination in the example. As an example of the transparency of the solution process, the table gives the amount of the total frame shearing deflection attributable to the vertical component (22% for the lightest combination) and the amount of that deflection that is attributable to the component shearing deformation (28% for the lightest combination).

The method presented in Table 9.1 is approximate in nature while still identifying the general relationships between behavior and member properties. Other assumptions could be made which would yield equally valid results. For instance, cantilever equations based on a variable moment of inertia and trapezoidal loading could be used. However, during the synthesis portion of conceptual design, the solution only has to be precise enough make a comparison among potential solutions. Even with the approximations used in the methods presented in Table 9.1, the material quantities can be estimated quite accurately, usually within 5%. Since the material costs are only a portion of the total costs (approximately 33% for steel), the approximate methods are sufficient for the intended purpose. Once a system is synthesized, other more accurate methods of analyzing the behavior are available to refine the detailed design.

9.3.4 Lateral Load Path System Behavior

The methodology presented in the previous section can be used to synthesize frames that have a desired stiffness. That capability makes it possible to synthesize structures which have a desired distribution of stiffness in plan, e.g., it is possible to alter frame stiffnesses to produce a symmetrical building stiffness even when there is no geometric symmetry. The method also makes it possible to tune the stiffness of different types of frames so that they have the same effective stiffness. The manipulation of overall system behavior quite often involves using the frame deformation characteristics in a complementary fashion, so that the combined system behaves differently than any of the subsystems taken alone. In this section we will examine one example of this type of behavior manipulation.

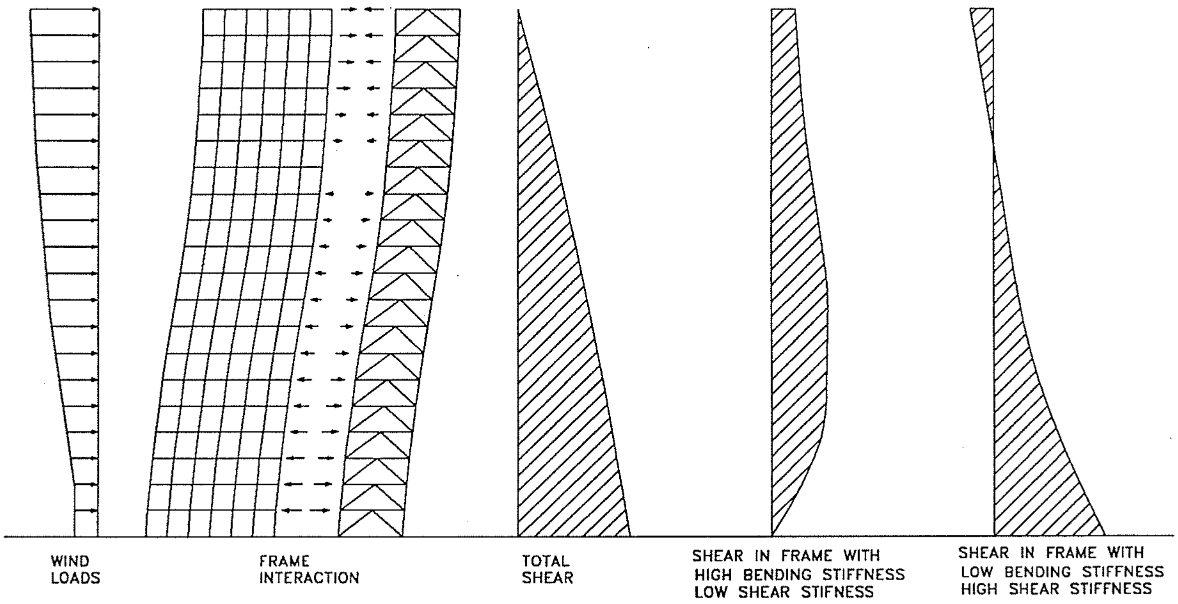


Figure 9.7 Frame Interaction

In systems in which the diaphragm is supported by three planar frames such as the left diaphragm in Figure 8.12, the forces in the diaphragms and frames are statically determinate and can be determined independently of the frame behavior. This is a special case that is analogous to the case of the simply supported beams in the gravity load path system. In the more common case where there are more than two frames in a direction, or where there are two or more non-collinear frames in both directions, then the three dimensional behavior of the frames must be considered in the determination of the forces. In this case the forces in the frames at a given level vary with the effective stiffness of the frame at that level as illustrated in Figure 9.7. The effective frame stiffnesses have two components, bending and shear, which result in a complex three dimensional interaction over the height of the building. The interaction is especially evident in the behavior of systems that include frames with widely varying bending and shear stiffnesses. This phenomenon is commonly referred to as 'frame/shearwall interaction', but is a phenomenon that is common to all systems that are not statically determinate and in which there is a variation in frame bending and shear stiffnesses.

The form of interaction shown in Figure 9.7 can be used to an advantage in systems that contain frames with widely varying widths. In wide frames, the verticals are more effective in resisting overturning moments since the frame bending stiffness varies as the square of the width for a given size of vertical. The frames in the building that have the highest bending stiffness will tend to pick up the shear high in the building, where the moment arm is the greatest while those with the highest shear stiffness will tend to pick up the shear in the lower part of the building where shear effects are predominant.

Braced frames which use axial loads to resist shear are inherently stiffer in shear than moment frames and are more cost effective in the lower part of the building where the shears are the highest. However, architectural constraints often confine the braced frames to the building core where the width is constrained, limiting the bending stiffness of the frames. By combining a braced frame in the core with a moment frame on the perimeter, the advantages of each of the frames can be used. Using the methodology presented in the previous section, it is possible to select the shear distribution that is desired and then proportion the frame components to produce compatible deflected shapes under the desired pattern of load sharing.

By manipulating the stiffnesses of the frames in plan and the interaction of the frames it is possible to bring the overturning moments down at selected locations in the building. This capability makes it possible to minimize the effects of uplift at the foundations, which are usually costly.

9.3.4 Three Dimensional Systems

All of the subsystems in the previous sections were two dimensional, a convenient simplification to make during conceptual design. However, on occasion there are advantages to recognizing the three dimensional interaction of the frames in a structure during conceptual design. One such case, which is discussed here, is the effect of continuity between frames that are perpendicular to each other.

When the boundary verticals in a frame are continuous with the horizontal components of an orthogonal frame the axial deformations of the vertical component are restrained by the axial rigidity of the vertical components in the orthogonal frame. The amount of restraint depends on the flexural and shear stiffness of the orthogonal beam as shown in Figure 9.8. The restraint offers advantages when the axial deformations have a significant influence on the frame behavior since the verticals in the orthogonal frame are mobilized to help in resisting the overturning moment.

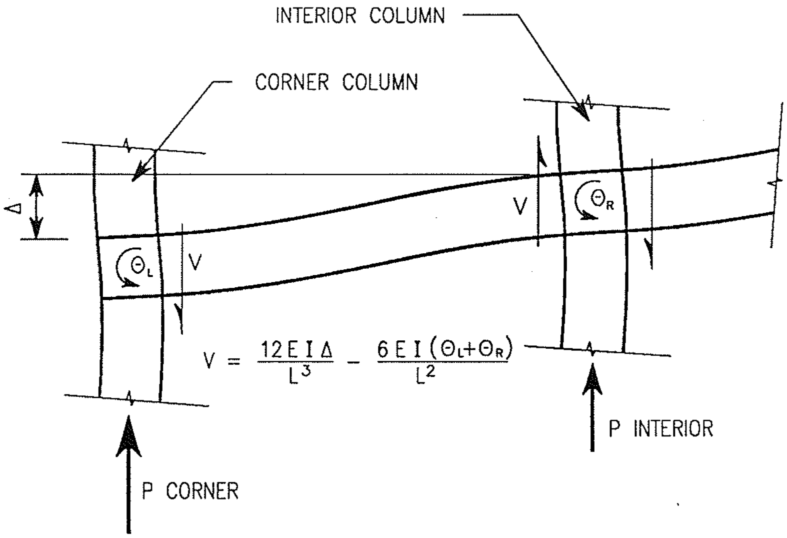


Figure 9.8 Orthogonal Restraint at Boundary Verticals

As can be seen from Figure 9.8, the translational restraint offered by the orthogonal beam is inversely proportional to the cube of the beam length. By contrast, the bending resistance the beams provide to the rotation of the verticals under the action of shear loads parallel to the frame is inversely proportional to the *first* power of the beam length.

A second phenomenon that occurs when there is continuity around the corner is that the axial component of the overturning moment can be distributed up the building as well as down. These two phenomena lead to the concept of tubular structures wherein the 'flange' verticals, those in the orthogonal frame, are mobilized in the resistance to overturning moments. In tall slender buildings, i.e., buildings with an aspect ratio greater than five, it is often necessary to proportion the structure to force tubular behavior in order to gain the added bending stiffness as well as to distribute uplift loads to mobilize more dead load resistance, reducing foundation costs.

When the arrangement of frames results in closed polygon (usually a rectangle) there are distinct advantages for loads containing a torsional component. In such a case, under pure torsional loads, there is no net overturning moment and the sum of the overturning moments resulting from couples in the individual frames must be zero. In a rectangular arrangement of frames with the same stiffness, the axial loads in the verticals of the orthogonal frames exactly balance each other, eliminating the contribution of axial deformations to the building deflection.

9.4 Conclusion

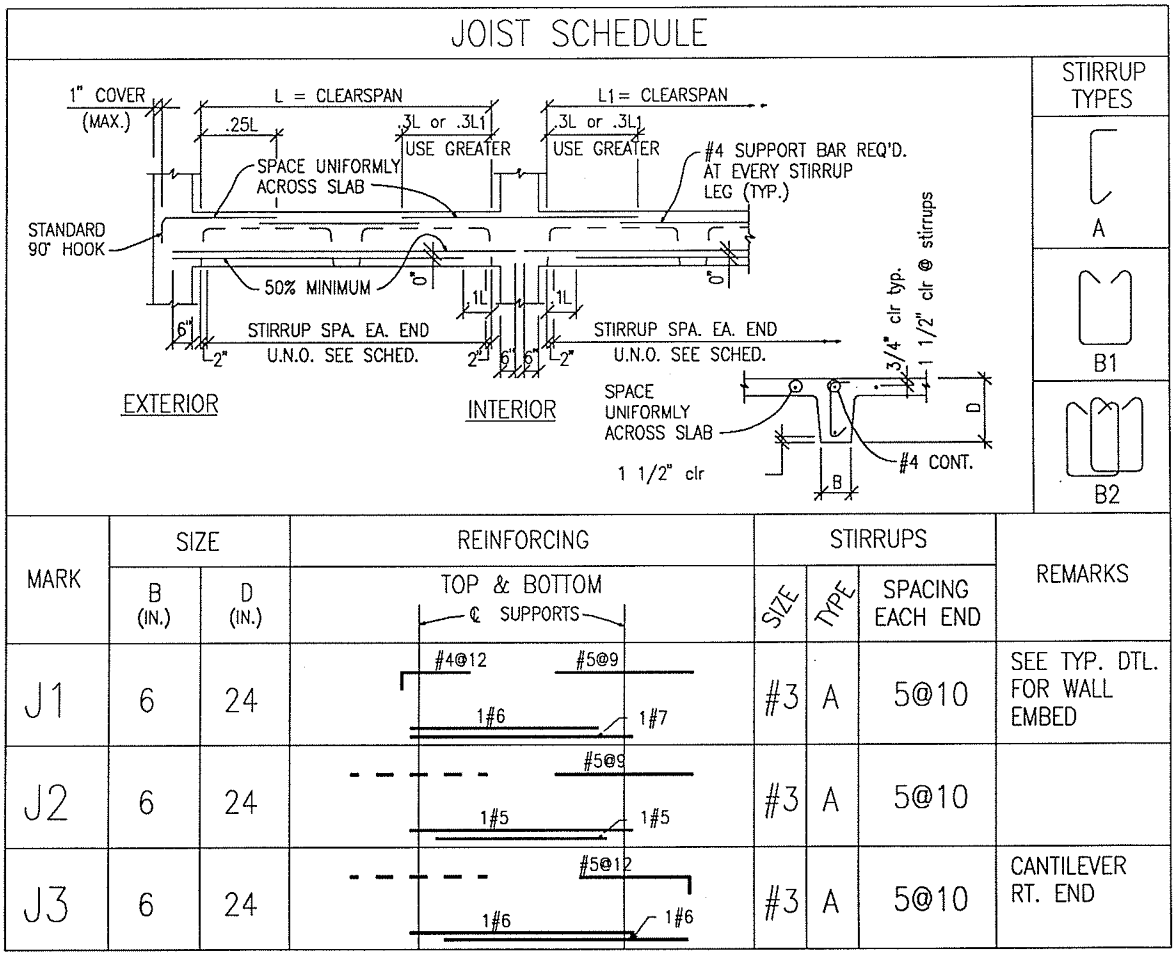
In this chapter we have presented samples of the type of reasoning that is used in the synthesis of structural systems. The concepts of bending, shear, and axial deformations and forces are important at the element level, while the concepts of shear and bending modes of deformations are extremely useful in ordering the reasoning strategy at the system level. This discussion is intended to illustrate some of the concepts rather than define the nature of the behavior reasoning and representation in a comprehensive fashion. The methods presented appear to be well suited for implementation in automated reasoning systems while offering insight into the behavior attributes at both the element and system levels that should be represented in the facility database to support the reasoning process and capture the design intent.

10

Structure Form

The form representation of the structure evolves with time as the structure description progresses from conceptual design through construction planning. The form representation required for conceptual design has to include the material properties and the member properties that are necessary for satisfying the performance constraints on the structure but need not include the detailed information that is required for fabrication. However, the representation scheme developed to support conceptual design should be flexible enough to accommodate the eventual needs of the project data base. This can be accomplished by maintaining the form representation independently of function and behavior. In the facility database the data necessary to define form should be stored only once for each unique type of form and referenced by each of the function objects to which that form applies.

The final form representation for each element includes the precise length and other geometric attributes like holes and copes, and the material properties, including ASTM material designations, strength grades, and, in the case of concrete, the shrinkage properties. The form representation should include all physical attributes that are necessary for fabrication or construction of the element, which includes a description of the reinforcing steel size and layout for concrete elements. When the structural element of interest is a prefabricated item with attributes that vary between suppliers, as in the case of metal deck, the form description should either incorporate a detailed description of the item from the manufacturer, or a detailed summary of the constraints on the attributes that have an impact on its function in the structure. A comprehensive discussion of form is not possible in the context of this dissertation and many of the aspects of form representation are familiar to most parties to the construction process. This brief discussion will focus on two examples that will illustrate the depth of detail required of the form representation to adequately serve the purpose of supporting the life cycle processes.



MARK	SIZE		REINFORCING	STIRRUPS			REMARKS
	B (IN.)	D (IN.)	TOP & BOTTOM ℄ SUPPORTS	SIZE	TYPE	SPACING EACH END	
J1	6	24	#4@12 #5@9 1#6 1#7	#3	A	5@10	SEE TYP. DTL. FOR WALL EMBED
J2	6	24	#5@9 1#5 1#5	#3	A	5@10	
J3	6	24	#5@12 1#6 1#6	#3	A	5@10	CANTILEVER RT. END

Figure 10.1 Concrete Joist Form Representation

Figure 10.1 is extracted from a concrete joist schedule, a typical method of describing the form of the joists on structural drawings. The schedule consists of two parts: generic information contained in the details at the top of the schedule that applies to all joists and detailed information about the attributes of specific instances of joists contained in the rows of the schedule.

The diagram at the top of the schedule summarizes the constraints that are to be used in developing the detailed bar lists for the joists and contains two complete sets of constraints on the lengths, one for exterior spans and one for interior spans (one end continuous or both ends continuous). Since the differences in the constraints occur at the discontinuous end, the conceptual constraint set represented in the diagram can accommodate the case where both ends are discontinuous. The constraints on the lengths of the bars are expressed parametrically in terms of member lengths that are obtained from the floor plans. The floor plans are analogous to the function description of the structure.

All reinforcing steel for the joists conforms to the standard lengths indicated on the diagram at the top of the schedule unless more specific information is contained in the bar diagram for the individual joist. This convention results in improved constructibility, because it facilitates repetition, while simultaneously improving the efficiency - and, therefore, the reliability - of the design, which takes the form of checking for conditions that would require a violation of the standard bar lengths. An example of the latter is the case of short and long span joists included in the same line, resulting in mid-span negative moment and a requirement for continuous top steel in the short joists.

The key at the top of the diagram also conveys the detailed form of the stirrup sub-elements and a picture of the joist cross section which clarifies the placement of the reinforcing steel. Below the key are bar diagrams for individual joists identified by the names, J1, J2, etc.. Each bar diagram is a description of an arrangement of functional elements consisting of a concrete cross section, the flexural reinforcing, and the shear reinforcing. Each diagram contains a description of some of the attributes of the form of the individual joist such as the depth and width.

One of the issues that has to be addressed in the database is the fact that the top reinforcing is continuous between joists and is, therefore, not totally included in either of the joists that share it. This has implications in the formulation of behavior constraints as well, since the top steel is constrained by the behaviors of both of the joists. It is important that the top steel be represented only once on the drawings, a condition that also applies to the database. In the case of the joist schedule, the convention that has evolved over the years (in the U.S) is that the top bars are scheduled with the 'first' joist and shown dashed in the 'second' joist. The convention regarding naming the joists establishes a unique definition of first and second positions. Joists in a given line are numbered sequentially left to right, the same way that this sentence is read. The numbers on the plan are situated on the left end of the member to which they apply, and the left end of the joist in the schedule is the left end of the joist on plan as the name is read. Though the detailed description of the top steel is contained in the representation of the first joist, the existence of the steel must be flagged in the second joist, a requirement that is fulfilled by the presence of the dashed line in the second joist, which is short hand for 'see previous joist for top steel this end.' Because of the subtleties of the representation in schedules such as that shown in Figure 10.1, the naming of the joists on the plan must be sequential from left to right for clear communication.

The remarks column on the right hand side of the schedule provides a mechanism for cross referencing special conditions which are quite often the result of exogenous constraints.

The information shown in the concrete joist schedule is schematic in nature since it is not possible to fabricate the bars from the information shown without further refinement of that information. The final product of the planning phases of the project - which include the construction planning phase - is a detailed bar list that the fabrication shop uses to cut the steel. Each bar or group of bars that is fabricated is tagged with a specific identifier that is keyed into the original joist schedule or to an erection drawing showing the plan location of the element to which the steel belongs. The bar placers work with the information in the schedule and the bar lists to identify the proper reinforcing for a given element and install it in its proper location. The entire process, when examined on a detailed level, is rather complex and one has to acknowledge the efficiencies of the communication tools that have evolved in practice for managing that complexity. The form representation for ISD should not be less comprehensive and efficient than the tools that are currently used.

Figure 10.2 shows a structural steel beam that is supported by another steel beam on the left side and by a column on the right side. Below the beam elevation is the type of representation that would appear on the project shop drawings which contain the information necessary for the shop to be able to fabricate the individual piece. The theoretical length of the functional element is 30 ft. which is also the length typically used to calculate the behavior of the beam. However, as can be seen from Figure 10.2, the exact length of the form object depends on the type of connection at each end.

Connections other than those depicted in the figure could be used. The connection on the left end of the beam could consist of either double angles that are welded to the beam rather than bolted, or a shear tab welded to the supporting beam. The connection on the right could use angles welded to the beam, a shear tab welded to the column, or a seat welded to the column. Each of these choices for the connections adds slightly different constraints to the form object. Since the beam is assumed to be pinned-ended and 30 ft. long for the purpose of design, regardless of which of the connections is used, the choice of connection type should be based on relative economy considering fabrication and erection constraints which are constructibility considerations.

For each connection type there is a parametric description and a method for calculating its capacity based on the precise physical description of the connected and connecting elements. In the example shown, the capacity of the connection can be controlled by bearing of the bolts on the web of the beam, by the capacity of the bolts themselves (which will vary between A307, A325, and A490 bolts), by bearing on the girder web, by bearing on the angles, or by block shear through the cope. If the capacity is controlled by block shear through the cope, then the connection on the left has less capacity than the one on the right. The dimensions of the cope, which may have an effect on the connection capacity, are controlled by the dimensions of the supporting beam, and are determined in accordance with detailing procedures contained in standard references such as the AISC detailing manual [1].

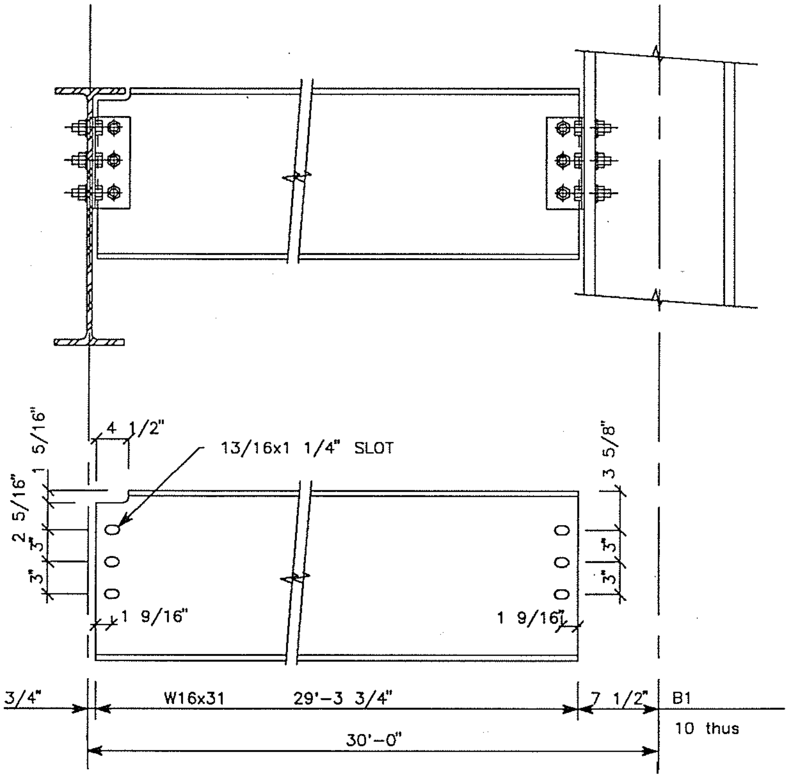


Figure 10.2 Structural Steel Beam Form Representation

The precise length of the beam and the size of the cope are depend on the geometry of the supporting elements. The information can be determined efficiently since the function representation explicitly identifies the supporting element which, in turn, contains a reference to its form object. The performance constraints that apply to the beam connections are contained in the MAXIMUM REACTION attributes of the corresponding behavior object. The parametric description of the connections themselves, along with methods for calculating their capacities can reside in a library of standard connections which are referenced by an individual form object such as the beam in Figure 10.2 to determine its detailed form description.

The connection angles that form the functional link between the beam and its supports are usually standardized, e.g., all angles with three lines of bolts are identical in size and dimension. In practice, the beam that is delivered to the site is treated as an assembly consisting of the actual beam along with its supporting angles and bolts. For other types of connections, the assembly takes different forms. For instance, in the case of shear tab connections, the girder assembly includes as a separate piece, the shear tab, which is shop welded to the girder.

While the information contained in Figure 10.2 may appear to be excessively detailed and the task of representing such information daunting, such representation is essential if ISD is to offer a viable alternative to current practice. Without the detailed description of the piece, including the copes, the capacity of the connection on either end of the beam cannot be determined. The advantage of such a representation in electronic form is that the link between design and fabrication can be automated and, in the case where the fabrication plant itself is automated, a detailed form representation will make it possible for all of the steps from conceptual design through fabrication to be automated, with no translation of data.

11
Strategic Reasoning

If the representation of the structure model is well founded in first principles and adequately captures the functional as well as the behavior and form characteristics of the structure, it will support many different reasoning strategies allowing for the evolution of those strategies as our understanding of the reasoning process matures and new systems and materials are developed.

In previous knowledge based systems, the approach to the strategic reasoning has been to use heuristic knowledge acquired from 'experts'[1] as the basis for the strategic reasoning. However, each 'expert' has had slightly different experiences in contexts that differ subtly from the contexts and experiences of other experts. Hence, there is ample opportunity for variations in heuristics that are derived from various sources.

The author had the privilege of assisting with concurrent research at Stanford by acting as the domain expert for Mr. Deepak Jain, who implemented some of the ideas set forth in this research [9]. Based on the experience gained from that exercise, it is clear that there are multiple impediments to the accurate transfer of the experiential knowledge of an 'expert' to a computer - or even to another engineer. Not the least of the impediments is the fact that most engineers rely to some degree on intuition, and have not had to formalize that intuition in rigorous manner.

The heuristic knowledge used by practitioners in the domain of structural engineering consists of at least three basic types: knowledge about the behavior of systems and elements, knowledge about synthesis techniques, and knowledge about the process of structural design.

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[1] Of course the first problem is in defining this term, which itself means different things to different people and is certainly context dependent.

The first type of knowledge is, itself, based on first principles and conclusions derived from that knowledge can, therefore, be duplicated by the application of analytical methods based on first principles. Heuristic limits on height to depth ratios of frames are an example of this type of knowledge. The experiential knowledge of practitioners is still useful in helping to identify and formally describe the essential modes of behavior of a systems and elements.

The second type of knowledge is closer to 'inspirational' in nature. There are probably principles underlying some of the knowledge (e.g., the relationships between efficiency and load path patterns), but the principles are not as readily apparent. Since this knowledge is used in the synthesis steps in the design, the validity of the knowledge is readily apparent in the relative success of the particular strategy in arriving at a useful result.

The strategic knowledge about the process of structural design - in the context of high rise office buildings - was the subject of earlier chapters, but is summarized here for convenience. The structural design process in high rise buildings includes the following sequence of activities:

I. Masterplan Phase
    A. Assemble sources of constraints based on building location, including applicable codes, wind loads, seismic exposure.
    B. Assemble constraint set resulting from building occupancy.
    C. Assemble constructibility constraint set based on local construction technology and material availability. To be useful these constraints should include detailed costs associated with various trades and systems.
II. Schematic Design Phase
    A. Reformulate attributes of mechanical and architectural systems into function constraints on the structure. Function constraints include a spatial component as well as a load component.
    B. Develop detailed lateral load function constraint description including the story forces, shears, and overturning moments.
    C. Synthesize alternative systems of load paths for gravity systems at the typical floor, considering the columns as full height. Specific attributes of the load paths may vary between materials. The load path synthesis must incorporate constructibility constraints such as available form dimensions.
        1. For each of the alternative systems proportion the typical elements while optimizing the mutual constraint sets that arise from interaction with other subsystems.
    D. Synthesize alternative systems of load paths for lateral loads. There should be one or more lateral systems for each material that is being considered for the gravity load systems.
        1. For each of the alternative systems proportion the typical elements

while optimizing the mutual constraint sets that arise from interaction with other subsystems.

E. Combine compatible lateral and gravity alternative systems and proportion foundations for the combined systems to create complete alternative structural solutions.

F. Using constructibility constraints, evaluate the costs of the alternative solutions, incorporating any penalties that may accrue to the other subsystems as the result of the final form of the mutual constraints.

G. Provide information on cost, reliability, and value of structural systems and information on constraints on other systems associated with each alternative to owner for use in selecting the structural alternative that offers the least *Cost / Value*.

H. Based on the system selected, formulate typical constraints that will apply during subsequent design phases, e.g., the grade of steel, the strength and type of concrete, type of metal deck, typical beams depths, typical girder depths, and column locations.

III. Design Development

A. Synthesize complete sets of load paths for nontypical floors, using column locations and material type selected during schematic design. Proportion typical elements at non-typical floors while optimizing the mutual constraints.

IV. Detailed Design

A. Perform detailed analysis on complete lateral and gravity systems synthesized in steps II and III.

B. Formulate detailed performance constraints and satisfy constraints by refining constraints on the structure form, within the context of previously optimized mutual constraints.

C. Satisfy all constraints on form through selection of final member attributes, including steel beam and column sizes and concrete reinforcing.

V. Construction planning Phase

A. Formulate detailed geometric descriptions of all elements that need to be fabricated including: all structural steel pieces, reinforcing bars, metal deck sections.[2]

Most of the heuristic knowledge regarding synthesis is applied during the conceptual design phase to generate feasible alternatives and trim the search space down to a manageable number of solutions. While a comprehensive discussion of the potential strategies that can be used during this phase is beyond the scope of this dissertation, a few examples are offered to illustrate the nature of the strategic knowledge that can be used. Much of the information relative to the synthesis of floor framing was implemented by Jain

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[2] In order to complete the task of constructing the building, the detailed design of the formwork is also performed during the construction planning phase. However, since the formwork is temporary construction, its description should not be included in the facility database.

[9] in his work with logic-based conceptual design.

The overall cost of the structure is directly related to the locations of columns which are established during conceptual design. Potential column locations must be synthesized based on the form of the architectural solution. Attributes of the architectural solution that can be used to systematically generate sets of potential column locations include the overall building length and width, the overall core length and width, the architectural planning module, the minimum (or typical) office dimension, the desired column free space, and the characteristic dimensions generated by the core. Characteristic dimensions consist of the dimension from front to back of a bank of elevators or the dimension across the core. The corners of the building and the core are usually candidate column locations. Integer multiples of the planning module, office dimension, or characteristic dimension that are equal to the overall building length or width define candidate column locations. Corners of shafts such as those for elevators, stairs, and mechanical chases are usually acceptable column locations since the shafts are typically enclosed in walls.

The underlying general strategy is to develop a pattern of column locations that relates to the patterns that are inherent in the architecture. Patterns by their nature are predictable, facilitating the coordination that is so essential to the reasoning process in design.

The sets of potential column locations can be trimmed based on heuristic rules regarding the maximum and minimum beam and girder spans, which usually range from 10 ft. to 60 ft. For each of the remaining potential sets of column locations a hierarchy of horizontal structural elements must be synthesized. The horizontal hierarchy may have one level, as in the case of two-way flat plates; two levels, as with one-way slabs and beams; or three levels, in which there are beams, slabs, and girders. While all three types of systems are theoretically possible for any arrangement of columns, the number of *economically feasible* levels can usually be determined based on heuristics, or, if not, based on a simplified typical bay cost comparison. Column spacings of 20 ft. x 20 ft., which are very economical using a reinforced concrete two-way flat plate system, are usually not economical for steel systems because of the high unit fabrication and erection costs due to the large number of small pieces. The reverse is also true, spans that are economical for steel systems are usually not well suited to the concrete flat plate system.

If there are two or three levels in the horizontal hierarchy, then for each set of column grids there are two classes of load paths that are characterized by the direction of the beam spans. For each of these systems of loads paths either concrete or steel may be used and within the context of those materials further refinements can be made based on the type of elements used, e.g., precast, cast-in-place, post-tensioned. Each of the element types has its own set of characteristic dimensions, leading to multiple potential patterns of load paths. Although there may be a great number of potential gravity systems, they are examined only on a superficial level to the extent that is required to make a qualitative cost comparison. Only a limited number of typical elements, which account for a majority of the structure costs in repetitive systems, need be designed for each potential solution.

The strategy for lateral system synthesis is highly dependent on the height of the building and the geographic location, since both wind and earthquake loads vary widely between regions. Building drift considerations usually control the design of lateral systems for high-rise buildings. There is also a requirement for ductility when the building is in an area of high seismicity. For very tall buildings, the effects of overturning are predominant, so the strategy involves resisting the overturning moment with as wide a base as possible. Hence, perimeter tubes that mobilize the entire width of the building for axial resistance are potential solutions for tall buildings. Uplift at the foundations, particularly under wind loads, is a primary concern with tall buildings, so a secondary strategy is to bring the overturning forces down at locations where the resisting dead load is maximum. Combinations of core and exterior frames can be tuned to bring a specified portion of the overturning down at each location.

As the height of the building decreases, it becomes more feasible to use frames situated in the core to resist lateral loads, particularly if the building is in an area of low seismicity. The backs of elevators which define vertical planes that cannot be penetrated by other building systems, are particularly good locations for braced frames or walls. The economical range of aspect ratios (H/D) of frames is from 0 to 7. It is more difficult to generate the required stiffness with frames that have an aspect ratio greater than 7 and such frames may have problems with uplift.

As a general rule, systems that utilize axially loaded elements to resist lateral loads are more efficient than systems that utilize flexure. The need for efficiency and stiffness has to be balanced against the need for ductility in seismic areas. Eccentrically braced frames offer a compromise between the ductility of a pure moment frame and rigidity of a braced frame.

In all systems tall or short, seismic or wind, there is a preference for symmetry in the lateral systems as well as for widely spaced frames or closed geometries that produce higher torsional resistance.

12

Concluding Remarks

The successful integration of the efforts of the many participants in the life cycle of a facility depends to a large extent on the availability of data in the proper form. The development of the next generation of 'intelligent' automated design assistants requires that the data be capable of capturing the design intent as well as the design results. Identifying the type of data and the form of the data are crucial to both of these endeavors. Just as crucial is the capability of generating the data at the earliest stages of the design process to support the most important phase of the decision making process - conceptual design - while avoiding costly double processing associated with delaying the data input.

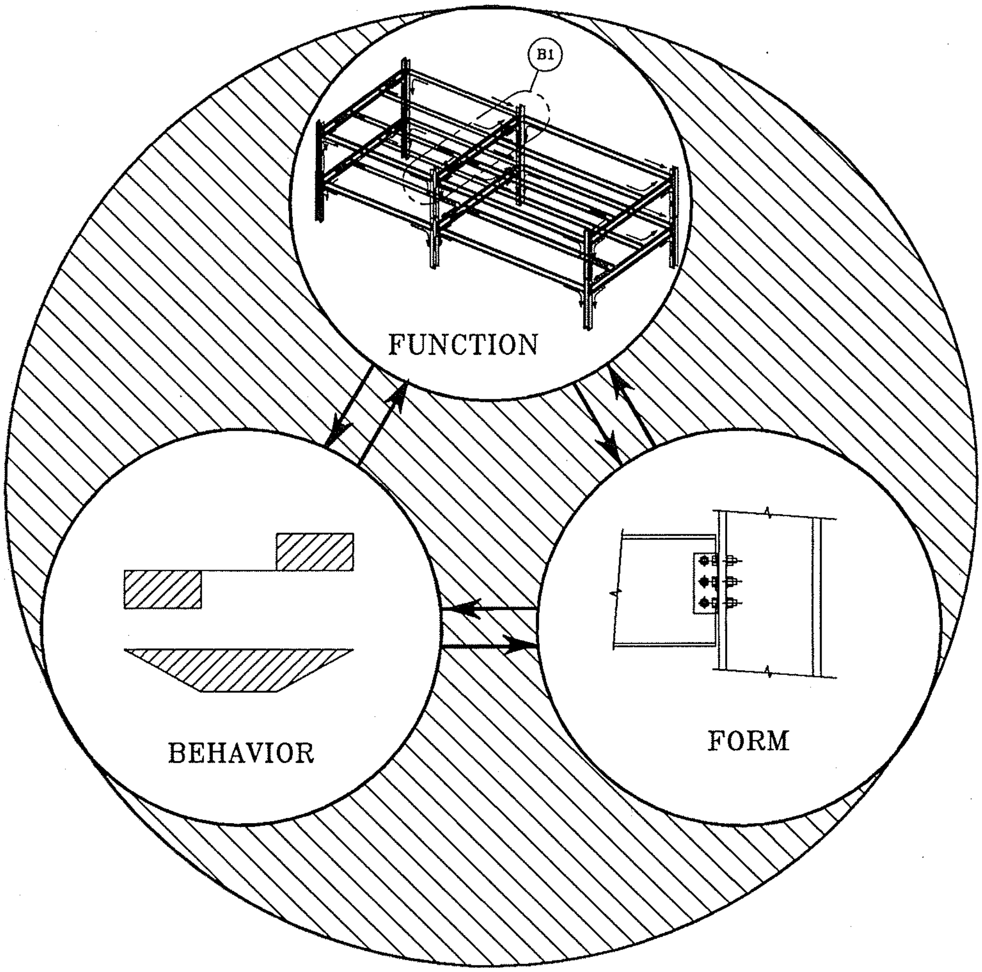
In this dissertation we have examined the life cycle processes from the perspective of structural design, defined the reasoning that takes place over time, and developed an approach to a representation that can capture the design intent while providing an efficient method for storing the data that is necessary to define the structure for use during all phases of design, construction, and facility management.

The work contained herein is a small step on what promises to be a long road. The qualitative reasoning required to define load paths needs to be implemented and a working model of the structural database developed in order to refine and validate the concepts that have been proposed in this work. Based on the work done to date, the concept of structure function appears to be crucial to both the qualitative reasoning process and the form of the data. The initial steps in the formalization of a method of representing and reasoning about structure function is the contribution of this work. Further work in this area will undoubtedly increase our understanding of both structures and the art of structural engineering.

Qualitative behavior was briefly touched on, but much work remains to be done to formalize the concepts in this area. Structure form was addressed even more briefly, but the examples cited highlight the fact that much can be learned through a close examination of the information that is currently generated in support of the construction activities and through relating that information to the concepts of form, function, and behavior.

The key to a successful implementation of the database in this domain is a disciplined approach that produces a comprehensive representation that supports both design and construction, which will require a far more detailed view of the data than is required to support either design or estimating alone. At the same time, the data must be organized in a fashion that conveys the design intent, which requires a different type of discipline in which the conceptual classification of the data is consistently maintained, no matter how tempting it is to combine form, function, and behavior in a single object, or worse, neglect function and behavior entirely in pursuit of form. If that discipline is maintained, aggregate objects containing all elements of the representation can be created as required. If the distinction is not maintained in the original data, it cannot be made at a later time.

From the point of view of the design professional, the key to implementing facility databases in practice is the ease with which the data is stored. The data acquisition must be the natural result of the design process, rather than an additional bureaucratic step that adds to the workload of an overtaxed profession. This will require that the database be tied in some fashion directly to a CAD platform. The CAD system should be a two way link to the database, so that drawings become a graphical report of the data. Translators should be able to project a graphical view of the data from any perspective and the data should be accessible for modification in multimedia form, i.e., modifications made in the graphical environment should appear in the project specifications and the data base and vice versa.


B1
FUNCTION
BEHAVIOR
FORM

Appendix A
Exogenous Systems Constraints

A.1 Introduction

At the global level, constraints result from considerations of the owner and construction functions. Owner originated constraints that are considered explicitly usually take the form of function and performance constraints such as specific load carrying capabilities or vibration characteristics. Construction constraints are of two types: constraints regarding the commonly used materials and system geometries in a given market, which are used during system synthesis; and constraints relating the costs and physical features of the systems, which are used in evaluation of system options. At the regional level exogenous constraints take the form of interaction between the physical features and functions of the building architectural and M.E.P. (mechanical electrical and plumbing) subsystems.

The following sections first discuss the function and form of the architectural, M.E.P., owner, and construction domains and how they interact with each other and with the structure in a typical high rise office building. This is not intended to be a comprehensive discussion of the subsystems in high rise office buildings but rather a discussion of those considerations that are relevant to conceptual design of the structure.

A.2 Architectural Constraints

In the following sections constraints arising the form and function of the architectural systems are examined.

A.2.1 Form

Creating an aesthetically pleasing design within the constraints imposed by the owner's program and budget is one of the primary challenges facing the architect. The art is in developing a solution that meets these requirements while allowing for a harmonious, and efficient, blending of the form and function of the other subsystems as well. The process of conceiving such a solution is a truly creative endeavor, since, initially, there are few constraints that can serve to organize the process. It is important to note that the aesthetics of the architectural solution have a direct bearing on *Cost/Value*, since the *value* of the building is quite often directly related aesthetics. As a result, constraints involving aesthetics are quite often treated as 'hard' constraints during conceptual design.

It is not uncommon for the architect to approach the design of the form of the structure as a mutual constraint problem. In this approach, the effect of the form on the other subsystems is studied on an abstract level, most often by utilizing heuristic knowledge, during the synthesis of the architectural solution. However, in this dissertation, the general form of the architecture is treated as a hard constraint.

In commercial office buildings, the primary features of the architectural form of the building, which are used in formulating geometric constraints on the structure during conceptual design, are the height of the building, the number and vertical location of floors, the plan dimensions of the floors, and the size and location of the core. Some of these may be 'hard' constraint, while other may vary within some acceptable range are determined during the resolution of mutual constraints. Within the context of these global geometric constraints, local constraints such as the locations of columns in the core, within the floor, and on the perimeter are formulated during the conceptual design process.

The building height and plan dimensions are used to formulate function constraints defining the lateral loads due to wind and earthquakes. The height also defines the geometric constraint on the length of the vertical elements in both gravity and lateral load paths. The overall height is composed of the individual floor heights which may be controlled by the solution of the mutual constraints involving structure depth, mechanical system depth, and ceiling height. The heights of some floors, such as the mechanical floor, are controlled by special subsystem constraints, e.g., headroom requirements for large components of the mechanical systems.

The *floor plate* is defined to be the space enclosed by the exterior walls at a given level. The floor plate dimensions are used to formulate constraints defining the extent of the horizontal components of the gravity load paths. In the general case, the floor plate dimensions vary over the height of the building to create the architectural form. This is related to the conceptual architectural design problem discussed above. In this dissertation, only rectangular floor plates are addressed, in order to confine the focus to fundamental considerations of structure function.

A.2.2 Occupancy Areas

The space in the building is divided into occupancy areas, each of which define a set of constraints on the structure of the surrounding space. This section examines the occupancy areas on the typical floors and the constraints that are associated with those areas that are addressed during conceptual design.

The primary architectural function of the typical floor, in the context of commercial office buildings, is to serve as office space. In office buildings the area around the perimeter is the most valuable space for offices, since it has natural light from the windows. As a result, the support functions are usually collected into a compact area near the center of the floor called the core. The office area normally occupies all of the space between the core and the perimeter of the building and is treated as shell space, i.e., the design is independent of a particular partition layout. Based on provisions in the applicable building code the function constraints defining the design superimposed loads can be formulated based on the architectural function of an area. For office buildings the required loads are typically 50 psf live load and 20 psf partition load, but may be modified to accommodate specific owner requirements for libraries, filing loads, or access floors.

The dimension from the outside wall to the core is typically in the range of 35 ft. to 45 ft., depending on the particular market. In order to maintain flexibility over the life of the structure, it is common for this space to be column free. Whether or not there can be columns is a geometric constraint on the structure that is addressed during conceptual design and depends on owner's perception of the value of this flexibility. When columns are introduced, their locations typically relate to the major building features such as the edges of the core or to the building planning module. This is a form of anticipation that results in more flexibility over the life of the facility. Since future space plans must accommodate constraints resulting from permanent architectural features such as core boundaries, relating the structural features to these decreases the potential for conflicts. Planning modules are also a form of anticipation that have evolved over time as a means of standardizing building components such as ceiling grids, lights, and cladding components. In the United States 4 ft. and 5 ft. are common planning modules for office buildings. When there is a specific planning module, an attempt is made to organize permanent building features, such as the structural columns, around that module decreasing the chances that a structural element will end up in the middle of a functional space such as an individual office. In this case the dimensions between these elements are some even multiple of the module.

A.2.3 Core

The core of the building typically contains the air shafts required for ventilating the building, restrooms, exit stairs and the elevators. Again, there are specific design loads, or structural function constraints, associated with each of these areas. In addition to these major features, there may be other small functional areas such as telephone and electrical closets which contain the control panels that service the floor. In order to maximize the efficiency of the floor, the functional areas are laid out as compact an arrangement as possible and usually in a rectangular shape, since irregular boundaries create space planning problems.

Most codes require two fire exits from each floor and limit the distance that any point on the floor can be from one of the exits. Elevators, which are discussed in the next section, are not considered fire exits. A common arrangement is to provide two stairs at opposite ends of the core. The building code specifies minimum and maximum dimensions for the treads and risers and minimum dimensions, which depend on the required exit capacity, for the width of stair runs and landings. Stairs can be designed and supplied as part of the primary structural system, but for economy they are often supplied as prefabricated elements by specialty subcontractors. In either case the method of delivering the load to the structure is typically through hangers and the function constraints take the form of loads at discrete points.

The predictability and uniformity of the architectural features of the core with height are what make it possible to use the core geometry to organize the structural solution. The stairs and elevators are continuous vertical elements requiring openings in every floor and enclosure by fire resistant partitions. The corners of these openings are candidate locations for columns, which are also continuous vertical elements, because the edges of the openings usually define beam locations and the corners define the intersections of two beams. The core is surrounded by partitions with predictable openings for lobbies and doors along lines that are usually regular, most often rectangular, and along which columns may be placed. The partitions at the backs of elevators define vertical planes through which there are no penetrations making them candidate locations for lateral bracing or structural walls.

In some cases there may be a defined corridor surrounding the core, although this is the exception rather than the rule since it decreases the amount of useable office space. When this architectural space is present, the edge of the corridor represents a line along which columns may be placed.

A.2.4 Elevator Systems

Elevators are provided for rapid vertical transportation of building occupants and equipment. The required number, size, and speed of the elevators is a function of the occupant load and building height. These are usually determined by a specialist based on the level of service (i.e., average wait time) desired by the owner.[1] Passenger elevators are usually arranged in banks of roughly equal numbers of elevators flanking a lobby to minimize the dimensions of the equipment rooms, minimize the length of control wiring, and to provide common lobby space. In addition to the passenger elevators, one or two service elevators, which have larger dimensions and a higher load capacity, may be provided in the core.

Each elevator in a bank has a clear hoistway requirement that is in the range of 8' to 10' square. The individual hoistways are separated by a beam whose function is to support the elevator guide rails laterally and, in the case of an emergency stop, vertically. The width of this beam is limited, commonly to 4 inches, to minimize the overall size of the elevator bank. The separator beam is not part of the primary structural system and the same size steel beam is used with both concrete and steel structures. For the purposes of conceptual structural design an elevator bank is treated as geometric constraint consisting of a single slab opening, the dimensions of which are equal to the aggregate dimensions of the individual hoistways.

The base of the hoistway consists of a pit which functions to isolate the hoistway from the spaces below, if any. The pit is also a structural feature since it is generally a concrete structure that must be designed for impact loads from both the elevator and the counterweight as well as for vertical reactions from the guide rails. The required pit depth

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[1] The approximate gross area (including core) served by a single elevator is usually 40,000 to 45,000 square feet.

depends on the speed of the elevator and is usually in the range of 5' to 10'.

The hoistway must be extended at the top for 'over run' a dimension which again depends on the speed of the elevator, usually in the range of 16 ft. to 25 ft. The sheave beams, which support the pulleys or 'sheaves' around which the support cables are looped, are located at the top of the over run. In the case of overhead traction elevators the sheave beams also support the electric elevator motors. The reactions from the sheave beams, which increase with the speed and capacity of the elevators, represent function constraints on the structure at the machine room level. In addition to the function constraints, there are stringent deflection limitations on the beams supporting the sheave beams in order to minimize the 'bounce' when the elevator stops. The control equipment for the bank of elevators is also located in this area which is called the elevator machine room. Quite often the roof of the elevator machine room extends 15 to 20 feet above the main roof in which case it is referred to as a penthouse.

The exact hoistway sizes and the location and magnitude of reactions at guide rails, pit slabs, and sheave beams vary between manufacturers and between different models offered by the same manufacturer and are not known until the actual supplier is selected by the contractor. The constraints on the structure are formulated based on past experience or based on information provided by an elevator consultant. The constraints at the top and bottom of the hoistways are not addressed until design development or, possibly, detailed design. The location, number, and approximate size of the hoistways is needed in order to formulate constraints on the structure for the typical floor during conceptual design.

A.2.5 Fire Ratings

Various functional spaces within the building must be separated by fire resistive floor or wall assemblies. In the U.S the degree of resistance of an assembly is based on published results of tests - many of which were performed and documented by the Underwriters Laboratory (UL) [22] - and is measured in hours. An assembly with a 2 hour rating is more resistive than one with a 1 hour rating. The separation required between functional spaces is dictated by the building code and constrains the attributes of the separating element. In the case of floors, the requirements usually constrain both the material and the dimensions of the structural elements.

Typically all vertical shafts in a high rise building, including the exit stairs and elevators, must be provided with a two hour enclosure. This enclosure may be constructed of multiple layers of gypsum board, or masonry, or it may be a special type of wall assembly designed for this application called shaft wall. If the architect chooses to use masonry, the resulting load that must be carried by the structure is substantially higher than with either of the other options, resulting in heavier beams, columns, and foundations in the core area. The constraint defining the actual material used around shafts may be formulated during either schematic design or design development.

A fire separation of 2 hours is required between the typical floors in a high rise building and may be provided by the structural slab alone, by a combination of the slab and spray-on fire proofing, or by an assembly consisting of the ceiling and the slab. In each these instances there is a minimum required slab thickness based on the type of concrete used, i.e., lightweight or normalweight. For the case of a concrete slab alone, the required thicknesses are 4.6 inches for normalweight concrete and 3.8 inches for lightweight concrete (Table 43C, Uniform Building Code, 1988 [8]). In the case of composite concrete on metal deck, the ratings are based on UL test assemblies, and the required thickness of concrete over the deck are 4.5 inches for normalweight and 3.25 inches for lightweight concrete. From a purely structural point of view, the required slab thickness is dependent on the slab span and the load. Constraints arising from fire ratings result in a limit on the span below which no further reduction in slab depth is possible. When the constraint on the slab thickness is not met, then constraints relating to the architectural ceiling details and/or fireproofing on the deck must be formulated. The evaluation of solutions during conceptual design should include the costs of all details required to obtain the fire rating.

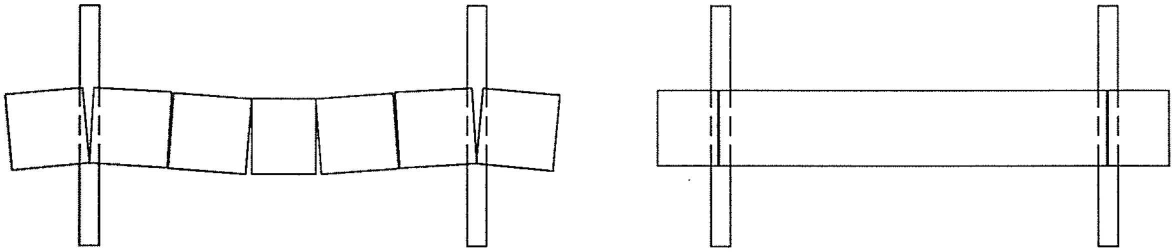
In addition to the requirement that there be separations between spaces within the building, there is also a requirement for protection of individual structural elements in the case of a fire. Concrete structural elements have inherent fire resistance provided the minimum cover requirements are met (UBC, Table 43A), however, steel members must be protected by the addition of a fireproofing material. The rating requirements are dictated by the building code, which also provides some guidelines for using generic materials such as concrete or gypsum board for fireproofing structural steel. In addition to the details provided by the code, the UL provides details for various fire rating assemblies, many of which use spray-on material whose cost is proportional to the area that must be fireproofed, e.g., the surface area of the steel. In floor systems using steel joists, the steel surface area is quite large and it becomes more economical to obtain the required protection by using a rated ceiling assembly. The structural conceptual design should consider the additional costs due to fireproofing in the comparison of concrete and steel and in the comparison of various steel schemes. Where spray-on fireproofing is used, the thickness of the fireproofing, which is typically 1" to 1-1/2" must be added to the depth of the steel members when checking the interaction constraints.

A.2.6 Cladding Systems

The building cladding serves the functional role of providing a weather enclosure as well as a primary aesthetic role. Cladding systems can be of many different types, each of which result in different function and performance constraints on the structure. In the case of the cladding, the function constraints involve both horizontal loads, which result from wind or seismic considerations, and vertical loads. Performance constraints on the structure arising from consideration of the cladding also involve both horizontal and vertical deflections. Both the performance and the function constraints on the structure may need to be altered to accommodate temporary conditions relating to the construction sequence. Quite often, the cladding system is supplied under a 'performance specification' and many of the details of the design, fabrication, and erection are left to the supplier. In this case, it is necessary to anticipate the costs that are likely to result from the interaction between the structure and cladding, formulate constraints on the structure accordingly, and then communicate these constraints back to the supplier via the performance specification.

The cladding is one of the primary considerations in formulating mutual constraints involving floor to floor height. When comparing various constraint sets, variations in floor to floor height result in changes in the cost of the cladding which is usually estimated on a square foot basis.

The weight of the cladding system can range from 120 psf for fully grouted masonry cavity walls or heavy architectural precast concrete to 10 psf for glass 'curtain' walls. The difference between the upper and lower ends of this range can have significant impact on the sizes of the exterior beams, columns, and foundations. Since that, in turn, can influence the selection of the lateral system for the building, it is necessary to establish cladding parameters during conceptual design. The weight of the cladding is usually not carried concentrically by the spandrel beams and the method of accommodating this eccentricity can be an important cost consideration in differentiating between conceptual design solutions. The function constraints resulting from consideration of the cladding details involve not only the value of the load that must be carried, but also the manner in which it must be carried.



CASE A: CLADDING RESTING ON BEAM

CASE B: CLADDING SPANNING TO COLUMN

Figure A.1 Interaction of Constructibility and Performance Constraints Related to Cladding

The horizontal and vertical deflections of the structure can have a significant impact on the cost of the cladding system. Failure to account for these deflections, as well as for thermal movements, in the design of the cladding system can result in unacceptable performance of the cladding after construction. The change in length of an aluminum curtain wall element one story tall (12'-6") between direct sunlight in summer (160^{O}F) and winter at night (-10^{O}F) is on the order of 0.3 inch. The structural live load deflection, if the code limit of L/360 is used as the performance constraint on span of 30 ft., would be 1" per floor. Some trade associations such as the Brick Institute of America recommend stringent deflection limitations (L/720) in order to avoid damage to the wall material. Many of these factors are not addressed in current building codes. Appropriate performance constraints must be formulated based on heuristic knowledge considering the individual circumstances.

Horizontal deflections result from the structure behavior under lateral loading. Performance constraints limiting the behavior must be formulated considering the impact of the deflections on the cladding cost. Usual limits are in the range of h/500 to h/400, where h is the floor to floor height. In the example above, the corresponding horizontal deflection range is 0.300 to 0.375 inches. Building codes typically give a value to be used for this constraint in the case of seismic loads, but not for wind loads.

The location of the cladding supports, the deflection of the structure, the erection sequence, and the cladding connection details are all integrally related. Figure A.1 illustrates two different approaches to the support of cladding elements. In the first approach, small segments of cladding are supported on the structure between columns. In this case, the full weight of the cladding is carried by the beam, increasing the required size, and the beam deflects as individual pieces are set. The connections between the cladding and the structure must have sufficient adjustment to accommodate the expected movement. Moreover, the deflections at each piece change as subsequent pieces are erected, necessitating readjustment. In the second case, shown on the right in the figure, the cladding elements themselves span between structural columns increasing the structural strength and stiffness constraints on the cladding elements, but relaxing the constraints on the structure. In this case, since the cladding spans between hard points, only a single pass is required for erection.[2]

The effect of cladding system parameters on the structural cost, the cladding cost, and the cost of construction operations must all be considered in order to formulate the appropriate set of constraints on the structure. The resulting function constraints include the value of the loads that must be carried and the location of those loads, while the performance constraints define the deflection limits under cladding weight during construction, under live loads during the life of the facility, and under lateral loads. Once the values of the constraints are selected, the information must be communicated (propagated) to the entity providing the design for the wall assembly. In the case of cladding supplied under a performance specification, the constraint propagation takes the form of including all of the constraints in that specification.

A.2.7 Finishes

The architectural finishes include ceilings, floor treatments, and partitions. Ceilings are significant primarily because they are one component of floor to floor height and because of the relationship between ceiling heights and value. Floor treatments can result in function and geometry constraints. Partitions are normally accounted for during conceptual design by using the minimum partition load required by code. They are of more interest during the facility management phase of the life cycle when actual partition loads may be used in lieu of the code minimum in checking for specific tenant load requirements.

Ceilings, which typically have weights in the 1 - 2 psf range, are normally suspended

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[2] The problem is worse when the beams are continuous, since the deflections of adjacent spans are not independent. If the cladding consists of deep precast elements, the strength an stiffness constraints required to enable the precast to span between columns are not severe. The real constraint on construction is the size of the piece that must be erected.

from the structure by means of wires. In seismic areas, the ceiling grid must be stabilized. The ceiling is generally aligned using a laser level and is unaffected by variations in the structure elevation resulting from construction tolerances and selfweight. As a result, there is very little interaction between the ceiling and the structure. The height of the ceiling is important because it is usually associated closely with the value of the office space. As a result, the ceiling height is often treated as a hard constraint when it is involved in a mutually constrained grouping.

Three types of floor finishes result in significant constraints on the structure: access floors, thin set tile, and thick set tile. Access floors result in function constraints in the form of dead load which should be considered in the design and may create geometric constraints if the clear ceiling height has to be measured from the top of the access floor. Thin set tile, which has a thickness ranging from 0.25" to 0.50" results in a function constraint in the form of additional dead load but do not create geometric constraints. Both geometric and function constraints result from thick set tile, which requires a depression in the structure on the order of 3" and results in additional dead loads in the range of 30 - 40 psf. In office buildings, tile finishes are usually confined to lobby areas and public spaces at the ground level.

A.3 M.E.P. Constraints

The mechanical, electrical, and plumbing systems, commonly referred to as the M.E.P. systems, serve to temper the building environment and provide power and water to the building occupants.

A.3.1 HVAC System

The HVAC systems are defined to be the origination, distribution, and delivery systems required for heating, ventilating, and air conditioning the building. The air within a building must be completely changed at suitable intervals. The basic functions of the HVAC system are to condition and supply fresh air to the building and to collect and exhaust old air from the building. It is usually necessary to alter the temperature and/or the humidity of the outside air before it is supplied to the occupied spaces in the building (i.e., condition it). The components that are necessary to condition the air are collectively referred to herein as the 'origination' system. Fans and ductwork transport the air from the point of origination to the actual point of delivery on the individual floors and form the 'distribution' system. In the case of the exhaust air the process is reversed and the components form a 'collection' system. The supply air is delivered to the floor through louvers which may be attached to a mixing box or diffuser, while the exhaust air is commonly collected through plenum. These components are referred to herein as the 'delivery' system. In general, the extent of the area affected by the HVAC subsystems decreases from regional (i.e. a whole floor) for the origination subsystem to local (i.e. a single beam) at the point of delivery.

A.3.1.1 Origination System

Conditioning the building air involves altering its temperature and humidity. In most buildings, cooling requirements are more significant than heating requirements since the building's lights, mechanical systems, and occupants all produce heat. Cooling the air is usually accomplished through a layered system of heat exchangers using multiple fluid types. At the center of this layered system are the chillers which use a system of heat exchangers to transfer heat from a 'chilled water loop' to a 'condenser loop'. The chillers that are used in commercial office buildings are quite large with 'operating' weights in the range of 40,000 lb. to 50,000 lb. (information obtained from the supplier) and occupying an area of approximately 10 ft. x 20 ft. It is common for the chiller installation to include a 'housekeeping pad', which is a 4(±) in. thick raised section of concrete. The total unit load under the chiller can approach 300 psf, which far exceeds the code minimum design load of 150 psf for mechanical rooms. This intensity of load may be sufficient to require special slab details as well as heavier beams at the location of the chillers.

Cooling towers use evaporation to dissipate the heat contained in the condenser loop into the environment. Since the cooling towers must be located outside in an area with unrestricted air flow and the evaporation process produces steam which is undesirable in a pedestrian environment, it is common for the cooling towers to be located at the roof of the building. Cooling towers have operating weights in the range of 50,000 lb. to 90,000 lb., plan dimensions in the range of 15 ft. x 20 ft., and heights in the range of 15 ft. Quite often, the cooling towers are raised above the deck in order to allow the condenser loop to feed into the tower from the bottom. Installations, which typically include multiple cooling towers, may have an overall height exceeding 20 ft.

When the cooling towers are located at the roof and the chillers are located near the base of the building, the transport of the liquid in the condenser loop becomes an important consideration in the design of the structure. These loops typically consist of 18 in to 24 in.

steel pipes with a wall thickness of 1/2 in. and are filled with an antifreeze solution that weighs 63(±) pcf. Since the pipes must be free to expand and contract relative to the floors, the entire weight of the pipe and fluid is usually carried at the bottom. The reaction at the base of two 20 story (250 ft.) 24 in. risers is 160,000 lb. a significant function constraint on the structure.

On the other side of the chillers, the fluid in the internal chilled water loop is transported to the air handling units (AHU) where it passes through a heat exchanger, absorbing heat from the building air. The AHU and heat exchanger assembly is considered to be part of the distribution system. The pipes forming the chilled water loop are similar to those in the condenser loop leading to similar function constraints at the bottom of tall risers. The risers for the chilled water and the condenser loops usually occur in a common mechanical chase located in the core. This chase may also include risers for the building sanitary and storm water systems.

The pumps and compressors that are common to the elements of the origination system create significant noise and vibration. When the elements are located adjacent to occupied space, it is common to include in the design special constraints on the architectural, structural, and M.E.P. subsystems to isolate the noise and vibrations in that space. The actual requirements are usually determined by an acoustical consultant when vibrations and noise are a concern. The vibration isolation is commonly accomplished by providing an inertia base consisting of a concrete slab resting on top of the spring isolators under individual pieces of equipment. A common way of providing sound isolation is to provide mass between the source of the sound and the occupied area. This mass is provided by using masonry wall enclosures around the mechanical space and increasing the slab thicknesses above and below the mechanical space. For this purpose, slab weights in the range of 100 psf to 130 psf can be anticipated. Again the significance is the increased weight that the structure must carry.

The constraints arising from the HVAC origination system take the form of loading requirements at specific locations in the building. Those locations are usually controlled by cost considerations within the architectural and M.E.P. systems. Since many of the components in the origination system require high ceilings, in the range of 12 to 15 ft. and have nontypical power requirements, it is common to locate all these elements on a single floor or in a specific area of the building which is designated the 'central plant'. The location of this floor and weight of the equipment are usually treated as 'hard' constraints in the conceptual design of the structure. Due to the weight of the equipment and slabs involved, the structural elements supporting the central plant are much deeper and heavier than the typical floor framing resulting in constraints on the floor-to-floor height, ceiling height, and mechanical equipment depth at the floor below. Constraints arising from the HVAC origination system are non-typical and are usually not addressed until design development unless the structural features (heavy slabs, etc.) that result are used as elements in the design of lateral or transfer systems.

A.3.1.2 Distribution System

The function of the HVAC distribution system is to carry the conditioned fresh air, commonly termed 'supply' air, from the point of origin to the point of delivery. In the case of supply air the point of origin is somewhere on the exterior of the building while the points of delivery are the diffusers, mixing boxes, and registers on the floors. In the case of the exhaust air, the path is reversed.

There are two fundamentally different methods of distributing supply air: 'centralized' and 'on floor'.

In centralized systems, supply intakes are located at a limited number of locations throughout the building height. At these locations there are large areas of louvers on the face of the building. Air handling units are located adjacent the louvers to force the air into one or more vertical shafts which carry it to the floors. Depending on the location of the mechanical floor(s) the air may be transported through ductwork up, down, or a combination of up and down. The volume of air that must be transported is highest near the point of origin resulting in a large shaft at that location (usually on the order of 10 ft. square) and decreases with distance from the origin. The locations and sizes of the air shafts, which are usually in the core, are important mutual constraints between the architectural and M.E.P. systems, and are treated as hard geometric constraints on the structure.

The 'on floor' system, utilizes AHU's distributed throughout the building which serve individual floors or small groups of floors. Aside from posing a different space planning problem for the architect, this type of system may require a two story space in the core to accommodate the units, resulting in additional geometric constraints on the structure. Air can be transported to the individual units through air shafts in the core, in which case the on floor system does not differ conceptually from the centralized system. In other cases intake and exhaust louvers are located in the exterior wall on every floor and accommodating the large ducts connecting the louvers to the AHU's becomes an issue in the conceptual design.

However, in this discussion, only centralized systems are addressed.

With either supply system, the air is moved to the point of delivery through ductwork. The primary supply duct forms a loop around the floor interfacing with the typical structural elements. The size of the duct depends on its shape (round, flat oval, or rectangular), the required volume of air, and the velocity of the air. The duct is largest near the point where it exits the air shaft and decreases in size with distance as air is dropped off at individual diffusers and mixing boxes. It is common to utilize two shafts, one at each end of the core. In this case there are two loops, each serving half the floor, and the maximum duct size is reduced. Since the duct sizes are largest next to the air shafts, it is advantageous to minimize the structural depth requirements in these areas a consideration in formulating a strategy for synthesizing load paths in this area. Figure A.2 illustrates the condition where the main supply duct comes out of the air shaft. Note the closely spaced columns that make it possible to minimize the beam depths in this area reducing the floor-to-floor height requirement.

At various points in the loop, the duct crosses beam lines and must either pass under the beams or through the beams. The depth of the duct, the depth of the structure (slab plus beam plus fireproofing), the space between the duct and the ceiling for lights, the ceiling height, and the floor to floor height form a mutually constrained grouping. The ceiling height, and to a lesser extent the space for lights, are usually treated as hard constraints since they affect value, whereas the structure depth, floor to floor height and the ductwork depths can all be varied to obtain the most economical solution. Lights vary in depth from 5" for a fluorescent fixture to 10" for can lighting. The deeper fixtures are used in special areas, in which case it is usually possible to avoid stacking the lights and duct work. The owner typically requires flexibility in the placement of the standard light fixtures, so the ceiling plenum must accommodate the sum of the light and duct dimensions. Changes in the floor to floor height have an impact on the cost of all the systems, since they translate directly to increased material requirements for the vertical elements of the systems. They have an additional impact on the mechanical systems because they affect the volume of air in the building that must be conditioned as well as the surface area exposed to sunlight. Once the optimum combination of vertical dimensions for the elements are determined, those dimensions are used as hard constraints during subsequent design activities.

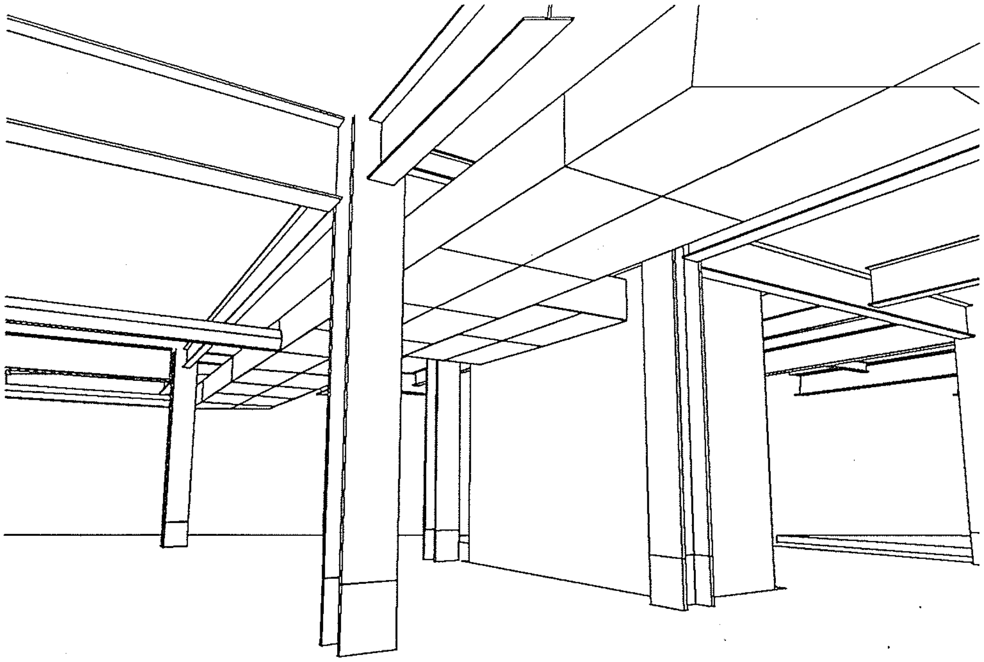

Figure A.2 Main Supply Duct

The amount of air that must be moved and the available pressure are treated as constant when studying the mutual constraints. Under these conditions the required area of the duct is related to the drag produced as the air moves past the side walls of the duct. As the duct is made flatter, the ratio of drag area to cross sectional area, A_d/A_x, increases, resulting in a higher cross sectional requirement. For instance, a 24 inch square duct has an A_d/A_x ratio of 2.0 while a 12 inch duct with the same A_x has a ratio of 2.5. In order to transport the same volume of air at the same pressure, the 12 inch duct cross sectional area must be increased. This means that the increase in the amount of material for the 12 inch duct over the 24 inch duct is more than 25%. There is a lower limit on the depth of the ducts at which noise and vibration starts to detract from the value of the facility. The range of sizes that can be used in a given situation is determined by the mechanical engineer while the variation in the cost of the ductwork with depth, which includes the incremental cost of the material as well as the cost of any special construction techniques (such as transitions) required, is determined from constructibility constraints.

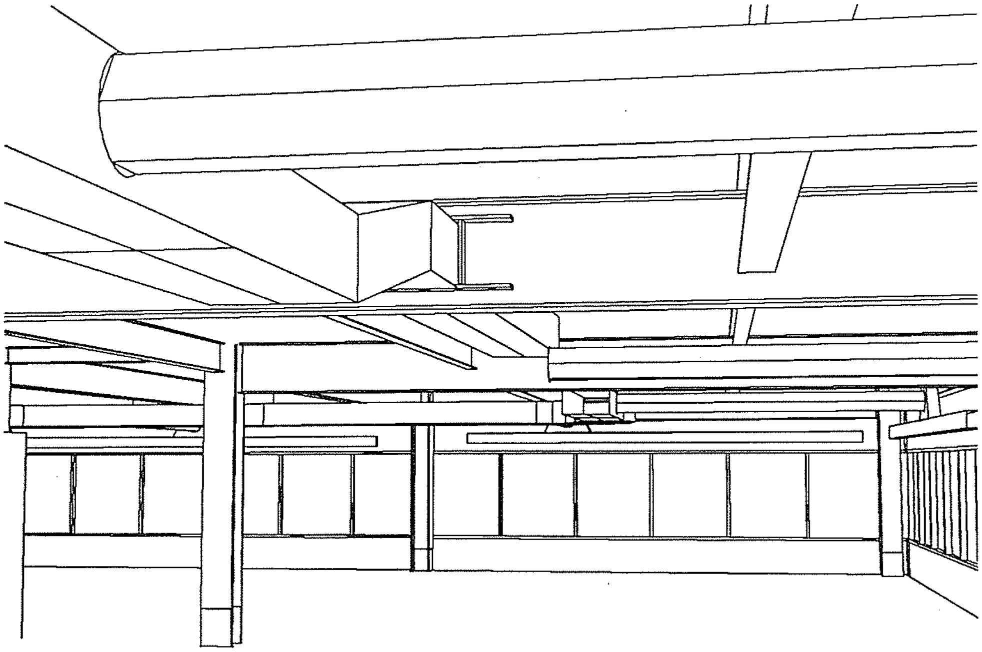

Figure A.3 Duct Penetration through Beam

In addition to the effect of varying the duct sizes, the effect of feeding the ducts through the structural members can be considered. This condition is illustrated in Figure A.3. This is usually an option only with steel beams, although it is occasionally used to solve isolated coordination problems in concrete buildings. Since penetrating the beams results in increased labor costs for installing the ductwork as well as increased fabrication costs for the steel beams, its use is typically limited to relatively few locations per floor, primarily at girders, in order to gain the advantages of a lower floor to floor height with a minimal premium. When this option is being considered, it may be necessary to increase the beam depth as well as vary the duct size. Both the width and the depth of the duct at the location of the penetration have an effect on the feasibility of this solution.

As fresh air is supplied to the floors, a corresponding amount of air must be removed. The space between the ceiling and the structure commonly functions as a return air plenum. Air from the plenum is drawn into exhaust air shafts - which are roughly the same size as the supply air shafts - and transported out of the building. Since there is no ductwork involved, this type of exhaust system does not interact with the structure.

A.3.1.3 Delivery Systems

The HVAC delivery system consists of the mixing boxes, linear diffusers, and registers that actually deliver the supply air to the floors. These components are small and can usually be positioned to avoid any interface with the structure. Occasionally the linear diffusers, which are long registers that direct air down past the windows on the building perimeter, must be coordinated with the spandrel (exterior) beam depths, especially where the beam is made deep for wind resistance. Although the normal location for the diffuser is directly over the window, it may be possible to pull it inside the beam line when the beam is adjacent to the wall. When the edge of the slab cantilevers several feet past the beam an alternative is feeding the diffuser supply duct, which is usually a round duct on the order of 12 inches, through the beam at a limited number of locations. In this case the alternative is evaluated similar to other beam penetrations, with special attention to the difficulty of installing the diffuser behind the beam. Another solution that is sometimes used is to incorporate the diffuser into an architectural feature or drapery pocket that extends below the ceiling, which, of course, involves value. Each of these must be evaluated and compared to the choices of decreasing beam depth or increasing floor to floor height.

A.3.1.4 HVAC Summary

During schematic design, the HVAC distribution and delivery systems are the primary source of interaction constraints with the structure. The HVAC origination systems are the source of some of the largest loads, or function constraints on the structure from exogenous systems, but usually effect only a small area of the building and are addressed during the design development phase.

A.3.2 Electrical System

The electrical subsystem carries electric current from the utility source (usually outside the building line) to the end users which include the building mechanical and vertical transportation systems and the building occupants. There is usually a central transformer vault where the voltage from the utility distribution system is reduced before the power is distributed to the various locations in the building. Often the transformer vault is considered to be quasi-property of the utility company, since it is, in essence, an extension of their distribution system. Everything between the building line up to, and including, the main transformer vault forms the 'origination' system. The emergency generator is also considered part of the origination system. Electric conduit carry the power from the transformer vault to the various floors. The voltage may be stepped down again at one or more locations elsewhere in the building. Various methods are used to distribute the power to all areas of the floors. These components all form the 'distribution' system. Eventually the power is delivered to the end user. In the case of building occupants, the method of delivery is through receptacles. These form the 'delivery' system for the electrical subsystem.

In some cases the distribution and delivery systems are combined in the floor of a steel building by utilizing special cellular deck. The wiring is run in closed cells that are created by welding a light gauge metal plate across the bottom the deck ribs. Periodically, the deck is interrupted by a trench header which functions to distribute all of the wiring from the primary power source out into the deck. This condition can result in severe design constraints, particularly if the structural system consists of composite beams. There is no concrete at the location of the trench header. If it is perpendicular to the beams near the center of the spans, it destroys the composite action. Trench header locations are also weak points in the floor diaphragm.

Normally, the primary interaction between the structural and electrical subsystems takes the form of function constraints resulting from the weights of the equipment associated with the origination systems. It is common for the conduit from the utility tap to the transformer vault to be encased in concrete for protection. Because of the number and size of conduit that are required for a high rise building, the size of this concrete element, which is suspended from the structure, can be on the order of 2'x6' resulting in a significant load on the structure. Fairly massive masonry construction is usually used for the transformer vault walls due to the stringent fire protection requirements. The transformers themselves are quite heavy and can approach a load intensity of 300 psf. When transformers are used throughout the building the concrete encasement extends all the way up to the transformer locations and provisions must be made for changing the transformer. This may involve designing removeable panels in the exterior walls and designing the structural slabs and beams along the removal path for a high load intensity. The last element of the origination system that needs to be considered in the design of the structure is the emergency generator which may be a large diesel powered unit with a weight in the range of 80,000 lb.

The elements of the electrical origination system are quite often located in the central plant area of the building. Since the constraints arising from these systems are non-typical, they are usually addressed during design development. The distribution and delivery elements of the electrical system seldom result in structural constraints.

A.3.3 Plumbing System

The office building plumbing subsystem performs three primary functions: the collection and disposal of rain water, the collection and disposal of waste water, and the distribution of hot and cold water to restroom and kitchen facilities. In the case of the sanitary and storm systems, there are multiple points of origin distributed throughout the building, since these systems function to carry something *out* of the building. The storm system originates at drains located on roof areas. (Here the term 'roof' is used generically to describe any horizontal enclosure which separates occupied space from the exterior of the building.) The sanitary system originates at the drains in the building restroom and kitchen facilities. In both cases, the collection system gathers the water and, after suitable treatment, delivers it to the municipal sanitary and storm drainage systems.

In the case of the water supply system the origination system includes the tap into the municipal utilities and any pumps and boilers that are necessary to heat the water and boost the pressure to accommodate the required vertical rise. The distribution system includes the hot and cold water risers (vertical pipe runs) and any horizontal distribution runs. The delivery systems consist of the plumbing fixtures in the sanitary facilities.

As with the electrical system, the primary interaction between the structure and the plumbing systems is at the origination system level. The tanks and boilers associated with the initial treatment of the water supply may exceed normal design loads for mechanical equipment. These elements are normally grouped in the central plant along with the mechanical origination systems and result in function constraints on the structure that are addressed during design development.

A second type of interaction occurs between the drainage systems and the structure at the roof slabs and slabs on grade. Drainage systems utilize gravity and as a result the pipes must be sloped. At the roof(s) of the building this may result in geometry constraints on the structure similar to those that result from the ductwork at the typical floor. Quite often the vertical elements of the storm drains are located next to structural columns and terminate below the slab on grade. When this is the case the geometric requirements for bending the pipes and interfacing with the below slab pipe network can result in geometric constraints for the vertical locations of foundation elements. These constraints are formulated during design development.

A.3.4 Fire Protection System

The fire protection subsystem serves as a fire retardant during emergencies. The origination system consists of the tap into the municipal utility and the dedicated pumps required to maintain pressure. The distribution system consists of vertical stand pipes, which are usually located in the core, and horizontal runs into the ceiling spaces on all floors. The delivery system consists of sprinkler heads which release the water when subjected to high heat. The pumps result in function constraints on the structure which are addressed during design development. The location of the distribution lines and sprinkler heads must be coordinated with the other architectural, structural, and M.E.P. requirements during the conceptual design of the typical floor and may contribute to the geometric constraints on the structure.

A.4 Owner Constraints

Constraints originating directly with the owner entity usually involve factors which affect the perceived value of the facility, the cost of managing the facility, and the schedule for construction of the facility.

Two factors associated with the value of the facility are the design live load and the vibration characteristics of the floors. Recently, the trend has been toward heavier design live loads, in the range of 80 to 100 psf, in some areas because the owners perceive this as giving them a marketing advantage. In this case, the design load greatly exceeds the code requirement of 50 psf which, in most cases, is itself conservative. While the costs associated with this constraint can be quantified, the value involves a judgement call on the part of the owner.

Most owners agree that floor vibrations are undesirable, but few can quantify the value of lower vibrations, a problem which is not helped by the fact that vibration perception is very subjective. In the past, the most reliable approach to vibration design was to allow the owner to experience vibrations of a variety of floor systems and balance his concept of the value of those systems against the cost of equivalent systems for the planned facility. At this point in time, it is possible to predict qualitatively that concrete systems have better characteristics than steel systems and it is possible to identify steel systems whose characteristics are universally unacceptable. However, we cannot predict the response of humans to vibrations with sufficient accuracy to reliably distinguish the difference between most ordinary structural steel systems.

The cost of managing the facility includes the cost of maintenance, the cost of operation (e.g., the cost of power for mechanical equipment), and the cost of modification. There are few, if any, operating costs associated with the structural system in a high rise office building. Maintenance costs are extremely important for facilities exposed to weather such as parking facilities, but are not significant in office building structures. The primary structural cost during the facility management phase is the cost of modifying the structure to suit changing tenant requirements.

It is not unusual for multi-floor tenants to want additional stairs linking their floors, requiring the creation of large openings in the structural slab, and the removal or interruption of floor beams. It is difficult to predict how much of this will occur and the only way of comparing the various structural systems is to examine hypothetical situations with each of the systems.

A more common requirement during the operation of the facility is for tenants to require areas of high load intensity. The most common occurrences involve high density filing systems which can approach a load intensity of 200 psf and libraries which require a 125 psf design live load. These loads exceed not only the code design load of 50 psf, but also the heavier loads of 80 and 100 psf favored in some markets. Structures which cannot be easily upgraded to accommodate these load capacities are at a disadvantage. There are a number of approaches that can be pursued during conceptual design to accommodate the need for flexibility. These systems are usually placed near the core, since natural light is not required, so one approach is to designate a limited area near the core that will be designed for a heavier load. If this alternative is used, the floor system on every floor is designed to accommodate the heavy load while a probabilistic approach is used to develop appropriate column design criteria, since the probability of having the heavy load at all floors is extremely small. In a building with composite beams a second approach is to use full composite design for the floor beams, which results in a few extra studs so that their capacity can be upgraded by the addition of a cover plate on the bottom.[3]

The owner may have specific schedule requirements based on the need for the facility. When this is the case, an additional constraint on the conceptual design is that it can be built in the required amount of time. Even when there is no specific schedule requirement,

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[3] Nothing is more frustrating than to find that a beam capacity cannot be upgraded because it is short two shear connectors worth $3.00. Sometimes the philosophy of attaining minimum cost backfires.

schedule is an important element in the evaluation of the various potential schemes as the result of the cost of financing. The cash flow history must be considered in the evaluation of the cost of the schemes. Schemes that require a large amount of cash early in the construction schedule are more costly due to the value of money over time. This concept is useful in developing and evaluating construction sequence alternatives.

A.5 Construction Constraints

Constraints resulting from consideration of construction activities help organize the solution process by identifying the most common types of systems in a given market. Once a system is selected, constructibility constraints are used to determine the best or most economical details within the context of that system. Constructibility constraints are used throughout the design process in evaluating the relative costs of the individual systems. This section discusses these three types of constructibility constraints, in the context of conceptual design of high rise office buildings, for concrete and structural steel systems.

A.5.1 Concrete Systems

A major portion of the cost of concrete systems results from the forming operations and, as a result, systems classifications are usually tied to the type of forms and the method of erecting and disassembling the forms. Much of the economy of the formwork depends on the ease with which it can be disassembled, moved, and reassembled, and the number of times a given piece of formwork material can be reused. The forming operations can be conceptually divided into forming of vertical elements and forming of horizontal elements (flatwork). In high rise buildings, there are distinctly different approaches to forming the different types of vertical elements, which include interior walls, columns, and exterior walls and frames, and these are addressed separately in the following discussion.

Within the context of the various forming systems concrete and reinforcing materials may be varied to create additional systems. Concrete materials include both lightweight and normalweight concrete of varying strengths while reinforcing commonly includes strength grades of 40 and 60 both weldable and nonweldable. (Reinforcing strengths of 75 ksi are available, but are not currently in common use.)

A.5.1.1 Formwork

Not all of the forming systems or materials discussed are used in every market. Because of differences in the cost of labor, the available technology, and the available material, as well as variations in the expertise of the designer and owner community, different areas of the country have developed preferred systems. This preference is usually apparent in the prices that are associated with various systems, with the more familiar systems generally being more economical.

Columns

Columns are the simplest of the elements that must be formed in a high rise building. They are normally formed and cast in sections that start at the top of the floor slab and end at the soffit of the floor framing above. Standard steel or fiberglass forms which utilize two pieces can be used for round, rectangular, or square columns. It is also possible to 'stick build' (build individual forms from wood) forms for the square and rectangular columns or use disposable cardboard tube forms for the round columns, but this is seldom cost effective. Since a new form is required for each different size or shape of column, a cost effective design incorporates as many reuses of a given size as possible so that the cost of the form material can be amortized over a number of individual elements. Since all of the columns at a given floor are normally formed and poured simultaneously in a high rise building because of the limited size of the floor plate, form reuse requires utilizing the same size columns for a number of stories. The economies that result from form reuse have to be balanced against any material penalties that may be incurred.

A capital is a flared section at the top of a column that is formed with the column. At one time capitals were commonly used with flat plate structures. However, due to the difficulty of forming the flared portions, they are no longer commonly used.

Walls

Walls can be formed and cast floor by floor similar to columns using either steel or wood forms. If the walls are clustered together, as is the case when they enclose the core or the elevator shafts, there is an opportunity for changing the construction sequence. In the alternative sequence, called jump forming, the individual sections of forms are 'ganged' together and lifted with a crane to allow the walls to be formed and poured ahead of the flatwork. In this case, the connection between the flatwork and the wall is different since the flatwork abuts the walls rather than bearing on the top of the walls. The economies that can be gained from jump forming must be balanced against the additional cost of the details required to render the flatwork connection equivalent to the normal wall/slab joint in terms of strength and reliability. Since this is normally the joint through which lateral loads due to earthquake and wind are transferred, in addition to gravity loads, it is a critical element of the lateral and gravity load paths, particularly in high seismic areas.

Slip forming is a logical extension of the jump forming concept in which the forms are equipped with jacks that allow continuous form movement and concreting operations. Slip forming requires special expertise and equipment and as a result there is usually a minimum number of stories below which one of the other methods is more economical. Slip forming is a very efficient operation in terms of time, but in order to take advantage of this the balance of the building systems must be able to keep up with the forming operation. If the other framing cannot keep pace with the slipforming operation, then the effective cost of the slip forming increases due to the effect of interest on the cost of the construction put in place.

Exterior Frames

In tubular structures which utilize closely spaced columns and relatively deep beams on the building perimeter there are several choices for the forming method. The most straightforward is simply forming the columns with the interior columns and the beams with the rest of the flatwork, in which case the 'frame', *per se*, does not exist as an entity in the construction operations. A second method uses a gang form that incorporates both the beams and columns similar to jump formed walls. In the third approach the gang forms are constructed of steel and equipped with a system of jacks that allows the form to 'climb' the building as construction proceeds. Climbing forms are similar to slip forms in that they are self propelled, but the reinforcement placement and concreting are discrete operations similar to jump forming. Changes in frame dimensions must be limited to those that can be accommodated by the climbing form since the substantial initial investment for the form must be amortized over the entire frame. Since the form itself is usually a custom built 'one of a kind' piece of equipment, some allowance for variation in structural dimensions can usually be incorporated in the form design. However, for conceptual design of climbing form systems, it is best to treat the structure dimensions as fixed over the height of the building and in plan (i.e. constant width and depth for beams and columns). These considerations have a significant impact on the strategy for proportioning members during conceptual structural design.

Flatwork

The flatwork includes all the slabs and beams that form the horizontal elements of the structural load paths. As with the vertical elements, there are various methods and materials that can be used to form the beams and slabs.

The simplest type of horizontal framing is the flat plate which consists solely of a slab of uniform thickness. Forms for flat plate structures are generally constructed of plywood which must be replaced after a certain number of uses. Steel forms may be used for flat plates but are not that common. Flat plates work best for short spans of up to 25 feet beyond which the slab thickness for requirements for punching shear and deflection result in very heavy structures. Flat plates tend to be very economical due to the simple forming, even when the material quantities are greater, a condition which is accentuated in high labor cost markets. There are very few constructibility constraints involved in the formwork of a flat plate. A modification of the flat plate that is used for intermediate spans is the flat slab with drops in which a section of slab extending out from the column a distance of about 1/6 of the span is thickened, forming the 'drop'. With drop panels, the efficient span range can be pushed to 35 ft. and the material costs can be reduced for shorter spans, but the economies must be balanced against the added labor costs for forming the drops.

As the spans get beyond the economical slab range, beams are introduced between columns to support the slabs. The beam elements disrupt the uniform flat formwork and require special carpentry to build. If the distance between columns is approximately the same in both directions, then beams must be formed in both directions in order to reduce the slab depth.

The concept of 'voided' slabs was developed to combine the advantages of the beam and slab system with those of the flat plate systems. In the voided slab, a flat form is built as with the flat plate, and then voids are formed by attaching steel elements called 'pans' or 'domes' to the top of the flat form. If the voids are elongated in plan, then the resulting structure, which is called a 'pan joist' system, is similar to a beam and slab system in which the span of the slab is equal to the width of the pan. If the voids are square in plan, then the resulting structure, which is called a 'domed' or 'waffle' slab, is similar to a flat plate with most of the concrete removed.

When pan joist systems first came into use in the 1920's and 1930's, the pans were made of corrugated steel and were left in place. Modern pan joists and waffle slabs use smooth steel pans and domes which are beveled for easy removal. Pans and domes are standardized and mass produced by manufacturers who either sell or rent them to forming contractors. Structural systems that utilize these elements must conform to the available sizes, in which case the constructibility constraint can be reformulated to a geometric constraint on the structure. In the case of pan joists the pan depths are typically limited to 10, 12, 14, 16, and 20 inches and widths are 15, 20, and 30 inches. The distance between the sides of the pans is equal to the secondary beam, or joist, width (usually 6" or 7") while the distance between the ends of the pans is equal to the primary beam width. Systems such as this usually have the greatest economy when the entire soffit is at a constant depth. The thickness of the concrete over the top of the pans is controlled by fire rating requirements. The available pan widths constrain the spacing of the secondary beams while the combination of required slab depth and available pan depths constrain the minimum beam depths, but not the maximum depth, since the soffit can be lowered at discrete locations.

The pan joist concept was extended to the 'skip joist' concept recognizing that the minimum slab thickness, which is controlled by fire rating requirements, is capable of spanning much further than the 15 to 30 inches required for standard pan dimensions. The first skip joists were actually formed by bridging between two pans and eliminating the intervening joist (hence the name skip joist). Pan manufacturers now produce 'super pans' which accomplish the same thing. In skip joist systems, the spacing of the joists, which is controlled by the standard pan dimensions, is typically 5 or 6 feet.

When the length of the primary beams exceeds the maximum length that can be accommodated with the standard joist or secondary beam depth, the primary beam must be made deeper. One approach is to deepen the entire beam, in which case the resulting system is similar to a conventional beam and slab system. A second approach, using haunched girders, minimizes the typical structural depth and the disruption to the forming operations by taking advantage of the fact that the highest moments and shears in a continuous concrete beam occur at the columns. In a haunched girder system, the centers of the girders and the bays between the girders are formed at a constant depth which is controlled by the span of the secondary beams. At the ends of the girder, the soffit is sloped down to create a deeper section. Unless the haunch is formed using a prefabricated form element similar to a pan, it involves custom carpentry with its attendant cost and schedule implications.

There are different methods utilizing a given type of material in forming large repetitive areas, as in the typical floors of high rise buildings. The basic method of forming that has been used for many years is the 'stick built' method in which plywood forms are constructed on steel or wood shores for each floor. A more sophisticated method uses a system of modular forms which rest on a combination of steel shoring 'tables' and aluminum form beams. In this system the modular panels and tables can be quickly disassembled and reassembled on the next floor, minimizing the labor and time required. A third method incorporates the forms and tables into a single channel shaped element, called a 'flying form', consisting of horizontal decking and form beams spanning to and built integrally with trusses which have adjustable legs. Individual flying forms are set side by side to form an entire floor. Gaps between forms to accommodate structural columns are formed with individual pieces of plywood after the forms are set and are ideal locations for beam elements. Once the concrete attains sufficient strength, the entire form is lowered using the adjustable legs, pulled out the side of the building, and raised ('flown') to the next floor with a crane. The depth of the structural elements on the perimeter of the building may be limited by the requirement for clearance during the flying operation. As with the gang forms and climbing forms, flying forms require an initial investment and work best when the dimensions of the structural elements are uniform throughout the height of the building. Each of the types of forming systems described previously can be constructed with any of the construction sequences described provided the column grid and structural element geometry is suitable.

A.5.1.2 Concrete and Reinforcing Materials

The availability and cost of concrete materials vary from one area of the country to another. Lightweight concrete has been used effectively for floors in concrete high rise buildings[4] and results in some economies due to the decrease in dead load. However, the cost of the aggregates and the ability of local suppliers to produce consistent strengths tend to vary significantly between locations. Available concrete strengths vary from 3000 psi to 20000 psi depending on the expertise and quality control of local suppliers and, in the case of strengths greater than 9000 psi, the availability of suitable aggregates. Within most markets, strengths up to 6000 psi can be obtained predictably with nominal increases in cost. It is usually cost effective to use the highest strength economically available for the building columns since, unlike beams and slabs, there is a direct relation between the strength of the concrete and the required area of the column resulting in an inverse linear relation between strength and concrete volume.

Reinforcing availability is not as variable as the concrete and formwork. Generally, both 40 ksi and 60 ksi steel are available, with 60 ksi now being the more common. Weldable grades (ASTM A706) of reinforcing are generally harder to get. Post tensioning material is

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[4] It has also been used for columns and frames in some buildings, notably on One Shell Plaza in Houston, but that is less common.

also generally available, although the technology for installing it is not. Any of the forming systems described above can be used with post tensioning.

A.5.1.3 Concrete Systems Details

Once a system is chosen, constructibility constraints can be used to select values for the detailed attributes of that system. In the case of concrete systems these normally involve the dimensions of the elements, the relationships between concrete surfaces which translate to relationships between form surfaces, and the arrangement of reinforcing. During the conceptual design phase only typical details at the typical floor are addressed.

Repetition is the key to economy in building construction. Once the construction crew has completed the 'learning curve', i.e., mastered the detailed tasks for a specific layout, the time required to replicate those tasks in subsequent cycles is reduced dramatically. The concept of a typical floor promotes repetition vertically in the building. Within the typical floor the concepts of typical beams, typical slabs, and typical girders also foster repetition. The desirability of repetition creates a preference for symmetry and antisymmetry as strategic goals in the synthesis of load paths.

All steps (i.e., vertical discontinuities) in the soffit of the structure must be formed and, therefore, the penalty associated with forming the step must be balanced against any savings in material resulting from the step. This requirement, along with the requirement for repetition, results in a characteristic depth for the structure, controlled by the spans of the typical elements. In this approach, the depth of all secondary beams on the floor is controlled by the longest span of any of those beams. A similar condition applies to the girders and, to a lesser extent, the slabs. This constraint simplifies coordination of trades both during design and during construction. Instead of checking interference on an element by element basis, this concept allows interference checking for the majority of cases simply by checking the envelope. Members whose depth exceeds the typical depth are then checked individually.

When structural elements are formed using a combination of dimensioned lumber and plywood, some economy can be gained by using dimensions that can readily be obtained from the standard material (similar to the planning module concept in the floor plans). Slab drops panel depths that correspond to standard dressed lumber dimensions of 3.5", 4.25", etc. can be formed without a ripping operation. Soffit dimensions, such as beam widths, that are uniform multiples or divisions of the standard 4'x8' sheet of plywood minimize waste. The most common column sizes are even whole inches. Special attention should be paid to the typical beam/column intersections, both interior and exterior, during conceptual design. Intricate connections with many intersecting surfaces are difficult to form and the forms, once constructed, are difficult to strip and reuse. If such conditions are a requirement of a particular scheme, then the additional costs should be accounted for during conceptual design.

Examples of typical reinforcing details that should be addressed during conceptual design include typical dowelling methods between abutting concrete elements, typical beam column intersections, and typical column splices. Dowelling is especially important when there is a possibility of slip forming or jump forming a core or when climbing perimeter forms are used. The method of dowelling must be reliable while accommodating the required cycle schedule. (A cycle consists of all the activities required to complete the structure on one floor.) Column splice details are particularly important when columns are heavily reinforced or when they involve large bars that need to be spliced for tension as in a moment frame. Lap splices can lead to congestion, especially in columns with more than 3% reinforcing, and difficulty in placing not only the steel but also the concrete. Tension lap splices can increase the amount of steel required by 30% to 40% as well as increase congestion. Mechanical couplers can be used to alleviate these problems, but may result in increased costs which must be balanced against quality considerations. Finally, the intersection of columns and beams, particularly at the perimeter where the beam bars are hooked, should be studied during conceptual design with an eye toward congestion.

A.5.2 Steel Systems

Individual steel elements are purchased, fabricated, and erected by specialty subcontractors, called fabricators and erectors. The individual steel pieces are supplied by one of a limited number of rolling mills to a fabricator who trims the pieces to the precise length and prepares the member for connections. After fabrication is completed the steel is shipped to the site and an erector puts it in place. Since fabrication requires a substantial investment in permanent equipment, there are a limited number of fabricators and it is not uncommon for the steel to be fabricated hundreds of miles from the construction site. Within a particular region, a relatively small group of fabricators compete for all the steel work and, as a result, the prices and technology tend to be more uniform in that region than with concrete construction. However, steel prices may vary considerably between regions, since

60% or more of the cost of the erected steel depends on labor rather than materials. Steel systems are usually classified according to the type of slab used, the strength of the steel, whether the steel acts compositely with the concrete, and the type of fabricated elements that are used as beams.

A.5.2.1 Slabs

Although conventionally formed slabs can be used with steel beams, slabs on steel deck are more common. Conventional formwork is constructed by carpenters whereas the steel deck is usually installed by the same ironworkers that are installing the steel, resulting in labor efficiencies. Steel deck is fabricated by rolling a sheet of steel into a corrugated form. Different manufacturers use different patterns of corrugation widths and, in the case of composite deck, different deformations in the ribs. The common method of classifying deck is according to the depth of the ribs, the gauge of the steel, and the finish on the steel. Common gauges range from 12 to 26 and both painted and galvanized finishes are available. The deck can be shored or unshored, composite or noncomposite.

The deck can act as just a form (noncomposite) in which case the concrete slab has conventional reinforcing. This type of deck is commonly used when the beam spacing is in the 3 ft. to 6 ft. range as with open webbed steel joists (OWSJ). Decks used for this purpose usually have depths of 9/16", 1", or 1-1/2".

Composite deck has deformations rolled into the ribs that grip the concrete and enforce compatibility between the two materials. The deck functions as both the tension reinforcing and the form. Composite decks tend to be used for the longer spans of 7 ft. to 12 ft. that are used with rolled steel beams and, as a result, are generally deeper. Commonly used depths of composite decks are 1-1/2", 2", and 3".

The concrete slab on top of the deck can be either lightweight (115 - 120 pcf) or normalweight (145 - 150 pcf). If a two hour rating with no fireproofing on the deck is required, then the required thicknesses of concrete are 4-1/2" and 3-1/4" for normalweight and lightweight, respectively. The deck must carry the weight of the wet concrete, and quite often the required gauge of composite deck is controlled by the unshored construction condition rather than the final service load condition. Since the deck geometry varies between individual manufacturers, the required deck gauge for a given situation may vary. To minimize the complexity of the field operations, the depth and gauge of the deck are generally kept constant at a given floor. If there are relatively few longer span conditions, these can be shored to minimize the depth and/or gauge of the deck throughout.

A.5.2.2 Steel Material and Shapes

Steel material properties in the U.S. conform to standard specifications produced by the American Society for Testing and Materials, ASTM. The commonly used material designations for structural steel rolled shapes are A36, which has a yield strength of 36 ksi, and A572 Grade 50, which has a yield strength of 50 ksi. Round steel pipes are usually A53 with a yield stress of 35 ksi while rectangular tubing is commonly supplied under A500 Grade B, with a yield stress of 46 ksi. Plates up to 8 inches in thickness in A36 have a yield stress of 36 ksi, while those over 8 inches have a yield stress of only 32 ksi. Plates in this thickness range are most commonly used as base plates. A572 grade 50 plates are available in thicknesses up to 4 inches (the limit was 2 inches prior to 1989) while Grade 42 plates can be as thick as 6 inches. High strength plates are generally used in plate girders or as cover plates in built up sections.

Standardized steel rolled shapes conforming to dimensions contained in ASTM A6 are available from most rolling mills in the common ASTM material designations. In the U.S. the shapes commonly used in high rise building construction are the wide flanges, standard channels, and angles.

A.5.2.3 Composite Construction

In composite construction, the steel floor beams and concrete slab work together in resisting the applied loads. In order to enforce compatibility, shear must be transferred across the interface between the two materials. The most common way of providing for this is through the use of welded shear connectors or ‘studs’. Shear studs are round steel bars with diameters of 1/2" to 7/8" and having flattened heads. They are generally field welded to the steel beams through the deck using resistance welding guns. Other types of shear connections are possible, but require manual welding and are not as cost effective. When the studs are welded through the deck, they replace the puddle welds that would normally be required to anchor the deck.

A.5.2.4 Floor Beams

A ‘simple’ floor system consists of standard rolled shapes for beams and girders, designed as either composite or noncomposite. Noncomposite is becoming less common due to the wide availability of stud welding guns and the significant reductions in material quantities that are gained through the use of composite action. In 'simple' construction the connections are designed for shear transfer only and there is no moment continuity between beams resulting in lower fabrication and erection costs.

In continuous systems moment connections are added to the beams, resulting in end moments that lower the midspan bending moments. Continuous systems involve higher fabrication and erection costs due to the complexity of the moment connections. There have been attempts made to develop efficient methods of making moment connections, one of which used a patented piece of hardware called an 'M Seat,' but these have not gained widespread acceptance. In theory, the advantage of continuous systems is that the stiffness of the system is increased while the material quantities are decreased. However, since the concrete can be used compositely for resisting the mid span moment while the steel section alone (or steel plus reinforcing in the LRFD approach) must resist the negative moment, the reduction in materials for the normal span ranges seldom offsets the increased connection costs.

In some cases shoring the floor beams during concreting operations can reduce the size of composite beams. When the beams are not shored, it is common to camber them to minimize the amount of concrete overrun that would otherwise be required to level the floors. If the beams are neither shored nor cambered, then the additional concrete weight must be included in the design, possibly increasing the beam and columns sizes. In the latter case the additional steel and concrete costs should be included in the evaluation.

The 'punched girder' system is a variation of the simple system in which deep girders are fabricated with openings for the mechanical ductwork. In punched girder systems, the mechanical clearance is set based on the typical floor beam rather than the girder, allowing a reduction in the floor to floor height. The weight of the girder is about the same as in the simple system, but the additional cost of fabrication involved in cutting and reinforcing the penetrations and the additional labor for installing the mechanical systems must be included in the evaluation.

Stub girders combine the advantages of punched girders and continuous beams by using a continuous bottom chord consisting of a shallow wide flange (W10 or W12) connected to the slab for composite action via intermittent stubs that are the same depth as the floor beams. Between the stubs, the floor beams can be continuous over the top of the bottom chord and ductwork can pass through the girder. Stub girders are usually somewhat heavier than an equivalent simple girder and require more fabrication. Unless they are provided with a top chord of structural steel, which increases the weight, stub girders must be shored both during erection as well as when the concrete deck is placed. In the latter case, the increase in erection costs must be considered as well as the increase in fabrication costs.

Haunched girder systems use continuity with the columns to reduce the depth of the girder at center span, allowing a reduction in the floor to floor height similar to the punched girder system, but eliminating the mechanical installation penalties. The haunch is fabricated from a split wide flange beam and is proportioned such that its noncomposite moment of inertia is similar to the composite moment of inertia at center span. The objective is to make the girder depth at midspan the same as the beam depth (or 2" deeper to eliminate the cope on the bottom flange of the beam) allowing the mechanical clearance to be set from the beams and for all mechanical systems to be installed from the bottom without the need to feed through the structural elements. Haunched girders are generally somewhat lighter than the equivalent simple girders but require more fabrication. Continuity at the columns results in heavier columns due to the moments induced and higher erection costs due to the necessity of making a moment connection between the girder and column.

In addition to the above systems, which are generally designed by the structural engineer and supplied by a structural steel fabricator, there are various pre-engineered systems that can be used for beams. Open web steel joists (OWSJ) are the most commonly used of these. OWSJ are trusses which utilize angles or cold-formed sheet metal for the chords and angles or round bars for the diagonals. Joist systems are usually noncomposite (although there are proprietary joist systems which are designed to be composite) and are generally deeper than the equivalent composite beam system. OWSJ are fabricated and supplied by specialty subcontractors who optimize the joist weight for each installation and take advantage of the economies of mass production. Joist systems are very susceptible to construction failures due to improper sequencing, and the erection sequence must be considered during conceptual design. It is common to use structural steel along the column grids in order to facilitate the erection and alignment of the frame prior to the installation of the joists. Since the joists are supplied under a performance specification, it is essential that all points of interface between the joists and other trades be completely identified. Since SJI specifications [18] do not require any provisions for transverse loading on the compression chords between panel points where the panel point spacing is less than 2', all concentrated loads must be identified explicitly in the design documents or provided for by the addition of members to the joists in the field. Where flexibility is important in the facility management phase, these factors should be considered when evaluating joist systems.

A.5.2.5 Steel Systems Details

The steel details that are addressed during conceptual design can be classified as those related to fabrication, those related to erection sequence, and those related to typical edge of slab conditions. When the floor slab cantilevers a short distance (1' to 2') beyond the edge of the spandrel beams suitable details which accommodate both the construction loads and the loads resulting from the attachment of the cladding must be developed. The edge details can result in significant costs and should be included in the conceptual comparison of steel and concrete systems.

The majority of the fabrication details have to do with the types of connections that are used. Each fabricator generally has a preferred method of making standard shear and moment connections from beam to beam and beam to column. Two approaches are used in practice. In the first approach the required type and magnitude of force to be transferred are provided and the fabricator selects connections that can carry the force and that minimize the cost. This approach is the most efficient approach to using the fabricator's available expertise and equipment and does not require anticipation during the conceptual design phase. If connections are to be detailed on the documents, then the conceptual design should address the typical girder/column, beam/column, beam/girder, and column splice connections, preferably using details that are familiar to the likely fabricators. Lamellar tearing potential should be considered where welds produce through-thickness strains in heavy steel elements such as in beam/column moment connections. It may be appropriate to specify special steel and/or special welding procedures for these connections, resulting in cost penalties that should be included in the conceptual design comparisons.

The erector and fabricator usually cooperate closely in working out the precise sequence of erection and the most suitable details given that sequence. The steel erection on high rise buildings is heavily dependent on the crane locations and capacities and the amount of time the cranes will be available to the erector, since the cranes are used by most other trades as well. In high rise buildings the steel is erected in tiers that are commonly two or three stories tall. The columns for a tier are erected first, then the girders and beams are attached. Splicing the columns at every floor may result in the minimum amount of column material but results in more connection costs and dictates a single floor tier resulting in more difficult alignment problems and more crane time. Splicing columns at intervals exceeding three floors results in long columns that are difficult to erect and stabilize and may also result in excessively heavy pieces.

B

Conceptual Design Example

The building used for this example is a 59 story structure proposed for Philadelphia. The example is based on an actual project for which cost data is available. Figures B.1 through B.9 represent an abridged version of the conceptual design. Since these designs were prepared during program development the intent was to establish the range of project costs for feasibility analyses. In an actual conceptual design phase more solutions, including solutions utilizing concrete, would be investigated.

B.1 Gravity System

The basic decisions that must be made in the process of synthesizing the gravity systems involve the magnitude of the design loads and the framing pattern for the typical floor. The framing, in turn, involves decisions about the ocations of the columns, the primary beams (girders), and the secondary beams. A fundamental decision that must be made involves the construction of the lowest horizontal element in the load path hierarchy - the slab.

Figures B.1, B.2, and B.3 illustrate three possible worlds for the gravity framing based on only the girder locations and slab type. The framing plans are diagrammatic representations of both the load path(s) and the physical structure. The solid lines on the plans indicate beams which collect load from the slab and deliver it to the girders which, in turn, deliver it to the columns. The lines representing beams, or segments of the load path, form a distinctive pattern.[1] Often, the pattern is similar for similar types of structures. Experts recognize and manipulate the patterns during conceptual design.

Figure B.1 illustrates Scheme 1 in which a 3-1/4 inch lightweight concrete slab on 3 inch composite deck is used. These dimensions result in a 2 hour fire rating for the deck which is a normal constraint in high rise office buildings. A primary beam (girder) with a depth of 30 inches spans between columns 15 ft. inside the edge of the building. The beams spanning from the core to this beam are 14 inches deep.

Since lightweight concrete is 50% more expensive than normalweight concrete in Philadelphia, Scheme IA with the same beam and girder spacing as scheme 1 (i.e., the same load path) but using 4-1/2 inches of normalweight concrete, shown in Figure B.2, is an alternate. The additional thickness of normalweight concrete is required to maintain the 2 hour fire rating of the slab.

Scheme 2, shown in Figure B.3, uses a different arrangement of beams (i.e., a different load path) with lightweight concrete. In Scheme 2, the 18 inch deep beams spanning from the core to the perimeter are both heavier and deeper than the beams in Scheme 1. However, the scheme uses less steel than Scheme I due to the elimination of the girder 15 feet inside the building.

In this example the pattern of four columns at intervals along the perimeter was an aesthetic feature of the architecture and thus was taken as a hard constraint. In the more general case, the column locations are a variable constraint to be determined during the conceptual design process. The design loads used for this structure are 50 psf live load and 25 psf superimposed dead load (20 partition and 5 ceiling) based on code requirements for office use.

In addition to the obvious constraints resulting from the architectural form and function some of the less obvious interaction constraints are considered at this point in the conceptual design process. The additional constraints for scheme 1 are shown in Figure B.4. Because the span of the spandrel beam is 60 ft., it is not possible for the cladding system to be self supporting between hard points. In order to minimize the problems due to structure deflections during erection of the cladding the spandrel beam of scheme 1 is somewhat heavier than would be required for either strength or code serviceability constraints. The typical floor beams are lightened considerably by using a deep girder 15 ft. inside the

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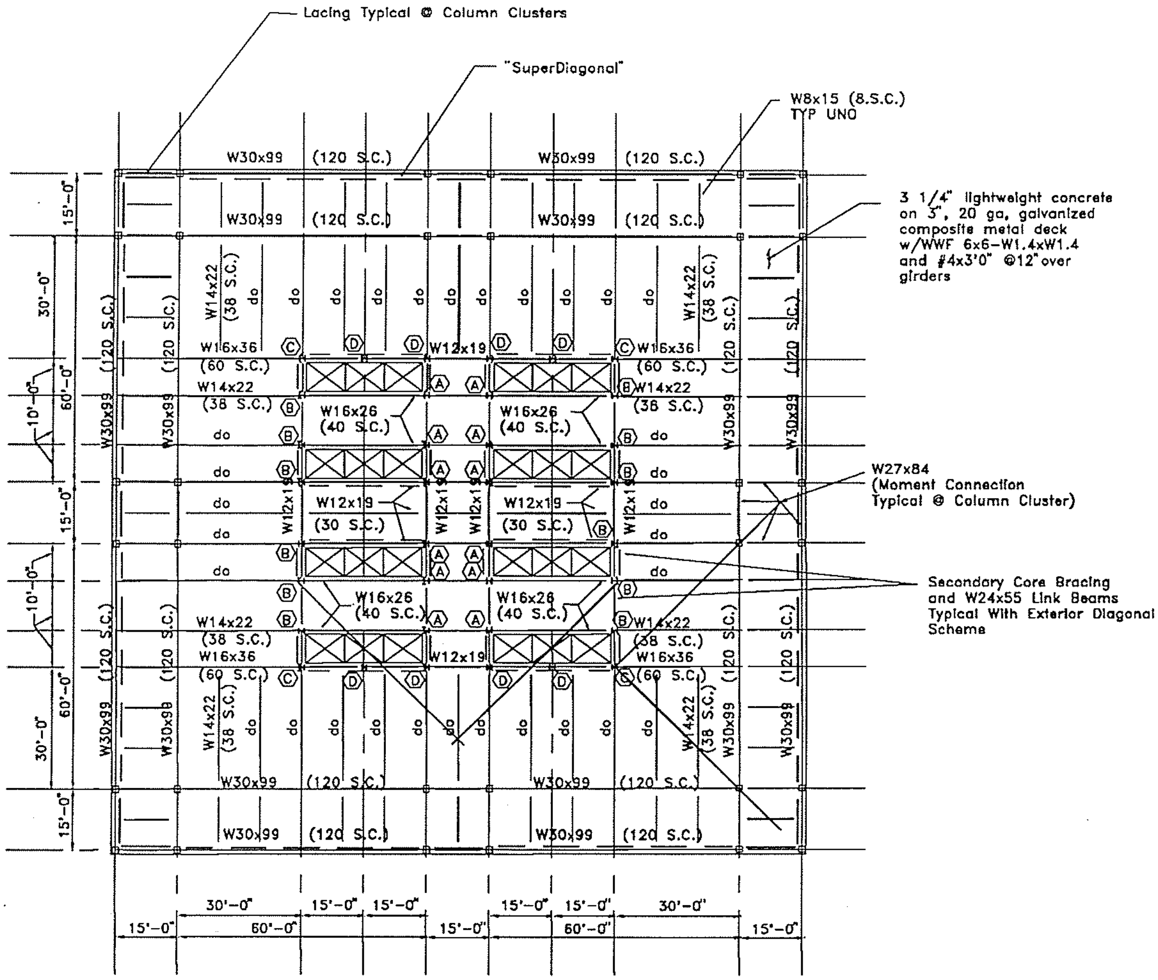
[1] Drawings are a powerful tool precisely because they have such rich semantics. They convey information about both physical concepts (wide flange beams) and abstract concepts (load paths)

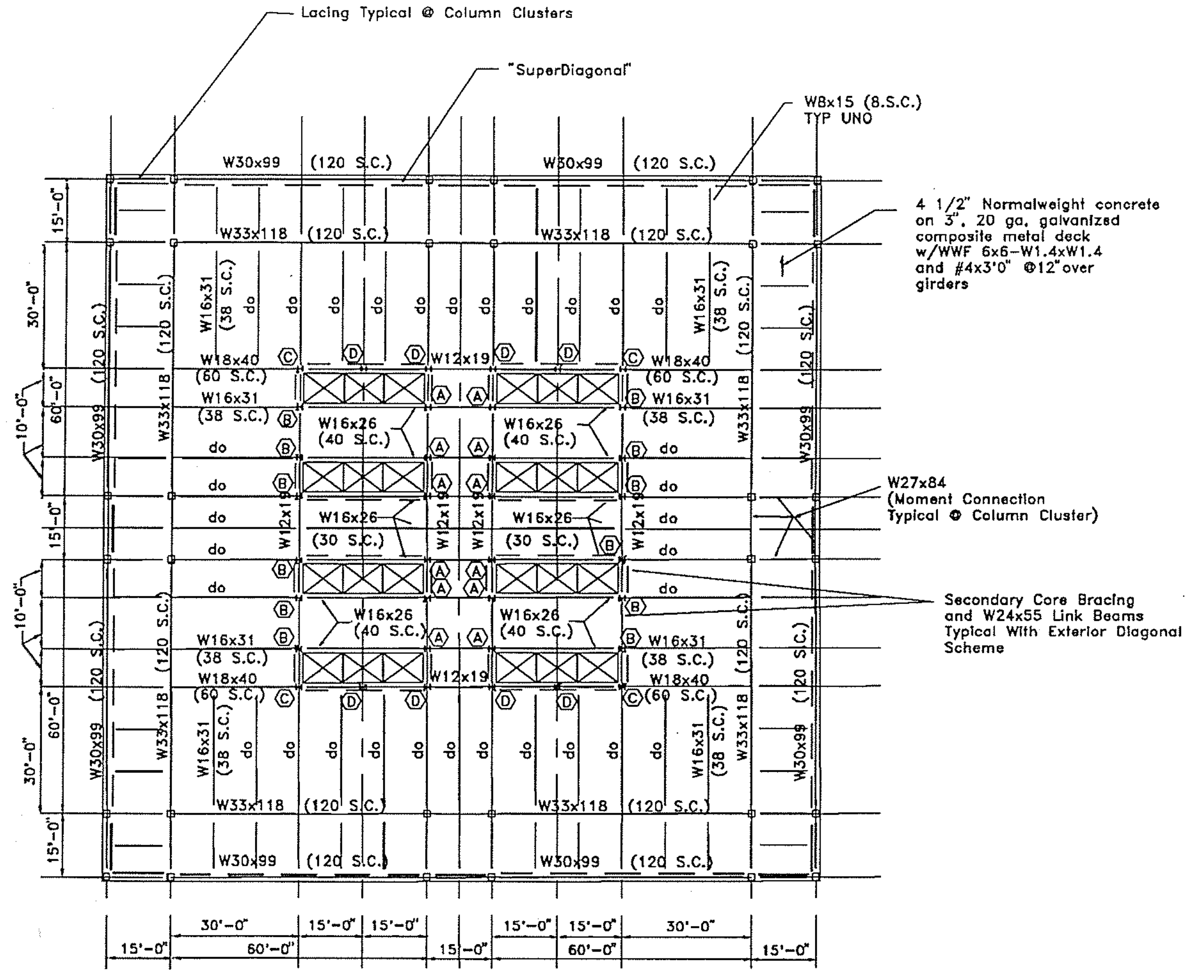


Ⓓ INDICATES CORE COLUMN TYPE

ALL STEEL IS A572 GRADE 50

GRAVITY SYSTEM COST SUMMARY			
ITEM	QUANTITY	UNIT COST	TOTAL COST
Steel In Floor Framing	6.44 PSF	$1200/TON	$3.86/SF
Steel In Interior Columns	3.22 PSF	$1200/TON	$1.93/SF
Steel In Spandrel	1.74 PSF	$1200/TON	$1.04/SF
Steel In Exterior Columns	5.58 PSF	$1200/TON	$3.35/SF
Floor Cloncrete	0.0147 CY	$95.00/CY	$1.39/SF
Shear Connectors	0.21 Ea/SF	$1.50/Ea.	$0.31/SF
Composite Metal Deck	1.00 SF/SF	$1.40/SF	$1.40/SF
	GRAVITY TOTAL COST		$13.29/SF

Figure B.1 Typical Floor Gravity Scheme 1 Composite (LRFD) Beams and Lightweight Concrete

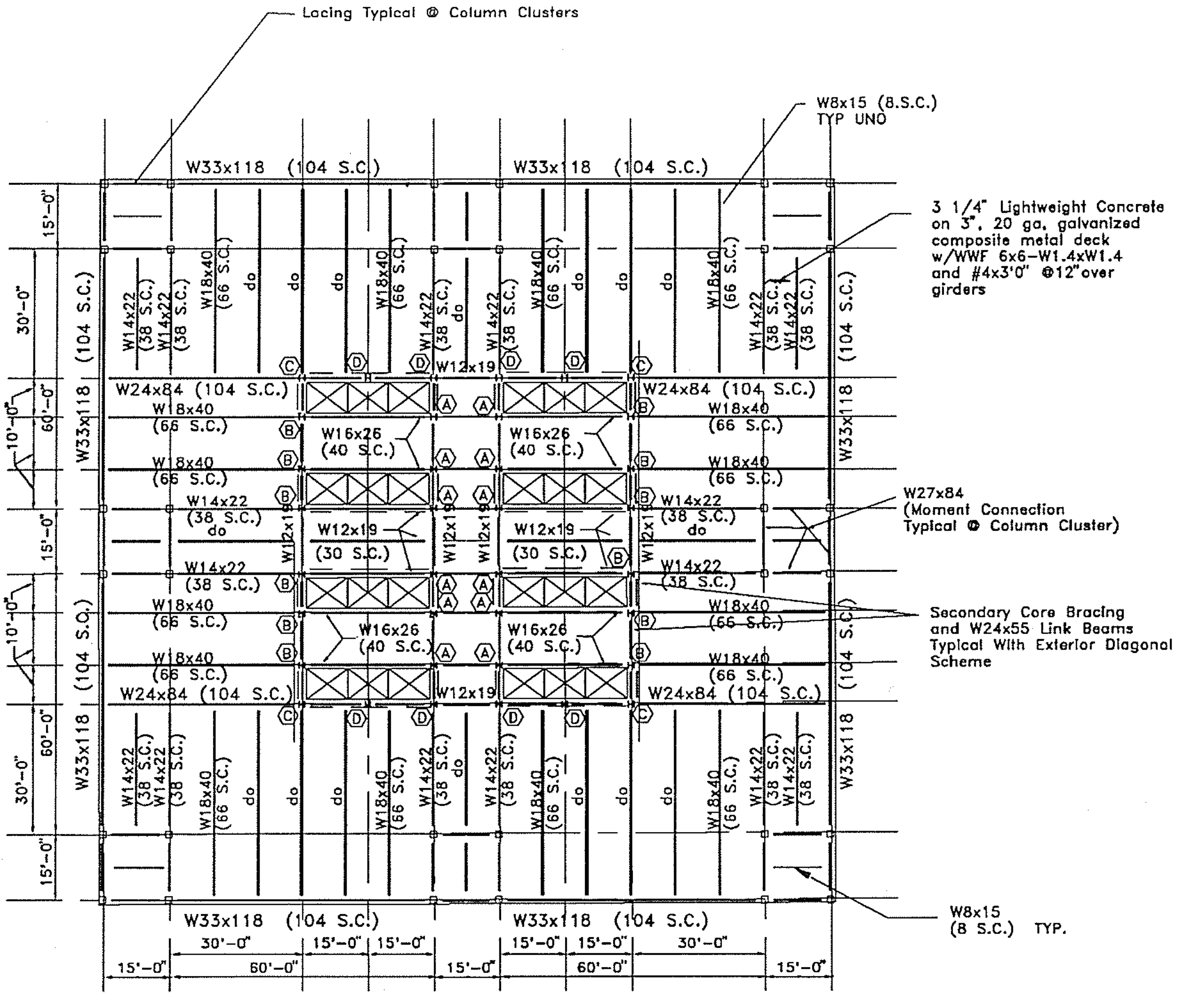


Ⓓ INDICATES CORE COLUMN TYPE

ALL STEEL IS A572 GRADE 50

GRAVITY SYSTEM COST SUMMARY			
ITEM	QUANTITY	UNIT COST	TOTAL COST
Steel In Floor Framing	9.08 PSF	$1200/TON	$5.45/SF
Steel In Columns	10.07 PSF	$1200/TON	$6.04/SF
Floor Concrete	0.0185 CY	$65.00/CY	$1.20/SF
Shear Connectors	0.23 Ea/SF	$1.50/Ea.	$0.35/SF
Composite Metal Deck	1.00 SF/SF	$1.40/SF	$1.40/SF
	GRAVITY TOTAL COST		$14.44/SF

Figure B.2 Typical Floor Gravity Scheme 1A Composite (LRFD) Beams and Normalweight Concrete



Ⓓ INDICATES CORE COLUMN TYPE

ALL STEEL IS A572 GRADE 50

GRAVITY SYSTEM COST SUMMARY

ITEM	QUANTITY	UNIT COST	TOTAL COST
Steel In Floor Framing	5.77 PSF	$1200/TON	$3.46/SF
Steel In Spandrel	2.07 PSF	$1200/TON	$1.24/SF
Steel In Exterior Columns	5.58 PSF	$1200/TON	$3.35/SF
Steel In Interior Columns	3.45 PSF	$1200/TON	$2.07/SF
Floor Clancrete	0.0147 CY	$95.00/CY	$1.39/SF
Shear Connectors	0.20 Ea/SF	$1.50/Ea.	$0.31/SF
Composite Metal Deck	1.00 SF/SF	$1.40/SF	$1.40/SF
	GRAVITY TOTAL COST		$13.22/SF

Figure B.3 Typical Floor Gravity Scheme 2 Composite (LRFD) Beams and Lightweight Concrete (Alternate Load Path)

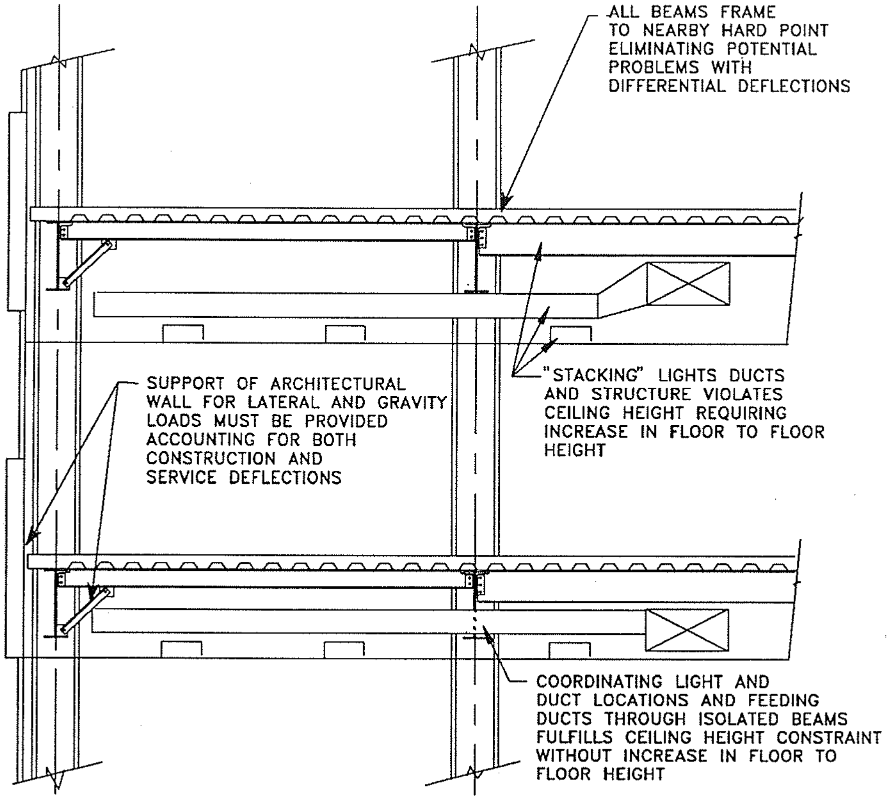
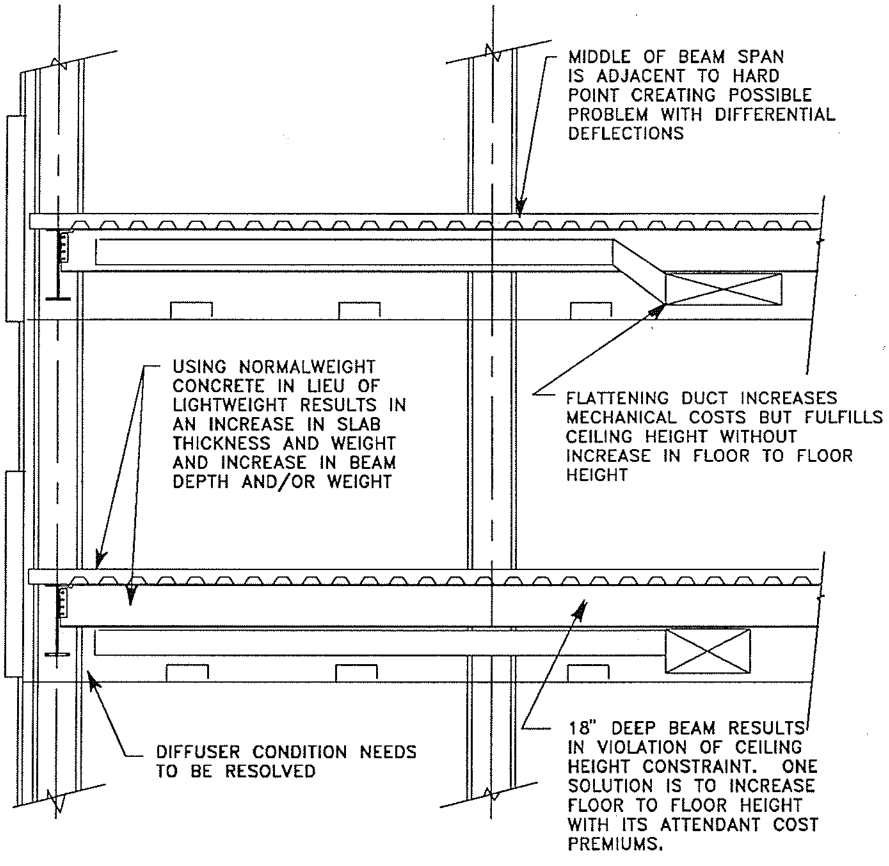


Figure B.4 Gravity System 1 Mutual Constraints

building, but the depth of that girder causes interference problems with ductwork and ceiling. The interference can be eliminated by increasing the floor to floor height, making the beam shallower or, as shown in the bottom of the Figure, the ducts can penetrate the beam. Although the penetration adds fabrication costs to the beam, in this case it is more economical than either of the other two options. These types of interactions can be quickly resolved during conceptual design by examining the costs for the two cases at the typical floor. This study, which uses constructibility constraints in the form of cost data, can be accomplished during the synthesis, since only one typical girder, which is repeated 8 times on the typical floor is involved, and the costs associated with increasing the floor to floor height can be estimated parametrically based on the average column weight per floor and the average cladding cost.

Figure B.5 shows the additional constraints that are considered with scheme 2. In this case the stiffness constraint on the spandrel is automatically satisfied because the spandrel picks up a large floor load and is, therefore, much larger. Penetrating the beams is not an option in this case, since that would cause the beams to be much deeper than required for performance constraints and installing the ductwork through a beam every 10 feet would be a severe constraint on the construction activities. The alternatives in this instance flattening the ductwork, making the beam shallower and heavier, or increasing the floor to floor height. Again the comparison can be made 'on the fly' during system synthesis. A potential problem with differential deflections is highlighted in the Figure.[2]



MIDDLE OF BEAM SPAN IS ADJACENT TO HARD POINT CREATING POSSIBLE PROBLEM WITH DIFFERENTIAL DEFLECTIONS

USING NORMALWEIGHT CONCRETE IN LIEU OF LIGHTWEIGHT RESULTS IN AN INCREASE IN SLAB THICKNESS AND WEIGHT AND INCREASE IN BEAM DEPTH AND/OR WEIGHT

FLATTENING DUCT INCREASES MECHANICAL COSTS BUT FULFILLS CEILING HEIGHT WITHOUT INCREASE IN FLOOR TO FLOOR HEIGHT

DIFFUSER CONDITION NEEDS TO BE RESOLVED

18" DEEP BEAM RESULTS IN VIOLATION OF CEILING HEIGHT CONSTRAINT. ONE SOLUTION IS TO INCREASE FLOOR TO FLOOR HEIGHT WITH ITS ATTENDANT COST PREMIUMS.

Figure B.5 Gravity System 2 Mutual Constraints

The tables included with the floor plans give the cost summaries for each of the schemes. It is interesting to note that the normalweight concrete scheme is significantly more costly than the other two schemes. This is due to the impact of the additional weight that must be carried by the beams and columns. (Unit weights of lightweight and normalweight concrete used in this comparison are 120 pcf and 150 pcf respectively.) A heuristic decision to use

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[2] Recognizing this type of problem involves reasoning about the spatial relationships and behaviors simultaneously and is usually not addressed in code provisions.

normalweight concrete based only on the relative costs of lightweight and normalweight concrete would not be justified. By basing the decision on 'first principles' a better solution can be achieved.

In addition to the intrinsic costs of Scheme 1A being higher, we can reason qualitatively that since the beams are deeper, this scheme will either require a severe constraint on the mechanical system depth or an increase in the floor to floor height. The former would increase the cost of the mechanical system while the latter would increase the cost of architectural cladding, the mechanical risers, and the structural columns. In addition to these considerations we know that, qualitatively, the foundation system for the normalweight scheme would be heavier and, therefore, more costly. The net result of all of these considerations would be to eliminate this scheme from further consideration barring extenuating circumstances involving the Value of the scheme.

The remaining two schemes have intrinsic costs, for the gravity system only, of $13.22/sf and $13.29/sf respectively. Costs that are within 5% of each other, like these, must be considered equal for purposes of this comparison, due to the approximate nature of both the design and the costs. Hence, additional investigation with both schemes is in order.

B.2 Lateral System

The building code for the city of Philadelphia is BOCA which references the ANSI Code for wind loading on buildings over 300 feet tall. This building is 59 stories tall with an architectural feature on top which stretches its height to nearly 1000 ft. as shown in Figures B.6 and B.7. Using the methods outlined in the code, the total wind shear on the building is 7,722 kips and the overturning moment is 3,733,692 ft.-kips. The seismic loads which are based on zone 2, result in a design base shear of only 1920 kips (using $K = 1.0$ and $Z = 0.375$) or 25% of the wind, indicating that wind governs. With wind governing, the appropriate performance constraints consist of an interstory drift limit of h/400 and the code limits on the member stresses. For buildings in this height range, the deflection limit usually controls both the system and element selection.[3]

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[3] The deflection under wind loads is not addressed by code specifications and is, therefore, based on heuristic rules. Typically, the limits used in practice range from H/300 to H/1000, unless an aeroelastic wind tunnel study has been performed, in which case acceleration limits are applied based on human comfort criteria.

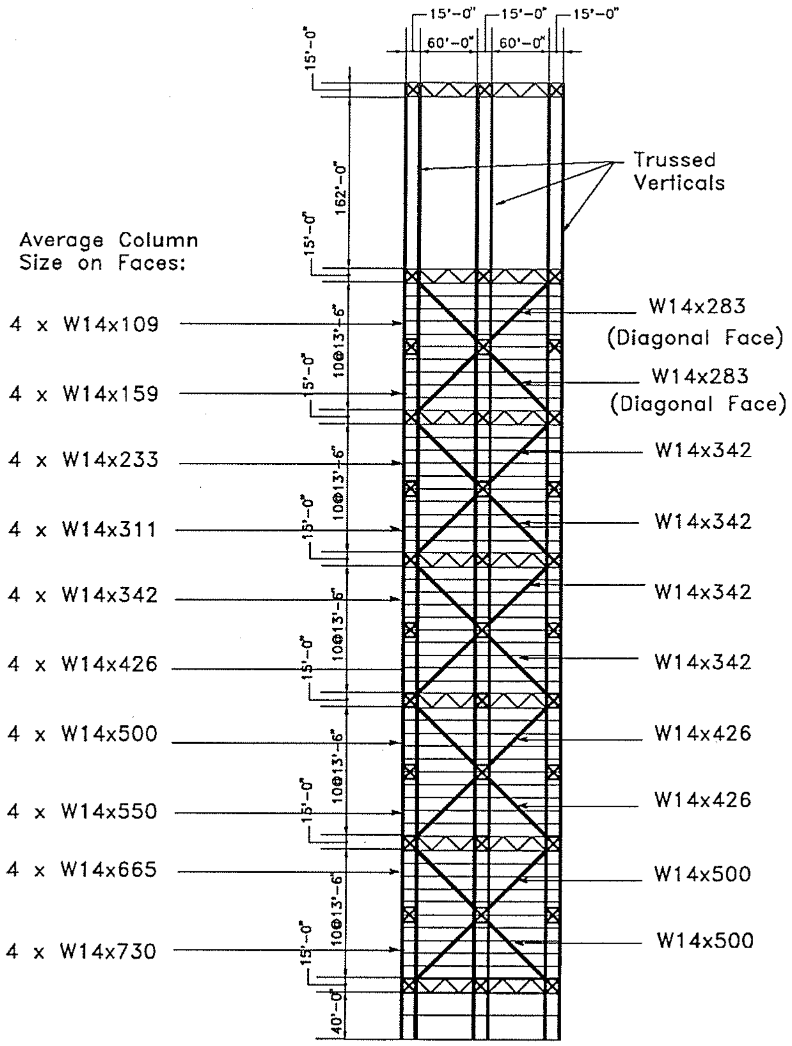


Figure B.6 Lateral Scheme 1 - Exterior Braced Tube

Figure B.6 shows a lateral system which consists of braced frames at the building perimeter while Figure B.7 shows a lateral system which consists of moment frames, also at the building perimeter. (The trussed verticals are too narrow to be effective at this height.) The only difference between these two schemes is that the braced frame carries the horizontal forces axially, by means of the horizontal component of the axial force in the diagonal members, while the moment frame carries the horizontal forces by means of shear and flexure in the vertical elements on the faces. This conceptual difference in the qualitative description of the load path has a substantial impact on the relative economy of the two schemes.

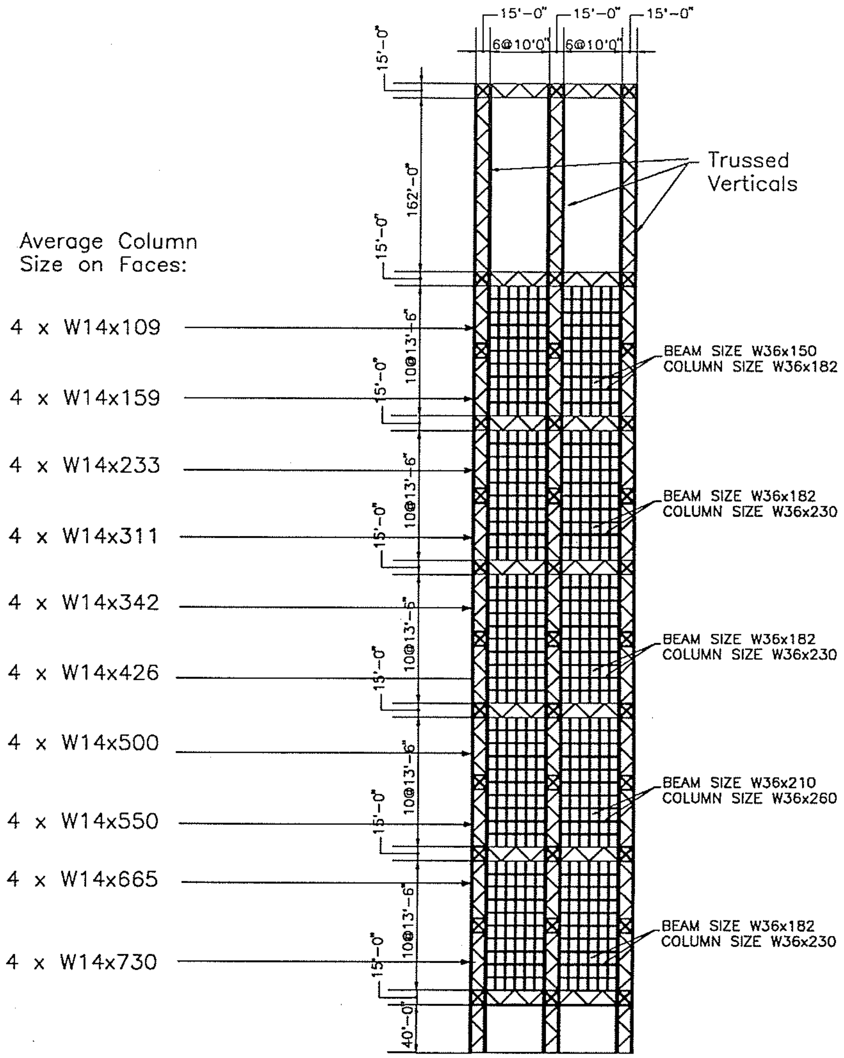


Figure B.7 Lateral Scheme 2 - Exterior Moment Tube

Again, the diagrammatic model of the structure serves the dual function of representing both the load path and the structural elements. In this case, the distinctive pattern of the diagonal braced scheme contrasts sharply with the pattern of vertical and horizontal lines in the moment frame scheme. The pattern is directly related to the manner in which the loads are being carried which, in turn, governs the efficiency of the scheme. Economy, therefore, is related to the qualitative aspects of the load path.

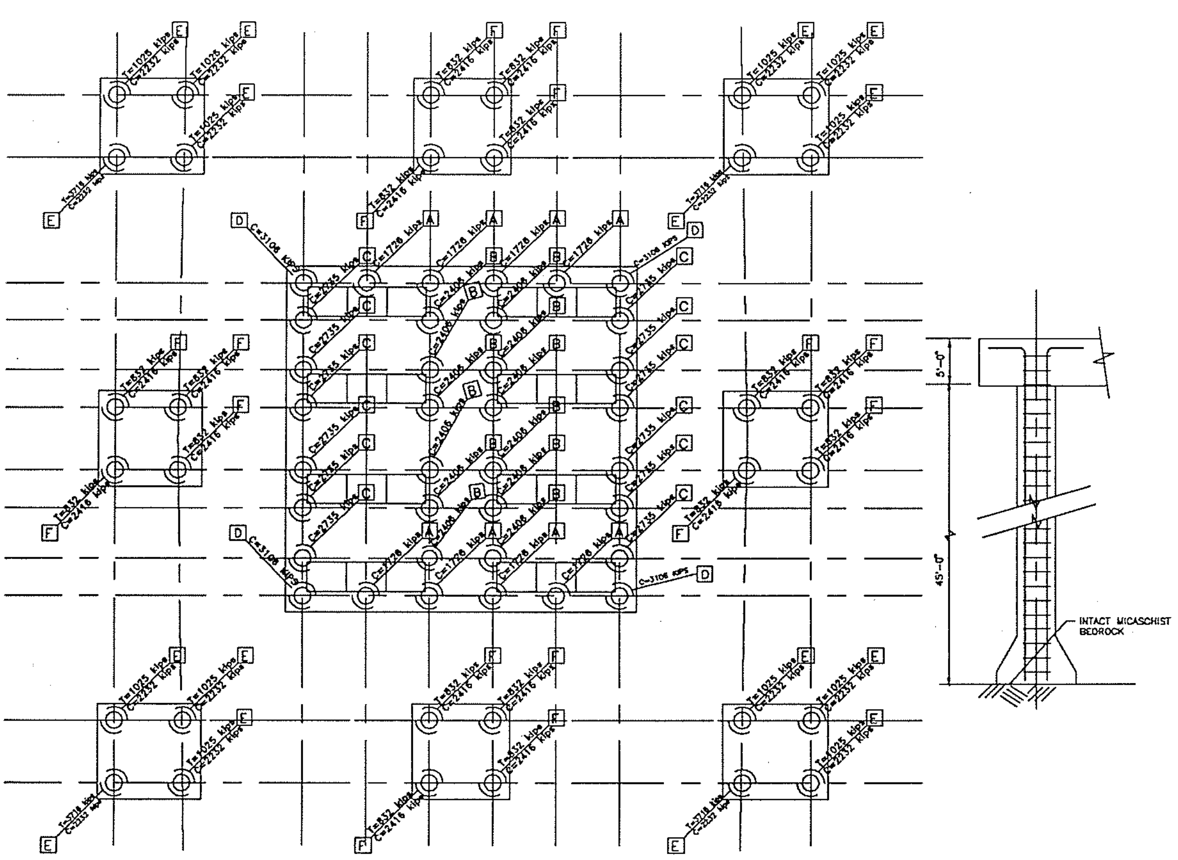
Both of the schemes shown in Figures B.6 and B.7 carry the overturning moment resulting from lateral loads as axial loads in the exterior columns on the building faces perpendicular to the lateral load direction. This mode of behavior is usually referred to as tubular action. This creates a requirement that the loads be uniformly distributed to the columns in the groups of four. To force this mode of behavior, relatively heavy W27x84 beams (shown on plans) are moment connected to the four columns forming a 'minitube.' This is an example of the manner in which constraints are manipulated to produce behavior that will result in the desired load path.

Another choice for carrying the lateral loads would use bracing in the core of the building to resist the shear. In this case, the overturning moment resulting from the shear would be carried as axial loads in the columns at the core boundaries. Since the core has a dimension of 75 ft., its aspect ratio (height/depth, where depth is parallel to direction of the load) exceeds 10, and one would not expect this scheme to be economical. Indeed, when a core scheme was considered it was found to require more than twice the material of either of the other two schemes. A core solution would also have large uplift forces resulting in significant penalties in the foundations. Based on this qualitative analysis, a core solution can be eliminated from further consideration.

Costs for the lateral systems were not split out separately in this example, but are included in the combined systems costs in Figure B.9.

B.3 Foundation System

Since the acceptable gravity schemes use the same column locations and lightweight concrete there is no difference in the total gravity design load at the foundation. The lateral loads are carried in the perimeter frames for both choices for the lateral system and there is a requirement of uniform load distribution to the four columns in the four column groups that was added as a constraint during the lateral design. Qualitatively, these constraints lead to the conclusion that there is no essential difference in the foundation requirements for the possible combinations of gravity and lateral systems. Therefore, no further investigation is needed during conceptual design in order to choose between the available schemes. The foundation costs will be the same for all possible combinations of the lateral and gravity systems that are considered in this limited example.



PIER SCHEDULE						
TYPE	SHAFT DIAMETER	BELL DIAMETER	REINFORCING	ALLOWABLE TENSION	ALLOWABLE COMPRESSION	COST **
A	48 in.	66 in.	7#10	383 kips	1900 kips	$7208.00
B	48 in.	78 in.	7#10	383 kips	2654 kips	$7620.00
C	48 in.	84 in.	12#11	674 kips	3078 kips	$8440.00
D	48 in.	90 in.	16#11	899 kips	3534 kips	$9138.00
E	48 in.	72 in.	20#11	1296 kips	2262 kips	$8771.00
F	48 in.	78 in.	20#11	1296 kips	2654 kips	$9080.00

** Costs are based on combined excavation and concrete placement costs of $500/cy for bells and $300/cy for shafts and reinforcing costs of $700/ton (from Philadelphia construction manager)

FOUNDATION COST SUMMARY *			
ITEM	QUANTITY	UNIT COST	COST
Piers	68 EA.	(schedule)	$564875.00
Cap Concrete	2200 cy	$100/cy	$220,000.00
Cap Reinf.	60 tons	$700/ton	$42,000.00
Cap Forming	8280 sf	$3.50/sf	$28,980.00
		TOTAL	$855,855.00

* Based on a building area of 1,600,000 sq. ft., the cost of the foundations amounts to $0.54 /sf

Figure B.8 Foundation Scheme for all Solutions

Even though there is no essential difference in the loads delivered to the foundation, there may be multiple choices for the foundation based on a geotechnical analysis of the foundation conditions. In this case, a preliminary geotechnical investigation indicated three possible foundation types: drilled piers with belled ends and an allowable bearing capacity of 80 ksf; drilled piers with straight shafts socketed into rock using an end bearing value of 48 ksf and side friction in the socket of 20 ksf; and steel H-piles with an allowable capacity of 300 kips each. A cost analysis prepared by the geotechnical engineer, considering the unit costs of each type of drilling or driving operation and the depth to rock showed that the cost of supporting a typical column load were substantially less with the belled shafts than with either of the other two options. This evaluation occurred concurrently with the structural schematics, since the soils engineer could work with an estimate of a 'typical' load or range of loads.

Athough their is no difference in foundation costs between schemes, the conceptual foundation design and costs are still required for the purpose of cost control. The diagrammatic plan of the foundations using the belled piers is shown in Figure B.8. These foundations are sufficient for both of the remaining schemes.

In the general case, there will be a difference in the design foundation loads due to differences in the system materials as well as vriations in where the overturning moments are delivered to the foundations. If this building were shorter, such that the core aspect ratio was less than 6, a braced core would probably be a viable alternative to the lateral systems shown. In that case there would be a difference in the load paths that would necessitate that the foundations for each scheme be evaluated. Also, in the general case concrete, as well as steel schemes would be considered for both gravity and lateral systems resulting in different gravity loads due to structure selfweight.

B.4 Combined Structural Systems

The combination of the two lateral schemes with the two remaining gravity schemes results in four possible 'worlds.' Figure B.9 gives the tabulated costs for each of the four 'worlds.'

The largest difference in the schemes arises from the lateral system which is the normal occurrence for buildings in this height range. As can be seen from Figure B.7, the difference between worlds in which the diagonally braced or moment frame tubes are used is in the range of \$4.00/sq.ft.. For this project, with an area of 1,600,000 sq. ft., that translates to a cost differential of \$6.4 million. A full conceptual design would investigate more alternatives for both the lateral an gravity systems and would probably yield worlds with a range of costs between those shown.

The basic decision that must be made in this case is which of these 'worlds' represents the lateral system constraint set for the next design phase. Although there is a significant difference in costs, the decision still depends on the Value considerations. It is possible that

COMBINED SYSTEMS COST SUMMARY
GRAVITY SCHEME II
WITH EXTERIOR MOMENT FRAME TUBE

ITEM	QUANTITY	UNIT COST	TOTAL COST
Steel In Floor Framing	6.44 PSF	$1200/TON	$3.86/SF
Steel in Interior Columns	3.31 PSF	$1200/TON	$1.98/SF
Steel in Spandrel	4.28 PSF	$1500/TON	$3.21/SF
Steel in Exterior Columns	6.94 PSF	$1200/TON	$4.16/SF
Steel in Wind Columns	4.60 PSF	$1500/TON	$3.45/SF
Steel in Core Bracing	0.75 PSF	$1200/TON	$0.45/SF
Miscellaneous Connections	1.00 PSF	$1200/TON	$0.60/SF
Steel Subtotals	27.32 PSF	$1300/TON	$17.71/SF
Floor Cioncrete	0.0147 CY	$95.00/CY	$1.39/SF
Shear Connectors	0.21 Ea/SF	$1.50/Ea.	$0.31/SF
Composite Metal Deck	1.00 SF/SF	$1.40/SF	$1.40/SF
Foundations (1)			$0.55/SF
Premiums on Other Sys.			$0.25/SF (2)
COMBINED TOTAL COST			$21.61/SF

NOTES:

1. Foundation cost does not include walls and slabs below grade.
2. There is a penalty due to the extra 4" of structure depth. In this case, the penalty is assessed on the floor-to-floor height, resulting in additional intrinsic costs (note columns compared to Scheme I) and a penalty on the cladding, which is evaluated at $35.00/sf for this example.

COMBINED SYSTEMS COST SUMMARY
GRAVITY SCHEME II
WITH EXTERIOR BRACED TUBE

ITEM	QUANTITY	UNIT COST	TOTAL COST
Steel In Floor Framing	5.76 PSF	$1200/TON	$3.46/SF
Steel in Interior Columns	3.31 PSF	$1200/TON	$1.98/SF
Steel in Spandrel	2.08 PSF	$1200/TON	$1.25/SF
Steel in Exterior Columns	6.94 PSF	$1200/TON	$4.16/SF
Steel in Exterior Diagonal	2.00 PSF	$1200/TON	$1.20/SF
Steel in Core Bracing	0.75 PSF	$1200/TON	$0.45/SF
Miscellaneous Connections	1.00 PSF	$1200/TON	$0.60/SF
Steel Subtotals	21.8 PSF	$1200/TON	$13.10/SF
Floor Cioncrete	0.0147 CY	$95.00/CY	$1.39/SF
Shear Connectors	0.21 Ea/SF	$1.50/Ea.	$0.31/SF
Composite Metal Deck	1.00 SF/SF	$1.40/SF	$1.40/SF
Foundations (1)			$0.55/SF
Premiums on Other Sys.			$0.25/SF (2)
COMBINED TOTAL COST			$17.00/SF

NOTES:

1. Foundation cost does not include walls and slabs below grade.
2. There is a penalty due to the extra 4" of structure depth. In this case, the penalty is assessed on the floor-to-floor height, resulting in additional intrinsic costs (note columns compared to Scheme I) and a penalty on the cladding, which is evaluated at $35.00/sf for this example.

COMBINED SYSTEMS COST SUMMARY
GRAVITY SCHEME I
WITH EXTERIOR MOMENT FRAME TUBE

ITEM	QUANTITY	UNIT COST	TOTAL COST
Steel In Floor Framing	6.44 PSF	$1200/TON	$3.86/SF
Steel in Interior Columns	3.22 PSF	$1200/TON	$1.93/SF
Steel in Spandrel	4.28 PSF	$1500/TON	$3.21/SF
Steel in Exterior Columns	6.76 PSF	$1200/TON	$4.06/SF
Steel in Wind Columns	4.49 PSF	$1500/TON	$3.36/SF
Steel in Core Bracing	0.75 PSF	$1200/TON	$0.45/SF
Miscellaneous Connections	1.00 PSF	$1200/TON	$0.60/SF
Steel Subtotals	26.94 PSF	$1300/TON	$17.47/SF
Floor Cioncrete	0.0147 CY	$95.00/CY	$1.39/SF
Shear Connectors	0.21 Ea/SF	$1.50/Ea.	$0.31/SF
Composite Metal Deck	1.00 SF/SF	$1.40/SF	$1.40/SF
Foundations (1)			$0.55/SF
Premiums on Other Sys.			$0.10/SF (2)
COMBINED TOTAL COST			$21.22/SF

NOTES:

1. Foundation cost does not include walls and slabs below grade.
2. Penalty for mechanical penetrations.

COMBINED SYSTEMS COST SUMMARY
GRAVITY SCHEME I
WITH EXTERIOR BRACED TUBE

ITEM	QUANTITY	UNIT COST	TOTAL COST
Steel In Floor Framing	6.44 PSF	$1200/TON	$3.86/SF
Steel in Interior Columns	3.22 PSF	$1200/TON	$1.93/SF
Steel in Spandrel	1.74 PSF	$1200/TON	$1.04/SF
Steel in Exterior Columns	6.76 PSF	$1200/TON	$4.06/SF
Steel in Exterior Diagonal	2.00 PSF	$1200/TON	$1.20/SF
Steel in Core Bracing	0.75 PSF	$1200/TON	$0.45/SF
Miscellaneous Connections	1.00 PSF	$1200/TON	$0.60/SF
Steel Subtotals	21.9 PSF	$1200/TON	$13.14/SF
Floor Cioncrete	0.0147 CY	$95.00/CY	$1.39/SF
Shear Connectors	0.21 Ea/SF	$1.50/Ea.	$0.31/SF
Composite Metal Deck	1.00 SF/SF	$1.40/SF	$1.40/SF
Foundations (1)			$0.55/SF
Premiums on Other Sys.			$0.10/SF (2)
COMBINED TOTAL COST			$16.89/SF

NOTES:

1. Foundation cost does not include walls and slabs below grade.
2. Penalty for making three penetrations per girder for mechanical through first interior girder. Evaluated at $100.00 per penetration.

GENERAL NOTES:

1. Each of the matrices above represents the costs of a single "World".
2. Square foot values are based on 59 floors of 27,275 sq.ft. each for a total of 1,600,000 sq.ft.

Figure B.9 Cost Summaries for Different Worlds

the owner and architect entities will consider the Value of the conventional moment frame, with its vertical and horizontal elements, to exceed that of the diagonally braced frame by more than the $6.4 million. In a region with higher seismicity, the diagonal braced scheme would be less desirable because of its lack of redundancy and ductility and it would not be allowed at all in Zone 4 areas such as California.

Once the basic decision on lateral system is made there is still the question of which 'world' will be used for the gravity system constraint set. This decision is not quite so straightforward. The choices use the same columns and have similar vibration characteristics so there should be no difference in the Value of the systems from the owner and architect points of view. The difference in cost due to the additional constraints placed on the other building systems has already been included in the cost summaries. After all the adjustments the difference in cost between the two gravity systems is $0.11/sq.ft. ($176,000) in the context of the braced tube and $0.39/sq.ft. ($624,000) in the context of the moment frame tube. In this case Scheme 1 is the least cost in either scenario. In the general case it is possible that the most economical gravity system will change depending on the lateral system context. (The systems are mutually constrained in terms of cost as well as function.)

The differences noted are significantly less than 5% of the subsystem cost and are, therefore, not significant at this level of abstraction. Since both differences favor gravity Scheme 1, this might be taken as an indication of the cost trend, and a decision made accordingly. However, in this case, there are additional factors that can be considered in making the decision. Referring once again to Figure B.3, it can be seen that ten feet to one side of the inside columns of the four column clusters is a floor beam. Qualitatively, we know that the floor beam deflected shape is parabolic. The relative deflection of the floor beam 10 feet from the column is not significantly different from its deflection at midspan. The relative deflection of the column is 0. Such a differential in a short distance is undesirable. Although there are no code requirements addressing this issue, and there are no costs or values associated with this condition (that can currently be identified), there is a design heuristic that favors Scheme 1 because of this 'intangible.'

Appendix C

Typical Floor Object Table

The table on the following pages contains a listing of the objects required to represent the typical floor structure depicted in Figure 7.2. The table layout models that of the proposed database representation scheme. In the table, Cxx indicates column objects, Bxx indicates beam objects, and Sxx indicates slab. The numbers are sequential for a given object type (i.e.,function, behavior, etc.), so the highest number in a column indicates the total number of objects of that type required, e.g., there are 46 gravity function objects but only 10 gravity behavior objects required to represent the columns.

There is a one to one correspondence between the gravity function objects (GFO), shown in the first column, and the elements shown on the plan and, as a result, the gravity function objects provide a key to the rest of the objects required for the complete representation.

There are only as many gravity behavior objects (GBO), shown in the second column, as need to cover the unique behavior patterns. Hence one gravity behavior object, B20, suffices to describe the behavior of the 24 gravity function objects corresponding to the typical floor beams. (See, for instance, GFO #B58, B60, B61, B63, etc.)

The lateral function objects (LFO) and the lateral behavior objects (LBO) corresponding to the gravity function objects are shown in columns 3 and 4 respectively. Note that many of the gravity function objects serve no function in the lateral systems.

The unified form object (FO) in column 4 corresponds to both the gravity and lateral function objects.

The last column gives the aggregate function object (AFO) of which the element is a component. Two aggregate function objects are used in this example: D1, the diaphragm; and F1, the perimeter frame.

GFO	GBO	LFO	LBO	FO	AFO
Columns					
C1	C1	C1	C1	C1	F1
C2	C2	C2	C2	C2	F1
C3	C3	C3	C3	C3	F1
C4	C3	C4	C4	C2	F1
C5	C3	C5	C5	C3	F1
C6	C3	C6	C6	C2	F1
C7	C3	C7	C5	C3	F1
C8	C3	C8	C4	C2	F1
C9	C3	C9	C3	C3	F1
C10	C2	C10	C2	C2	F1
C11	C1	C11	C1	C4	F1
C12	C4	C12	C7	C5	F1
C13	C4	C13	C7	C5	F1
C14	C5	C14	C8	C6	F1
C15	C6	--	--	C7	--
C16	C7	--	--	C8	--
C17	C8	--	--	C9	--
C18	C8	--	--	C10	--
C19	C7	--	--	C11	--
C20	C6	--	--	C12	--
C21	C5	C15	C8	C6	F1
C22	C9	C16	C9	C13	F1
C23	C10	--	--	C14	--
C24	C10	--	--	C14	--
C25	C9	C17	C9	C13	F1
C26	C5	C18	C8	C6	F1
C27	C6	--	--	C12	--
C28	C7	--	--	C11	--
C29	C8	--	--	C10	--
C30	C8	--	--	C9	--
C31	C7	--	--	C8	--
C32	C6	--	--	C7	--
C33	C5	C19	C8	C6	F1
C34	C4	C20	C7	C5	F1
C35	C4	C21	C7	C5	F1
C36	C1	C22	C1	C4	F1
C37	C2	C23	C2	C2	F1
C38	C3	C24	C3	C3	F1
C39	C3	C25	C4	C2	F1
C40	C3	C26	C5	C3	F1
C41	C3	C27	C6	C2	F1
C42	C3	C28	C5	C3	F1
C43	C3	C29	C4	C2	F1
C44	C3	C30	C3	C3	F1
C45	C2	C31	C2	C2	F1
C46	C1	C32	C1	C1	F1
Beams					
B1	B1	B1	B1	B1	F1
B2	B2	B2	B2	B2	F1
B3	B3	B3	B3	B3	F1
B4	B3	B4	B4	B2	F1
B5	B3	B5	B5	B3	F1
B6	B3	B6	B5	B2	F1
B7	B3	B7	B4	B3	F1
B8	B3	B8	B3	B2	F1
B9	B2	B9	B2	B3	F1
B10	B1	B10	B1	B4	F1
B11	B4	--	--	B5	--
B12	B4	--	--	B5	--
B13	B5	--	--	B6	--
B14	B6	--	--	B7	--
B15	B7	--	--	B8	--
B16	B8	--	--	B9	--
B17	B9	--	--	B10	--
B18	B6	--	--	B7	--
B19	B5	--	--	B6	--
B20	B10	--	--	B11	--
B21	B11	--	--	B12	--
B22	B11	--	--	B12	--
B23	B4	--	--	B5	--
B24	B12	--	--	B13	--
B25	B13	--	--	B14	--
B26	B4	--	--	B5	--
B27	B11	--	--	B12	--
B28	B11	--	--	B12	--
B29	B14	--	--	B15	--
B30	B5	--	--	B6	--
B31	B6	--	--	B7	--
B32	B9	--	--	B10	--
B33	B8	--	--	B9	--

KEY:
GFO - Gravity Function Object
LFO - Lateral Function Object
FO - Form Object
GBO - Gravity Behavior Object
LBO - Lateral Behavior Object
AFO - Aggregate Function Object

Table C.1 Typical Floor Objects

GFO	GBO	LFO	LBO	FO	AFO
B34	B7	--	--	B8	--
B35	B6	--	--	B7	--
B36	B5	--	--	B6	--
B37	B4	--	--	B5	--
B38	B4	--	--	B5	--
B39	B1	B11	B1	B4	F1
B40	B2	B12	B2	B3	F1
B41	B3	B13	B3	B2	F1
B42	B3	B14	B4	B3	F1
B43	B3	B15	B5	B2	F1
B44	B3	B16	B5	B3	F1
B45	B3	B17	B4	B2	F1
B46	B3	B18	B3	B3	F1
B47	B2	B19	B2	B2	F1
B48	B1	B20	B1	B1	F1
B49	B15	B21	B6	B16	F1
B50	B16	B22	B7	B17	F1
B51	B17	B23	B8	B18	F1
B52	B17	B24	B8	B18	F1
B53	B16	B25	B7	B17	F1
B54	B15	B26	B6	B19	F1
B55	B18	--	--	B20	--
B56	B19	--	--	B21	--
B57	B18	--	--	B20	--
B58	B20	--	--	B22	--
B59	B21	--	--	B23	--
B60	B20	--	--	B22	--
B61	B20	--	--	B24	--
B62	B21	--	--	B25	--
B63	B20	--	--	B24	--
B64	B20	--	--	B26	--
B65	B22	--	--	B27	--
B66	B22	--	--	B27	--
B67	B20	--	--	B26	--
B68	B23	--	--	B28	--
B69	B24	--	--	B29	--
B70	B20	--	--	B22	--
B71	B20	--	--	B22	--
B72	B23	--	--	B28	--
B73	B20	--	--	B30	--
B74	B24	--	--	B31	--
B75	B20	--	--	B30	--
B76	B20	--	--	B22	--
B77	B25	--	--	B32	--
B78	B20	--	--	B22	--
B79	B20	--	--	B22	--
B80	B25	--	--	B32	--
B81	B20	--	--	B22	--
B82	B20	--	--	B30	--
B83	B24	--	--	B31	--
B84	B20	--	--	B30	--
B85	B23	--	--	B28	--
B86	B26	--	--	B33	--
B87	B20	--	--	B22	--
B88	B20	--	--	B22	--
B89	B23	--	--	B28	--
B90	B27	--	--	B29	--
B91	B20	--	--	B26	--
B92	B22	--	--	B27	--
B93	B22	--	--	B27	--
B94	B20	--	--	B26	--
B95	B20	--	--	B24	--
B96	B21	--	--	B25	--
B97	B20	--	--	B24	--
B98	B20	--	--	B22	--
B99	B21	--	--	B23	--
B100	B20	--	--	B22	--
B101	B18	--	--	B20	--
B102	B19	--	--	B21	--
B103	B18	--	--	B20	--
B104	B15	B27	B6	B19	F1
B105	B16	B28	B7	B17	F1
B106	B17	B29	B8	B18	F1
B107	B17	B30	B8	B18	F1
B108	B16	B31	B7	B17	F1
B109	B15	B32	B6	B16	F1
Slabs					
S1	S1	S1	S1	S1	D1
S2	S1	S2	S2	S2	D1
S3	S1	S3	S3	S2	D1

KEY:
GFO - Gravity Function Object
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Table C.1 Typical Floor Objects (cont'd)

GFO	GBO	LFO	LBO	FO	AFO
S4	S1	S4	S4	S2	D1
S5	S1	S5	S5	S2	D1
S6	S1	S6	S6	S2	D1
S7	S1	S7	S7	S2	D1
S8	S1	S8	S8	S2	D1
S9	S1	S9	S7	S2	D1
S10	S1	S10	S6	S2	D1
S11	S1	S11	S5	S2	D1
S12	S1	S12	S4	S2	D1
S13	S1	S13	S3	S2	D1
S14	S1	S14	S2	S2	D1
S15	S1	S15	S1	S1	D1
S16	S1	S16	S9	S1	D1
S17	S1	S17	S9	S1	D1
S18	S1	S18	S10	S3	D1
S19	S2	S19	S11	S3	D1
S20	S3	--	--	S4	--
S21	S3	--	--	S5	--
S22	S3	--	--	S5	--
S23	S1	--	--	S5	--
S24	S1	S20	S11	S3	D1
S25	S1	S21	S10	S3	D1
S26	S1	--	--	S6	--
S27	S1	--	--	S6	--
S28	S4	--	--	S7	--
S29	S5	--	--	S8	--
S30	S1	--	--	S6	--
S31	S1	--	--	S6	--
S32	S6	--	--	S9	--
S33	S1	S22	S11	S3	D1
S34	S1	S23	S10	S3	D1
S35	S3	S24	--	S5	--
S36	S3	S25	--	S5	--
S37	S3	S26	--	S5	--
S38	S2	S27	--	S4	--
S39	S1	S28	S11	S3	D1
S40	S1	S29	S10	S3	D1
S41	S1	S30	S9	S1	D1
S42	S1	S31	S9	S1	D1
S43	S1	S32	S2	S2	D1
S44	S1	S33	S3	S2	D1
S45	S1	S34	S4	S2	D1
S46	S1	S35	S5	S2	D1
S47	S1	S36	S6	S2	D1
S48	S1	S37	S7	S2	D1
S49	S1	S38	S8	S2	D1
S50	S1	S39	S7	S2	D1
S51	S1	S40	S6	S2	D1
S52	S1	S41	S5	S2	D1
S53	S1	S42	S4	S2	D1
S54	S1	S43	S3	S2	D1
S55	S1	S44	S2	S2	D1
S56	S1	S45	S1	S1	D1
S57	S1	S46	S1	S1	D1

KEY:

GFO - Gravity Function Object
LFO - Lateral Function Object
FO - Form Object
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AFO - Aggregate Function Object

Table C.1 Typical Floor Objects (cont'd)

Appendix D
Additional Function Considerations

D.1 Lateral Load Representation

Design wind loads are anticipatory in nature, similar to occupancy loads. Wind loads are generally given in terms of unit intensity on the projected area of the building and the code may differentiate between loads on the windward face and loads on the leeward face. Most codes recognize local zones of higher wind pressures near discontinuities in the surfaces such as the building corners for the design of cladding elements, but such local maxima are not used in the design of the primary Lateral system.

The Uniform Building Code refers explicitly to the ANSI code for wind pressures for buildings over 400 ft. in height, and allows that code to be used for any building. In order to determine the wind loads using the ANSI procedure, an estimate of the dynamic properties of the structure must be made. This can be done in an efficient manner during conceptual design utilizing the Rayleigh approach, combined with an assumed deflected shape under the wind loads. During conceptual design, the properties of the structure will be tuned to yield the assumed deflected shape.

An alternative to using the design loads specified by code is to use pressures that are based on wind tunnel studies of scale models of the proposed building. In this case, wind pressures are sampled at points on the face of the model and pressure contours on the building faces are developed for various return periods. Usually, wind tunnel results are not available at the time the conceptual design is performed and the code approach must be used.

The equivalent static force procedure outlined in the code uses the total dead load at each floor in the determination of the seismic loads. This includes the weight of all permanent features, the partition allowance that is part of the function loads, the weight of the slab, and the weights of the structural elements at the floor. With the exception of the structural element weights, each of these is explicitly defined in the representation scheme for gravity loads outlined in Chapter 8 and, in the case of the structure self weight, in the form representation.

Unlike gravity systems, lateral load systems are always cantilevered, since they are supported only at the ground. In one fashion or another, the lateral loads are delivered to the floor slabs which are analogous to the beams in the gravity load path system. Since the locations of the floor slabs are invariant for a given cycle of conceptual design, it is convenient to represent the lateral loads in terms of not only the applied area loads but also the internal "forces" in the cantilever, i.e. the total shear and overturning moment at each floor to facilitate the reasoning process. It is common to represent this information in tabular form as shown in Figure 5.14. The usefulness of this form of representation will be seen in the following section on lateral load paths and in the later discussion of reasoning.

The center of application of both the wind loads and seismic loads is of importance in the conceptual design. With wind loads this can be calculated as the center of the projected area for any portion of the load (usually taken on a floor by floor basis). In this discussion we address only symmetrical rectangular buildings and the center of application of the wind load will always be the center of the face perpendicular to the wind. In a general integrated approach, the cladding, which serves a function in the lateral system analogous to the slabs in the gravity would be included in the load path representation and the center of application of the load would be automatically computed as a consequence of the representation. For seismic loads the representation scheme outlined makes it possible to calculate the actual center of mass on a floor by floor basis, although for the scope of this discussion the center of load will again be nearly the center of the building.

The table representation of lateral loads can readily be converted to an object representation in which the object names are the identifiers that appear in the first column of the table and the object attributes correspond to the columns of the table. Since the methods of computing wind loads and seismic loads differ, and the seismic loads vary between structural schemes, at least two classes of load objects are required and within each class of objects, seismic and wind, subclasses corresponding to loads in two orthogonal directions are required. Certain attributes associated with the building as a whole such as the wind pressure at various heights or total base shear for seismic loads would be assigned to the classes while the force quantities at the floors would be objects within a class.

Y_WIND_FORCES (NORTH-SOUTH)					
FLOOR	FORCES_CENTER	STORY_FORCE	STORY_SHEAR	CENTER_OF_SHEAR	STORY_OT_MOMENT
PH_ROOF	X_{CPH}	F_{PHR}	V_{PHR}	X_{VCPHR}	0
MACHINE_RM	X_{CMR}	F_{MR}	V_{MR}	X_{VCMR}	M_{MR}
ROOF	X_{CR}	F_R	V_R	X_{VCR}	M_R
FLOOR_N	X_{CN}	F_N	V_N	X_{VCN}	M_N
FLOOR_N-1	X_{CN-1}	F_{N-1}	V_{N-1}	X_{VCN-1}	M_{N-1}
FLOOR_i	X_{Ci}	F_i	V_i	X_{VCi}	M_i
.	.	.	..	.	.
.	.	.	.	.	.
FLOOR_1	X_{C1}	F_1	V_1	X_{VC1}	M_1

WHERE:

PH_ROOF is the penthouse roof

MACHINE_RM is the elevator machine room

ROOF is the main roof

N is the nominal number of floors (the number of stories typically does not include the machine room or roofs)

X_{Ci} is the center of the applied wind or seismic story force and is equal to the center of projected area in the case of wind loads and center of mass in the case of seismic loads

F_i is the applied story force from wind or seismic loads and is calculated from the projected area tributary to the floor and the unit intensity of wind load at the height of the floor in the case of wind. In the case of seismic loads it is calculated using the code equation and is a function of the height and dead load at floor N. Note that the height of the floor is a building attribute.

V_i is the total shear at story N. $V_N = SUM(F_1, F_{i+1}..F_N, F_R, F_{MR}, F_{PHR})$

X_{VCi} is the effective center of the shear at story i. $X_{VCi} = SUM((F_i{*}X_{Ci}),(V_{i+1}{*}X_{VCi+1}))/V_i$

M_i is the building overturning moment at floor i. $M_i = SUM(M_{i+1},((V_{i+1}{*}(Z_{i+1}-Z_i)))$, where Z is the height of the floors above the ground.

Figure D.1 Table Representation of Lateral Loads

D.2 Braced Frame Load Path Rules

In the following set of rules, level number refers to the level within the frame starting from the bottom. Components are grouped by level with the I end of a component being the end with the lowest Y coordinate, or, in the case of horizontals, the lower X coordinate. All coordinates are relative to the lower left hand corner of the level, which is assumed to line up with the edge of the frame. Diagonals and verticals are assumed to begin and end at levels, therefore, the Y coordinates of the I and J ends are the Y coordinates of the levels. It is assumed that there are complete horizontals at all levels.

Rules for Existence of Complete Braced Frame Internal Load Path

1) For all components, C1, of level i if there exists a component, C2, at level i-1 whose J end X coordinate is the same as C1 I end X coordinate then C2 is connected to C1 end I and C1 is connected to C2 end J
2) For all components, C1, of level i if there exists a component, C2, at level i whose I end X coordinate is the same as C1 I end X coordinate then C2 is connected to C1 end I and C1 is connected to C2 end I
3) For all components, C1, of level i if there exists a component, C2, at level i whose J end X coordinate is the same as C1 J end X coordinate then C2 is connected to C1 end J and C1 is connected to C2 end J
4) If there is no vertical at level i with an X coordinate of 0 then the load path is NOT complete at level i
5) If there is no vertical at level i with an X coordinate equal to the frame width, then the load path is NOT complete at level i
6) If a horizontal, H1, is connected to a component, C1, or if it is connected to another horizontal, H2, and H2 is ATTACHED to C1 then H1 is ATTACHED to C1
7) The end of a member is supported for vertical if "supported by for vertical" is not equal to NONE
8) The end of a member is supported for horizontal if "supported by for horizontal" is not equal to NONE
9) For all components, C1, if the level number, i, is 1, and component type is vertical or diagonal, then the component end I is supported for vertical by SUPPORT
    a) ELSE If C1 end I is connected to end J of a supported vertical, V1, then C1 end I is supported for vertical by V1
    b) ELSE If C1 end I is connected to end J of a supported diagonal, D1, then C1 end I is supported for vertical by D1
    c) ELSE If C1 end I is connected to end I of a diagonal, D1, and D1 end J is supported for vertical and C1 end J is connected to a horizontal that is attached to D1 end J then C1 end I is supported for vertical by D1
    d) ELSE If C1 type is diagonal and C1 end I is connected to a diagonal, D1, and D1 and C1 are collinear and D1 end I is supported for horizontal and vertical, then C1 is continuous with D1 and C1 end I is supported for vertical by D1
    e) ELSE C1 end I is supported for vertical by NONE
10) For all components, C1, if the level number, i, is 1, and component type is vertical or diagonal, then the component end I is supported for horizontal by SUPPORT
    a) ELSE If C1 end I is connected to end J of a supported diagonal, D1, then C1 end I is supported for horizontal by D1
    b) ELSE If C1 end I is connected to a supported horizontal, H1, then C1 end I is supported for horizontal by H1
    c) ELSE If C1 type is diagonal and C1 end I is connected to a diagonal, D1, and D1 and C1 are collinear and D1 end I is supported for horizontal and vertical, then C1 is continuous with D1 and C1 end I is supported for horizontal by D1
    d) ELSE C1 end I is supported for horizontal by NONE
11) For all components, C1, if C1 type is vertical then C1 end J is supported for vertical by NONE
    a) ELSE If end J is connected to end J of a supported vertical, V1, then C1 end J is supported for vertical by V1
    b) ELSE If C1 end J is connected to end J of a supported diagonal, D1, then C1 end J is supported for vertical by D1
    c) ELSE If C1 type is diagonal and C1 end J is connected to end J of a diagonal, D1, and D1 end I is supported for vertical and C1 end I is connected to a horizontal that is attached to D1 end I then C1 end J is supported for vertical by D1
    d) ELSE C1 end I is supported for vertical by NONE

12) For all components, C1, if C1 end J is connected to end J of a supported diagonal, D1, then C1 end J is supported for horizontal by D1
    a) ELSE If C1 type is horizontal and end J is connected to a horizontal, H1, and H1 end J is supported for horizontal then C1 end J is supported for horizontal by H1
    b) ELSE If C1 type is diagonal and C1 end J is connected to a horizontal, H1, and H1 end I and H1 end J are supported for horizontal, then C1 end J is supported for horizontal by H1
    c) ELSE If C1 end J is connected to end I of a diagonal, D1, and D1 end J is supported for horizontal and vertical then C1 end J is supported for horizontal by D1
    d) ELSE C1 end I is supported for horizontal by NONE
13) If a diagonal, D1, is supported for horizontal *and* vertical at end I and for vertical *or* horizontal at end J, then it is supported
    a) ELSE If D1 is supported for horizontal *or* vertical at the I end and for horizontal *and* vertical at the J end, then it is supported
    b) ELSE D1 is NOT supported
14) If a vertical is supported for vertical at end I and is supported for horizontal at end I and end J, then it is supported
15) If all the verticals at level i are supported for horizontal at end J then level i is supported and level i Y is a valid load point
    a) ELSE level i requires supplemental support and for all verticals at level i if end J is connected to a horizontal then the vertical is supported for horizontal at end J
16) If the top level of the frame is a valid load point, then there is a complete frame load path

In the above set, rules 1 - 3 are set up rules which establish connectivity from general existence and location data, and are included for the sake of completeness. It is anticipated that these rules would actually be applied in reverse during conceptual design, with connectivity established by the mode of behavior desired. Connectivity definitions generated by rules 1 - 3, taken with the constraint that support can be provided only by a connected member and the definition of members in a braced frame carrying only axial load, is used throughout the balance of the rule set to establish conditions of support. Rules 4 and 5 enforce the arbitrary constraint of boundary columns. Rule 6 is a special "definitional" rule that is required as support for rules 9 (c) and 11 (c), which, in turn, are used to reason about the existence of a vertical support which is horizontally "remote." Rules 7 and 8 are again definitional and are required in order to avoid the necessity of slots containing the status of supported relationships at the member ends while accommodating NIL values for slots that are "unknown". The short hand used is that a value of NONE for "supported by" is the same as an unsupported condition. Rules 9, 10, 11, and 12 determine the support conditions in the X and Y directions at ends I and J of the individual components, and are used for all component types. Rule 13 combines the results of rules 9 - 12 to determine overall member support which is distinct from an element of member support. Rule 14 is a special rule for the support of verticals. Rule 15 tests for valid load points while rule 16 tests for the existence of a complete frame load path. The definition of a complete load path is very simple - if the top level of the frame is supported, then there is a complete load path. There may be multiple supported levels between the bottom and the top, or there may be none.

D.3 Moment Frame Load Path Rule

The rule set previously presented for determining a complete load path in braced frames can be modified to accommodate both braced frames and moment frames by the addition of a single rule as follows:

12(d) If C1 type is vertical and C1 end I is supported for vertical and horizontal and Ci end I or C1 end J is continuous with a horizontal whose opposite end is supported for vertical then C1 end J is supported for horizontal by SELF

D.4 Eccentric Braced Frame Load Path Rules

In order for there to be a complete frame load path in an eccentrically braced frame, the system of beams must be capable of spanning between vertical supports. Rather than change representation methods at this point, we'll continue to work with the representation adopted for braced frames. The support will be satisfied if the horizontals are continuous between points of vertical support. The points of continuity are represented by the solid triangles in Fig. 8.17. This requirement can be tested by making the following additions to the rule set used for braced and moment frames:

9(e) If C1 type is horizontal and C1 end I is continuous with a horizontal, H1, and H1 end I is supported for vertical, then C1 end I is supported for vertical

9(f) If C1 end I is connected to a horizontal, H1, and H1 is supported for vertical at end I and end J, then C1 end I is supported for vertical by H1.

11(d) If C1 type is horizontal and C1 end J is continuous with a horizontal, H1, and H1 end J is supported for vertical, then C1 end J is supported for vertical by H1

11(e) If C1 end J is connected to a horizontal, H1, and H1 is supported for vertical at end I and end J, then C1 end J is supported for vertical by H1.

Accommodating horizontal elements that are continuous between verticals does not change the object representation, since only the end coordinates would have to be modified. It would change the rule set for testing for a complete load path. The rules for connectivity would have to be augmented by a rule that states that if the end of a member lies along the axis of another member, then the members are connected.

If this approach is adopted, any level that contains a diagonal element that is supported for horizontal and vertical at the I end and is connected to a horizontal at the J end is supported for horizontal loads.

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This dissertation was prepared using Microsoft Word. The figures were drawn in AutoCad, and plotted to Postscript files that were linked to the Word document. AutoCad was provided by Autodesk, Inc., a member of the Center for Integrated Facilities Engineering.