CIFE CENTER FOR INTEGRATED FACILITY ENGINEERING

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by Yasunaga Tatsumi [1], Paul M. Teicholz [2],
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1. Abstract

An expert system for evaluating the risk to a construction project at all stages of the project is proposed as a means of mitigating the risks in the Japanese construction industry which has seen rapid growth in recent times. The purpose of such an expert system would be to identify the risks which are likely at different stages of the project from conception, design, construction to operation. Such a system would aid management to identify and evaluate potential risks at all stages of the project and if necessary to take early action so as to have the most impact.

In this research we have concentrated our efforts on some of the aspects of the construction risk management system. We have built prototypes of modules which can assess the risk at the construction stage, the operational stage and seismic risk over the lifetime of the building. The modules have been written in NEXPERT OBJECT, an expert system shell, and the prototype system presently consists of knowledge bases, structural failure and construction accident databases, external subroutines written in Fortran and some user-supplied information. The inputs to the prototype system are information that is interactively entered by the user and the rest of the data is read directly from project databases, which are now becoming increasingly common with the bigger construction companies in Japan.

At the heart of the modules which assess the risk at the construction and operation stages is a fuzzy pattern-matching technique for matching the causes of the project to those found in the instances which experienced structural failure and, or construction accidents. Pattern-matching is used to identify those cases of failure/accident in the failure/accident database which are highly correlated with the project. The seismic risk module consists of an external Fortran program for calculating the stochastic response spectra and procedures based on ATC-13 and ATC-21 for determining the expected damage factor using the concept of structural scores.

The prototype system that we have built, though it is a long way from being implemented for practical use, and needs further refinements, has shown that the technology of expert systems as embodied in an object-oriented frame is a very powerful tool in this field.

2. Introduction

2.1. Background

The construction industry in Japan in recent decades has experienced a period of expansion. In the domestic market the scale of projects and the value of the investments have expanded dramatically and overseas projects have been increasing at the same time. Accompanying the growth is an increase in the associated risks. Increasingly the construction environment is turning more uncertain and unpredictable and the need for more sophisticated risk management of construction projects is becoming more apparent.

In Japan the amount of construction has stepped up in the last four years due to the success of the Japanese economy. Additional impetus has come from the reconstruction of many old buildings, facilities and infrastructure which were constructed just after World War II. The current expansive situation has resulted in an increase in the number of construction failure/accidents because of the shortage of trained labor, deficiency of administration, and so on. Also, the complexity of the urban structure and the limitations of space have not helped matters. In this situation, research on risk management systems for the construction industry is necessary so as to be able to to cope with what will inevitably be even more complicated in the future.

Initially, risk management may be required for limited range of tasks. However, the experience of many organizations suggests a risk engineering approach provides other benefits which may prove far more important in the long term. These benefits, Cooper and Chapman (1987), include:

(1) Better and more definite perceptions of risks, their effects on the project, and their interactions.

(2) Better contingency planning and selection of response to those risks which do occur, and more flexible assessment of the appropriate mix of ways of dealing with risk impacts.

(3) Feedback into the design and planning process in terms of ways of preventing or avoiding risks.

(4) Feedforward into the construction and operation of the project in terms of ways of mitigating the impacts of those risks which do arise, in the form of response selection and contingency planning.

(5) Following from these aspects, an overall reduction in project risk exposure (which

causes reduced insurance premiums because of fewer accidents).

(6) Sensitivity testing of the assumptions in the project development scenario.

(7) Documentation and integration of corporate knowledge which usually remains the preserve of individual minds.

(8) Insight, knowledge and confidence for better decision making and improved risk management.

For, a risk management system to be applicable to real world situations, it needs the knowledge and the reasoning undertaken by human experts. Human experts reason and arrive at conclusions on the potential risks for new construction projects based on their experiential knowledge gained from years of observing failure/ accident/ deficiency in the construction industry.

Expert systems and knowledge bases have been accepted by many in the business, industrial, and professional spheres as a way of making expertise routinely available wherever it is needed, Maher (1987), Parsaye et al., (1988). These technologies look very suitable to the field of risk management since our everyday decision making is greatly dependent on human expertise in the construction industry. In addition, some of the larger construction companies have started to build Project Databases which include all the relevant data related to a particular project, Ishii et al., (1990). We might efficiently utilize these databases in a risk management system using current database technology.

As an example of the current research efforts in risk management in the construction field which utilizes expert systems and knowledge bases is the book "Knowledge-Based Risk Management in Engineering", Niwa (1989). This remarkable book provides a glimpse of what risk management systems in the future will look like. According to Dr. Niwa these systems will be characterized by careful implementation of human-computer relationships and effective employment of multidisciplinary approaches consisting of AI, management science, and systems thinking. A large power plant construction project is used as an example and a prototype system that covers all activities of the project, from proposal stage to operation, are outlined. Dr. Niwa has concluded that structured production systems are suitable to project risk management systems because the characteristics of structured production systems and domain knowledge are both procedural and structured.

Another example of research in the same field is an Intelligent Risk Identification System (IRIS) to help construction project management identify possible problems.

This system has been developed at The University of Texas by Ashley et al., (1987). IRIS is an expert system which centers on a problem statement database and an inference system using cause-effect linkages to establish risk relationships. The inferencing approach is to create a subset database of problems matching conditions and criteria of the proposed project and then build a cause-effect network of potential risks. The "influence diagram" ties early project decisions and risk elements to critical project outcomes such as cost, schedule and quality. In the paper, they pointed out that "Due to the high interdependency between the activities of a construction project, the earlier risks are managed, the more influence management can have on the outcome of the project" (Figure 2.1.1).

The ultimate objectives of our research are the same as those of the above two references. Figure 2.1.2 shows the entire concept of a "Construction Risk Management System". In our research, we have tried to apply object-oriented knowledge bases and fuzzy set theory in a prototype expert system as a first attempt. We think that object-oriented knowledge bases are suitable to the pattern matching in this system and that the fuzzy set theory is a useful approach to utilize the subjective expertise in this field. However, the application of the theory requires the evaluation of fuzzy transit matrices which are also subjective. To construct the practical system, we need to make efforts to verify and refine the matrices through the performance of the system in the future.

We believe that our construction risk management system will in the near future be one of many important tools for supporting decision making within a construction company.

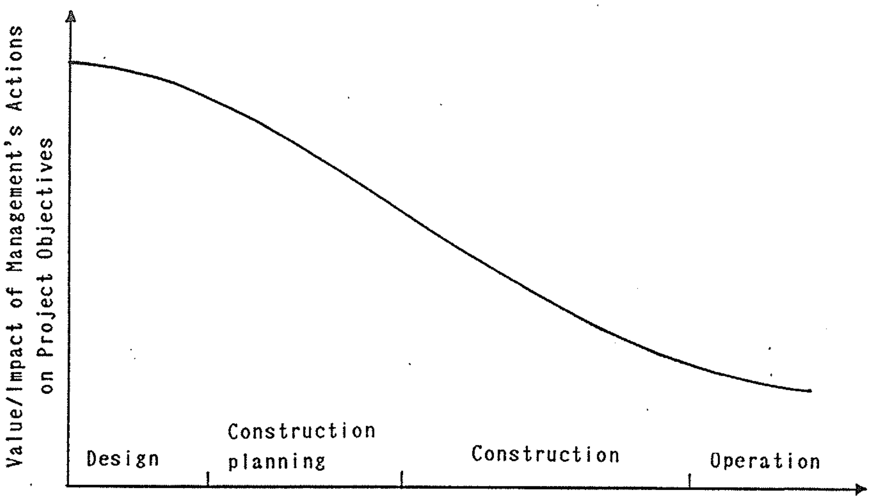

Figure 2.1.1. Value/Impact of Management's Actions on Project Objectives (Ashley, 1987)

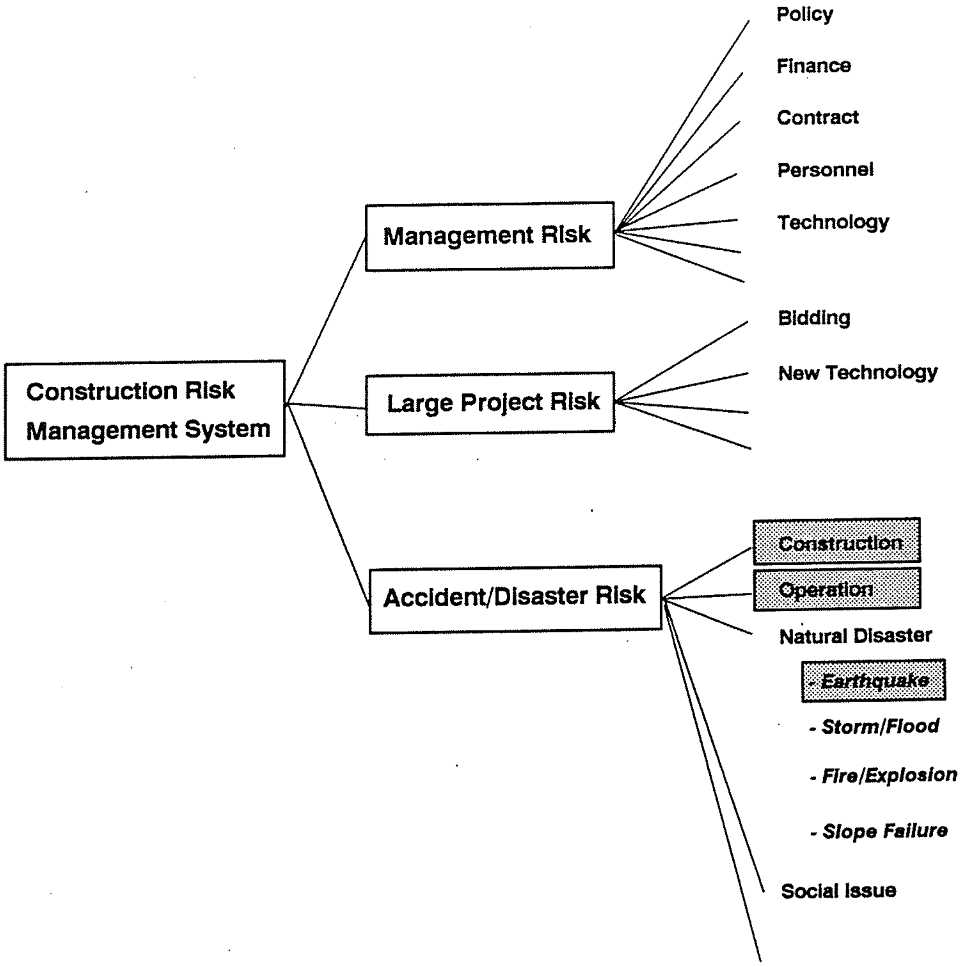

Figure 2.1.2. Construction Risk Management System for a Construction Company

2.2. Objectives

The ultimate objective of the risk management system which we are developing is to build a tool for decision making for evaluating the risks of a construction project. The risk management system will examine all phases of the project and

- identify the financial and accidental risks which have high probabilities, and
- suggest countermeasures through all stages, planning, design, construction and operation, to avoid damage or accidents.

The system will base its judgment on the information on all aspects of the project such as design, construction, geography, geology, meteorology, etc. and information on previous incidents of failure or accidents during construction.

Through the above functions this system will enable a construction company to

(1) make a proper decision if the company should participate in a specific construction project,
(2) show the client the risks and make an appropriate contract,
(3) avoid financial and accidental risks through proper countermeasures such as change of the design at the planning or design stage,
(4) provide alarms of the risks at each stage in the construction and provide the proper measures and suggestions to administrative staffs at construction sites,
(5) accumulate the knowledge of experienced experts who are knowledgeable about construction risks,
(6) train inexperienced administrative staffs and foremen about the risks at the construction stage,
(7) make a proper risk transfer such as construction/earthquake insurance in the case that a project cannot avoid some level of possibility of risk (Freeman, 1932; Aetna Life & Casualty et al., 1987; Dong et al., 1987).

Due to the limitation of time at CIFE of one of the authors *, the objective of the research has been limited to the development of a prototype expert system which can, at the early design stage of new projects of building constructions do the following:

- identify structural failure/accident risks based on high correlation with historical failure/accident cases at the construction and operation stages and show the causes

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* This study was officially started on January 1990 and ends on September 30, 1990 when Mr. Tatsumi, the main author of this study, leaves for Japan.

of the corresponding risks, and (Construction/Operation Module),

- estimate the seismic risk (expected damage cost) over the lifetime of the project and provide suggestions for risk mitigation (Seismic Risk Module).

The part of the risk management system that accomplishes the above tasks and which constitutes the subject of this report is shown by dotted boxes in Figure 2.1.2. In this study we have limited checking of new projects to the early design stage based on the observation made by Ashley et. al. (1987) , see Figure 2.1.1, that the biggest impact on project objectives comes from the actions taken at the design stage.

In the course of the development of the system, the research has stressed on

- knowledge acquisition of structural failure/accident cases,
- reasoning to perform pattern matching between historical cases and a new project in the early design stage utilizing object-oriented knowledge base and fuzzy set theory,
- way to utilize the expertise on seismic ** damage obtained from earthquake engineers.

For the purpose of this study we have concentrated on just a few aspects of construction risk management but it is our belief that the procedure developed in our research can be expandable to the other parts of the entire risk management system.

** The Seismic Risk Module, which is used to evaluate the seismic risk at a given site, is based on previously published works of the principal author, Tatsumi (1985), (1987), (1988).

2.3. Outline of the Construction Risk Management System

The prototype construction risk management system which we have developed consists of a main module and three submodules called Construction Stage, Operation Stage and Seismic Risk. Each module is an object-oriented knowledge base made using the expert system shell "NEXPERT OBJECT." These modules are linked to some databases, image data files and external subroutines.

Figure 2.3.1 shows the outline of the prototype system. Each part of the system is briefly explained in the following section.

Main Module

The module controls the whole system and also contains

- object-oriented knowledge frame of a construction project (Figure 2.3.2),
- object-oriented knowledge of risk causes,
- rules to retrieve the comments of the causes from Cause Databases,
- rules to retrieve the values of fuzzy membership functions from the Fuzzy Value Database,
- rules to retrieve the required data from the Project Database (Figure 2.3.3) and to set up the data to the knowledge frame (Figure 2.3.2),
- rules to chose the potential causes in a project,
- rules to select the results and write into an output file.

Construction Stage Module

The function of this module is to make the pattern-matching between the new project and the various historical failure/accident cases which took place during the construction stage. It contains

- rules to identify the causes for each historical case using the object-oriented knowledge of risk causes,
- rules to make pattern-matching using the fuzzy set theory,
- rules to show the images of failure/accident cases which are strongly correlated to the project,
- rules to output the summary of the results to the result file.

Operation Stage Module

The function of this module is to make the pattern-matching between a project and historical cases of failure/accident at the operation stage (which means "after construction"). It contains the same kinds of rules as the Construction Stage Module.

Seismic Risk Module

The function of this module is to calculate the expected damage cost of the project over its lifetime due to earthquakes. It contains

- rules to obtain the required data to calculate the stochastic response spectra and damage factor-maximum response acceleration function, from the project data,
- rules to transfer the data to an external Fortran program (which performs the actual calculations for the stochastic response spectra and expected damage cost) and to retrieve the results,
- rules to show the results with appropriate suggestions,
- rules to output the summary of the results to the result file.

Cause Database

The database contains the comments of causes such as " Reinforced Concrete Structure." on the cause ID, C00_01 and " Error in the goal formulation of the project." on C01_01. The database file is written using the LOTUS Database format.

Fuzzy Value Database

This database contains the coherence values at which the membership functions take the gravity center or maximum, for each combination of subsidiary causes (large, medium and small). In order to make the LOTUS Database file, the values have been calculated by a Fortran program and imported to the database.

User Interface Image Files

Image files are used in order to give the users some explanation on how to choose the options and technical values. These files are written in Microsoft Windows Paint format.

Project Database

In some Japanese construction companies, project databases have been constructed to improve the efficiency of jobs and attempts have been made to utilize this database at all stages of the project. In this system, we have used Takenaka's Project Database (Ishii, et al., 1990) as a sample of a project database. The Takenaka Project Database contains more than 1,100 items (from financial, managerial to architectural and engineering) for each project. A part of the database is shown in Figure 2.3.3 after translation from Japanese into English. Each of the items has a concrete definition and value for a specific project.

In the main module the required data is retrieved from this database which is written in LOTUS Spreadsheet format.

Construction Failure/Accident Database

We have decided to use the failure/accident case data obtained from Dr. Eldukair (1988), because this was the only structural failure/accident database that we could get in the form of a computerized database in the United States. This database was made based on reports of failure/accidents in the "ENR, Engineering News Record". It contains data on structural failures and construction accidents at the construction or operation stage of buildings, industrial structures and civil structures. The database is written in dBASE III^+ format.

This Construction Failure Database we have used is a portion of Dr. Eldukair's database as it is a selection of only those data from buildings and industrial structures at the construction stage.

Operation Failure/Accident Database

As in the case of the Construction Failure Database this this database is a sub-database as it is a selection of only those data from buildings and industrial structures at the operation stage.

Failure/Accident Case Image Files

Image files of typical failure/accident cases have images taken from the original articles in which the case is described. The image file for a case consists of the visual images of the failure/accident and the comments on the causes of the failure/accident. The image files is stored using the MacPaint Format.

Earthquake Damage Program

The original Fortran program was developed by one of the authors, Tatsumi, (1985), (1987), (1988). This program does the following:

- calculates the Stochastic Response Spectra taking account the local time-dependent seismicity, structural natural period, damping and lifetime,
- calculates the damage factors using the Stochastic Response Spectra and Damage Factor-Maximum Response Acceleration function for a specified site and given structure.

The original program had to be modified to enable it to

- account for the effect of local ground conditions assuming that the local ground conditions can be expressed by a linear single-degree-of-freedom system,
- show the results graphically,

- link to the Seismic Risk Module through the input and output files written in NEXPERT OBJECT Spreadsheet format.

Result File

Selected results from all the modules are listed using the LOTUS database format. The result file contains such things as

- list of selected potential causes of risk for the project,
- list of strongly correlated historical cases,
- the expected damage cost due to earthquakes.

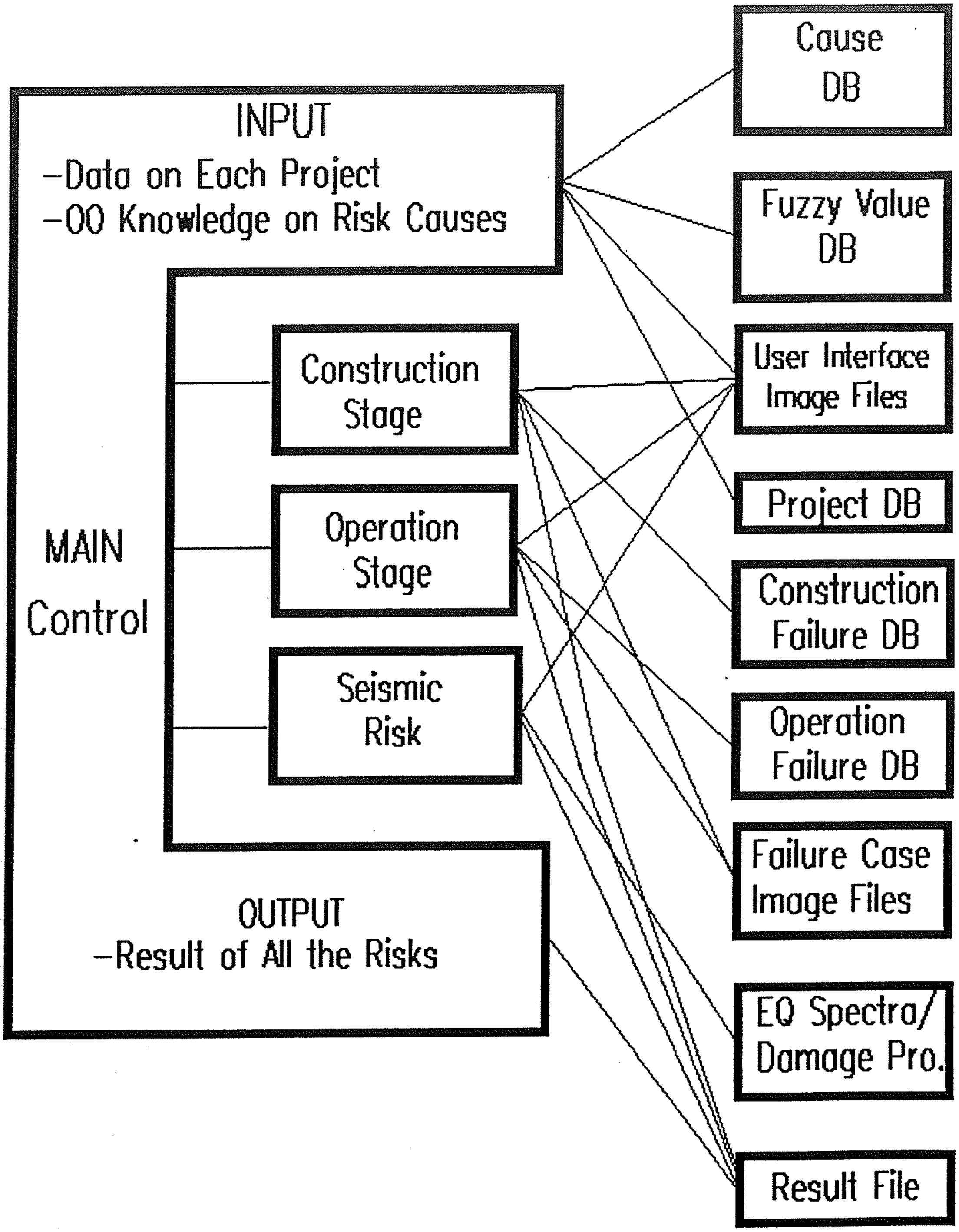


Figure 2.3.1. Outline of the Prototype System

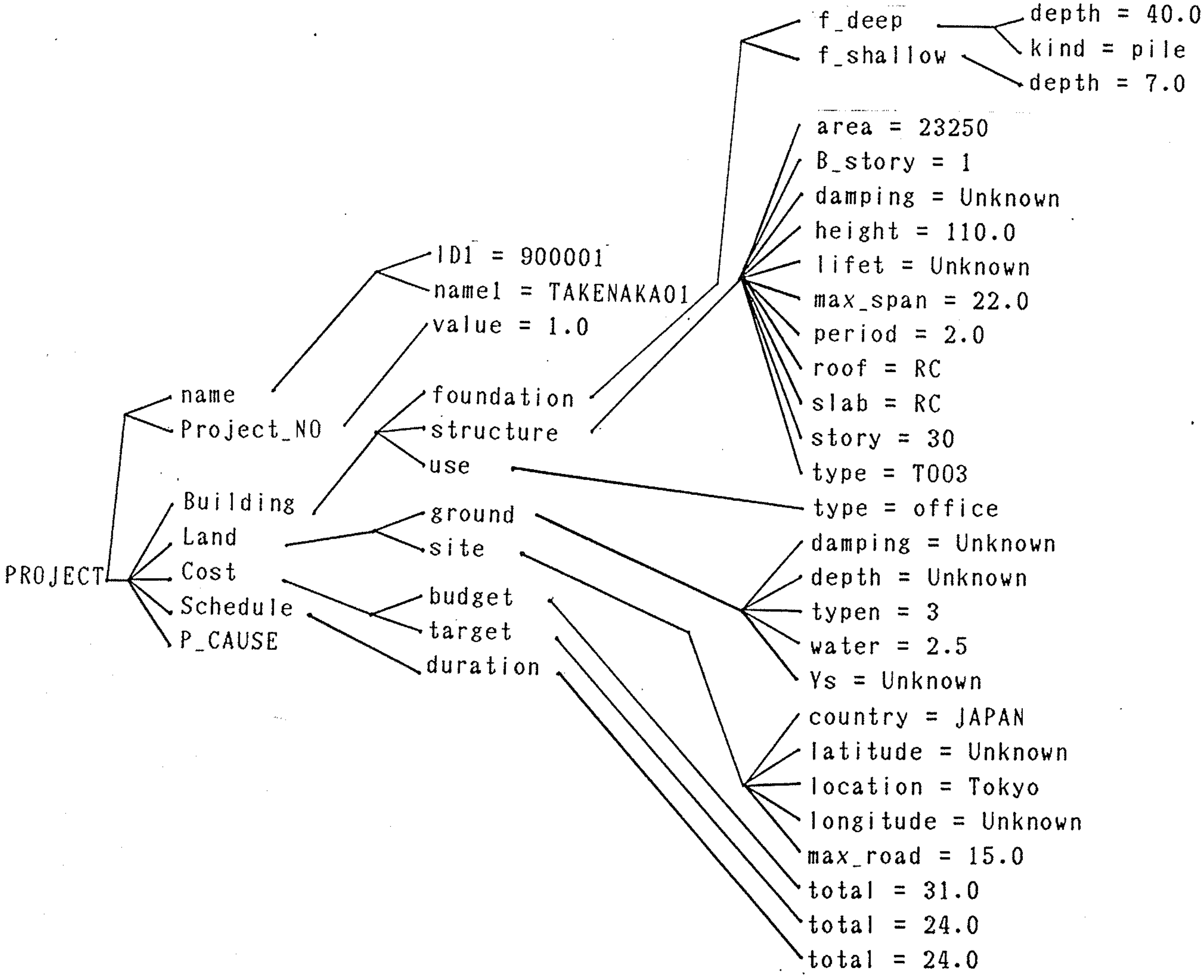
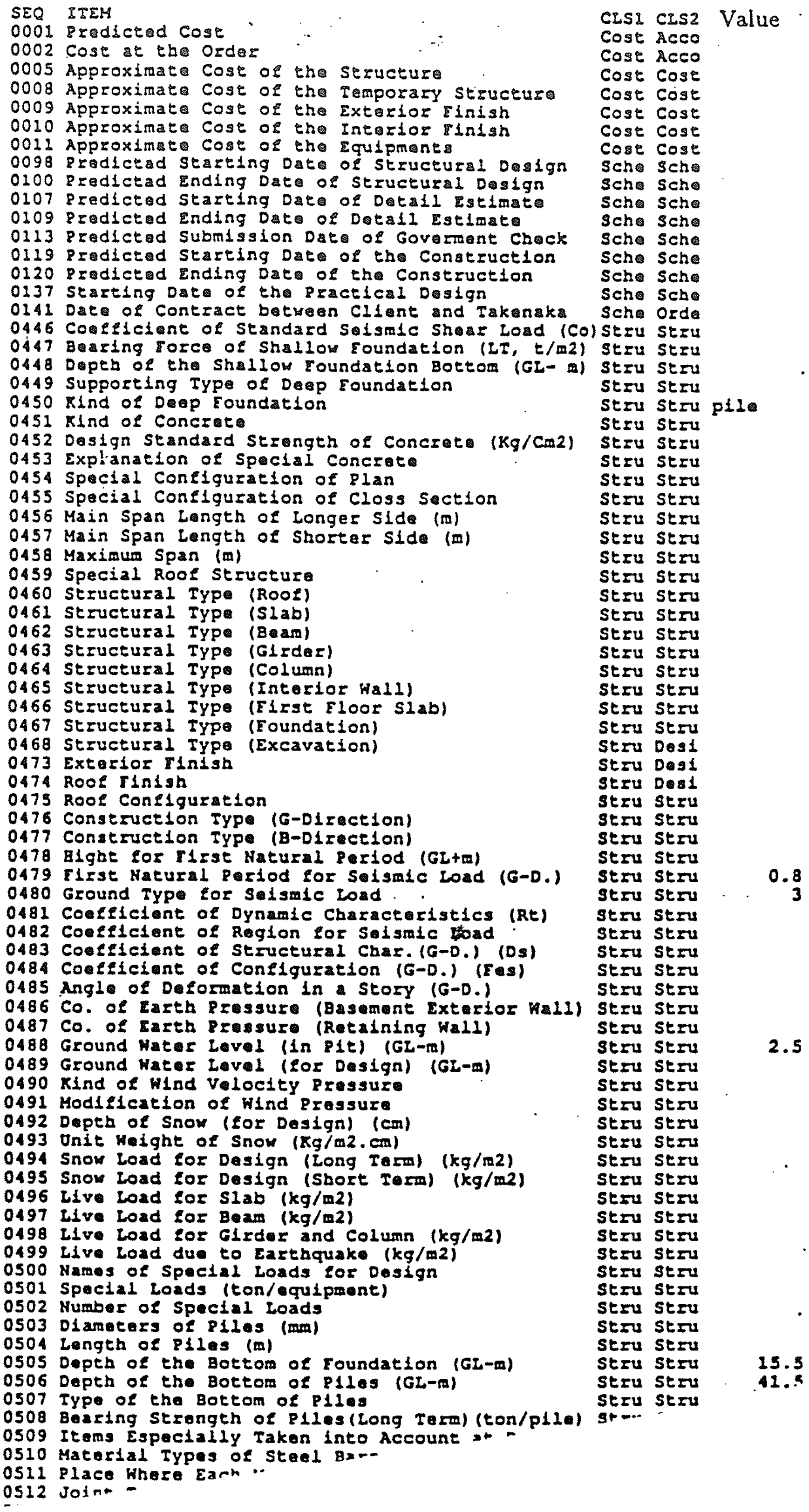


Figure 2.3.2. Object Network of the Project



SEQ	ITEM	CLS1	CLS2	Value
0001	Predicted Cost	Cost	Acco	
0002	Cost at the Order	Cost	Acco	
0005	Approximate Cost of the Structure	Cost	Cost	
0008	Approximate Cost of the Temporary Structure	Cost	Cost	
0009	Approximate Cost of the Exterior Finish	Cost	Cost	
0010	Approximate Cost of the Interior Finish	Cost	Cost	
0011	Approximate Cost of the Equipments	Cost	Cost	
0098	Predictad Starting Date of Structural Design	Sche	Sche	
0100	Predictad Ending Date of Structural Design	Sche	Sche	
0107	Predicted Starting Date of Detail Estimate	Sche	Sche	
0109	Predicted Ending Date of Detail Estimate	Sche	Sche	
0113	Predicted Submission Date of Goverment Check	Sche	Sche	
0119	Predicted Starting Date of the Construction	Sche	Sche	
0120	Predicted Ending Date of the Construction	Sche	Sche	
0137	Starting Date of the Practical Design	Sche	Sche	
0141	Date of Contract between Client and Takenaka	Sche	Orde	
0446	Coefficient of Standard Seismic Shear Load (Co)	Stru	Stru	
0447	Bearing Force of Shallow Foundation (LT, t/m2)	Stru	Stru	
0448	Depth of the Shallow Foundation Bottom (GL- m)	Stru	Stru	
0449	Supporting Type of Deep Foundation	Stru	Stru	
0450	Kind of Deep Foundation	Stru	Stru	pile
0451	Kind of Concrete	Stru	Stru	
0452	Design Standard Strength of Concrete (Kg/Cm2)	Stru	Stru	
0453	Explanation of Special Concrete	Stru	Stru	
0454	Special Configuration of Plan	Stru	Stru	
0455	Special Configuration of Closs Section	Stru	Stru	
0456	Main Span Length of Longer Side (m)	Stru	Stru	
0457	Main Span Length of Shorter Side (m)	Stru	Stru	
0458	Maximum Span (m)	Stru	Stru	
0459	Special Roof Structure	Stru	Stru	
0460	Structural Type (Roof)	Stru	Stru	
0461	Structural Type (Slab)	Stru	Stru	
0462	Structural Type (Beam)	Stru	Stru	
0463	Structural Type (Girder)	Stru	Stru	
0464	Structural Type (Column)	Stru	Stru	
0465	Structural Type (Interior Wall)	Stru	Stru	
0466	Structural Type (First Floor Slab)	Stru	Stru	
0467	Structural Type (Foundation)	Stru	Stru	
0468	Structural Type (Excavation)	Stru	Desi	
0473	Exterior Finish	Stru	Desi	
0474	Roof Finish	Stru	Desi	
0475	Roof Configuration	Stru	Stru	
0476	Construction Type (G-Direction)	Stru	Stru	
0477	Construction Type (B-Direction)	Stru	Stru	
0478	Hight for First Natural Period (GL+m)	Stru	Stru	
0479	First Natural Period for Seismic Load (G-D.)	Stru	Stru	0.8
0480	Ground Type for Seismic Load	Stru	Stru	3
0481	Coefficient of Dynamic Characteristics (Rt)	Stru	Stru	
0482	Coefficient of Region for Seismic Load	Stru	Stru	
0483	Coefficient of Structural Char.(G-D.) (Ds)	Stru	Stru	
0484	Coefficient of Configuration (G-D.) (Fes)	Stru	Stru	
0485	Angle of Deformation in a Story (G-D.)	Stru	Stru	
0486	Co. of Earth Pressure (Basement Exterior Wall)	Stru	Stru	
0487	Co. of Earth Pressure (Retaining Wall)	Stru	Stru	
0488	Ground Water Level (in Pit) (GL-m)	Stru	Stru	2.5
0489	Ground Water Level (for Design) (GL-m)	Stru	Stru	
0490	Kind of Wind Velocity Pressure	Stru	Stru	
0491	Modification of Wind Pressure	Stru	Stru	
0492	Depth of Snow (for Design) (cm)	Stru	Stru	
0493	Unit Weight of Snow (Kg/m2.cm)	Stru	Stru	
0494	Snow Load for Design (Long Term) (kg/m2)	Stru	Stru	
0495	Snow Load for Design (Short Term) (kg/m2)	Stru	Stru	
0496	Live Load for Slab (kg/m2)	Stru	Stru	
0497	Live Load for Beam (kg/m2)	Stru	Stru	
0498	Live Load for Girder and Column (kg/m2)	Stru	Stru	
0499	Live Load due to Earthquake (kg/m2)	Stru	Stru	
0500	Names of Special Loads for Design	Stru	Stru	
0501	Special Loads (ton/equipment)	Stru	Stru	
0502	Number of Special Loads	Stru	Stru	
0503	Diameters of Piles (mm)	Stru	Stru	
0504	Length of Piles (m)	Stru	Stru	
0505	Depth of the Bottom of Foundation (GL-m)	Stru	Stru	15.5
0506	Depth of the Bottom of Piles (GL-m)	Stru	Stru	41.5
0507	Type of the Bottom of Piles	Stru	Stru	
0508	Bearing Strength of Piles(Long Term)(ton/pile)	St		
0509	Items Especially Taken into Account			
0510	Material Types of Steel B			
0511	Place Where Each			
0512	Joi			

Figure 2.3.3. A Part of the Project Database for a Specific Project (Takenaka)

3. Risk at the Construction and Operation Stage of Buildings

3.1. Overview of the Construction and Operation Modules

In the construction and operation submodules, a pattern-matching is performed by comparing the potential causes inferred from the data in the Project Database with the causes for each historical failure/accident case in the Failure/Accident Database to identify those cases which are strongly correlated with the project. In the course of the pattern-matching, fuzzy membership functions of coherence values are used as a measure. Figure 3.1.1 shows the flow for the pattern matching using the inferred causes.

Each submodule in Figure 3.1.1 retrieves a different failure/accident database and has different knowledge to identify the causes of each historical case but has the same system frame. The function of the modules are:

(1) retrieve the required data from each Failure/Accident Database,
(2) identify the causes that each historical case has using the Object-Oriented (OO) knowledge of risk causes,
(3) make the pattern-matching using the fuzzy set theory,
(4) show the images of the failures/accidents which are strongly correlated with the project,
(5) output the summary of the results to the result file.

In section 3.2, the causes used in this system and the manner in which the pattern-matching is conducted using object-oriented cause network are described. In section 3.3, fuzzy set theory as applied in pattern-matching is explained. In section 3.4, the effort to collect the historical data of failures/accidents used in the system are explained.

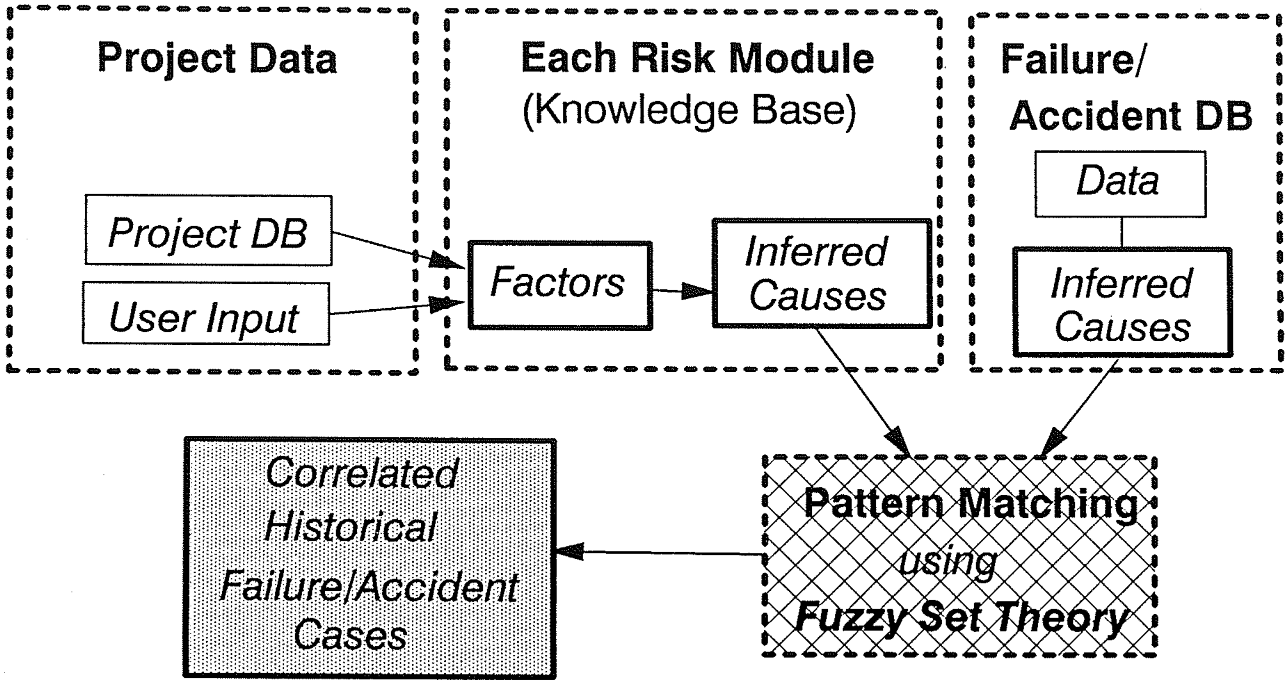


Figure 3.1.1. Flow for the Pattern Matching

3.2. Pattern Matching Based on Object-Oriented Cause Network

3.2.1. Causes Used in This System and the Cause Network

Causes are defined as characteristics of an incident which have some influence on the resulting failure/accident. The causes in this system are classified into two classes, Required Causes and Subsidiary Causes. The subsidiary causes are in turn categorized into three sub-categories, Large, Medium and Small Causes.

$$\mathit{Causes} \begin{cases} \bullet\ \mathit{Required} \\ \bullet\ \mathit{Subsidiary} \begin{cases} \cdot\ \mathit{large} \\ \cdot\ \mathit{medium} \\ \cdot\ \mathit{small} \end{cases} \end{cases}$$

The Required Causes are those without one of which each of the historical failure/ accident cases could not occur. On the other hand, the Subsidiary Causes are the secondary causes which are considered to have contributed to the occurrence of each case. The sub-categories Large, Medium and Small Secondary Causes are defined respectively as:

Large: Direct cause which has large influence to each case,
Medium: Direct cause which has medium influence to each case,
Small: Indirect cause which has small influence to each case by itself and possibly trigger some other causes.

Examples of Required Causes are the type of the structure, existence of some material, existence of some objects, etc. The subsidiary causes have been taken from Eldukair (1988). All the causes used in the system are listed in Table 3.2.1 with their respective codes, C00_01 through C08_06.

The Cause Network is shown in Figure 3.2.1 with the causes represented by their respective codes. Some of the causes have other causes under them which are triggered only if they are present. For example, C08_02 (Financial Pressure) triggers C02_05 (Error in material selection), C05_09 (Improper construction method) and C06_05 (Inadequate time and cost integration management). The network shown in Figure 3.2.1 is for the prototype system only and it needs to be further refined.

3.2.2. Inference to Pick Up the Potential Causes for the Project

Using the Object Network of the project shown in Figure 2.3.2, the potential causes in the project can be picked up. The inference to pick up the potential causes is carried out by the rules in the main module just after the project data are retrieved from the Project Database. The rules have been made by one of the authors using the available information on finance, schedule, location, site, ground, structural type and weather based on his experience in a construction company. When making the rules in NEXPERT OBJECT (Neuron Data Inc., 1988), we have tried as much as possible to use object-oriented knowledge.

Some examples of the rules to pick up the potential causes are as follows:

- Structural type $\Longrightarrow$ Attached causes.
  Most of the objects of structural types (T001-T013) has some Required Causes related to structure as subobjects (see Figure 3.2.2). The causes of the subobjects under the structural type corresponding to the project are automatically picked up.
- Building use type is stadium, auditorium, chapel, factory or pavilion$\Longrightarrow$ C00_24 (Existence of long-span roof).
- Depth of the bottom of the basement $\geq 15.0m$ $\Longrightarrow$ C00_25 (Existence of deep underground/excavation).
- Type of the structure belongs to Reinforced Concrete structure (see Figure3.2.2) and the project has the cause C08_03 (Schedule pressures)
  $\Longrightarrow$ C05_03 (Premature removal of falsework).
- Type of the structure belongs to Steel Structure (see Figure3.2.2) and the project has the causes C04_05 (Indefinite specifications), C06_08 (Lack of supervision and control) and C06_09 (Poor material management). $\Longrightarrow$ C05_07 (Poor welding quality).
- $\frac{\text{Total budget of the client} - \text{Expected total cost}}{\text{Total budget of the client}} < 0.2$ $\Longrightarrow$ C08_02 (Financial pressures).
- $\frac{\text{Total period of construction (months)}}{\text{Total floor area (m}^2\text{)}} < 0.002$ $\Longrightarrow$ C08_03 (Schedule Pressures).
- Story of the structure $\geq$ $8\ andthelocationisTokyo$ $\Longrightarrow$ C08_04 (Severe weather effects).
  As the building is a high-rise, it is likely that at the upper part of the building the weather is windy and cold if the location is Tokyo.

The rules in this system are simplistic and in the real world situation the rules are more complicated and in the near future we * plan to revise them, for instance by using empirical equations for some of the rules.

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* Tatsumi (after return to the company).

When a cause that has been picked up has some causes under it as subobjects, the causes of subobjects are also automatically picked up. The above process is repeated until all the potential causes are picked up. For instance in the case that C08_03 (Schedule pressures) is picked up by the above rule, first C01_03 is picked up, secondarily C02_07, C04_02 and C04_05 and so on (see Figure 3.2.3). Altogether 17 causes are picked up as potential causes for the project. All the potential causes are attached to the Project Network for later pattern matching. Figure 3.2.4 shows an example of a Project Network to which the potential causes have been attached.

3.2.3. Inference to Identify the Causes of Each Historical Case

First of all, the required data on each historical failure/accident case are retrieved from the Construction or Operation Failure/Accident Database for each module. Figure 3.2.5 shows the retrieved data for an example case. Some of the values of the fields, known as properties, are unknown and their values are obtained after pattern-matching.

At the next stage, the dynamic objects ** for each case are attached to some of the classes using the information obtained from the database. The classes (representing the building types, failure modes, related activities or objects such as Stadium, Collapse, Formwork, Earth work, Roof, Slab, Scaffold and Machine) are used to classify the historical cases. Some examples of the classifications are shown in Figure 3.2.6.

Using the above classifications, the rules to identify the causes of each historical case have been written. Some examples of the rules are as follows.

- Material of failed elements $\Longrightarrow$ Corresponding required causes.
  For example, the material is timber, C00_03 (Existence of Major Timber Elements) is given.
- The case is a member of the classes of Stadium, Roof and Collapse. $\Longrightarrow$ C00_24 (Existence of Long-Span Roof).
- The case is a member of the Roof and Collapse, and has a primary cause *** of "Grossly inadequate appreciation of loading conditions or real behavior of the structure" $\Longrightarrow$ C02_01 (Error in shear calculation).
- The case is a member of the classes of Slab, Collapse, Timber and Formwork $\Longrightarrow$

** "Dynamic objects" means the objects which are created temporarily by rules or by retrieving from databases. The dynamic objects do not exist in the original knowledge bases. They are shown using (+) in the object networks.

*** The information is given in Dr. Eldukair's database.

C02_05 (Error in material selection).

- The case has the primary cause of "Grossly inadequate execution and erection procedures" $\Longrightarrow$ C02_07, C06_08, C06_09 and C06_10 (see Table 3.2.1).
- The case is a member of the class of Formwork, and has the environmental effects of "Schedule pressures" *** $\Longrightarrow$ C05_03 (Premature removal of falsework).
- The case is a member of the class of RC Structure, and has the environmental effects of "Weather effects" *** $\Longrightarrow$ C05_04 (Inadequate curing of concrete).
- The object of the case is a member of the class of Crane, and does not have any primary cause $\Longrightarrow$ C06_03, C06_04, C06_06, C06_08, C06_10 and C06_11 (see Table 3.2.1).

  This type of case which does not have any primary cause mostly related to the planning or design stage is considered to be mainly related to management deficiencies or human errors at the construction stage.

The causes are identified one by one in this inference part but the causes under a cause picked up here are not automatically assigned to the case. An example of the causes picked up in a case is shown under (+)F_Cause79 in Figure 3.2.7.

Using the causes picked up for a case and the potential causes of the project, the pattern matching is carried out as explained in the following section.

3.2.4. Pattern Matching Using the Cause Sets

P is defined as the set whose samples are the causes picked up for the project and C_i as the set of the causes for the Number-i historical failure/accident case. Then PC_i is defined as the intersection of P and C_i as follows.

$$PC_i = P \cap C_i \tag{3.2.1}$$

Next, R is defined as the set whose samples are the Required Causes, L as the set of the Large Causes, M as the set of the Medium Causes and S as the set of the Small Causes. The intersection between C_i or PC_i and the set of the different cause categories are:

$$CR_i = C_i \cap R \tag{3.2.2}$$

$$CL_i = C_i \cap L \tag{3.2.3}$$

$$CM_i = C_i \cap M \tag{3.2.4}$$

$$CS_i = C_i \cap S \tag{3.2.5}$$

$$PCR_i = PC_i \cap R \tag{3.2.6}$$

$$PCL_i = PC_i \cap L \tag{3.2.7}$$

$$PCM_i = PC_i \cap M \tag{3.2.8}$$

$$PCS_i = PC_i \cap S \tag{3.2.9}$$

The sample sizes of the above sets are denoted as n_{CRi}, n_{CLi}, n_{CMi}, n_{CSi}, n_{PCRi}, n_{PCLi}, n_{PCMi} and n_{PCSi}. The difference of size between the original Cause Set of each case and the intersection with the Project Cause Set is written respectively for each cause category as:

$$nd_{CRi} = n_{CRi} - n_{PCRi} \tag{3.2.10}$$

$$nd_{CLi} = n_{CLi} - n_{PCLi} \tag{3.2.11}$$

$$nd_{CMi} = n_{CMi} - n_{PCMi} \tag{3.2.12}$$

$$nd_{CSi} = n_{CSi} - n_{PCSi} \tag{3.2.13}$$

For example, the cause set under (+)F_Cause79 corresponds to C_i and the cause set directly under (+)F79 to PC_i in Figure 3.2.7. *Sum_old* = 1444 under (+)F79 means $n_{CRi} = 1$, $n_{CLi} = 4$, $n_{CMi} = 4$ and $n_{CSi} = 4$, and *sum_new* = 1344 means $n_{PCRi} = 1$, $n_{PCLi} = 3$, $n_{PCMi} = 4$ and $n_{PCSi} = 4$. Then *sum_dif* = 100 shows the results that $nd_{CRi} = 0$, $nd_{CLi} = 1$, $nd_{CMi} = 0$ and $nd_{CSi} = 0$.

In this case, since $nd_{CRi} = 0$, none of the required causes in the case is missing in the project. Otherwise if $nd_{CRi} \geq 1$, the case is not selected as correlated case to the project. The other values (nd_{CLi}, nd_{CLi}, and nd_{CSi}) are used for the Fuzzy membership function of coherence value in the next section.

Table 3.2.1. Causes Used in the System

0. Required Causes.

(Material)

C00_01	Reinforced Concrete Structure.
C00_02	Existence of Major Steel Elements.
C00_03	Existence of Major Timber Elements.
C00_04	Existence of Prestressed Concrete Elements.
C00_05	Pre-cast Concrete Structure.

(Object-1)

C00_21	Existence of Major Bolt Elements.
C00_22	Existence of Major Bracing Elements.
C00_23	Existence of Long-Span Slab.
C00_24	Existence of Long-Span Roof.
C00_25	Existence of Deep Underground/Excavation.

(Object-2)

C00_41	Existence of Crane.
C00_42	Existence of Derrick.
C00_43	Existence of Hoist.
C00_44	Existence of Elevator.
C00_45	Existence of Helicopter.

(Condition)

C00_61	Heavy Rain.
C00_62	Heavy Snow.
C00_63	Strong Wind.

1. Planning Deficiencies.

C01_01	Error in the goal formulation of the project. (S) *
C01_02	Error in the situation assessment of the project. (S)
C01_03	Error in the building concept of the project. (S)
C01_04	Underestimation of safety measures. (S)

2. Design Deficiencies.

C02_01	Error in shear calculation. (L)
C02_02	Underestimation of shrinkage or creep. (M)
C02_03	Error in structural deflection calculation. (M)
C02_04	Failure to consider thermal deformation in members. (M)
C02_05	Error in material selection. (L)
C02_06	Error in load estimation. (L)
C02_07	Error in erection sequence. (L)
C02_08	Error in roof and drainage design. (M)
C02_09	Error in calculation of foundation settlement. (L)

3. Design Detailing Deficiencies.

C03_01	Error in bolt detailing. (L)
C03_02	Failure to consider movement of connected elements. (M)
C03_03	Inadequate bracing details. (M)
C03_04	Inadequate checking of detail modifications. (M)

---

* (L), (M) and (S) stand for Large, Medium and Small Subsidiary Causes respectively.

4. Contract Deficiencies.

C04_01 Unclear contact language and phrases. (S)
C04_02 Imprecise definition of contract requirements. (S)
C04_03 Misinterpretation of contract information.
C04_04 Unclear drawing documents. (S)
C04_05 Indefinite specifications. (S)

5. Construction Deficiencies.

C05_01 Defective falsework/formwork. (L)
C05_02 Improper falsework/formwork connections. (L)
C05_03 Premature removal of falsework. (L)
C05_04 Inadequate curing of concrete. (L)
C05_05 Improper mixing of concrete. (L)
C05_06 Improper connection between structural members and supports. (L)
C05_07 Poor welding quality. (L)
C05_08 Inadequate bracing of structural members. (L)
C05_09 Improper construction methods. (L)
C05_10 Inadequate equipment usage. (L)

6. Management Deficiencies

C06_01 Improper work schedules. (M)
C06_02 Improper planning procedures. (M)
C06_03 Inadequate levels of workmanship. (M)
C06_04 Improper training and orientation sessions. (M)
C06_05 Inadequate time and cost integration management. (M)
C06_06 Lack of coordination and cooperation among work parties. (M)
C06_07 Lack of defining proper responsibilities for executing work tasks. (M)
C06_08 Lack of supervision and control. (L)
C06_09 Poor material management. (M)
C06_10 Poor equipment and tool usage. (M)
C06_11 Lack of communication procedures. (M)

7. Operation Deficiencies.

C07_01 Improper utilization of building documents. (M)
C07_02 Improper utilization of safety procedures. (M)
C07_03 Inadequate inspection and maintenance procedures. (M)
C07_04 Rapid deterioration of elements. (L)
C07_05 Corrosion of steel elements. (L)
C07_06 Scouring of foundation. (L)

8. External Deficiencies.

C08_01 Political pressures. (S)
C08_02 Financial pressures. (S)
C08_03 Schedule pressures. (S)
C08_04 Severe weather (temperature/dryness/humidity) effects. (S)
C08_05 Impact of equipment loads. (L)
C08_06 Overload or accident during construction. (L)

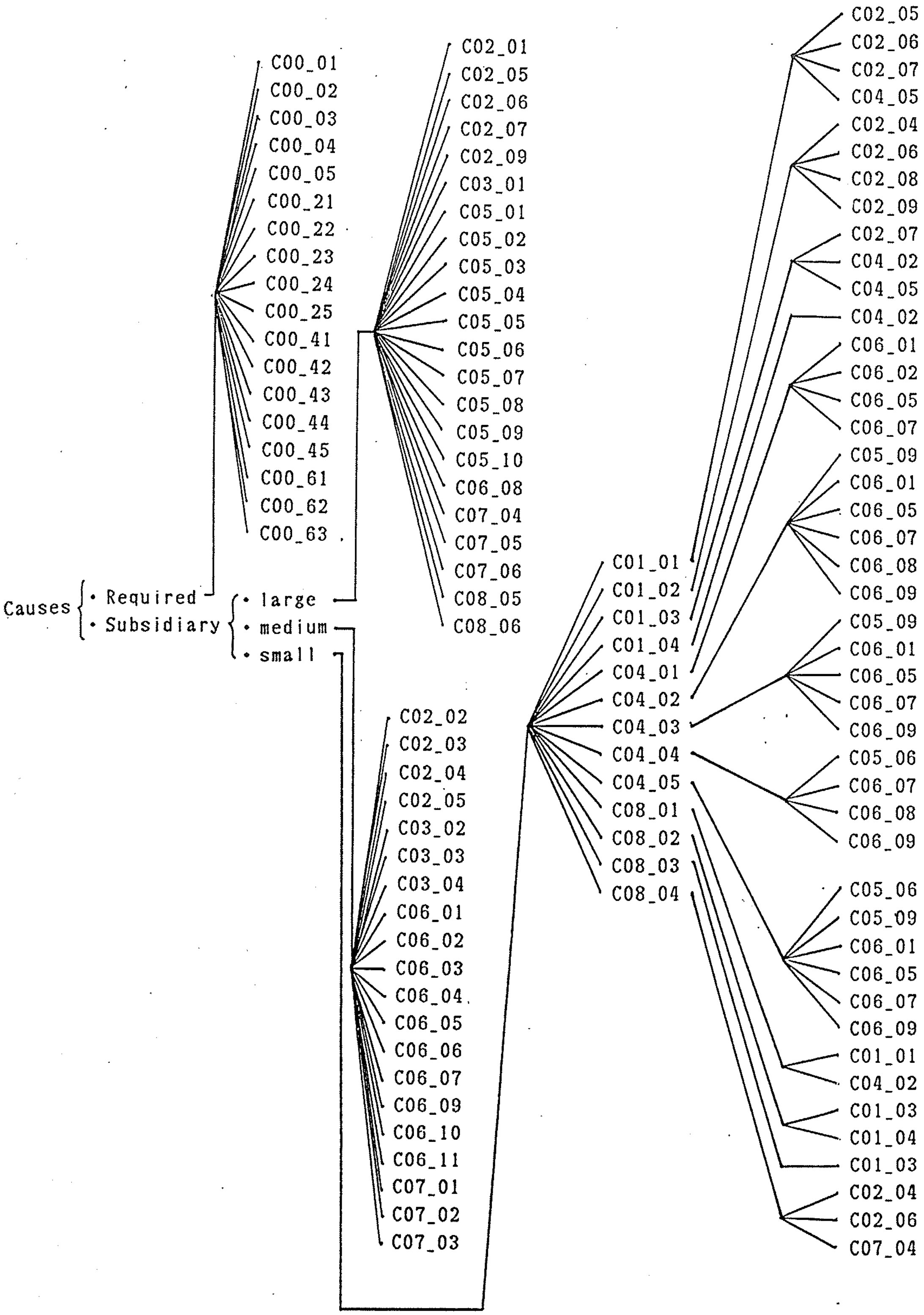
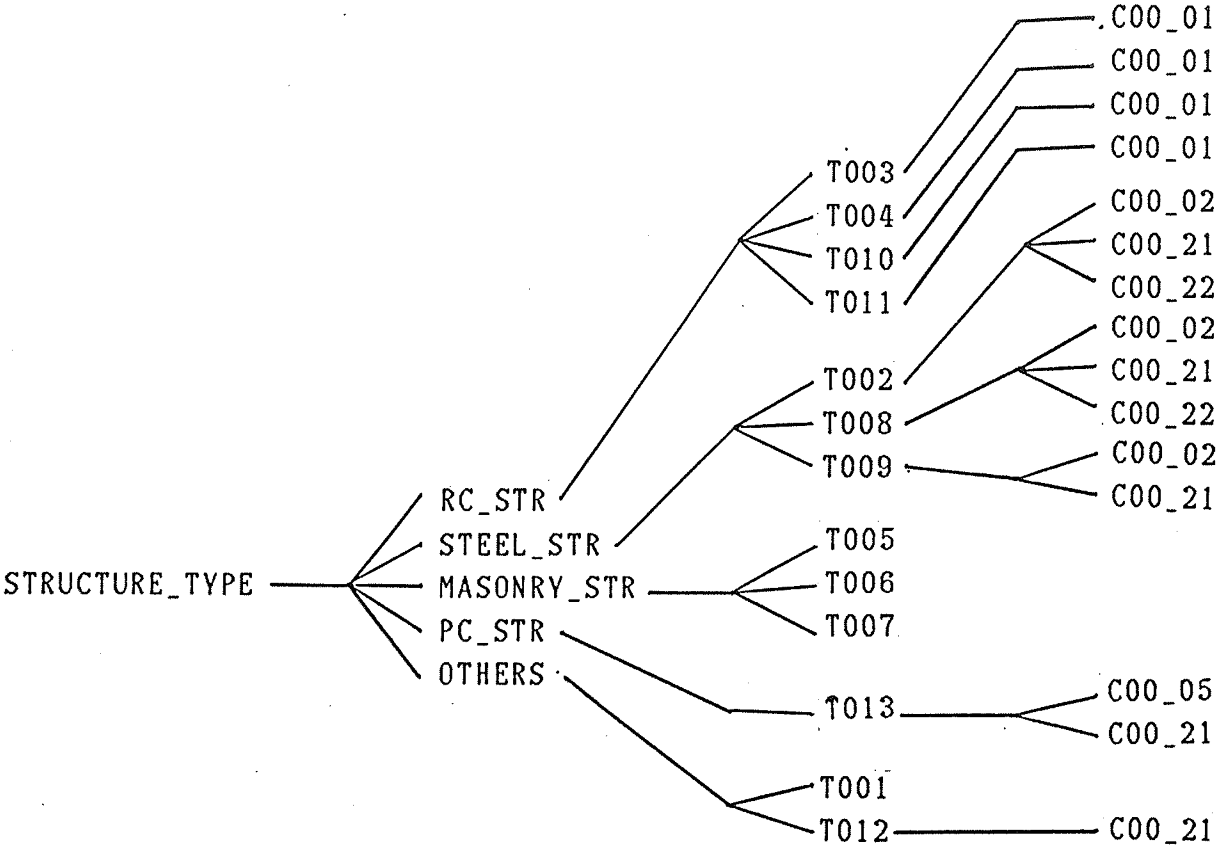


Figure 3.2.1. Object Network of the Causes



(TYPE OF STRUCTURE)

T001	Wood Frame
T002	Light Metal
T003	Concrete Shear Wall w/Frame
T004	Concrete Shear Wall wo/Frame
T005	Masonry Shear Wall w/Frame
T006	Masonry Shear Wall wo/Frame
T007	Unreinforced Masonry
T008	Braced Steel Frame
T009	Moment-Resisting Steel Frame
T010	Moment-Resisting Ductile Concrete
T011	Moment-Resisting Non-Ductile Concrete
T012	Tilt-up
T013	Pre-Cast Concrete Frame

Figure 3.2.2. Structural Types and Causes

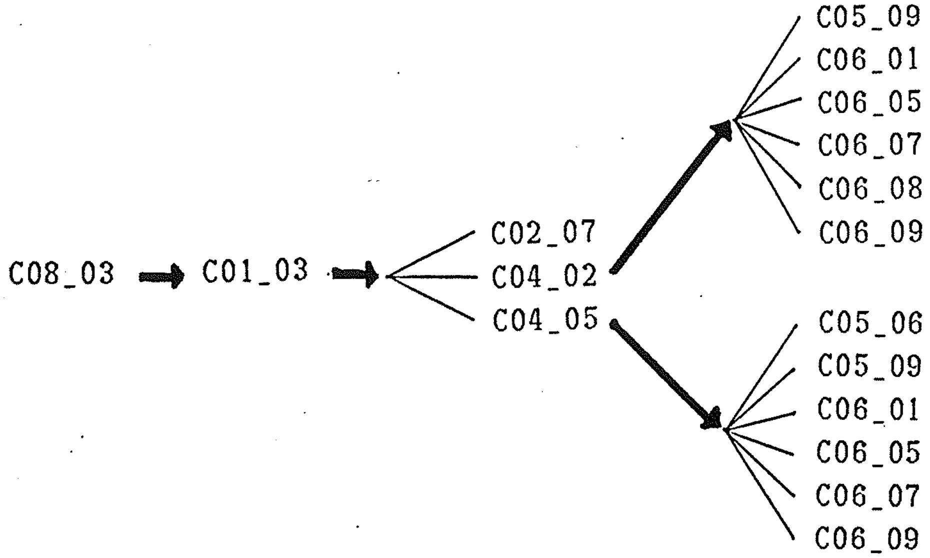


Figure 3.2.3. Extension of the Causes

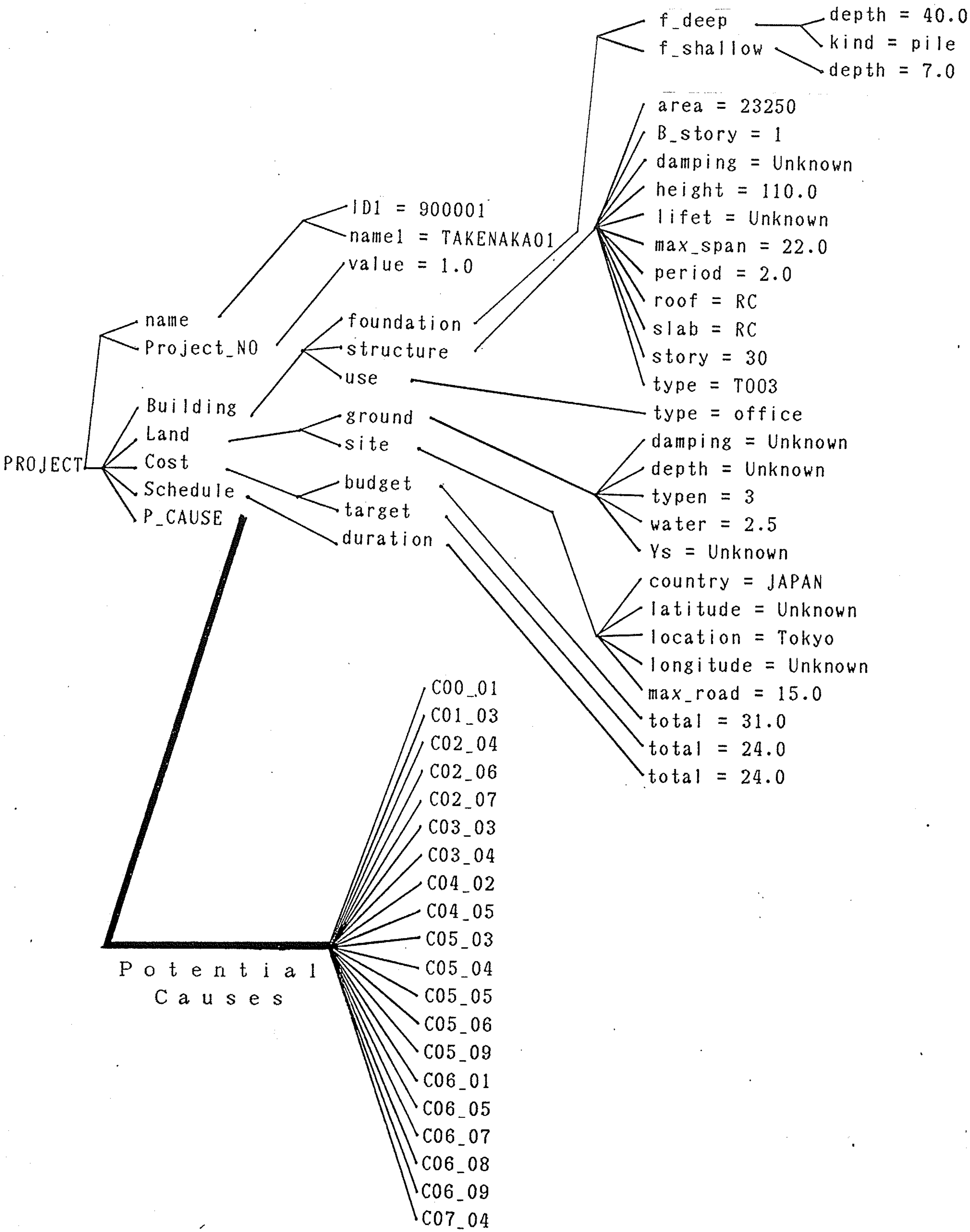


Figure 3.2.4. Object Network of the Project with the Potential Causes Attached

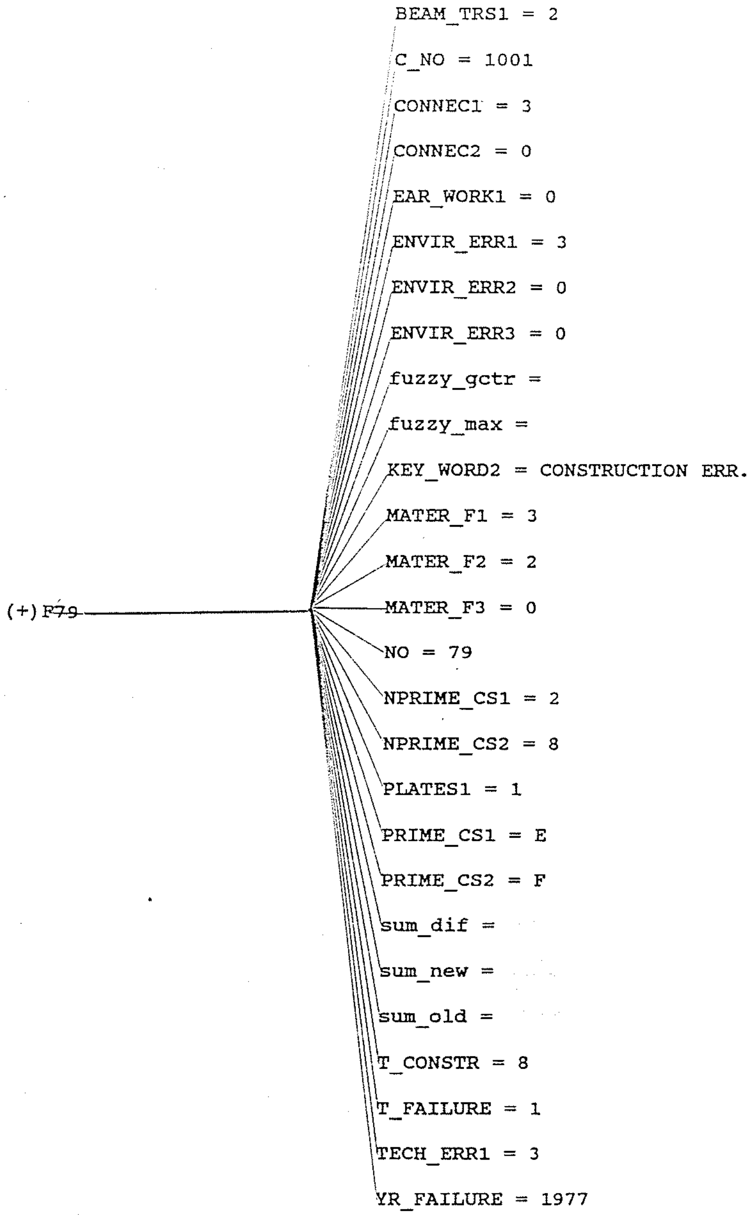


Figure 3.2.5. Properties of a Historical Case

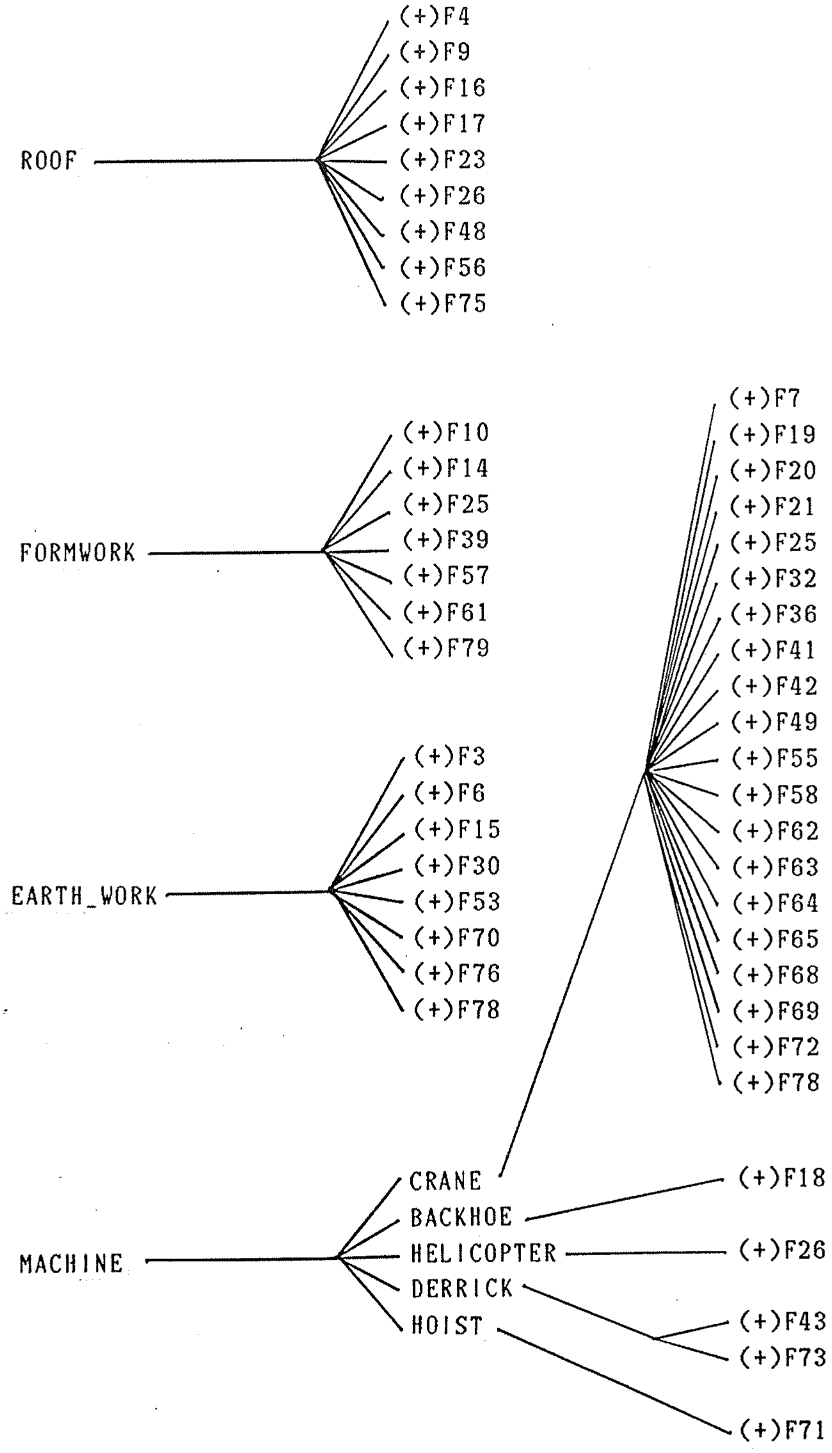


Figure 3.2.6. Examples of the Classification of the Historical Cases

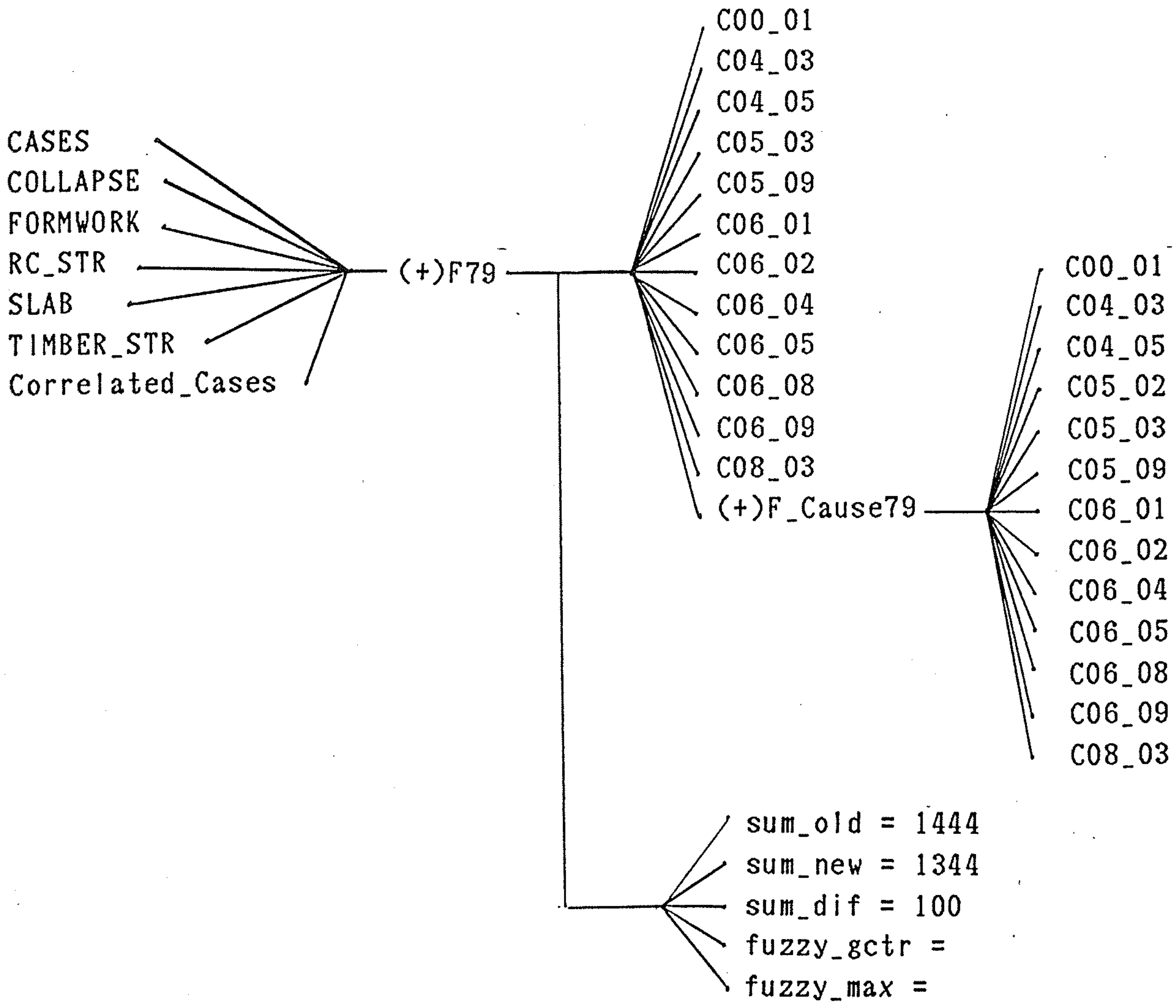


Figure 3.2.7. Object Network of a Historical Case after the Pattern Matching of the Causes

3.3. Introduction to the Fuzzy Set Theory as Applied to Pattern Matching

In the previous section, we have discussed how the Cause Network is used in pattern matching. The subsidiary causes have been categorized into Large, Medium and Small causes and as this is based on the experience and intuition of human experts there is inevitably some fuzziness in their definition. The utilization of the fuzzy set theory in this kind of field is considered to be appropriate (Dong, 1986; Klir et al., 1988).

The coherence between the project and each historical failure/accident case, is represented by the fuzzy vector of coherence value, $\mathbf{C}_V$. In this study, the coherence value is discretised into 11 values, from 0 to 100 % at equal intervals of 10 %. In the case of perfect matching (which means that all the causes for a case match those of the project), $\mathbf{C}_V$ is equal to $\mathbf{C}_{V_0}$ shown by Eq.(3.3.1).

$$\bar{\mathbf{C}}_{V_0} = [0,0,0,0,0,0,0,0,0,0,1] \tag{3.3.1}$$

The large, medium and small subsidiary cause have respectively the transition matrices $\mathbf{M}(l)$, $\mathbf{M}(m)$ and $\mathbf{M}(s)$. Those transition matrices have a function to change the membership functions of coherence value to the left-hand side when some subsidiary causes are missing. This idea is based on the theory of fuzzy system (Mizumoto, 1988).

$$Subsidiary\ Causes \begin{cases} \cdot\ large & \mathbf{M}(\mathrm{l}) \\ \cdot\ medium & \mathbf{M}(\mathrm{m}) \\ \cdot\ small & \mathbf{M}(\mathrm{s}) \end{cases} \tag{3.3.2}$$

When i large, j medium and k small causes in the case are missing in the project, the $\mathbf{C}_V$ can be calculated as shown below.

$$\mathbf{C}_V = \mathbf{M}(l_i) \circ ... \circ \mathbf{M}(l_1) \circ ... \circ \mathbf{M}(m_j) \circ ... \circ \mathbf{M}(m_1) \circ \mathbf{M}(s_k) \circ ... \circ \mathbf{M}(s_1) \circ \mathbf{C}_{V_0} \tag{3.3.3}$$

where

$\mathbf{C}_{V_0}$: Fuzzy Vector of Coherence Value at Total Matching

$\mathbf{C}_V$: Fuzzy Vector of Coherence Value at Partial Matching

$\mathbf{M}(l)$: Fuzzy Transition Matrix of Large Causes

$\mathbf{M}(m)$: Fuzzy Transition Matrix of Medium Causes

$\mathbf{M}(s)$: Fuzzy Transition Matrix of Small Causes

$\mathbf{M}(l_i) = ... = \mathbf{M}(l_1) = \mathbf{M}(l)$

$$\mathbf{M}(m_j) = ... = \mathbf{M}(m_1) = \mathbf{M}(m)$$
$$\mathbf{M}(s_k) = ... = \mathbf{M}(s_1) = \mathbf{M}(s)$$

At present, any methodology to obtain the transition matrices from experience does not exist yet. The first approximations of $\mathbf{M}(l)$, $\mathbf{M}(m)$ and $\mathbf{M}(s)$ have been obtained intuitively as shown in Equations 3.3.4 - 3.3.6, by comparing the effects of large, medium and small causes. They need to be verified and refined by experts in this field through the performance of the system in the future.

$$\mathbf{M}(l) = \begin{pmatrix} 1.0 & 1.0 & 1.0 & 0.9 & 0.9 & 0.7 & 0.3 & 0.2 & 0 & 0 & 0 \\ 0 & 0 & 0.7 & 0.7 & 0.8 & 0.8 & 0.5 & 0.3 & 0.2 & 0 & 0 \\ 0 & 0 & 0 & 0.5 & 0.5 & 0.8 & 0.8 & 0.5 & 0.3 & 0.2 & 0 \\ 0 & 0 & 0 & 0 & 0.4 & 0.5 & 0.8 & 0.8 & 0.5 & 0.3 & 0.2 \\ 0 & 0 & 0 & 0 & 0 & 0.2 & 0.5 & 0.8 & 0.8 & 0.5 & 0.3 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.2 & 0.5 & 0.8 & 0.8 & 0.5 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.2 & 0.5 & 0.8 & 0.8 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.2 & 0.5 & 0.8 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.2 & 0.5 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.2 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \tag{3.3.4}$$

$$\mathbf{M}(m) = \begin{pmatrix} 1.0 & 1.0 & 1.0 & 0.9 & 0.6 & 0.2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.5 & 0.6 & 0.9 & 0.6 & 0.4 & 0.2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.3 & 0.5 & 0.9 & 0.6 & 0.4 & 0.2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.2 & 0.5 & 0.9 & 0.6 & 0.4 & 0.2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.2 & 0.5 & 0.9 & 0.6 & 0.4 & 0.2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.2 & 0.5 & 0.9 & 0.6 & 0.4 & 0.2 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.2 & 0.5 & 0.9 & 0.6 & 0.4 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.2 & 0.5 & 0.9 & 0.6 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.2 & 0.5 & 0.9 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.2 & 0.5 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.2 \end{pmatrix} \tag{3.3.5}$$

$$\mathbf{M}(s) = \begin{pmatrix} 1.0 & 0.9 & 0.7 & 0.2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.6 & 0.9 & 0.5 & 0.2 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.5 & 0.9 & 0.5 & 0.2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.5 & 0.9 & 0.5 & 0.2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.5 & 0.9 & 0.5 & 0.2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.5 & 0.9 & 0.5 & 0.2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.5 & 0.9 & 0.5 & 0.2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.5 & 0.9 & 0.5 & 0.2 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.5 & 0.9 & 0.5 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.5 & 0.9 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.5 \end{pmatrix} \tag{3.3.6}$$

Figure 3.3.1 shows how the membership functions of coherence value changes from $\mathbf{C}_{V_0}$ (membership function at total matching) when a single Large, Medium or Small cause is missing.

As the measure of the pattern matching, the largest coherence value which a membership function takes the maximum values is used in the current system. When the value is more than or equal to 50%, the case is selected as a strongly correlated case.

In the remaining section, the mathematics of the fuzzy set theory used in this research is briefly described below.

Let $\mathbf{M}_P = [p_{i,k}]$, $\mathbf{M}_Q = [q_{k,j}]$ and $\mathbf{M}_R = [r_{i,j}]$ be the membership matrices of the relations such that

$$\mathbf{M}_R = \mathbf{M}_P \circ \mathbf{M}_Q. \tag{3.3.7}$$

We can then write, using this matrix notation,

$$[r_{i,j}] = [p_{i,k}] \circ [q_{k,j}], \tag{3.3.8}$$

where

$$r_{i,j} = \max_k \ min(p_{i,k},\ q_{k,j}). \tag{3.3.9}$$

To make those equation simple, the following definitions are used.

$$\begin{aligned} a \wedge b &= min(a, b) \\ a \vee b &= max(a, b) \end{aligned} \tag{3.3.10}$$

To explain how Eq.(3.3.3) can be calculated, a simple example is shown as follows.

$$\begin{aligned} &\begin{pmatrix} 1 & 0.2 & 0.1 \\ 0.3 & 1 & 0.2 \\ 0.1 & 0.2 & 1 \end{pmatrix} \circ \begin{pmatrix} 1 \\ 0.2 \\ 0.1 \end{pmatrix} \\ = &\begin{pmatrix} (1 \wedge 1) \vee (0.2 \wedge 0.2) \vee (0.1 \wedge 0.1) \\ (0.3 \wedge 1) \vee (1 \wedge 0.2) \vee (0.2 \wedge 0.1) \\ (0.1 \wedge 1) \vee (0.2 \wedge 0.2) \vee (1 \wedge 0.1) \end{pmatrix} = \begin{pmatrix} 1 \\ 0.3 \\ 0.2 \end{pmatrix} \end{aligned} \tag{3.3.11}$$

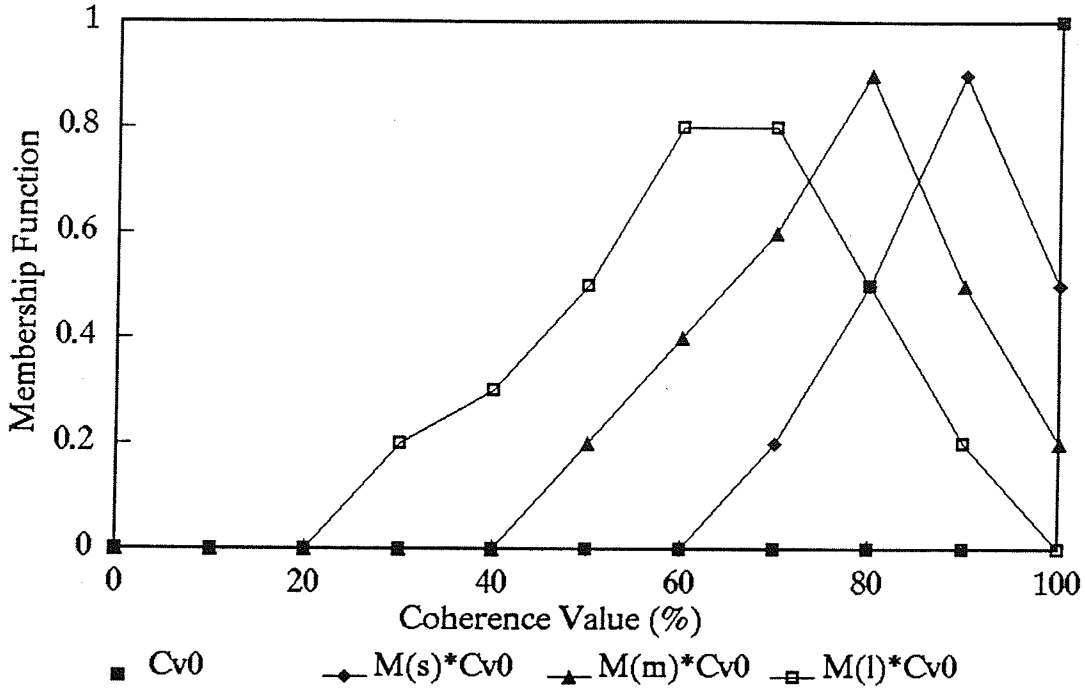


Figure 3.3.1. **Transition of the Membership Function by Missing Causes**

3.4. Collection of Failure/Accident Data

3.4.1. Introduction

Incidents of structural failure and, or construction accidents are routinely covered in the popular media, more so if the case results in loss of human life and, or great financial damages. Undoubtedly, these kinds of events are newsworthy and the public has every right to know if constructed facilities and the construction process itself are safe. However, for engineers and architects, these incidents provide opportunities for obtaining invaluable lessons for reviewing and, where necessary, modifying the state of art of the construction methods, materials and the theories of design and analysis. The engineering community has in the recent past moved away from its reluctance and appears to be more ready to talk about failures. The importance of studying failures is being increasingly recognized and calls have been made for establishing a database of such events based on the results of impartial studies by staff qualified in forensic engineering, design and construction methods.

A primary task in creating a database of structural failure and, or construction accidents is classifying the incident. An incident can be classified in one of many ways but for it to be useful a careful analysis of the causes is necessary. Only then can minor insignificant errors, some of which inevitably arise even in the best projects, can be weeded out and the primary and secondary causative mechanisms identified. This is an important task, made even more urgent as a result of the litigious climate that often follows a failure or accident. Given the present situation in the United States regarding insurance for the construction industry and the litigations following a failure and, or accident gathering information is at times not easy but the importance of such a venture has been recognized by all concerned parties.

For each incident information on the nature, sources, causes, consequences and measures to control failures and accidents needs to be collected. This information can then be stored in a database using a format that makes the the database readily accessible to users. In addition, modifications or additions to the database as more data becomes available should be made possible. Also, if the procedure for reporting, entering, modifying, retrieving can be standardized then sharing of data is facilitated.

The importance of studying failure and accidents and creating a database of such events to disseminate the knowledge gained from their study has prompted various engineering and architectural societies to organize committees on forensic engineering and dissemination of failure information. The ASCE for instance created the ASCE Technical Committee on Forensic Engineering, ASCE-TCFE in 1982, the Committee on Dissemination of Failure Information, ASCE-CDFI, and the Committee on Publications for the "Journal of Performance of Constructed Facilities". Engineers, architects, insurance companies and the legal profession have in some cases joined hands. The most promising example of this is the Architecture and Engineering Performance Information Center, AEPIC, at the University of Maryland. AEPIC has been created for the express purpose of gathering a database on failure and making it available * to the larger community. While there is no similar type of center which gathers data on construction accidents the Office of Safety and Health Administration, OSHA, does maintain an extensive nationwide database. **

Besides the above databases, there are other databases which contain information on structural failure. Some of these databases such as WestLaw, a legal database, are privately owned and accessing the database is possible on payment of a fee. Also, there have been several reports published by researchers who have investigated failure incidents. Some of them are:

(1) Eldukair (1988) reported 1198 cases of structural failure and construction accidents. This database was compiled by the author as part of his doctoral dissertation based on reports in "Engineering News Record" from 1975 to 1986.
(2) Matousek and Schneider (1976) described 800 European failures from 1960 to 1976.
(3) Smith (1976, 1977) described 147 bridge failures from 1896 to 1975.
(4) Walker (1980) reviewed 120 building failures in Britain.
(5) Melchers, Baker and Moses (1983) reported 212 cases of failure.
(6) Hadipriono (1982, 1985) analyzed 150 cases in the US and elsewhere.
(7) FitzSimmons (1978) is a review of the report, in German, by Matousek and Schneider (1976).
(8) Frazek (1979) is a summary of errors in concrete structures conducted by the ACI

The above reports except for the first one are mostly of a statistical nature which do not provide enough information on the individual cases. These studies provide overall

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* As of this writing the database is still in the process of being entered into the computer and is unavailable to anyone. (Oral communication from Prof. John Loss, AEPIC, July, 1990).

** The OSHA database can be accessed under the Freedom of Information Act by sending a written request to the their office in Washington, D.C.

trends and for the most part contain summaries based on statistical analysis of failure and, or accident data. The exception is the database compiled by Eldukair (1988). This database provides an extensive record of information for each structural failure and construction accident. In addition, extensive references are given for each incident.

Data on structural failure can also be found in the many books and publications that have appeared in the field of forensic engineering spurred partly by the increasing role of engineers in the lawsuits which inevitably arise following a failure or accident. The information contained in the books and publications tend for the most part to be of a more general nature and discussions of specific structural failure and construction accidents are avoided. Even if information on individual cases are provided, it is brief and not sufficiently detailed for the purpose of compiling a database. The exception to this rule are the very in-depth analysis of structural failure conducted by the National Bureau of Standards, Leyendecker, et. al. (1973) Lew, et. al. (1978), and Carino, et. al. (1982), Lew, et. al. (1983), and Culver, et. al. (1987).

As part of the effort for this project we set out to determine the sources of information of structural failure and, or construction accidents in the United States. A great amount of effort was spent in searching books, journal articles, publications of conventions of various professional societies, seminar and workshop publications, individual case study publications, university publications, private company publications and publications Also, many experts in the fields of structural design, construction engineering, and forensic engineering were contacted.

In the next part of the this section the various sources of information are listed and following this we discuss the dataset that is used in this report.

3.4.2. Sources of Information

A lot of information on structural failure and, or construction accidents is available in the open literature. The sources that we looked into are for the most part readily accessible in just about any engineering library. At the beginning of the data collection phase we were of the opinion that information of this nature is difficult to come but what we found is that there is a lot of information that is accessible. The sources of information * that we were able to identify are briefly discussed below.

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* Given the time that we had for this study we have concentrated on United States sources.

Books on Structural Failure and Construction Disasters

There are quite a few books which discuss the subject of structural failure and, or construction accidents but most treat the subject from a very general perspective and are not useful for creating a database of failure and accidents. Books on structural failure and construction disasters which provide brief case histories have been available for some time. The books that discuss structural failure and, or construction accidents are:

- "Construction Failure" by Jacob Feld (1968)
- "Lessons from Failures of Concrete Structures" by Jacob Feld (1972)
- "Construction Disasters: Design Failures, Causes, and Prevention" by Steven Ross (1984)
- "Structural and Foundation Failures", by Barry B. LePatner and Sidney Johnson (1982)
- "Concrete Problems, Causes and Cures", by John C. Ropke (1982)
- "Building Failures: Case Studies in Construction and Design", by T. H. McKaig (1962)
- "Engineering Structural Failures", by Rolt Hammond (1956)
- "Foundation Failure", C. Szechy (1961)
- "Learning from Failures", R. N. Raikar (1987)
- "Failure and Repair of Concrete Structures", S. Champion (1961)
- "Engineering Failures and Their Lessons", E. Godfrey (1924)

Of the books listed above, the books by Feld (1968) and McKaig (1962) even though they were published many years ago are the most useful. Both books present brief case histories of various incidents of structural failure and construction disasters. The book"Construction Disaster" is an outline of reports of structural failure and construction disasters taken from the Engineering News Record, a weekly McGraw-Hill publication for the construction industry. The book by LePatner and Johnson (1982) examines thirty-two disasters from a technical and legal point of view. The book by Ropke deals with the specific issues associated with curing of concrete structures during construction. The books by Hammond (1956), Szechy (1961), Champion (1961) and Godfrey (1924) are outdated. The book by Raikar (1987) is based on the author's experience in India. As useful as some of the above books are the information contained in them are lacking in sufficient detail for creating a database of building failures and, or construction accidents.

Besides the books listed above, there are other books, such as "Forensic Engineering", Carper (1988), which are of a more general nature and they discuss various aspects of failure, forensic engineering, and the increasing role of engineering and architectural professionals as expert witnesses in litigations ensuing from a structural failure and, or construction accidents. Also, there are many books on construction accidents and safety. However, these books do not contain information on specific cases of structural failures and, or construction accidents but they do provide useful information on related issues. They have been useful to us in among other things in developing a scheme for classifying the causative mechanisms.

Professional Journals

In the last few years the importance of the invaluable lessons that can be learnt from the analysis of failure has been recognized by many professional organizations and many articles have appeared in the traditional publications of various professional organizations. This interest has been partially driven by the increasing role of engineers and architects in lawsuits stemming from structural failures and, or construction accidents. The monthly magazine, "Civil Engineering", published by the ASCE routinely covers various aspects of failure of constructed facilities and the ASCE has formulated an aggressive policy for collecting and disseminating information on failure. The most visible aspect of this policy is the publication of the monthly " Jornal of Performance of Constructed Facilities". In addition, many articles on structural failure can be found in various other journals such as:

- "Engineering News Record", McGraw-Hill
- "Journal of Structural Engineering", ASCE
- "Journal of Construction Engineering & Management", ASCE
- "Journal of Geotechnical Engineering", ASCE
- "Journal of Professional Issues in Engineering", ASCE
- "Structural Safety", Elsevier
- "Journal of Engineering and Technology Management", ASCE
- "Concrete International"

Many of the above publications also cover the field of construction accidents. Articles on construction accidents can also be found in the journals listed below:

- "Journal of Occupational Accidents", Elsevier

- "Journal of Safety Engineering"
- "Journal of Safety Research", Pergammon
- "Accidents", Pergammon

For the most part the coverage of events involving failure and, or accidents in the above journals tend to be of a general statistical summary of various cases. Only a few important case histories are treated individually but the vast majority of the smaller and, or less spectacular incidents are not fully reported. Among the above publications only the "Engineering News Record", has articles which provide information on specific instances but even these are usually brief. However, for the moment only this journal publishes information of this nature on a regular basis. At the same time the articles in the other journals, though they do not discuss individual events, have been useful in locating sources of raw information and in developing methodologies for classifying the causes of failure.

Conferences, Workshops, Lectures

In addition, to the extensive coverage of structural failures and construction accidents in engineering journals, there have been many conferences, special workshops and lectures on failure sponsored by the ASCE, the AIC, etc. The participation of architects, lawyers and those in insurance have greatly enhanced the value of some of these proceedings. A few of the conferences, workshops and lectures are listed below.

- "Reducing Failures of Engineered Facilities", ASCE, 1985
- "Structural Failures: Modes, Causes, Resposibilities", ASCE, 1973
- "Seminar Course Manual: Lessons from Failures of Concrete Buildings", ACI, 1982
- "Symposium on Structural Failure in Buildings", The Institution of Civil Engineers, London, 1980
- "Construction Failures: Legal and Engineering Perspectives", ABA, 1983
- "Learning from Experience / Avoiding Failures", Canadian Building Congress, 1985
- "Engineering Foundation Conferences on Structural Failures-I & II", Engineering Foundation, 1983 & 1987
- "Structural Failures: Lecture Notes", University of Colorado at Boulder, 1987

As in the case of the journal articles the coverage of events involving structural failure and, or construction accidents tend to be of a more general nature. Only a few cases are treated individually and most of the discussion is on failure classification, statistics of failure, forensic engineering, the role of engineers, architects and lawyers in lawsuits emanating from failures, etc. Undoubtedly, a lot of these are motivated by the increasing role of engineers and architects in the litigation following structural failure and, or construction accident.

Architecture and Engineering Performance Information Center

AEPIC is a non-profit center formed in 1982 at the University of Maryland for the purpose of collecting and disseminating information on failure. AEPIC received its initial grant from the National Science Foundation with additional support from the University of Maryland, Victor O. Schinnerer & Co., the American Society of Civil Engineers, the National Society of Professional Engineers, Sperry/Univac Corporation and others. AEPIC has been successful in collecting an extensive amount of information on structural failure and its data are stored in computer files and, or in hard copies. The data when it is ready will be accessible * by computer and an on-line search can be made by selecting keywords which will then be used to search for those events with the matching keywords.

The data at AEPIC is made up of:

- computerized databases containing relevant information on individual cases.
- computerized "Performance Incident" or "Case Files" which contain professional and informed reports on performance and malfunctions.
- computerized "Citation Files" on references to published information.
- dossier library containing documentation of factual information.
- visual materials library for photographs, slides and other visual material.
- reference library for current and historical codes, standards and pertinent technical references.

From the point of view of this study, the raw, factual information, free of sensitive personal information only, at AEPIC represented the best potential source of data. However, for the moment the computerized database and the vast literature are inaccessible. However, the report "Identification of Performance Failures in Large Structures and Buildings", AEPIC (1987) provides a useful summary of building failures in the United States.

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* The database is likely to be unavailable to anyone in the foreseeable future. (Oral communication from Prof. John Loss, AEPIC on July, 1990).

Other Databases

OSHA

The Office of Safety and Health Administration maintains a computerized database of accidents in the work place throughout the United States in its national headquarters in Washington, D.C. The OSHA database can be accessed under the Freedom of Information Act. The OSHA database at OSHA is based on reports of accidents at the work place and violations, if any, of OSHA safety regulations. A search of the database using the keywords "building" and "collapse", as advised by the staff at the Office of Management Data Systems, resulted in a thick report made up of citations of inspections by the Federal OSHA and certain states which operate their own safety and health programs under OSHA guidelines. As the OSHA database is geared towards safety violation and observance of OSHA regulations the report produced by the above search did not contain much information relevant for this study.

Legal Databases

An example of a legal database is WestLaw which is owned privately by West Inc. This database is a compilation of Federal and State Appellate Court proceedings and the cases that involve building and civil structures failures can be found. The information in this database could conceivably be biased because of its heavy reliance on expert opinions given by engineers and architects hired by attorneys representing various interests in the lawsuits. We did not make use of this database in our study.

Private Databases

As engineers and architects have become more involved in lawsuits following structural failures and, or construction disasters many firms and individuals have built a private database of the cases that they have been involved in. These databases represent a treasure of useful information but given the circumstances in which they were compiled they may for the most part be inaccessible. Once in a while there is a book like Feld (1968) based on the authors' experience of investigating failures. We did receive two invitations * to examine the private records of prominent consulting engineers, one of which we accepted and the other we couldn't because of our time limitation.

National Bureau of Standards

The National Bureau of Standards does not collect data on structural failure or

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* Dr. Piotr Moncarz, Failure Analysis, Menlo Park, Ca. and Mr. Neal FitzSimmons, Principal Engineers, agreed to let us look at their private records.

construction accidents but NBS has produced a few special publications that deal with the subject of failure. The reports, altogether five in number, from 1973 to 1987 are the results of very detailed, in-depth analysis of the technical causes of well-publicized, catastrophic failures, Leyendecker, et. al. (1973) Lew, et. al. (1978), and Carino, et. al., (1982), Lew, et. al. (1983), and Culver, et. al. (1987),. The quality of the reports are impeccable and though it is not reasonable to expect the same detailed investigation for other incidents, if for nothing else the cost involved, the information contained in these reports are almost ideal for compiling the type of database that is required for this study.

Eldukair's Database (1988)

Eldukair (1988) compiled a computerized database of 604 cases of structural failure and 594 cases of construction accidents in the United States as part of his doctoral dissertation at the University of Maryland. His database has been compiled from "Engineering News Record" and other independent investigations of structural failure and construction accidents for the period 1975-1986.

This database contains information on the nature, sources, causes, consequences and measures to control failures and accidents for each incident. Dr. Eldukair was generous in his willingness in sharing his database with us and his database forms the main nucleus of the data that we have used in this study. In the next section we discuss his database and the changes that we introduced.

3.4.3. Database Used in This Study

Eldukair's Database (1988)

Eldukair's database (1988) contains information on structural failures and construction accidents resulting from the variation within and departure from common practices and failures from purely natural disasters have been excluded. The information contained for each incident is shown in Table 3.4.1. The items used in the modules are shown down to the smallest items in the figure. Figure 3.4.1 shows the data structure of an example record in the original database.

Modifications to Eldukair's Database

Eldukair's (1988) reporting scheme for structural failure and construction accidents is quite comprehensive and his database compiled in dBase III^+ is in a form which can be readily accessed by the expert system shell NEXPERT OBJECT that we had selected to use for this study. Therefore, we made very little structural changes to his database. The changes that we introduced are:

- addition of the field "Fail Stage" which has information on whether the failure occurred during the construction or the operation stage,
- exclusion of civil structure cases,
- splitting the data into two subdatabase, one on failure/accident during construction and the other during operation, stages,
- addition of the field "No." which is the sequential number of the case in the subdatabase, and
- addition of a new item "Schedule Pressures" under environmental effects of Item 4.

We attempted to verify the information contained in the database by referring to sources other than those referred in the database, as explained in Item 1 above. Unfortunately, for the most of the cases it was not possible to provide an independent verification * and we were forced to look at the same references Eldukair used while constructing his database.

Out of the 322 structural failure/accident case records in the original database, 79 cases have been retained in the construction subdatabase and 88 cases in the operation subdatabase.

Eldukair's (1988) database is based on reports in the "Engineering New Record" for the period 1975 to 1986 and we have been collecting information for the period since 1986. The data after 1986 will be entered in exactly the same format used by Eldukair (1988).

3.4.4. Conclusions

We were able to find in the literature a lot of information on structural failure and construction accidents. The information is available from books, journals, private records of individuals and companies, publications of governmental organizations, data centers like AEPIC, proceedings of conferences, seminars and workshops, etc. While AEPIC could in the future be a very good, if not the best, source of information, for the moment the other sources need to be relied on.

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* Once the database at AEPIC is available then it might be possible to do this kind of independent verification by examining other sources.

In most cases, the information on individual incidents is not sufficiently detailed for it to be used in creating a database. We were fortunate in obtaining the database compiled by Eldukair (1988) and his database is in a form which is compatible with our needs and is easily accessible. Information on each individual case is broken down in terms of the nature, sources, causes, consequences and measures to control failures and, or accidents. We have used his database with very little modification in our study.

Table 3.4.1. Eldukair's Database Structure

Item 1. Source of the case

- case report number
- reporter page number
- reference information
- date of the report

Item 2. Type of Failure

- collapse
- loss of safety
- loss of serviceability
- reasons

Item 3. Type of Construction

- commercial Building
- industrial project
- highway project
- tunnel project
- dam project
- underground / excavation
- bridge project
- residential project
- stadium project
- hospital project

Item 4. Sources of Error in the Building Process

- errors in the technical procedures
    - errors in planning
    - errors in design
    - errors in construction
    - errors in operation
- errors in management practice
    - errors in defining responsibilities
    - errors in communications
    - errors in cooperation
- construction accident effects
    - errors in the work preparation & execution
    - errors in supervision & control
- environmental effects
    - political pressures
    - financial pressures
    - schedule pressures
    - weather effects

Item 5. Type of Failing Element and Principal Material

Classification of elements

- foundation elements
    - soil
    - pile
    - raft
    - footings
    - basement wall, sheet piling, trench

- vertical elements
    - column, pier
    - wall
    - tie, hanger
    - bracing
- beam & truss elements
    - foundation beams
    - floor beams
    - roof beams
    - floor truss
    - roof truss
    - brackets
- Plate and slab elements
    - flat slabs
    - non-flat slabs
    - waffle slabs
- connection elements
    - cables
    - anchorage
    - formwork

Classification of materials of failed elements

- masonry and mass concretes
- timber
- reinforced concrete
- prestressed concrete
- pre-cast concrete
- steel elements
- aluminum elements
- plastic elements
- glass and cladding elements
- rock and earth materials

Item 6. Manner of Failure

Item 7. Age and Year of Deficiency

- number of years after completion of the structure
- during construction

Item 8. Sources of Errors by Participation / Human Behavior

- persons involved
- human behavior
    - insufficient knowledge
    - lack of education/training
    - lack of foresight/imagination
    - lack of ability to communicate
    - lack of authority in decision
    - reliance on others
    - underestimation of influence
    - ignorance, negligence, carelessness
    - objectively unknown situations

Item 9. Principal Causes of Failure

Primary Causes (may act independently to cause failures)

— Grossly inadequate appreciation of loading conditions or real behavior of the structure.
— Grossly inadequate appreciation of loading conditions or real behavior of the connections.
— Grossly excessive reliance on construction accuracy.
— Serious mistakes in design calculations and detail drawings.
— Grossly inadequate information of contract documents.
— Gross contravention of contract documents requirements and instructions.
— Gross complexity of the project system.
— Grossly inadequate execution and erection procedures.
— Gross, but unforeseeable, misuse, abuse and/or sabotage, deterioration

Secondary Causes of Failure (may cause failure, only if two or more factors act together)

— lack of engineering responsibilities.
— neglect of environmental effects (political, financial, weather).
— deficiencies in material and equipment usage.
— deficiencies in engineering specialization.
— improper workmanship.
— lack of training and orientation sessions for the work force.
— lack of cooperation and coordination of work activities.
— lack of supervision and control of work activities.
— improper work communication procedures.
— inadequate application of new technologies.
— unforeseen, but foreseeable, deterioration.

Item 10. Causes of Construction Accidents

— inability to work
— unwillingness to work
— inadequate signals, instructions or briefings toward the accomplishment of work tasks
— inadequate supervision while executing work activities
— defective plant, equipment, fittings, tools and details (overload or unsuitable for purpose)
— failure to provide and use suitable personal safety equipment (i.e. belts, helmets, nets, etc.)
— failure to control suspended loads from swinging and handling
— insufficient or inadequate guys, props, shores, formwork or falsework
— poor or careless operation of operators (car, crane, train, ship)
— inadequate levels of labor skills
— effect of severe weather conditions
— failure to provide crane hooks with safety catches
— failure to isolate electrical power lines in working areas
— failure to provide guards on machinery
— fire and explosions of unsecured materials
— inadequate or unsuitable temporary work or erection procedures

Item 11. Prime Causes of Bridge Failures

Item 12. Stage Where Failure and Accident Cases Originate

— planning procedures
— design procedures
— design analysis and detailing
— contract information
— construction procedures
— operation procedures

Item 13. Actual Casualties

— number of injuries
— number of deaths

Item 14. Economic and Time Delay Consequences

- cost for recovering the damage
- time expected for recovering the damage

Item 15. Possibility of Error Deficiency

- Discovery possible with additional checking in:
    - planning
    - design
    - construction
    - operation
- Discovery impossible
- Discovery probable without any additional checking

Item 16. Measures to Minimize Recurrence of Construction Failures and Accidents

- Personnel
- Checking Procedures
- Work Procedures
- Codes of Practice
- Research

```
CASE_NO         73
REF_INFO      ENR            STRUC_AGE     0      ACC_CAUSE4    0
REF_DATE      05/04/78       YR_FAILURE   1978    ACC_CAUSE5    0
FAILURE       T              NPRIME_CS1    8      ACC_CAUSE6    0
ACCIDENT      F              NPRIME_CS2    0      CONTROL_1    A3
T_FAILURE      1             NPRIME_CS3    0      CONTROL_2    B3
SUB_DIVIS      3             NPIME_CS4     0      CONTROL_3    C1
SYMPTON1       0             PRIME_CS1    B       CONTROL_4    0
SYMPTON2       0             PRIME_CS2    E       CONTROL_5    0
SYMPTON3       0             PRIME_CS3    0       CONTROL_6    0
REASON1        0             PRIME_CS4    0       CONTROL_7    0
REASON2        0             STAGE_FAL1   B8      CONTROL_8    0
REASON3        0             STAGE_FAL2   C6      CONTROL_9    0
T_CONSTR       2             STAGE_FAL3   D6      CONTROL_10   0
TECH_ERR1      3             STAGE_FAL4   0       BRG_FAIL1     0
TECH_ERR2      0             STAGE_FAL5   0       BRG_FAIL2     0
TECH_ERR3      0             STAGE_FAL6   0       BRG_FAIL3     0
TECH_ERR4      0             STAGE_FAL7   0       BRG_FAIL4     0
MANAG_ERR1     1             STAGE_FAL8   0       BRG_FAIL5     0
MANAG_ERR2     0             STAGE_FAL9   0
MANAG_ERR3     0             PER_INVOL1    3      BRG_FAIL5     0
MANAG_ERR4     0             PER_INVOL2    5      CASUALTY_I     0
CONST_ACC1     0             PER_INVOL3    0      CASUALTY_D    51
CONST_ACC2     0             PER_INVOL4    0      COST_DAMAG          7000000
ENVIR_ERR1     0             HUMAN_BEH1    1      TIME_DAMGM    0
ENVIR_ERR2     0             HUMAN_BEH2    5      TIME_DAMGY    1
ENVIR_ERR3     0             HUMAN_BEH3    7      KEY_WORD1    FAILURE_COLLAPSE.
EAR_WORK1      0             HUMAN_BEH4    8      KEY_WORD2    CONSTRUCTION ERR.
EAR_WORK2      0             HUMAN_BEH5    0      KEY_WORD3    IND. BUILDING(TOWER
V_ELEMENT1     0             HUMAN_BEH6    0      COMMENTS     MEMO
V_ELEMENT2     0             HUMAN_BEH7    0
BEAM_TRS1      0             HUMAN_BEH8    0
BEAM_TRS2      0             PROJ_WKS1     2
PLATES1        0             PROJ_WKS2     6
PLATES2        0             PROJ_WKS3     7
CONNEC1        5             PROJ_WKS4     8
CONNEC2        0             ERR_DISCO1   A3
MATER_F1       2             ERR_DISCO2   0
MATER_F2       3             ERR_DISCO3   0
MATER_F3       0             ERR_DISCO4   0
MANNER_FL1     2             ACC_CAUSE1    0
MANNER_F2      0             ACC_CAUSE2    0
MANNER_F3      0             ACC_CAUSE3    0
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A JACK-UP FORMWORK SYSTEM ATOP A POWERPLANT COOLING TOWER IN WEST
VIRGINIA COLLAPSED SENDING 51 WORKERS PLUMMETING 168 ft TO THEIR
DEATH IN ONE OF THE WORLD'S WOREST CONSTRUCTION TRAGEDIES.THE
CAUSE OF THE COLLAPSE RELIES WITH DESIGN OF THE FORMWORK,METHOD
OF CONSTRUCTION (JACKING SYSTEM).THE ESTIMATED COSTS AND TIME
REQUIRED TO RECOVER THE PROBLEM ARE $7 MILLION AND 1 YEAR.
```

Figure 3.4.1. Example of a Historical Case Record by Dr. Eldukair

4. Seismic Risk of Buildings

4.1. Overview of the Seismic Risk Module

The expected damage factors (dollar loss/replacement value) of buildings due to earthquakes over the lifetime can be obtained by using the Stochastic Response Spectra (SRS) together with the Damage Factor - Maximum Response Acceleration (DF-MRA) functions. The procedure to calculate the SRA was developed by one of the authors in his previous research, Tatsumi, (1985), (1987), (1988). The DF-MRA functions have been obtained based on the procedure outlined in ATC-21, (Applied Technology Council) and the method that we have used is described in section 4.3. Figure 4.1.1 shows a graphical representation of the system for calculating the expected damage factor for a given building. Most of the required data in the various parts of the system are obtained by the knowledge base in the Seismic Risk Module using the data retrieved from the Project Database and given to the external Fortran program which performs the calculations. The results of the calculations are supplied to the Seismic Risk Module and the conclusions based on them are shown. The various parts of the system are briefly explained below.

Epicentral Regions

Based on the distribution of the magnitudes and epicenters of the historical damaging earthquakes in Japan, epicentral regions in which the seismicity is considered to be approximately homogeneous have been set as R1 through R6 as shown in Figure 4.1.1.(a).

Frequency Distribution Functions of Earthquake Magnitude

The frequency distribution functions shown in Figure 4.1.1.(b) have been obtained by regressing the frequency distribution of magnitudes of historical earthquakes in each epicentral region to the Gutenberg-Richter equation. The maximum magnitude in each epicentral region is assigned to be equal to the maximum magnitude recorded in the historical past in the region.

Calculation of the Stochastic Response Spectra

Based on the above information, the theory of stationary random response of linear single-degree-of-freedom system and empirical attenuation-distance equations the stochastic response spectra can be calculated at the given site for the known conditions of ground and structure.

The required input data such as the longitude and latitude of the site, structural damping and predominant period of the local ground are given by the knowledge in the Seismic Risk Module obtained from the project data.

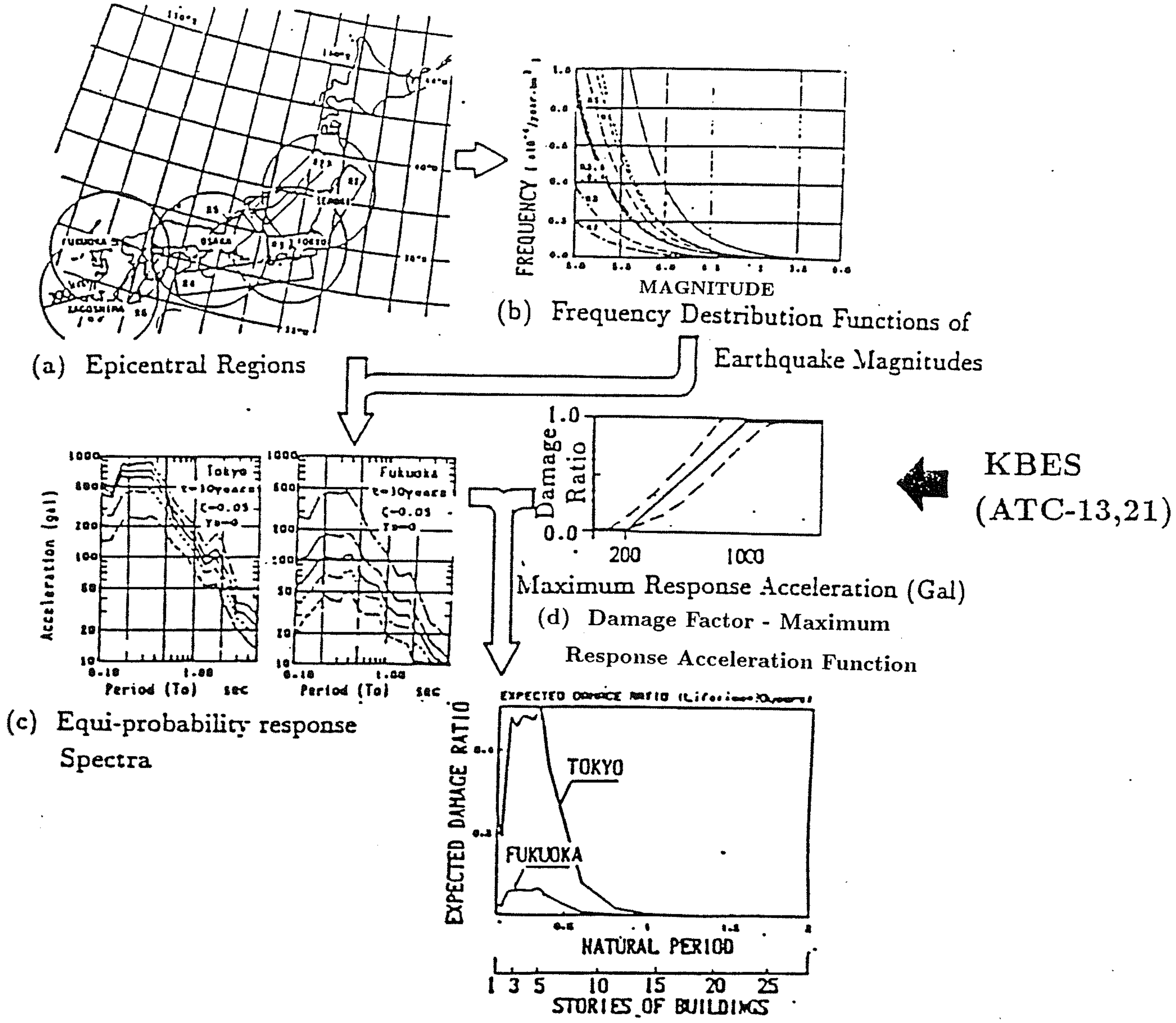
The mathematical methods and more detailed procedures are explained in the following sections. In figure 4.1.1.(c), the calculated equi-probability response spectra for Tokyo and Fukuoka are shown.

Damage Factor-Maximum Response Acceleration (DF-MRA) Functions

The DF-MRA functions give the relationship between damage factors (dollar loss/replacement value) and the maximum response acceleration of structures. The functions depend on the structural type, configuration and some other details of the structure. There is as yet no established method for calculating the DF-MRA functions and the method that we have adopted is based on the knowledge of earthquake engineers as embodied in ATC-21. The details of our method are explained in section 4.3.

Expected Damage Factors of Buildings

The expected damage factors of buildings over its lifetime due to future earthquakes can be calculated as shown in Figure 4.1.1.(a)-(d). As an example, the expected damage factors for Tokyo and Fukuoka are shown in Figure 4.1.1.(e) using the procedure outlined in Figure 4.1.1.(a)-(d).



(a) Epicentral Regions

(b) Frequency Destribution Functions of Earthquake Magnitudes

(c) Equi-probability response Spectra

(d) Damage Factor - Maximum Response Acceleration Function

(e) Expected Damage Factor of Buildings

Figure 4.1.1. Total System for the Seismic Risk Module

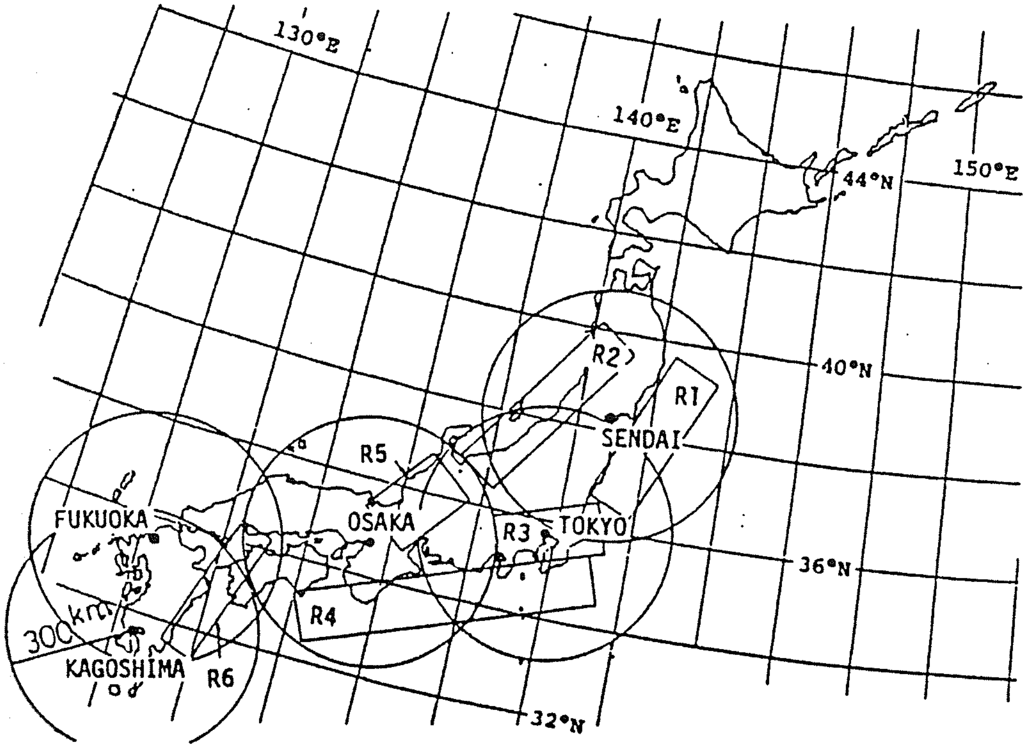


Figure 4.1.2. Epicentral Regions in Japan

4.2. Procedure for Stochastic Response Spectra

4.2.1. Introduction

One of the authors, has studied the stochastic characteristics of earthquake response spectra which incorporate the dynamic characteristics of the structures and are therefore superior as seismic forces for actual design. In the previous research, a methodology for calculating the probability distribution of earthquake response spectra has been developed and applied to major cities in Japan, China and Taiwan, Tatsumi (1985) & (1987).

The characteristics of the maximum response value of a linear single-degree-of-freedom have been studied using the theory of stochastic processes by many researchers, Rosenblueth et al. (1962), Vanmarcke (1972), Der Kiureghian (1979), among others. Spanos (1980) has made further developments and applied his results for calculating earthquake response spectra. Spanos has obtained an approximate probability distribution on the non-stationary response using the Fokker-Plank equations and carried his analysis forward to obtain the probability distribution of earthquake response spectra. However, in Spanos's papers, a jump of logic is seen in the definition of maximum response value and an evaluation of his procedure for practical use has not been carried out.

On the other hand, many observed earthquake response spectra have been statistically studied by Anderson and Trifunac (1977), (1978) & (1979), Dalal (1975), Katayama (1978) & (1982), etc. Anderson and Trifunac, and Dalal have obtained the probability distribution of response by means of regression of response spectra values calculated from recorded earthquake waves for a specified natural frequency and damping ratio. The parameters in the regression function are the magnitude of earthquake, M, epicentral distance, R, local ground condition, etc. Their method requires an enormous amount of calculation as at each pair of natural frequency and damping ratio the response spectra has to be calculated for all the records following which the spectral values are regressed using the chosen function. In both studies, the effect of the local seismicity is incorporated into the probability distribution. Katayama (1978) has performed a similar type of analysis but in place of regression he has used quantification theory to obtain respective coefficients at each natural frequency with the damping ratio set at 0.05 for various combinations of magnitude of earthquakes, epicentral distances and types of ground conditions. These coefficients can then be used to calculate the mean response spectrum for each category of magnitude of earthquake, epicentral distance and the type of ground condition.

In the study by Tatsumi (1985) & (1987) a practical procedure has been developed for calculating the nonexceedance probability of earthquake response spectra at a given site and for a specified lifetime based solely on information on the local seismicity and the ground condition at the site. This procedure is used in the Seismic Risk Module and it is explained in detail in the rest of this section.

4.2.2. Random Response of a Linear Single-Degree-of-Freedom System

The differential equation governing the motion of a linear single-degree-of-freedom system, (Figure 4.2.1), is as follows

$$\ddot{\mathbf{X}}(t) + 2\zeta\omega_0\dot{\mathbf{X}}(t) + \omega_0^2\mathbf{X}(t) = \mathbf{W}(t) \tag{4.2.1}$$

where $\mathbf{X}(t)$ = the random response, ζ = the damping ratio and ω_0 = the undamped natural frequency. It is assumed that $\mathbf{W}(t)$ is Gaussian white noise, ζ is small enough and $\mathbf{X}(t)$ is a stationary narrow-band random process.

Then, the joint probability density of $\mathbf{X}(t)$ and $\dot{\mathbf{X}}(t)$ can be determined by solving the Fokker-Plank equation governing the transition probability density using the Markov-vector approach, Lin (1967). Assuming that K is the power-spectrum density of the Gaussian white noise, we obtain

$$p_{\{X\}\{\dot{X}\}}(x, \dot{x}) = C\ exp[-\ \frac{\zeta\omega_0}{\pi K}\ (\omega_0^2 x^2\ +\ \dot{x}^2)] \tag{4.2.2}$$

Next, the expected rate of threshold crossings from below is

$$E[\mathbf{N}_+(\xi)] = \int_0^\infty \dot{x} p_{\{X\}\{\dot{X}\}}(\xi, \dot{x}) d\dot{x} = C\ \frac{\pi K}{2\zeta\omega_0}\ exp(-\frac{\zeta\omega_0^3}{\pi K}\xi^2) \tag{4.2.3}$$

where ξ is the threshold, Lin (1967).

The expected equivalent frequency is obtained by $\xi = 0$ in Eq.(4.2.3). This coincides with the undamped natural frequency, and then Eq.(4.2.4) and Eq.(4.2.5) follow.

$$E[\mathbf{N}_+(0)] = C\frac{\pi K}{2\zeta\omega_0} \simeq \frac{\omega_0}{2\pi} \tag{4.2.4}$$

$$C \simeq \frac{\zeta\omega_0^2}{\pi^2 K} \tag{4.2.5}$$

The response spectrum is the maximum absolute value of the response of a linear single-degree-of-freedom system vibrating over a duration T. So the probability distribution function of the response spectrum is equivalent to the probability $P_0(\xi)$ that the absolute value of $\mathbf{X}(t)$ does not exceed the threshold ξ once in the duration T. $P_0(\xi)$ is obtained from Eq.(4.2.3) and Eq.(4.2.5), assuming the threshold crossings of $\mathbf{X}(t)$ occur with Poisson processes.

$$P_0(\xi) = exp(-2E[\mathbf{N}_+(\xi)]T) = exp[-\frac{\omega_0 T}{\pi} exp\{-\frac{\zeta\omega_0^3}{\pi K}\xi^2\}] \tag{4.2.6}$$

Furthermore, ξ is obtained from Eq.(4.2.6) as follows.

$$\xi = \sqrt{-\frac{\pi K}{\zeta\omega_0^3} ln[-\frac{\pi ln P_0}{\omega_0 T}]} \tag{4.2.7}$$

Equations (4.2.6) and (4.2.7) can be used to calculate the distribution function of the response spectrum and also the value of the response spectrum correspond to the nonexceedance probability P_0.

4.2.3. Determination of the Spectral Density and the Duration

The parameters K and T are characteristics of the earthquake and the local ground condition. From now on, the duration T (sec) will be assumed to be equivalent to that of the earthquake motion.

K is assumed to be a wide-band function which varies slowly with respect to frequency. In this case, considering that $\mathbf{X}(t)$ is a narrow-band random process, K may be assumed to be constant in the vicinity of ω_0 and then the foregoing assumption that K is the power-spectral density of a white noise is approximately satisfied.

Based on strong earthquake records observed in the United States, McGuire (1978) has shown that the absolute value of the Fourier spectrum $FS(T_0)(cm/sec)$ may be written as

$$FS(T_0) = exp(b_1 + b_2 M + b_4 Y_s)R^{b_3} \tag{4.2.8}$$

where M is the magnitude of the earthquake, R (km) is the hypocentral distance and Y_s represents the local ground condition, McGuire (1978). The coefficients b_1 through b_4 have been given for periods in the range $T_0 = 0.04 - 5.0sec$ by McGuire (1978). The relationship between the power-spectral density $K(T_0)(cm^2/sec^2)$ and $FS(T_0)$ in

Eq.(4.2.8) is given by

$$K(T_0) = \frac{FS^2(T_0)}{2\pi T} \tag{4.2.9}$$

Next, the duration of the earthquake motion T (sec) is taken from Esteva (1964) and is expressed by the duration of white noise equivalent to the earthquake motion, as

$$T = 0.02exp(0.74M) + 0.3R \tag{4.2.10}$$

The hypocentral distance R in Eq.(4.2.8) and Eq. (4.2.10) is lacking for some of the older data so that it is determined from the epicentral distances Δ for which there are more data available. The radius D(km) of the volume of aftershocks correspond to the magnitude of earthquake M has been expressed by Iida (Iida, 1963) as

$$D = 10^{0.353M-1.134} \tag{4.2.11}$$

Assuming that this radius is equivalent to the depth of the focus, R can be expressed as

$$R = \sqrt{\Delta^2 + D^2} \tag{4.2.12}$$

Using the above results, if M, Δ and Y_s are given K and T can be calculated. Furthermore, the probability distribution of the response spectrum can also be determined using Eq.(4.2.6). The above equations are used in Tatsumi (1985) & (1987).

4.2.4. Introduction to Seismicity

In this section, the methodology for calculating the nonexceedance probability of the response spectrum for a given site and a specified lifetime of the structure is discussed.

Gutenberg and Richter obtained an empirical equation which express the relation between the frequency, n, of earthquake occurrences and the magnitude, M, of earthquake, as

$$logn(M) = a^G - b^G M \tag{4.2.13}$$

The total number $N(M)$ of earthquakes whose magnitude is equal to or greater than M is

$$N(M) = \int_M^\infty n(M)dM \tag{4.2.14}$$

From Eq.(4.2.13) and Eq.(4.2.14), the relation between $N(M)$ and M may be written as

$$logN(M) = A_G - b_G M \tag{4.2.15}$$

In Eq.(4.2.13)-(4.2.15), a_G, b_G and A_G are constants and b_G is generally known to be close to 1.0 , Asada (1978). The probability distribution function $F_M(m)$ of the magnitude of earthquake may be written from Eq.(4.2.15) as

$$F_M(m) = 1 - exp[-\beta(m - m_0)] \tag{4.2.16}$$

where m_0 is the minimum value of M, $\beta = b_G ln10$, Cornell (1968). From equation (4.2.16) the probability density function $f_M(m)$ is given by

$$f_M(m) = \beta exp[-\beta(m - m_0)] \tag{4.2.17}$$

Next, given the epicentral region R_i, in which the probability of earthquake occurrences can be assumed to be uniform, the probability distribution function of epicentral distances $F_\Delta^{(i)}(\Delta)$ with respect to R_i may be written as

$$F_\Delta^{(i)}(\Delta) = P_{R_i}[\boldsymbol{\Delta} \le \Delta] = \int_{R_i(\Delta)} \frac{dS}{S_{R_i}} = \frac{S\{R_i(\Delta)\}}{S_{R_i}} \tag{4.2.18}$$

where S_{R_i} is the total area of the region R_i and $S\{R_i(\Delta)\}$ expresses the area of the portion which belongs to R_i for which the epicentral distance is equal to or less than Δ (refer to Figure 4.2.2). When an earthquake occurs in the epicentral region R_i , the probability that the displacement response spectrum S_d does not exceed ξ at a given site $F_{\{S_d\}}^{(i)}(\xi)$ may be written using Eq.(4.2.17) and Eq.(4.2.18) as

$$\begin{aligned} F_{\{S_d\}}^{(i)}(\xi) &= \int_{R_i} \int_{m^0}^{m_1} P_0(\xi;\ m, \Delta) f_M^{(i)}(m) \frac{dF_\Delta^{(i)}(\Delta)}{d\Delta} dm d\Delta \\ &= \int_{R_i} \int_{m_0}^{m_1} P_0(\xi;\ m, \Delta) f_M^{(i)}(m) \frac{1}{S_{R_i}} dm dS \end{aligned} \tag{4.2.19}$$

where

$$P_0(\xi;\ m, \Delta) = P_0[S_d \le \xi | \mathbf{M} = m, \boldsymbol{\Delta} = \Delta]$$

can be obtained using Eq.(4.2.6) and Eq.(4.2.8)-(4.2.12), m_0 and m_1 are respectively the minimum and maximum values of the magnitude of earthquakes in Ri. Also, $f_M^{(i)}(m)$

in equation (4.2.17) has been normalized so that the area in the range $m_0 \leq m \leq m_1$ is equal to unity.

Next, the probability $p_{N_s}^{(i)}(n_s)$ that the displacement response spectrum will exceed ξ n_s times in t years by the earthquakes which may occur in the epicentral region R_i can be written as Eq.(4.2.20), assuming that these events occur in accordance with the Poisson process.

$$p_{N_s}^{(i)}(n_s) = P_{R_i}[\mathbf{N_s} = n_s] \; = \; \frac{exp(-p_\xi^{(i)}\nu_i t)(p_\xi^{(i)}\nu_i t)^{n_s}}{n_s!} \tag{4.2.20}$$

where $p_\xi^{(i)} = P_{R_i}[\mathbf{S_d} > \xi] \; = \; \mathbf{1 - F_{\{S_d\}}^{(i)}}(\xi)$, ν_i is the annual expected arrival rate of the earthquakes in R_i whose magnitudes lies in the range $m_0 \leq \mathbf{M} \leq m_1$. Therefore, the probability that the response spectra will not exceed ξ once in t years as a result of earthquakes in R_i may me written as

$$p_{N_s}^{(i)}(0) = exp(-p_\xi^{(i)}\nu_i t) \tag{4.2.21}$$

Finally, with respect to all the earthquakes which may occur in all the epicentral regions $R_i(i = 1,..,n_R)$, which are considered to influence this site, the probability $F_{S_d,t}(\xi)$ that the displacement response spectra will not exceed ξ once in t years is

$$F_{S_d,t}(\xi) = \prod_{i=1}^{n_R} p_{N_s}^{(i)}(0) \; = \; \prod_{i=1}^{n_R} exp[-\{1 - F_{\{S_d\}}^{(i)}(\xi)\}\nu_i t] \tag{4.2.22}$$

We have used equation (4.2.22) to calculate the probability distribution of earthquake response spectra.

4.2.5. Time-Dependent Seismicity

In 4.2.4 we assumed that earthquakes occur in each epicentral region in accordance to the Poisson process whose mean is related to the average historical seismicity. However, the cumulative earthquake energy in each epicentral region changes with time and it can have a large influence on the probability of earthquake occurrence with time. Therefore, it is necessary to consider the time-dependent characteristics of the occurrence rate when calculating stochastic response spectra. In this section, the occurrence of earthquakes is assumed to be a non-stationary Poisson process, in which the annual expected arrival rate of earthquakes, (AEAR) is considered to be time-dependent.

A procedure for evaluating the time-dependent AEAR based on the cumulative earthquake energy is described (Tatsumi, 1988). This time-dependent AEAR is then used to calculate the stochastic response spectra.

Procedure to Obtain Time-Dependent AEAR

The energy, E_n, of an earthquake whose magnitude is M can be expressed as follows.

$$E_n = 10^{11.8+1.5M} \tag{4.2.23}$$

The probability density function of M which is bound by the lower and upper limits, m_L and m_U respectively, can be expressed as

$$f_M(m) = C_1 \beta e^{-\beta(m-m_L)} \tag{4.2.24}$$

where $\beta = b\ ln10$ (b is the same as the Gutenberg-Richter's b-value) and C_1 is given as $C_1 = 1/[1 - exp\{\beta(m_L - m_U)\}]$. From Eq.(4.2.23) and (4.2.24) the expected value of the energy of earthquakes whose magnitudes lie in the range $m_L \leq M \leq m_U$ is

$$E_{E_n} = \int_{m_L}^{m_U} E_n f_M(m) dm = \frac{C_1}{C_2} \beta e^{\beta m_L + 27.17} (e^{C_2 m_U} - e^{C_2 m_L}) \tag{4.2.25}$$

where $C_2 = 1.5\ ln10 - \beta$.

In order to estimate the value of the time-dependent AEAR, $\nu(t)$, we assume the relations given by Eq.(4.2.26), (4.2.27) and (4.2.28).

$$\nu_I = a / E_{E_n} \tag{4.2.26}$$

$$\nu(t) = \nu_I\ g(t)/g_m \tag{4.2.27}$$

$$n = \int_0^t \nu(t) dt = \frac{g(0) + at - g(t)}{E_{E_n}} \tag{4.2.28}$$

where, ν_I is AEAR assuming time-independence, n is the expected earthquake occurrence rate in t years and the other notations are illustrated in Figure 4.2.3. Eq.(4.2.27) and (4.2.28) can be used to obtain a differential equation in $\nu(t)$ as

$$\dot{\nu}(t) + \frac{E_{E_n} \nu_I}{g_m} \nu(t) = \frac{a\ \nu_I}{g_m} \tag{4.2.29}$$

Applying $\nu(0) = \nu_I\ g(0)/g_m$ as a initial condition, we can solve for $\nu(t)$ and express it as

$$\nu(t) = \nu_I\{1 + (\frac{g(0)}{g_m} - 1)e^{-\frac{a}{g_m}t}\} \tag{4.2.30}$$

The expected time-dependent AEAR during time 0 to t can then be expressed as

$$\nu = \frac{1}{t}\int_0^t \nu(t)dt = \nu_I + \frac{g_m}{E_{E_n}t}(\frac{g(0)}{g_m} - 1)(1 - e^{-\frac{a}{g_m}t}) \tag{4.2.31}$$

Eq.(4.2.31) can be used to define AEAR by substituting the value of the lifetime for t.

4.2.6 Application and Discussion

The procedures described in the previous sections have been implemented in our construction risk management system. The information that is required for starting the calculations are:

- Structural natural period, T_0, is retrieved from the Project Database.
- Structural damping, ζ, is obtained based on the type of the structure retrieved from the Project Database.
- Ground condition, Y_s, is discussed in the next section.
- Lifetime is specified by the user.
- Initial year, I_y, for calculating the period of the lifetime of the structure is taken as the completion date of the construction from the Project Database.

The other postulates of the system are explained along with the sample calculations below.

The non-exceedance probabilities of the acceleration response spectra for a lifetime of 30 years are obtained for three major cities in Japan, Tokyo ($139.7°E, 35.7°N$), Osaka ($135.5°E, 34.7°N$), and Fukuoka ($130.4°E, 33.6°N$). The various postulates that are made in the program are:

(1) Based on the distribution of the epicenters of historical damaging earthquakes, Tokyo Astronomical Observatory (1982), six epicentral regions, R1 through R6, in which the seismicities are inferred to be relatively high are set up as shown in

Figure 4.1.2. The probability of earthquake occurrence is assumed to be uniform over each epicentral region.

(2) The cumulative earthquake energy, $C_E(t)$, of the historical, damaging earthquakes after 1700 A.D. in each epicentral region is used. Figures 4.2.4.(a) to (f) show $C_E(t)$ of each epicentral region along with the regression line and the upper and lower bounds of $C_E(t)$. The upper and lower bounds are taken as the lines whose slopes are equal to that of the regression line and which pass through the farthest points of $C_E(t)$ from the regression line in the upper and lower direction, respectively.

(3) The expected time-dependent AEAR, ν, of each epicentral region, R1-R6, is obtained by using the cumulative energy plots shown in Fig.4.2.4. In the derivation, $b = 1$, $t = 30$ years (that is equal to the lifetime of the structure) and the initial years ($t = 0$) are taken from 1700A.D. to 1980 at 10-year increments. The lower bound magnitude m_L is taken as 5.0 and the upper bound value m_U as the highest value which has been recorded historically in the region. The AEAR per unit area ($1km^2$) versus initial year is plotted for regions 1 to 6 in Fig.4.2.5.

(4) The range of influence is assumed to be within a radius of $300km$ of each site and the effect of seismic regions outside this radius is neglected. The epicentral regions, R7-R9, within a radius of $300km$ of each site and outside the specified regions, R1-R6, is taken to have uniform seismicity. The AEAR of each of the regions, R7-R9, is assumed to be time-independent.

(5) The damping ratio, ζ, for response spectra calculations is taken as 0.05, the lifetime as 30 years and the ground as hard ($Y_s = 0$: no influence of local ground condition).

Figure 4.2.6 shows the equi-probability response spectra (EPRS) for Tokyo, Osaka and Fukuoka as the initial year, I_y, of the structure is changed. Figure 4.2.7 shows the probability density functions (PDF) of the response spectra at the period $T_0 = 0.6sec$ also with I_y as a parameter. The results are summarized below.

(1) The equi-probability response spectra (EPRS) shown in Figure 4.2.6 of Tokyo are roughly similar to those of Osaka, but those of Fukuoka are much smaller.

(2) For Tokyo,the EPRS with $I_y = 1920$ (before the 1923 Kanto Earthquake) are very large and the EPRS with $I_y = 1950$ are much smaller. The EPRS with $I_y = 1980$ are between those of $I_y = 1920$ and 1950. These results show the dominant influence of the Kanto Earthquake which occurred in the region R3 [Figure 4.2.6.(a) to (c)].

(3) For Osaka, the EPRS increase as I_y approaches the present time, from a value

of 1920 to 1980. The increase can be ascribed to the increase in the cumulative earthquake energy in the region R5 [Figure 4.2.6.(d) to (f)].

The validation of the above procedure and more detailed discussions on the results can be found in Tatsumi (1985), (1987) & (1988).

4.2.7. Amplification due to Local Ground Condition

It is a well-known fact from the recent damaging earthquakes such as the 1985 Mexico Earthquake and the 1989 Loma Prieta Earthquake that the earthquake damage of buildings has been greatly influenced by the amplification of ground motion due to the local ground condition. In this research, the amplification factor (AF) is used to take account of the influence of local ground condition.

Simplifying the local ground by a linear single-degree-of-freedom system, Figure 4.2.8, the AF can be obtained. The system is written as

$$\ddot{y} + 2\zeta\omega_0\dot{y} + \omega_0^2 y = -\ddot{x}_0 \qquad (4.2.32)$$

where x_0 is the displacement of the rigid base, x is the total displacement of the mass, $y = x - x_0$ is the displacement of the mass relative to the rigid base, $\omega_0 = \sqrt{\frac{K}{M}}$ is the undamped natural frequency, and $\zeta = \frac{C}{2\omega_0 M}$ is the damping ratio.

For the steady state vibration due to a harmonic motion (frequency ω) of the rigid base, AF (= the ratio of $\ddot{x}$ amplitude to $\ddot{x}_0$ amplitude) can be written as

$$AF = \sqrt{R^2 + I^2} \qquad (4.2.33)$$

where

$$R = \frac{1 - (1 - 4\zeta^2)(\frac{\omega}{\omega_0})^2}{(1 - (\frac{\omega}{\omega_0})^2)^2 + (2\zeta\frac{\omega}{\omega_0})^2}$$

$$I = \frac{2\zeta(\frac{\omega}{\omega_0})^3}{(1 - (\frac{\omega}{\omega_0})^2)^2 + (2\zeta\frac{\omega}{\omega_0})^2}$$

In order to calculate the Eq.(4.2.33), the values of ω_0, ω and ζ have to be assigned. In this case the ω_0 is considered as the predominant frequency of the ground. We assume that

(1) the depth where the N-values (results of Standard Penetration Test) at the construction site reach 30 is the top of the rigid base,

(2) N-values change linearly from 0 at the surface of the ground to 30 at the top of the rigid base,
(3) because of (2), the mean value of N-value is 15,
(4) the surface soil layer is homogeneous having the same N-value of 15.

The relationship between the elastic shear wave velocity, $Vs(m/sec)$, of the soil and N-value has been given empirically (Toki, 1981) as:

$$Vs = 90N^{0.34}. \tag{4.2.34}$$

Since the mean N-value is 15 in this case, Vs is equal to

$$Vs = 90 \times 15^{0.34} = 226\ m/sec. \tag{4.2.35}$$

By assuming elastic homogeneity the predominant frequency, f_p ($\approx \frac{\omega_0}{2\pi}$), can be obtained as:

$$f_p = \frac{Vs}{4H} \tag{4.2.36}$$

where H is the thickness (m) of the surface layer.

In order to calculate the value of f_p, we need to know H. Since a value of 30 for N is used as a standard for defining the base of the shallow foundation or the bottom of the deep foundation, we can get the value of H from the data on foundation design in the project database. Once H is known then we can calculate ω_0. The frequency ω of the harmonic motion of the rigid base corresponds to $2\pi/T_0$, where T_0 is the period used in calculating the stochastic response spectra. The damping ratio ζ is taken to equal to 0.1 here empirically. Now that the values of ω , ω_0 and ζ are set up, the AF can be calculated by Eq.(4.2.33). It is directly used as a magnifying factor for the stochastic response spectra.

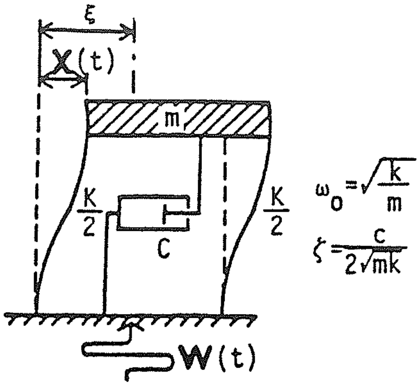


Figure 4.2.1. Linear Single-Degree-of-Freedom (SDOF) System

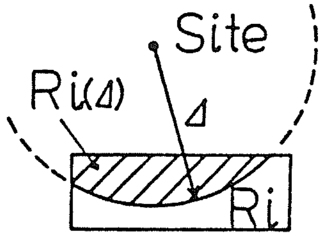
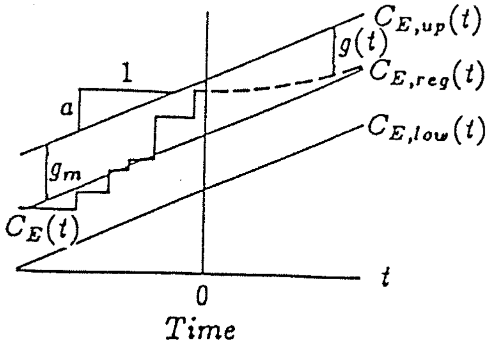
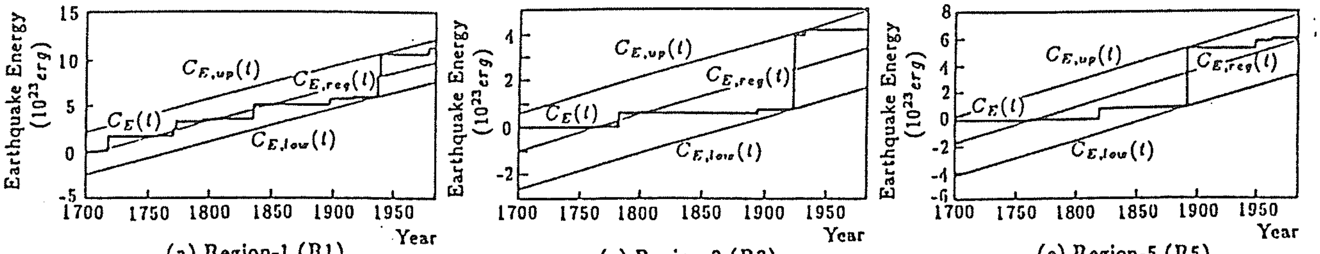


Figure 4.2.2. Concept of an Epicentral Region



$C_E(t)$: Cumulative Earthquake Energy
$C_{E,up}(t)$: Upper Bound of $C_E(t)$
$C_{E,reg}(t)$: Regression Line of $C_E(t)$
$C_{E,low}(t)$: Lower Bound of $C_E(t)$
$g(t) = C_{E,up}(t) - C_E(t)$
$g_m = C_{E,up}(t) - C_{E,reg}(t)$
a : Slope of the Regression Line

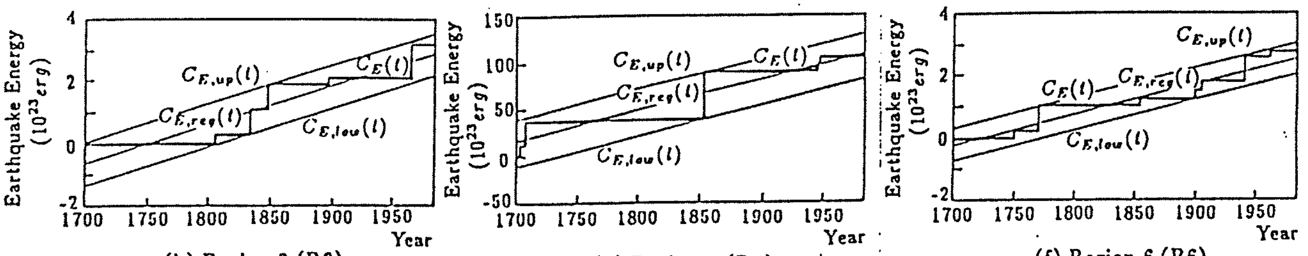
Figure 4.2.3. Schematic Diagram Showing Cumulative Earthquake Energy



(a) Region-1 (R1)

(c) Region-3 (R3)

(e) Region-5 (R5)



(b) Region-2 (R2)

(d) Region-4 (R4)

(f) Region-6 (R6)

Figure 4.2.4. Cumulative Earthquake Energy in Epicentral Regions R1 - R6

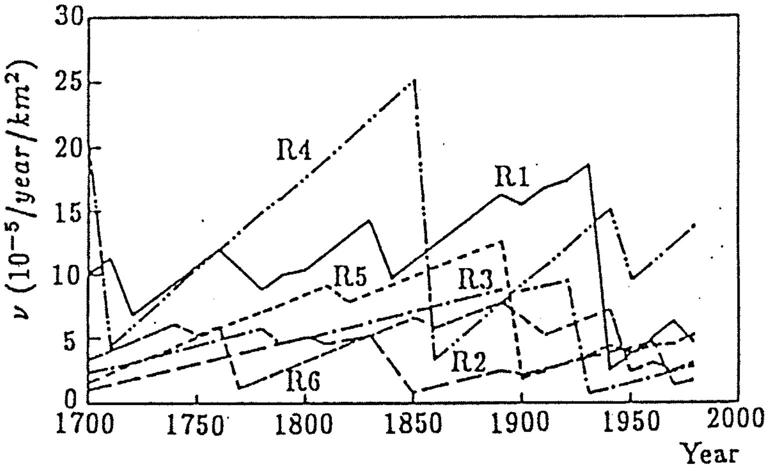
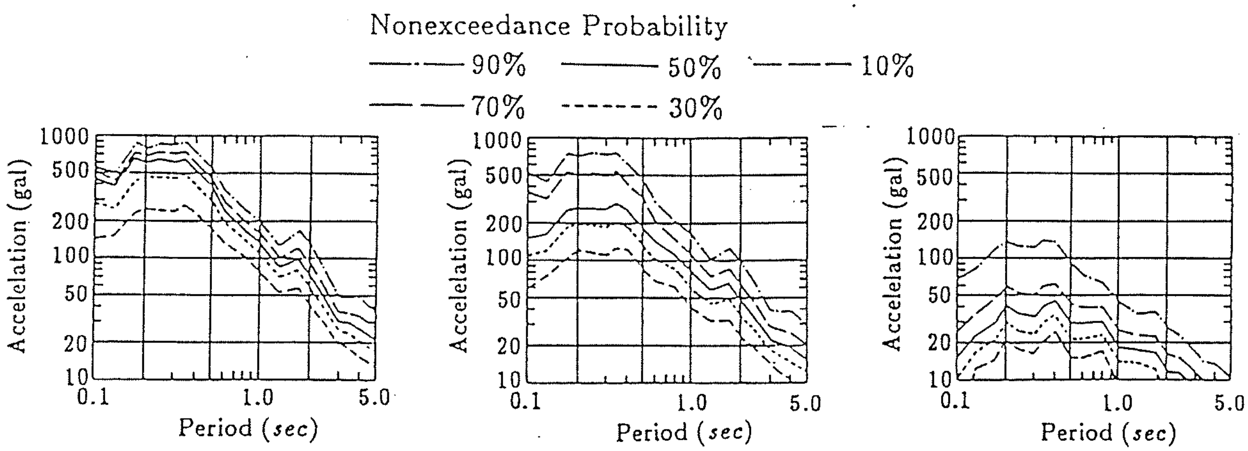
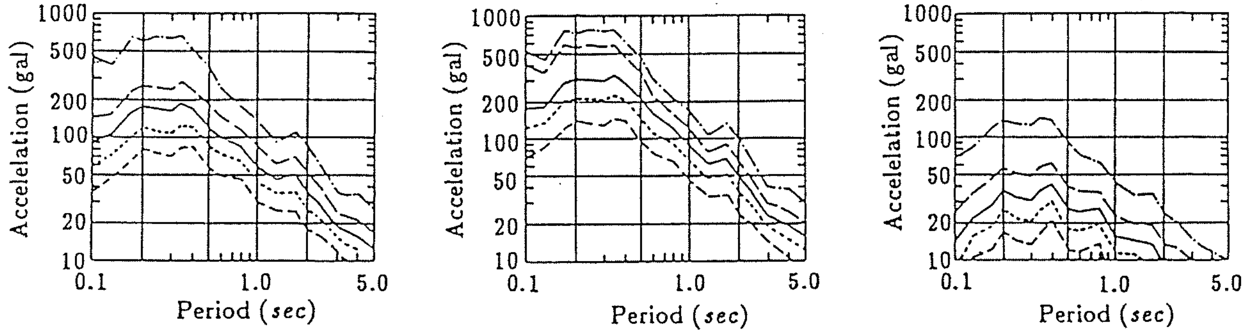


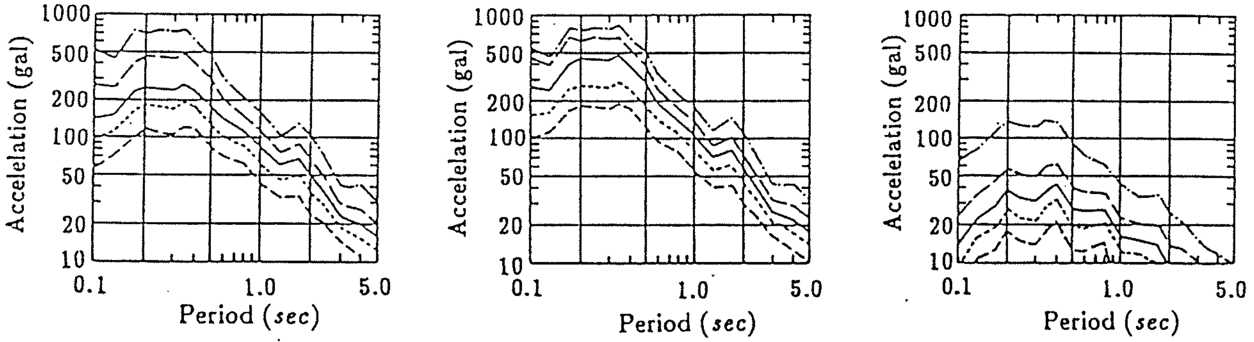
Figure 4.2.5. Annual Expected Arrival Rates of Earthquakes (AEAR) in Epicentral Regions R1 - R6



(a) Tokyo, $I_y = 1920$ (d) Osaka, $I_y = 1920$ (g) Fukuoka, $I_y = 1920$



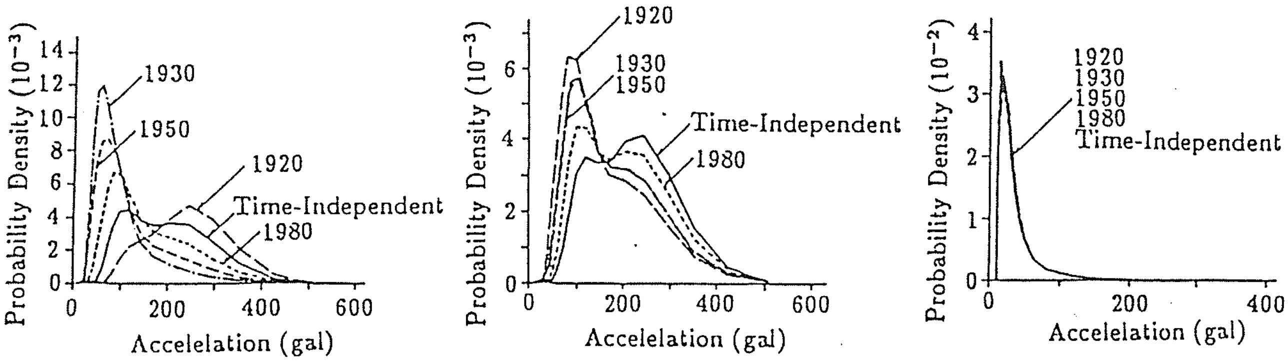
(b) Tokyo, $I_y = 1950$ (e) Osaka, $I_y = 1950$ (h) Fukuoka, $I_y = 1950$



(c) Tokyo, $I_y = 1980$ (f) Osaka, $I_y = 1980$ (i) Fukuoka, $I_y = 1980$

Figure 4.2.6. Equi-Probability Response Spectra for Major Cities in Japan, Changing Initial Year, I_y, of Lifetime as a Parameter

($\zeta = 0.05$, $Lifetime = 30years$, $Hard\ Ground$)



(a) Tokyo (b) Osaka (c) Fukuoka

Figure 4.2.7. PDF of Maximum Response Spectra, Changing Initial Year, I_y
($T_0 = 0.6sec,\ \zeta = 0.05,\ Lifetime = 30years,\ Hard\ Ground$)

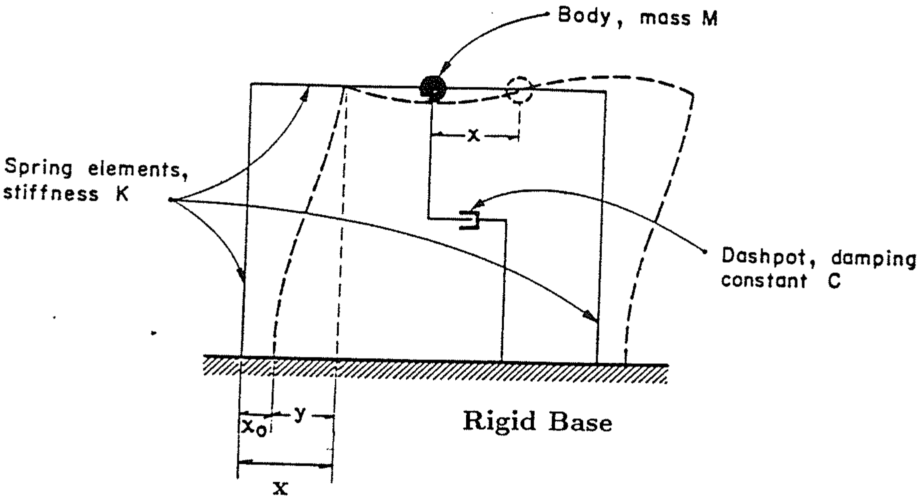


Figure 4.2.8. Linear Single-Degree-of-Freedom System for the Local Ground

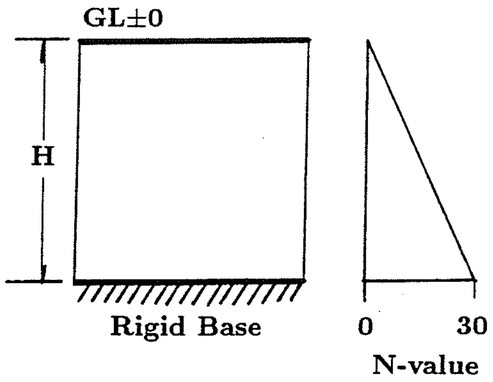


Figure 4.2.9. Simplification of the Local Ground Condition

4.3. Damage Factor-Maximum Response Acceleration (DF-MRA) Function

4.3.1. Introduction to ATC-21 Methodology

One way of calculating the expected seismic damage factor for a given structure is to use the damage factor-maximum response acceleration, DF-MRA, function of the structure in its current state. This task is complicated by the fact that the DF-MRA function is influenced by many factors, some of which are themselves not easy to evaluate. Also, as far as possible we would like to have the DF-MRA function to have been validated by the response of similar type of structures to historical damaging earthquakes.

In this study, we decided to use the concepts developed in ATC-21, Applied Technology Council (1987), which is itself largely based on ATC-13 (1985), "Earthquake Damage Evaluation Data for California,". ATC-13 represents the collective expertise of many earthquake engineers in the United States. The ATC-21 titles "Rapid Visual Screening of Buildings for Potential Seismic Hazards: A Handbook" and "Rapid Visual Screening of Buildings for Potential Seismic Hazards: Supporting Documentation" contains detailed methodology and supporting background information for damage evaluation.

The Rapid Screening Procedure (RSP) utilizes a methodology based on a "sidewalk" survey of a building and a Data Collection Form (see Figure 4.3.1), which an inspector completes based on a visual observation of the building. The handbook provides the inspector with background information and data required to complete the form.

As shown in Figure 4.3.1, the methodology begins with identifying the primary structural lateral load resisting system and materials of the building. Basic Structural Hazard scores for various building types are provided on the form, and the inspector circles the appropriate one. The inspector then modifies this Basic Structural Hazard score by adding or subtracting Performance Modification Factors, which related to significant seismic-related defects the inspector may observe, in order to arrive at a final Structural Score, SS. The Basic Structural Hazard score, Performance Modification Factors and final Structural Score, SS are all related to the probability of the building sustaining major structural damage.

Since the concept and values of structural scores have been based on the expertise of many earthquake engineers, we decided to utilize this idea for determining the DF-MRA Functions.

4.3.2. Application of the Structural Scores

First of all we repeat the definition of the structural scores from ATC-21. The Basic Structural Hazard (BSH) is defined for a type or class of building as the negative of the logarithm (base 10) of the probability of the damage factor, *DF*, (dollar loss/replacement value) exceeding 60 percent for a specified NEHRP (National Earthquake Hazards Reduction Program) Effective Peak Acceleration (EPA) loading as:

$$BSH = -log_{10}[Pr(DF \geq 60\%)] \tag{4.3.1}$$

The BSH is a generic score for a type or class of building, and is modified for a specific building by Performance Modification Factors (PMFs) specific to that building, to arrive at a Structural Score, SS. That is,

$$SS = BSH + PMF \tag{4.3.2}$$

where SS is defined as

$$SS = -log_{10}[Pr(DF \geq 60\%)] \tag{4.3.3}$$

Therefore, SS is the measure of the probability or likelihood of damage being greater than 60 percent of building value for the specific building. Incidentally, in ATC-21 sixty percent damage was selected as the generally accepted threshold of major damage.

Each expert whose opinions were solicited in ATC-13 was asked to provide a low, best and high estimates of the damage factor for various categories of buildings. The mean low and mean high estimates were defined to be the 90% probability bounds of the damage factor distribution. The best estimate was defined as the *DF* most likely to be observed for a given MMI (Modified Mercalli Intensity) and facility class. Therefore, the mean best estimate was interpreted as the median DF.

Based on the concept of the Japanese New Aseismic Design Code, we fixed 200 Gal as the value of maximum response acceleration (MRA) below which the *DF* is expected to be zero, as shown in Figure 4.3.2. The *DF* value for MRA equal to 1000 is assumed to be equal to the median DF which corresponds to NEHRP Map Area 7 (the highest seismically active area). The rationale for this assumption is that in the case of NEHRP Map Area 7, the design spectra (the same as the maximum response acceleration) of average buildings is 1.0 g (about 1000 Gal), Green (1987), and also that the median DF is considered to be the best estimate of the ATC-13 experts.

The median of the damage factor, DF_{median} can be obtained from Eq.(4.3.3) as follows.

$$Pr(DF \geq 60\%) = 10^{-SS} \tag{4.3.4}$$

$$EF(\frac{ln60 - lnDF}{s}) = 1 - 10^{-SS} \tag{4.3.5}$$

$$DF_{median} = \begin{cases} e^{ln60 - EF^{-1}(1-10^{-SS})s}, & \text{if } SS > 0; \\ 1.0, & \text{otherwise.} \end{cases} \tag{4.3.6}$$

where EF is the error function and s is the standard deviation. The mean values of the low and high estimates (ML, MH) are taken as the 90% probability bounds on the damage factor distribution so that the standard deviation, s, may be calculated as follows:

$$s = (ln(MH) - ln(ML))/3.28 \tag{4.3.7}$$

4.3.3. Structural Scores for a Type or Class of Building

In our study, the structure classes of the buildings are classified into 39 categories according to ATC-13, as shown in Table 4.3.1. Based on ATC-21, the Basic Structural Hazard (BSH) and the Performance Modification Factors (PMFs) of each class are given in Table 4.3.2. Since the standard deviation of each class can be calculated using Eq. (4.3.7) by substituting for the values of the mean low and mean high estimates by the ML, MH values in ATC-13 for that structure class, Eq.(4.3.6) can then be used to calculate the median DF.

In the Seismic Risk Module that we are building because of the following reasons

(a) the module is not for existing buildings but for new coming ones,

(b) the local soil condition is taken into account in the stochastic response spectra as described in 4.2.7, and

(c) the height of the building is already taken into account for each structure class

the modifiers that have been selected from those in ATC-21 are:

- Vertical Irregularity (PMF_V): steps in elevation, inclined walls, discontinuities in load path, building on hill, etc.
- Soft Story (PMF_S): open on all sides of building, tall ground floor, discontinuous shear walls, etc.
- Torsion (PMF_T): eccentric stiffness in plan, (e.g. corner building, wedge shaped building with one or two solid walls and all other wall open), etc.
- Plan Irregularity (PMF_P): "**L**", "**U**", "**E**", "**T**" or other irregular building shape.
- Pounding (PMF_{Po}): floor levels of adjacent buildings not aligned and less than 4" of separation per story.
- Large Heavy Cladding (PMF_L): many large heavy stone or concrete panels. (glass panels and masonry veneer do not qualify).
- Short Columns (PMF_{SC}): some columns restrained by half walls or spandrel beams.

Some of the above modifiers can be inferred directly from the information stored in the Project Database while others are supplied by the user. For those that the user needs to supply, the system shows the meaning of each modifier in the display and ask the users if each modifier is true. Examples of such displays are shown in Chapter 5.

A few sample runs are shown below for the purpose of explaining this procedure. In the case that the building belongs to Class-4 (concrete shear wall with frame - medium rise), the scores of the BSH (Basic Structural Hazard) and the modifiers are given in Table 4.3.2 as follows.

Item	Score
BSH	5.0
PMF_V	-0.5
PMF_S	-2.0
PMF_T	-1.0
PMF_P	-0.5
PMF_{Po}	N/A
PMF_L	N/A
PMF_{SC}	-1.0

Some calculations are carried out to obtain the structural score, SS, and the median damage factor, DF_{median}, by evaluating the modifiers which are true.

Case-1: No deficiency (all the modifiers are not true)

$$SS = BSH = 5.0$$

$$DF_{median} = 13.9\%$$

Case-2: Soft Story

$$SS = BSH + PMF_S = 5.0 - 2.0 = 3.0$$

$$DF_{median} = 20.7\%$$

Case-3: Soft Story, Torsion and Plan Irregularity

$$SS = BSH + PMF_S + PMF_T + PMF_P = 5.0 - 2.0 - 1.0 - 0.5 = 1.5$$

$$DF_{median} = 31.6\%$$

Case-4: Soft Story, Torsion, Plan Irregularity, Vertical Irregularity and Short Columns

$$SS = BSH + PMF_S + PMF_T + PMF_P + PMF_V + PMF_{SC}$$

$$= 5.0 - 2.0 - 1.0 - 0.5 - 0.5 - 1.0 = 0.0$$

$$DF_{median} = 100.0\%$$

The DF-MRA function of the above example cases are shown in Figure 4.3.3.

We have used this procedure to determine the DF-MRA function in the Seismic Risk Module.

Table 4.3.1. Structure Classes in ATC-13

Class	Type of Structure
1	Wood Frame (Low Rise)
2	Light Metal (Low Rise)
3	Concrete Shear Wall w/Frame (Low Rise)
4	Concrete Shear Wall w/Frame (Medium Rise)
5	Concrete Shear Wall w/Frame (High Rise)
6	Concrete Shear Wall wo/Frame (Low Rise)
7	Concrete Shear Wall wo/Frame (Medium Rise)
8	Concrete Shear Wall wo/Frame (High Rise)
9	Masonry Shear Wall wo/Frame (Low Rise)
10	Masonry Shear Wall wo/Frame (Medium Rise)
11	Masonry Shear Wall wo/Frame (High Rise)
12	Braced Steel Frame (Low Rise)
13	Braced Steel Frame (Meidum Rise)
14	Braced Steel Frame (High Rise)
15	Moment-Resisting Steel Frame (Perim.)(Low Rise)
16	Moment-Resisting Steel Frame (Perim.)(Medium Rise)
17	Moment-Resisting Steel Frame (Perim.)(High Rise)
18	Moment-Resisting Duct. Concr. (Low Rise)
19	Moment-Resisting Duct. Concr. (Medium Rise)
20	Moment-Resisting Duct. Concr. (High Rise)
21	Tilt-up (Low Rise)
72	Moment-Resisting Steel Frame (Distri.)(Low Rise)
73	Moment-Resisting Steel Frame (Distri.)(Medium Ris)
74	Moment-Resisting Steel Frame (Distri.)(High Rise)
75	Unreinforced Masonry (Bearing Wall)(Low Rise)
76	Unreinforced Masonry (Bearing Wall)(Medium Rise)
77	Unreinforced Masonry (Bearing Wall)(High Rise)
78	Unreinforced Masonry (w/Interior Frame)(Low Rise)
79	Unreinforced Masonry (w/Interior Frame)(Medium Ri)
80	Unreinforced Masonry (w/Interior Frame)(High Rise)
81	Pre-Cast Concrete Frame (Low Rise)
82	Pre-Cast Concrete Frame (Medium Rise)
83	Pre-Cast Concrete Frame (High Rise)
84	Masonry Shear Wall w/Frame (Low Rise)
85	Masonry Shear Wall w/Frame (Medium Rise)
86	Masonry Shear Wall w/Frame (High Rise)
87	Moment-Resisting Non-Duct. Concr. (Low Rise)
88	Moment-Resisting Non-Duct. Concr. (Medium Rise)
89	Moment-Resisting Non-Duct. Concr. (High Rise)

Table 4.3.2. BSH and PMFs for the Structural Scores

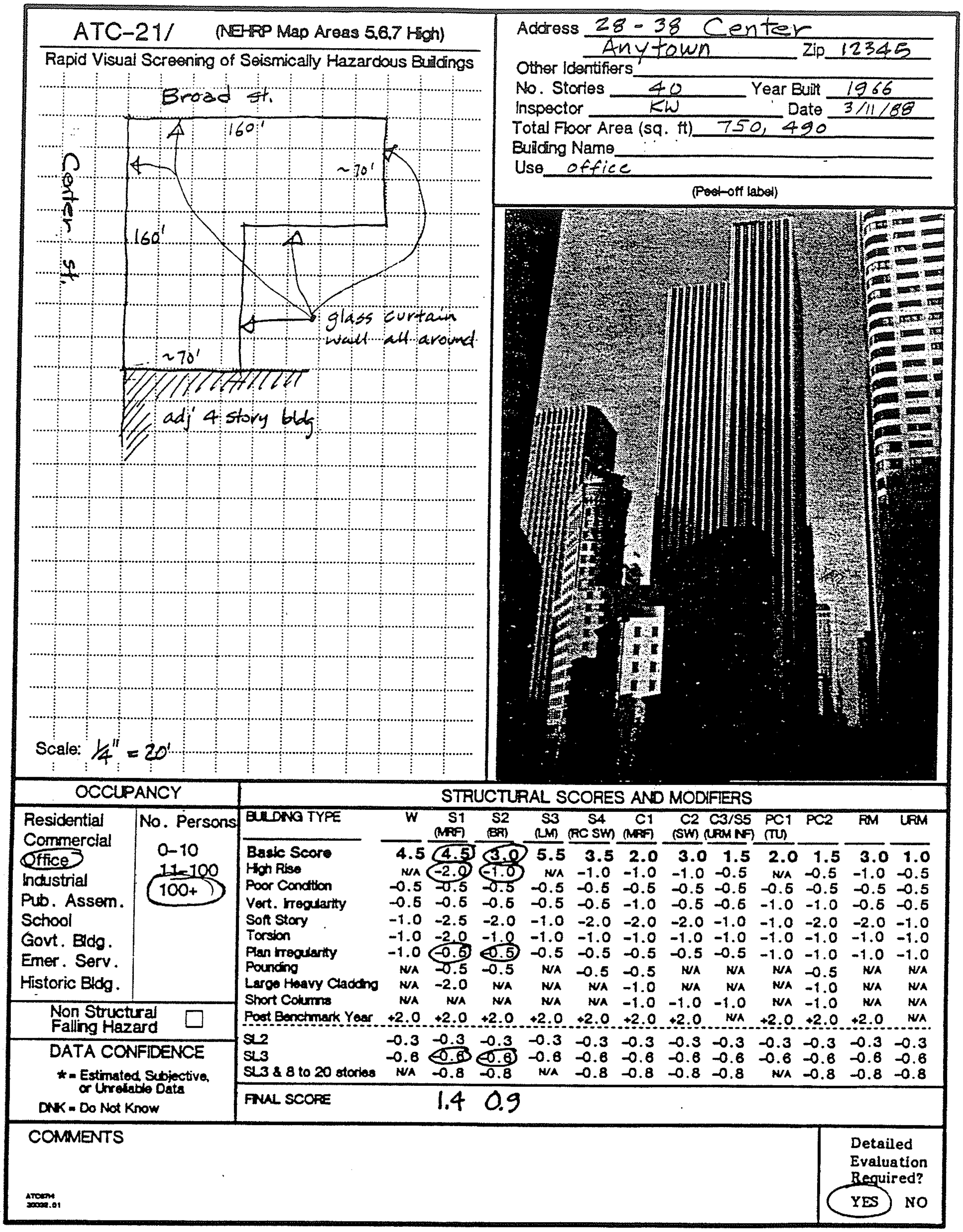
STRUCTURAL SCORES

Class	1	2	3	4	5	6	7	8	9	10
Basic Score	4.5	5.5	6.0	5.0	4.0	4.0	2.5	2.0	3.0	2.5
Vert. Irregularity	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5
Soft Story	-1.0	-1.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0
Torsion	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0
Plan Irregularity	-1.0	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-1.0	-1.0
Pounding	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Large Heavy Cladding	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Short Columns	N/A	N/A	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	N/A	N/A

Class	11	12	13	14	15	16	17	18	19	20
Basic Score	2.0	3.0	3.0	2.0	5.5	4.0	2.5	6.0	5.0	3.5
Vert. Irregularity	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-1.0	-1.0	-1.0
Soft Story	-2.0	-2.0	-2.0	-2.0	-2.5	-2.5	-2.5	-2.0	-2.0	-2.0
Torsion	-1.0	-1.0	-1.0	-1.0	-2.0	-2.0	-2.0	-1.0	-1.0	-1.0
Plan Irregularity	-1.0	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5
Pounding	N/A	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5
Large Heavy Cladding	N/A	N/A	N/A	N/A	-2.0	-2.0	-2.0	-1.0	-1.0	-1.0
Short Columns	N/A	N/A	N/A	N/A	N/A	N/A	N/A	-1.0	-1.0	-1.0

Class	21	72	73	74	75	76	78	79	80	81
Basic Score	2.0	4.5	4.0	2.5	1.5	1.0	1.0	1.0	1.0	1.5
Vert. Irregularity	-1.0	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-1.0
Soft Story	-1.0	-2.5	-2.5	-2.5	-1.0	-1.0	-1.0	-1.0	-1.0	-2.0
Torsion	-1.0	-2.0	-2.0	-2.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0
Plan Irregularity	-1.0	-0.5	-0.5	-0.5	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0
Pounding	N/A	-0.5	-0.5	-0.5	N/A	N/A	N/A	N/A	N/A	-0.5
Large Heavy Cladding	N/A	-2.0	-2.0	-2.0	N/A	N/A	N/A	N/A	N/A	-1.0
Short Columns	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	-1.0

Class	82	83	84	85	86	87	88	89
Basic Score	1.5	1.0	4.0	3.5	4.0	2.5	2.0	2.0
Vert. Irregularity	-1.0	-1.0	-0.5	-0.5	-0.5	-1.0	-1.0	-1.0
Soft Story	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0
Torsion	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0
Plan Irregularity	-1.0	-1.0	-1.0	-1.0	-1.0	-0.5	-0.5	-0.5
Pounding	-0.5	-0.5	N/A	N/A	N/A	-0.5	-0.5	-0.5
Large Heavy Cladding	-1.0	-1.0	N/A	N/A	N/A	-1.0	-1.0	-1.0
Short Columns	-1.0	-1.0	N/A	N/A	N/A	-1.0	-1.0	-1.0



ATC-21/ (NEHRP Map Areas 5,6,7 High)

Rapid Visual Screening of Seismically Hazardous Buildings

Scale: 1/4" = 20'

Address 28 - 38 Center
Anytown Zip 12345
Other Identifiers
No. Stories 40 Year Built 1966
Inspector KW Date 3/11/88
Total Floor Area (sq. ft) 750, 490
Building Name
Use office

(Peel-off label)

OCCUPANCY	No. Persons
Residential Commercial [✓ Office] Industrial Pub. Assem. School Govt. Bldg. Emer. Serv. Historic Bldg.	0–10 11–100 [✓ 100+]

Non Structural Falling Hazard ☐

DATA CONFIDENCE

* = Estimated, Subjective, or Unreliable Data

DNK = Do Not Know

STRUCTURAL SCORES AND MODIFIERS

BUILDING TYPE	W	S1 (MRF)	S2 (BR)	S3 (LM)	S4 (RC SW)	C1 (MRF)	C2 (SW)	C3/S5 (URM INF)	PC1 (TU)	PC2	RM	URM
Basic Score	4.5	[✓ 4.5]	[✓ 3.0]	5.5	3.5	2.0	3.0	1.5	2.0	1.5	3.0	1.0
High Rise	N/A	[✓ -2.0]	[✓ -1.0]	N/A	-1.0	-1.0	-1.0	-0.5	N/A	-0.5	-1.0	-0.5
Poor Condition	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5
Vert. Irregularity	-0.5	-0.5	-0.5	-0.5	-0.5	-1.0	-0.5	-0.5	-1.0	-1.0	-0.5	-0.5
Soft Story	-1.0	-2.5	-2.0	-1.0	-2.0	-2.0	-2.0	-1.0	-1.0	-2.0	-2.0	-1.0
Torsion	-1.0	-2.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0
Plan Irregularity	-1.0	[✓ -0.5]	[✓ -0.5]	-0.5	-0.5	-0.5	-0.5	-0.5	-1.0	-1.0	-1.0	-1.0
Pounding	N/A	-0.5	-0.5	N/A	-0.5	-0.5	N/A	N/A	N/A	-0.5	N/A	N/A
Large Heavy Cladding	N/A	-2.0	N/A	N/A	N/A	-1.0	N/A	N/A	N/A	-1.0	N/A	N/A
Short Columns	N/A	N/A	N/A	N/A	N/A	-1.0	-1.0	-1.0	N/A	-1.0	N/A	N/A
Post Benchmark Year	+2.0	+2.0	+2.0	+2.0	+2.0	+2.0	+2.0	N/A	+2.0	+2.0	+2.0	N/A
SL2	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3
SL3	-0.6	[✓ -0.6]	[✓ -0.6]	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6
SL3 & 8 to 20 stories	N/A	-0.8	-0.8	N/A	-0.8	-0.8	-0.8	-0.8	N/A	-0.8	-0.8	-0.8
FINAL SCORE		1.4	0.9									

COMMENTS

ATC87M4
30008.01

Detailed Evaluation Required? [✓ YES] NO

Figure 4.3.1. Data Collection Form of ATC-21

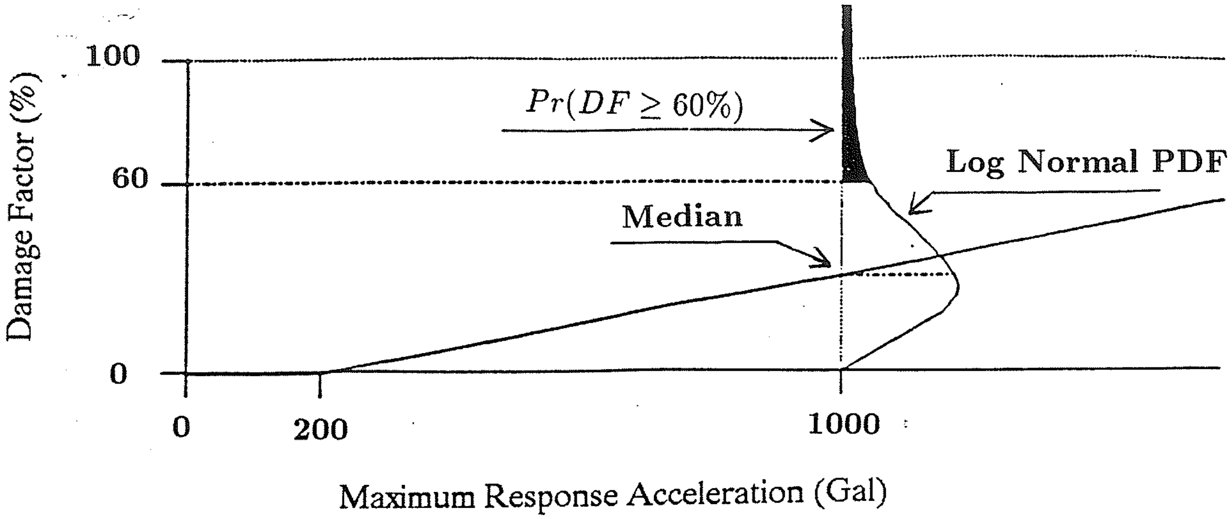


Figure 4.3.2. Determination of DF-MRA Function by ATC-21

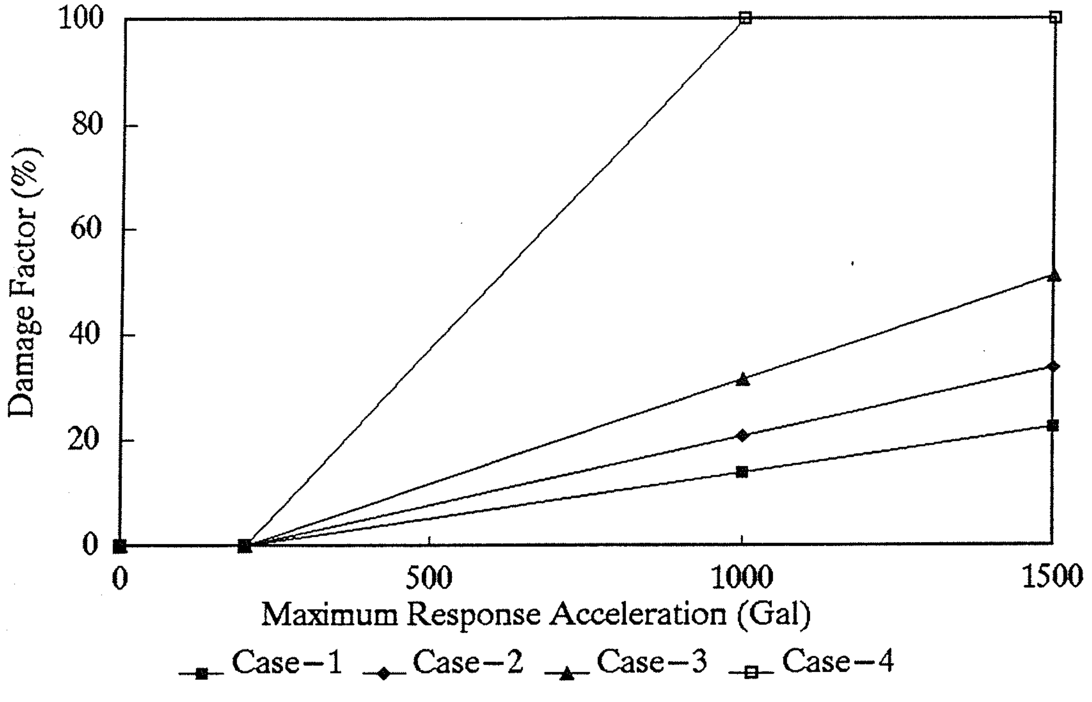


Figure 4.3.3. DF-MRA Functions of the Example Cases

5. Performance of the System

5.1. A Construction Project Model

In order to check the knowledge and performance of the system, a building completed in Tokyo in 1988 by Takenaka Corporation has been selected as a project model. The construction project was an interesting case in Tokyo, because some new technology was required to construct the 30 story reinforced concrete building, Figure 5.1.1. The number of basement stories is 1 and the floor area is 23,250 (m^2). The data of the project has been retrieved from the project database into the main module and it is shown as an example in Figure 3.2.4 of Chapter 3.

In the near future, one of the authors is planning on using real data such as those contained in a Takenaka Project Database and carry out experiments by changing some of the parameters. Also he is planning on verfiying the system by using historical failure/accident data from another data source.

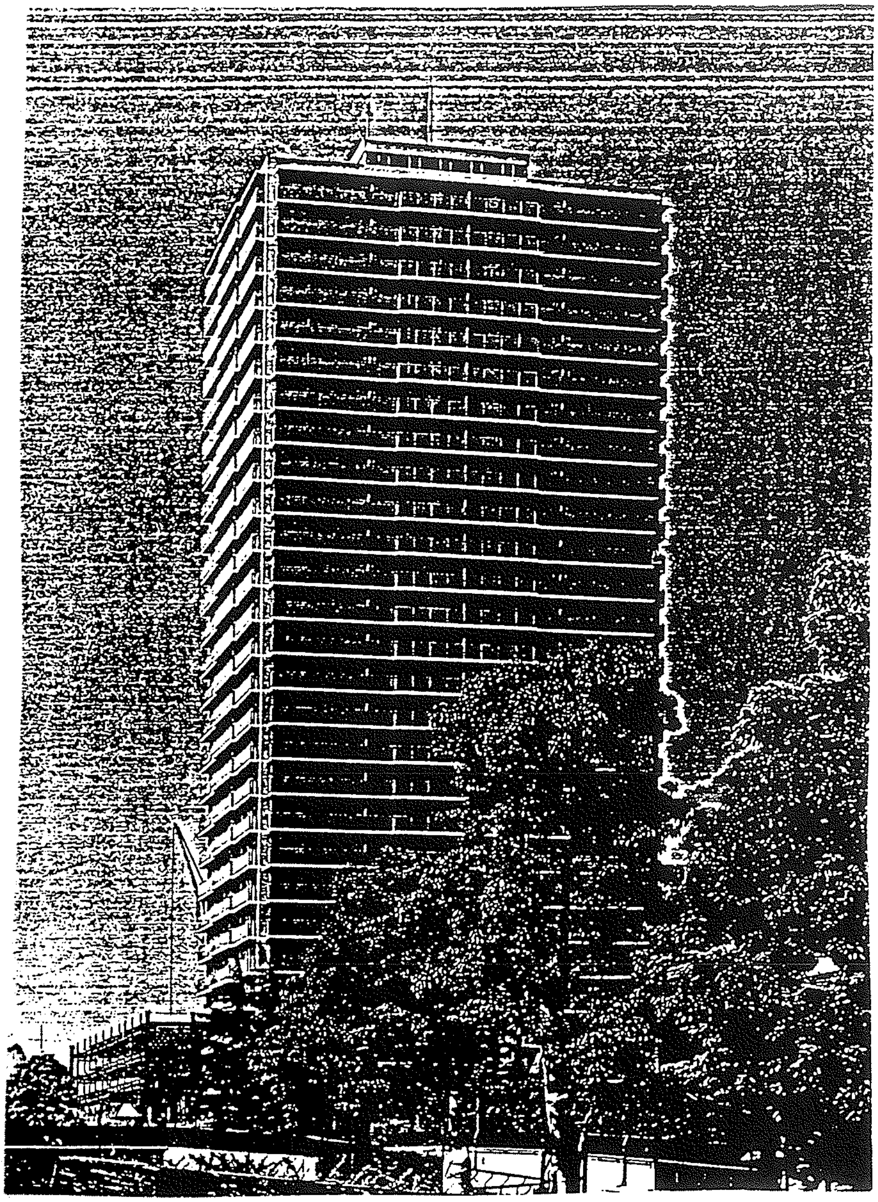


Figure 5.1.1. A Project Model for the Case Study

5.2. Performance of Each Module

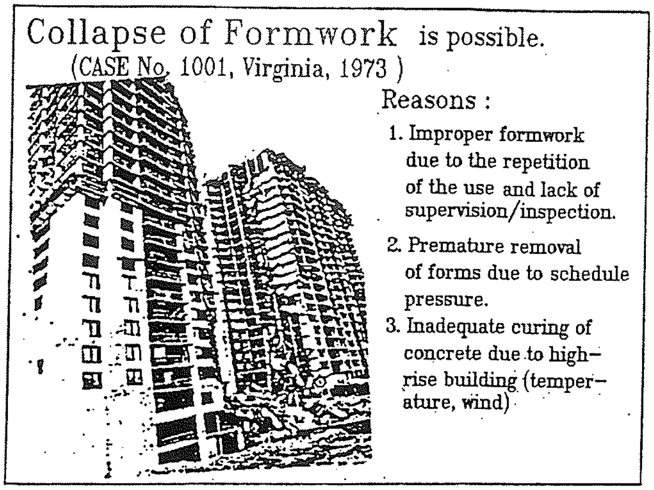
Construction and Operation Stage Modules

The two modules run automatically retrieving the required data from the project database. Visual images of typical instances from the historical failure/accident database which are strongly correlated to the project are shown on the display along with appropriate comments. Some examples are shown in Figure 5.2.1. These visual images together with the comments can provide the user with some helpful suggestions and insight on potential risks for the project. All the lists of the selected cases are written in the output file (see Figure 5.2.2). If the user so desires, the Case Record Book, which is the collection of the original documents, can be consulted for more details on the cases that are strongly correlated with the project. In the case of the model building, Figure 5.2.1.(a) and (c) are the results obtained from the Construction Stage Modules.

Seismic Risk Module

Most of the data required in the module are obtained directly from the Project Database or through some inference. However, some data have to be obtained by users' help. In that case some explanations are shown on the display to help the users. One example is shown in Figure 5.2.3.

A few examples of the results of this module are shown in Figure 5.2.4. When the expected damage is large, some countermeasures and the people who should be consulted are shown in Figure 5.2.4.(c). In the case of the building model discussed in section 5.1, Figure 5.2.4.(a)shows the result. The results are also written in the result file as in Figure 5.2.2.

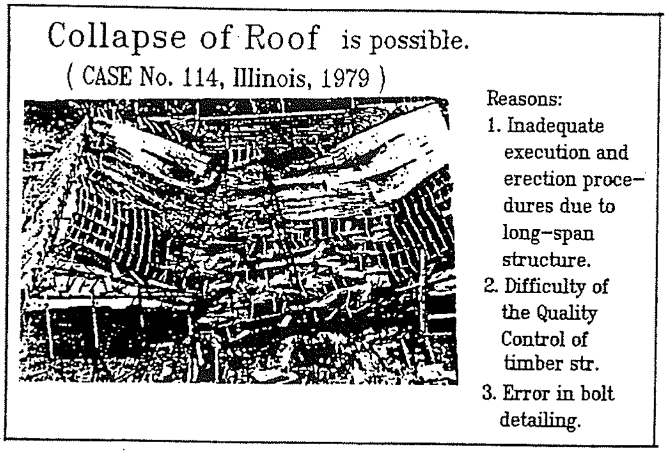


Collapse of Formwork is possible.
(CASE No. 1001, Virginia, 1973)

Reasons :

1. Improper formwork due to the repetition of the use and lack of supervision/inspection.
2. Premature removal of forms due to schedule pressure.
3. Inadequate curing of concrete due to high-rise building (temperature, wind)

(a) Example-1

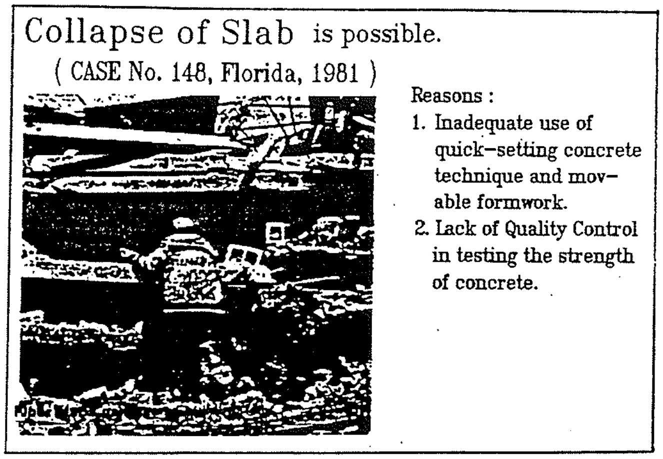


Collapse of Roof is possible.
(CASE No. 114, Illinois, 1979)

Reasons:

1. Inadequate execution and erection procedures due to long-span structure.
2. Difficulty of the Quality Control of timber str.
3. Error in bolt detailing.

(b) Example-2



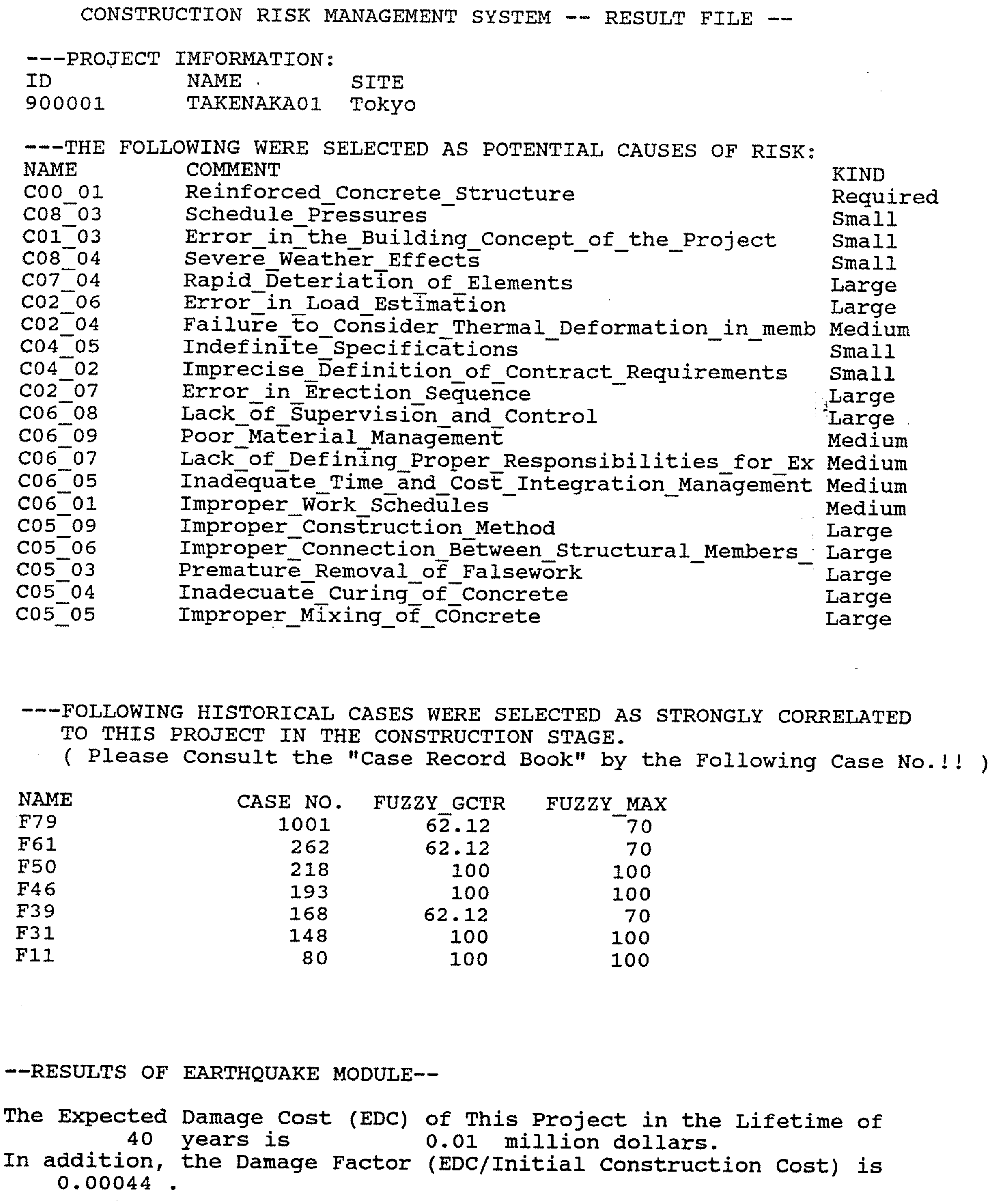
Collapse of Slab is possible.
(CASE No. 148, Florida, 1981)

Reasons :

1. Inadequate use of quick-setting concrete technique and movable formwork.
2. Lack of Quality Control in testing the strength of concrete.

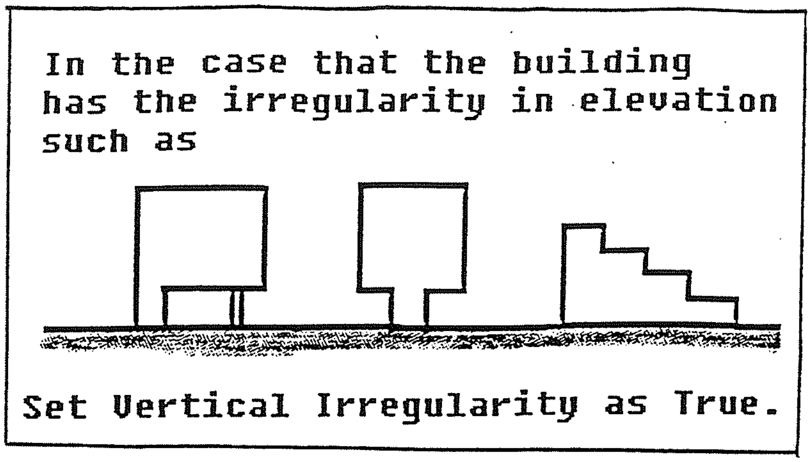
(c) Example-3

Figure 5.2.1. Examples of the Image Outputs in the Construction Module



```
        CONSTRUCTION RISK MANAGEMENT SYSTEM -- RESULT FILE --

   ---PROJECT IMFORMATION:
   ID           NAME          SITE
   900001       TAKENAKA01    Tokyo

   ---THE FOLLOWING WERE SELECTED AS POTENTIAL CAUSES OF RISK:
   NAME         COMMENT                                           KIND
   C00_01       Reinforced_Concrete_Structure                     Required
   C08_03       Schedule_Pressures                                Small
   C01_03       Error_in_the_Building_Concept_of_the_Project      Small
   C08_04       Severe_Weather_Effects                            Small
   C07_04       Rapid_Deteriation_of_Elements                     Large
   C02_06       Error_in_Load_Estimation                          Large
   C02_04       Failure_to_Consider_Thermal_Deformation_in_memb   Medium
   C04_05       Indefinite_Specifications                         Small
   C04_02       Imprecise_Definition_of_Contract_Requirements     Small
   C02_07       Error_in_Erection_Sequence                        Large
   C06_08       Lack_of_Supervision_and_Control                   Large
   C06_09       Poor_Material_Management                          Medium
   C06_07       Lack_of_Defining_Proper_Responsibilities_for_Ex   Medium
   C06_05       Inadequate_Time_and_Cost_Integration_Management   Medium
   C06_01       Improper_Work_Schedules                           Medium
   C05_09       Improper_Construction_Method                      Large
   C05_06       Improper_Connection_Between_Structural_Members_   Large
   C05_03       Premature_Removal_of_Falsework                    Large
   C05_04       Inadecuate_Curing_of_Concrete                     Large
   C05_05       Improper_Mixing_of_Concrete                       Large


   ---FOLLOWING HISTORICAL CASES WERE SELECTED AS STRONGLY CORRELATED
      TO THIS PROJECT IN THE CONSTRUCTION STAGE.
      ( Please Consult the "Case Record Book" by the Following Case No.!! )

   NAME             CASE NO.   FUZZY_GCTR   FUZZY_MAX
   F79                 1001        62.12          70
   F61                  262        62.12          70
   F50                  218          100         100
   F46                  193          100         100
   F39                  168        62.12          70
   F31                  148          100         100
   F11                   80          100         100


  --RESULTS OF EARTHQUAKE MODULE--

  The Expected Damage Cost (EDC) of This Project in the Lifetime of
          40   years is         0.01  million dollars.
  In addition, the Damage Factor (EDC/Initial Construction Cost) is
      0.00044 .
```

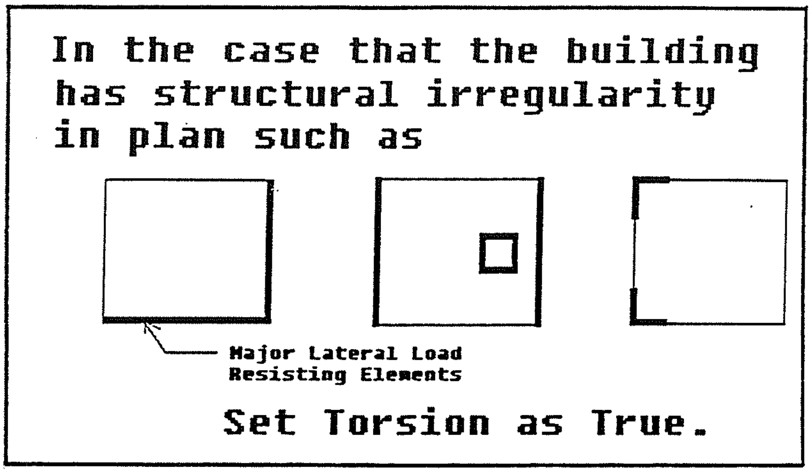
Figure 5.2.2. An Example of the Result File



In the case that the building has the irregularity in elevation such as

Set Vertical Irregularity as True.

(a) Example-1

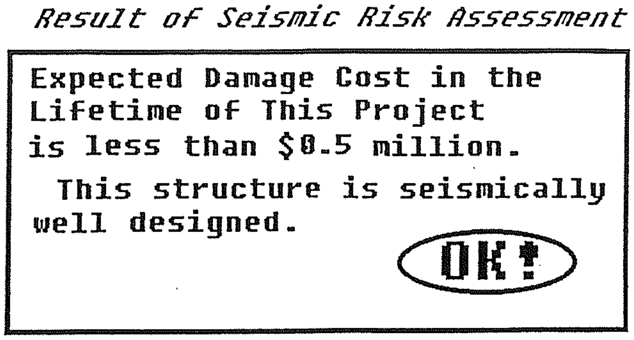


In the case that the building has structural irregularity in plan such as

Set Torsion as True.

(b) Example-2

Figure 5.2.3. Examples of the User Interface in the Seismic Risk Module

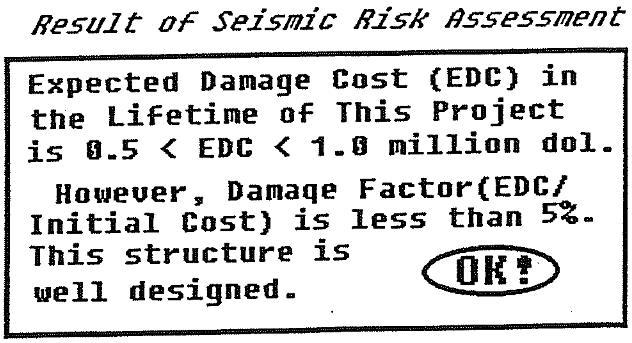


Result of Seismic Risk Assessment

Expected Damage Cost in the
Lifetime of This Project
is less than $0.5 million.

This structure is seismically
well designed.

(a) Example-1

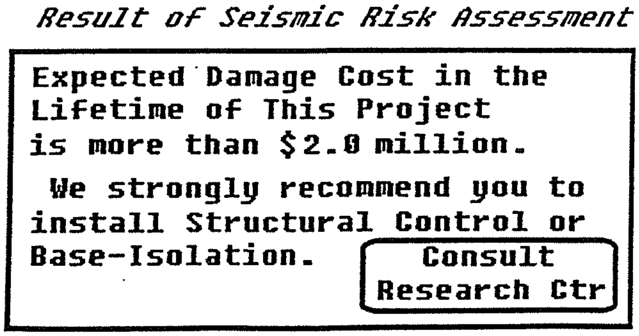


Result of Seismic Risk Assessment

Expected Damage Cost (EDC) in
the Lifetime of This Project
is 0.5 < EDC < 1.0 million dol.

However, Damaqe Factor(EDC/
Initial Cost) is less than 5%.
This structure is
well designed.

(b) Example-2



Result of Seismic Risk Assessment

Expected Damage Cost in the
Lifetime of This Project
is more than $2.0 million.

We strongly recommend you to
install Structural Control or
Base-Isolation.

(c) Example-3

Figure 5.2.4. Examples of the Final Outputs in the Seismic Risk Module

6. Conclusions

We have developed a prototype construction risk management system. The current system is limited to the risk from structural failure/accident and seismic risk over the lifetime because of time constraints on the first author.

The prototype system is an integrated system which contains object-oriented knowledge bases, databases, external Fortran program and input/output files. This system is built using the expert system shell NEXPERT OBJECT. The knowledge bases consist of a main module and three submodules called Construction Stage, Operation Stage and Seismic Risk.

The Construction and Operation Stage Modules are made up of object-oriented knowledge structures such as the cause and project networks and a structural failure/accident database, based primarily on the database compiled by Eldukair (1988). Pattern-matching using fuzzy set theory is used to identify those cases in the failure/accident database which are highly correlated with the project. The information on the project is obtained from the project database and a few additional information is supplied by the user.

The Seismic Risk Module utilizes an external Fortran program to calculate a stochastic response spectra, Tatsumi (1985), (1987) & (1988) and the knowledge on structural damage due to earthquakes is compiled from ATC-13 and ATC-21.

The performance of the prototype system has been checked by applying it to a real construction project in Tokyo. The knowledge bases and user interfaces of the system have been improved based on our initial tests. The prototype system is by no means complete and further improvements will be made by the first author when he returns to Japan.

In the course of the development of the system, we have obtained important insights on what a practical construction management system should be like in the future. The suggestions that we have are:

- better and more well-defined historical case databases
- verification of the system using real failure/accidents data at the construction sites from different sources,
- better links to real project databases in a construction company,
- better links to CAD data,
- improving the expertise in the risk field,

- checking of the system by experts in this field,
- function to update the knowledge in the system.

It will take some time to implement all the above suggestions as some of them are by themselves very big tasks. However, through our research we have learned an important lesson, namely that the technology of expert systems based on object-oriented knowledge bases can be a very powerful tool in this field. We believe that our prototype system has showed us the future direction for a practical construction risk management system which will be one of the important decision-making support systems in a construction company.

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