

A seismic damage evaluation system for buildings

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ABSTRACT: We have developed an expert system to quantitatively and, or qualitatively evaluate the expected seismic damage to buildings from future earthquakes as part of a seismic risk management by construction companies in Japan. The system integrates building specific information contained in its project database, the knowledge of structural and earthquake engineers, a database of historical seismic damage of buildings and an external subroutine in one package.

The paper outlines the expert system and discusses its performance in risk management. The paper, also, describes the quantitative part in which the expected damage factors (dollar loss/replacement value) are calculated. In the quantitative part use is made of the Stochastic Response Spectra, SRS, together with the Damage-Factor Maximum Response Acceleration, DF-MRA, functions which can be defined based on the concept of Aseismic Index of Structure, I_s , as defined in the Japanese Earthquake Resistance Diagnoses Standard.

1 INTRODUCTION

In recent decades as construction projects in urban areas have become bigger and their concentration more dense, the construction industry has felt the need for a practical construction risk management based on scientific methods (Cooper et al. 1987 and Niwa 1989). In the broad area of construction risk, "Seismic Risk" is one of the more important items. So far, its importance in damage evaluation and role in suggesting countermeasures against the probable damage have not been fully utilized in spite of its big probable impact on corporate activities. Therefore, methods to quantitatively and qualitatively evaluate the probable future damage of buildings form the kernel of seismic risk management systems.

Expert systems and knowledge bases have in recent times been enthusiastically welcomed by many in industrial and professional spheres as a way of making expertise routinely available wherever it is needed. These technologies look very promising in the field of risk management since our everyday decision-making is greatly dependent on human expertise in the construction industry. Information specific to a project can be found in Project Databases which some of the larger construction companies have begun to build (Ishii 1990). The information contained in these can be efficiently utilized in an integrated expert system using current database technology.

Our system integrates the building specific information stored in a project database, knowledge base acquired from structural and earthquake engineers, historical seismic damage database and calculation modules. The system enables an easy and straightforward evaluation of the quantitative and quali-

tative damage of buildings in future earthquakes. The system is based on the prototype expert system developed for construction risk management utilizing knowledge bases and fuzzy set theory (Tatsumi 1990). In this updated system, the knowledge base and the seismic damage database have been newly constructed based on Japanese seismic design code, historical damage data and structural engineers' expertise.

The objectives and contents of the system are outlined in this paper together with some details of the newly proposed method to obtain the Damage Factor - Maximum Response Acceleration (DF-MRA) used in the quantitative evaluation of the probable seismic damage. Finally, we have attempted to interpret the results from a risk management point of view.

2 OBJECTIVES OF THE SYSTEM

The objectives of our risk management support system are

1. the quantitative/qualitative evaluation of seismic damage of buildings at all stages of planning, construction and operation, and
2. assessments of countermeasures for mitigating the impact of probable future damaging earthquakes.

The measure of quantitative damage is the expected damage factor (dollar loss/replacement value) over the lifetime of the building. The damage factor is based on the Stochastic Response Spectra (SRS) in conjunction with the Damage Factor - Maximum Response Acceleration (DF-MRA) functions. The

qualitative damage evaluation is performed by means of pattern-matching of the potential causes inferred from the data of the given building with the causes for each historical seismic damage case to identify the cases which are strongly correlated with the building. (The qualitative part of the system for identifying the historical damage cases which are strongly correlated with the inferred causes for the given building is discussed separately in Sato et al., 1992.)

The results of a quantitative and qualitative assessment of the seismic risk can be used to design countermeasures to reduce the loss in probable future earthquakes, such as

- optimal site selection taking account the importance factor of a facility,
- aseismic reinforcement/replacement of an existing building,
- appropriate dispersion of capital assets,
- holding of building materials and capital,
- restructuring of disaster-mitigation organizations, and
- employee education and training for disaster-mitigation.

3 OUTLINE OF THE SYSTEM

The system which we have developed runs in a PC and has a main module and two sub-modules called Damage Factor Evaluation (Quantitative) and Pattern Matching (Qualitative). Each module is an object oriented knowledge base made using the expert system shell, "NEXPERT OBJECT" (Neuron Data 1988). These modules are linked to databases, image data files and an external subroutine. Figure 1 shows the outline of the system. The more important parts of the system are briefly explained in the following sections.

3.1 Main control module

The main module controls the whole system and it contains

- an object oriented knowledge frame of a building,
- object oriented knowledge of damage causes,
- rules to retrieve the required data from the Project Database and to set up the data in the knowledge frame,
- rules to infer the potential causes of seismic damage in a building, and
- rules for outputting the results into the result file.

3.2 Project Database

The Project Database contains information of the buildings relevant in the planning, construction, and operation stages. The Project Database has been reconstructed picking up only those items related to configurations, structure and ground conditions in another database (Ishii et al. 1990). The items stored in the database are:

1. Profile (project code, location, use and years of design/construction)
2. Scale (number of floors, total height, floor

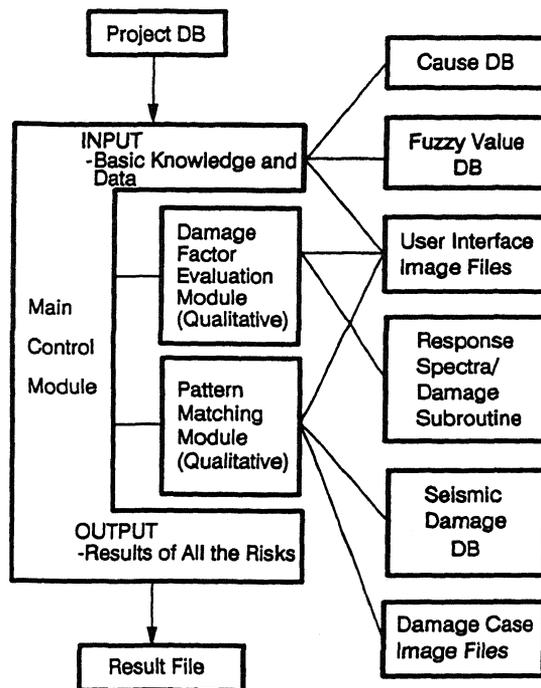


Figure 1. Outline of the system

height, building/basement areas and total floor area)

3. Structure (type of structure, number of columns, total length of aseismic walls, type of facing and type/size of foundation)

4. Others (existence of short columns, irregularity of plan, ratio of two sides of plan, existence of pilotis/wells and liquefaction potential)

The items listed in 4. are evaluated based on the method described in the Japanese Earthquake Resistance Diagnoses Standard, JERDS (the Japan Building Disasters Prevention Association, JBDPA 1990) and the Tokyo Liquefaction Potential Map.

3.3 Seismic Damage Database

The damage survey reports of the 1968 Tokachi-oki Earthquake (the Architectural Institute of Japan, AIJ 1968) and the 1978 Miyagiken-oki Earthquake (AIJ 1978) which are the latest damaging earthquakes in Japanese urban areas provide about 60 cases of damages to reinforced concrete buildings. The information in these reports have been encoded in a survey form and stored as a database using dBASE IV. The database is described in more detail in Sato et al. (1992).

3.4 Damage Factor Evaluation Module (Quantitative Module)

This module is described in section 4.

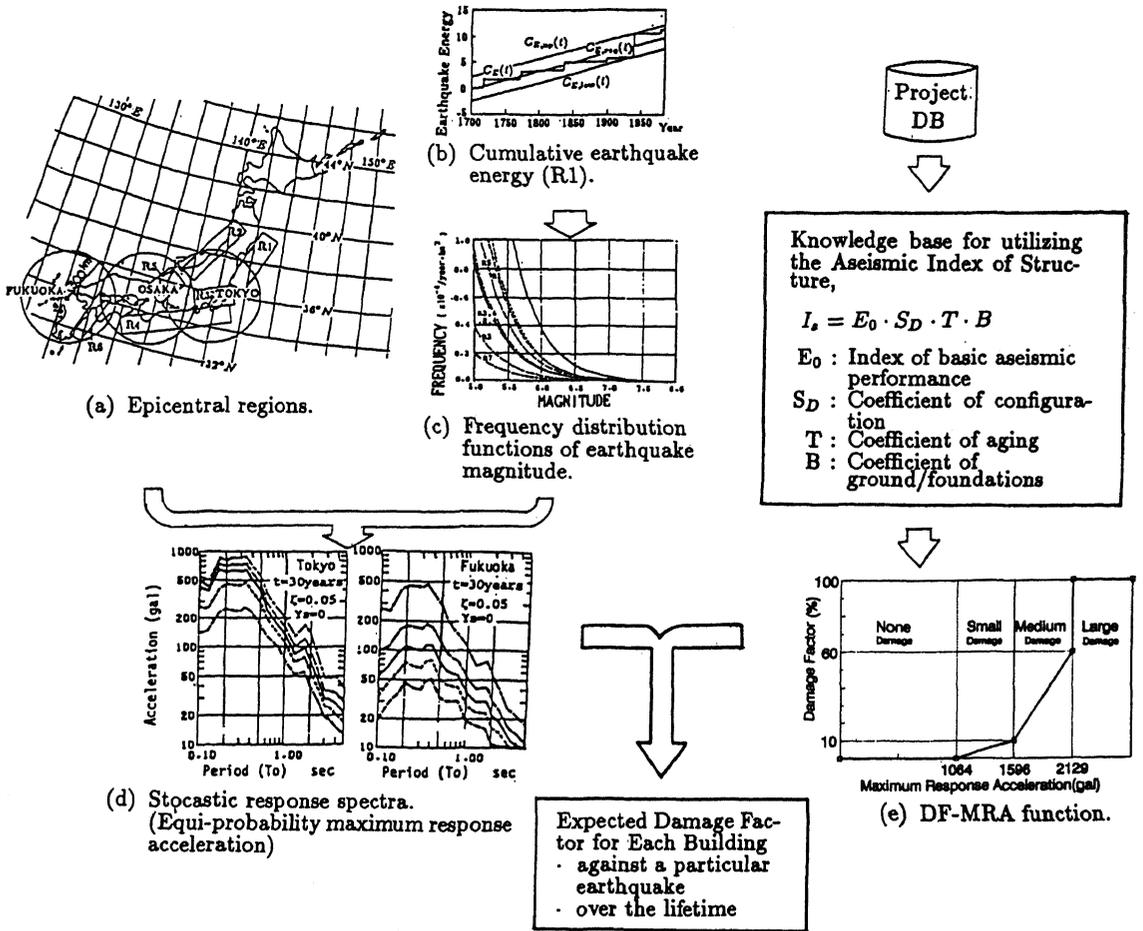


Figure 2. Graphical representation of the Damage Factor Evaluation Module

3.5 Pattern Matching Module (Qualitative Module)

In this module pattern-matching is done between the inferred causes for the given building and the causes for each historical seismic damage case to identify those cases in the historical seismic database that are strongly correlated with the building. Also, the relevant images and comments pertaining to the cases can be viewed.

Since the evaluation of the significance of the contribution of the causes is based on the experience and intuition of human experts, it is inevitably vague and not very precise. Fuzzy set theory has been applied in this module to process this kind of information. More detail of this module is provided in Sato et al. (1992).

4 DAMAGE FACTOR EVALUATION MODULE

The expected damage factors (dollar loss/replacement value) of buildings due to a particular earthquake or earthquakes over the lifetime of the build-

ing can be obtained by using the Stochastic Response Spectra (SRS) in conjunction with the Damage Factor - Maximum Response Acceleration (DF-MRA) functions. The procedure to calculate the SRS was developed by one of the authors in his previous research, Tatsumi (1987 and 1988). The DF-MRA functions are defined using the Aseismic Index of Structure, I_s , as described in the JERDS (JBDPA 1990). Figure 2 shows a graphical representation of the system for calculating the expected damage factor. The data required in this module is obtained by the knowledge bases of the system from the data retrieved from the Project Database and is input to an external Fortran program which performs the calculations. The results of the calculations are supplied to the Damage Factor Evaluation Module and the conclusions based on them are output. The various parts in this module are briefly explained below.

4.1 Epicentral regions

Based on the distribution of the magnitudes and epicenters of historical earthquakes in Japan, epicen-

tral regions in which the seismicity is considered to be approximately homogeneous have been defined. These regions are shown as R1 through R6 in Figure 2 (a).

4.2 Expected arrival rate of earthquakes in each epicentral region

The cumulative earthquake energy in each epicentral region shown in Figure 2 (b), is used to define the time-dependent Annual Expected Arrival Rate (AEAR) of earthquakes, as described in Tatsumi (1988).

4.3 Frequency distribution functions of earthquake magnitude

The frequency distribution functions shown in Figure 2 (c) are obtained using the above AEAR by assuming that the frequency distribution of magnitudes in each epicentral region follows 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.

4.4 Calculation of the Stochastic Response Spectra (SRS)

Based on the information on arrival rates and frequency distributions of earthquake magnitudes, empirical attenuation-distance equations and the theory of stationary random response of linear single-degree-of-freedom system, the stochastic response spectra can be calculated at a given site for the known conditions of ground and structure (Tatsumi 1987 and 1988).

The required input data on the longitude and latitude of the site, structural damping and predominant period of the local ground are given by the knowledge in the Damage Factor Evaluation Module which accesses the Project Database. The life-time of the building or the choice of a particular earthquake is supplied by the user.

In Figure 2 (d), the calculated equi-probability response spectra for Tokyo and Fukuoka are shown.

4.5 Damage Factor-Maximum Response Acceleration (DF-MRA) functions

The DF-MRA function gives the relationship between damage factor and the maximum response acceleration of a structure. The functions depend on the structural type, configuration and other details of the structure. There are no established method for calculating the DF-MRA functions and the method we adopted in our previous research, Tatsumi (1988), was based on the knowledge of US earthquake engineers as embodied in ATC-21.

Since the history and contents of aseismic design codes and the knowledge of structural/earthquake engineers in Japan are different from those in the U.S., we propose a method to utilize the concept of Aseismic Index of Structure, I_s described in the JERDS for reinforced concrete buildings (JBDPA

1990). Figure 2 (e) shows an example of the DF-MRA functions obtained from I_s .

In our method, a coefficient B which takes into account the characteristics of the ground and, or foundation is added to the coefficients of the JERDS equation, as shown below.

$$I_s = E_0 \cdot S_D \cdot T \cdot B \quad (1)$$

where E_0 is the index of basic aseismic performance, S_D , T and B are the coefficients of configuration aging and ground and, or foundations, respectively. The values of the above index and coefficients are obtained by the knowledge base encoded based mainly on the JERDS using the information stored in the Project Database. For the given building, E_0 can be evaluated from the amount of columns/walls and the presence of short columns, S_D from the irregularity in plan, ratio of two sides, structural imbalance, existence of wells/pilotis, basement ratio and so on, T from the age and quality of exterior walls, and B from the liquefaction potential, type of foundations, length of piles and basement ratio.

As Equation (1) shows, the index of basic aseismic performance, E_0 , is corrected by some coefficients to obtain the I_s -value corresponding to the characteristics of the building. I_s signifies "the earthquake response acceleration (G) at which the columns/walls of the building start failing." The practical usefulness of I_s has been verified by some researchers, Fire and Marine Insurance Rating Association of Japan, FMIRAJ (1991), by using the statistics of building damages in recent damaging earthquakes in Japan, such as the 1968 Tokachi-oki and the 1978 Miyagiken-oki.

As the validity of I_s appears to be confirmed by the data recorded in the cases of historical seismic damages, we have decided to use I_s to define the DF-MRA functions, as shown in Figure 3.

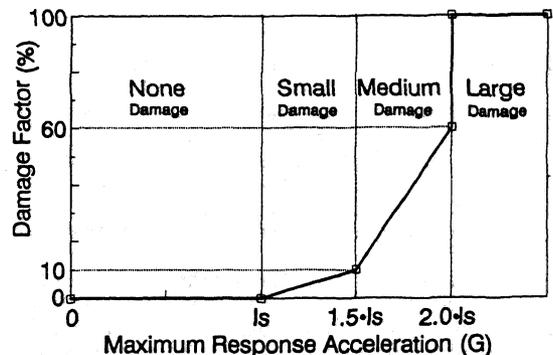


Figure 3. Definition of the DF-MRA function by I_s .

4.6 Expected damage factors of buildings

By combining the SRS and DF-MRA the expected damage factor of a building due to a particular earthquake or all the earthquakes expected over the life-time can be evaluated.

5 PERFORMANCE AND RESULTS OF THE SYSTEM

The user inputs the building code to be checked and a particular earthquake or the assumed lifetime of the building. The system runs automatically from that point on retrieving the required data from the Project Database. Based on the location, structural type, configuration, characteristics of ground/foundations, etc., the quantitative and, or qualitative seismic risk is calculated and the results output on the display and to a file.

As an example, we discuss the results for an existing reinforced concrete building located in Tokyo in the case of a recurrence of the 1923 Kanto Earthquake. This building has three stories above ground level and one floor in the basement. The total floor area is about 1580 m^2 .

Figure 4 shows the probability distribution function of the maximum response acceleration of the building. Figure 5 is the DF-MRA function corresponding to $I_s = 1.086$ of this building. Combining the above two functions, the expected damage factor is calculated as 9.5%.

Based on the expected damage factor and the intermediate results in the inference process such as I_s , amplification factor of ground, potential causes, etc., the diagnostic results are shown on the display for this building against a recurrence of the 1923 Kanto Earthquake, as in Figure 6.

On the other hand, three historical damage cases strongly correlated to this building are shown on the display, as in Figure 7. The visual images suggest that the damage is likely to go no further than some shear cracks on the columns and walls. We can get much more information from those images and comments as described in Sato et al. (1992).

This system is used to check about 100 existing RC buildings in Tokyo against a recurrence of the 1923 Kanto Earthquake. The damage factor of each building is plotted against the I_s -value in Figure 8. We can observe the followings from this figure.

- The I_s -values are distributed between 0.5 and 3.0 centering around 1.0.
- The damage factors of roughly 80% of the buildings are almost zero.
- Damage factors more than 0.1 are exceptional.
- In general the damage factors decrease as the I_s -values increase.
- The damage factors are widely scattered even if the I_s -values are very close distributed. ("The amplifications of earthquake motions due to the local ground conditions" are considered to be the major cause.)

The above results suggest the followings:

- the majority of the existing RC buildings in Tokyo will sustain almost no damage even in the case of a recurrence of the 1923 Kanto Earthquake,
- the buildings expected to sustain more than moderate damage are very few and we need to focus on only these few for risk management,
- for the few buildings with the high damage factors more information on countermeasures can be provided by this system, and

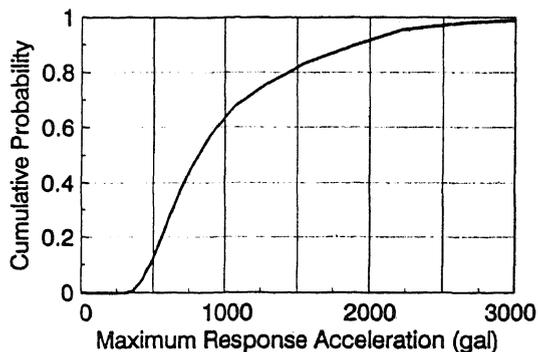


Figure 4. Probability distribution function of MRA for the example.

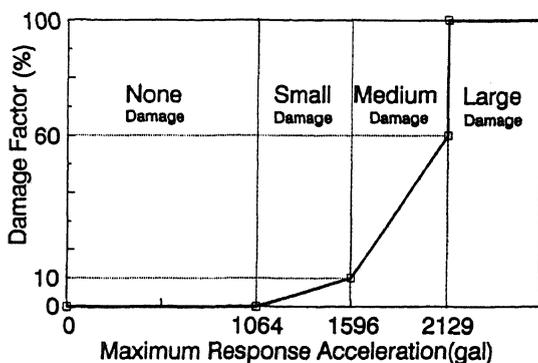


Figure 5. DF-MRA function for the example.

Results of Diagnosis

- The structure of this building is seismically well-designed in terms of the aseismic design code.
- The expected damage factor is about 10%.
- The structure itself sustains light damage and needs only a minor repair.
- The probability of sustaining the functional damages related to lifelines and equipments is high.
- The major cause of the damage is the resonant vibration of the local ground and building.

Figure 6. Display of the diagnostic results for the example.

the required time to quantitatively and, or qualitatively check one building on a PC is just around two minutes so this system is very suitable in checking many buildings and providing basic information for conducting seismic risk management.

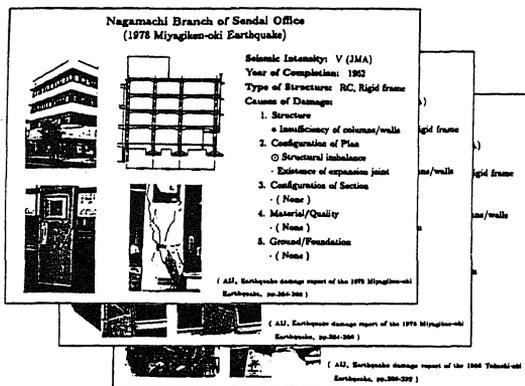


Figure 7. Display of the strongly correlated damage cases for the example (Sato et al. 1992).

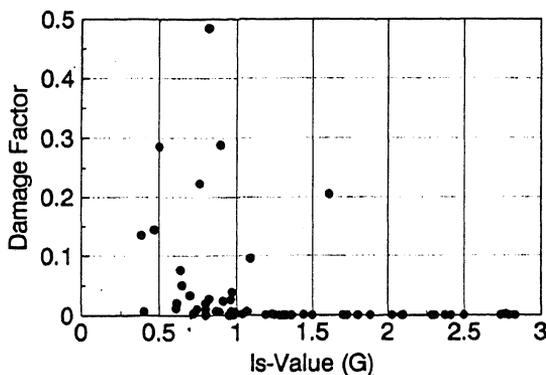


Figure 8. Relationship between the damage factor and the I_s -value for about 100 existing RC buildings in Tokyo against a recurrence of the 1923 Kanto Earthquake.

6 CONCLUSIONS

This system which is an updated version of an earlier system, has proved to be very useful for a rapid quantitative and, or qualitative evaluation of the seismic damage of buildings in Japan. This system can, also, be utilized for objectives such as:

- selecting optimal site
- selecting reasonable structural design
- planning provisions for great earthquakes
- simulating accurate building damage in future probable earthquakes
- providing preliminary knowledge to structural engineers
- providing education for disaster mitigation.

The system is for the time being limited to the evaluation of seismic structural damages of buildings and further improvements such as implementing the evaluation of equipment/function/human damages are required for the system to be truly useful. At the same time, our research has taught us an important lesson, namely that the technology of expert systems

based on object oriented knowledge bases can be a very powerful supporting tool for risk management. We believe that our system has pointed in the future direction for generic decision-making support systems.

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