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A MODEL FOR ASSESSMENT OF THE TOTAL LOSS IN A BUILDING EXPOSED TO EARTHQUAKE HAZARD

by

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ABSTRACT

A probabilistic model for assessment of the losses of a single building exposed to strong earthquake ground motion is presented in this report. The model is general and can be applied to other systems exposed to natural hazards, such as fire, tsunami wind e.t.c.. The assessed losses include structural and nonstructural damage, damage to installations and equipment, loss of function, and other indirect losses that can be translated into monetary costs.

So far, procedures and computer programs have been available to estimate only generic losses of buildings belonging to one of previously defined classes. However, for decision making on how much should be invested in strengthening of an individual building, which buildings in a community should be strengthened first, or what is the optimum design level for new buildings, a model is needed that could predict the losses for individual buildings. The purpose of the work presented in this report is to initiate development of such a model. When it is completed, this model can also be used by insurance companies for calculating the premiums on a more realistic basis.

In the model analysed in this work, the building is considered as a system consisting of subsystems which, themselves, consist of elements at risk. The elements at risk are those that suffer physical damage and contribute to the monetary loss of the subsystem to which they belong. The total loss of the system is represented as a sum of the losses of the subsystems. The subsystems can be different floors of a building, or functional units such as telephone installations, electrical installations, or air conditioning and heating systems. The losses are treated as random variables, defined by their probability distribution functions. So far, empirical probability distribution functions are not available for such a detailed analysis. Therefore, analytical physically admissible probability distribution functions are suggested to be used on an interim basis.

To demonstrate how the model works, a computer code ESTIMATE was written and applied to a hypothetical building model, using hypothetical probability distribution functions. In this report, the estimated losses of the hypothetical building, caused by a given level of shaking at the building site, are presented. In the example, the Beta distribution function is used for the element losses. Resistance classes are defined to discriminate between elements with different susceptibility to damage, and indirect loss proportionality factors are assigned to the subsystems to include, in a simple manner, the indirect losses. The estimates of the losses are shown for several states of the example building, each state requiring some additional investment. Then, the optimum configuration is suggested that optimizes the total cost to the owner. (The total cost to the owner is a sum of the additional investment and the expected value of the future losses.)

To implement the model in practice, 1) realistic probability distribution functions for the losses of the elements at risk are needed, and 2) a database on the inventory, the occupancy and the ongoing activities in all the buildings of the community to which the model is applied (e.g., a community can be a university campus). Also, 3) an interactive user friendly computer program is needed to be used by the owner or by the manager of the

property in the process of decision making. To demonstrate such a decision making tool, the computer program EQLOSS was written. This program is interfaced with the database for all the buildings, with the database on the probability distribution functions for the losses, and with the program that estimates the losses. It is interactive and has the possibility to illustrate the results graphically. At present, this program can be demonstrated on the hypothetical building example described in this report.

A major future task is to gather appropriate empirical data, results of detailed linear and nonlinear building response analyses, to define realistic damage probability distribution functions, and to complete and organize databases for the building community.

ACKNOWLEDGEMENTS

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CHAPTER I

INTRODUCTION

I.1 General Introduction

The earthquake engineering was initiated as a separate discipline of the civil engineering science in the 1930's, when strong earthquake ground motion was recorded for the first time during the Long Beach, California, earthquake of 1933. As a result of the strong motion data base that has been created since then (Lee and Trifunac, 1982, 1987a; Jordanovski et al. 1987) and of the availability of digital computers, significant advances were made in understanding where, how and how often the earthquakes may happen (Trifunac 1972, 1974; Jordanovski and Trifunac, 1990), and what their effects might be at a particular location (Lee and Trifunac 1987b; Trifunac 1989, 1990a,b; Westermo and Trifunac 1976). The advances in the construction technology, and the development of computer software for analyses and for design of structures, made it possible to predict, with considerable level of confidence, the level of the response of various structures to a prescribed strong motion at the base. This resulted in the current provisions in the building design codes and, in general, in building safer structures.

In a technologically advanced society, where there are possibilities for advanced research and for implementation of its results in practice, the damage caused by stronger earthquakes, and the loss of life and injury can be reduced. For example, earthquakes, such as the Whittier-Narrows 1987 earthquake and the Loma Prieta 1989 earthquake in California, would have had much more devastating consequences if they had happened in a third world country. However, on the other hand, the more technologically advanced the society is the more vulnerable it becomes even to moderate earthquakes. These events do not cause major physical damage to the structure and loss of life, but can induce significant financial losses as a result of the interruption of work, depreciation of the property value, lost opportunities, and other long term consequences (Tiedemann 1984a,b, 1987, 1989). These types of losses are called indirect losses, in contrast with the direct losses that are related only to the physical damage. Even though earthquakes cannot be prevented to happen, many of their consequences can be predicted and prevented. Therefore, the excessive losses due to earthquakes cannot any longer be considered only as acts of nature, but also as a result of lack of adequate planning, preparation and management.

The code provisions for earthquake safer structures have evolved several times since the 1930's (Leslie and Biggs 1972). The most recent provisions are described in the 1988 Uniform Building Code. The survey of damage after the San Fernando, 1971, California, earthquake showed that those buildings that have been built following the most recent provisions have suffered less damage than the buildings built prior to 1930's when there were no such provisions (Whitman et al. 1973). Guidelines have been established for seismic evaluation of existing buildings (ATC, 1987), and provisions have been defined for strengthening of existing buildings that do not meet the code requirements (Sabol et al. 1988a,b). However, the code requires strengthening only to the nominal level which improves the safety of human life. Considering the high cost of labor and the cost of interruption of work during the time of the construction (Sabol et al. 1988a,b), the code required level of strengthening is probably not the optimum one in the long range. Once the rehabilitation process of a building is started, with a slight increase of the investment, the financial losses from future earthquakes may be significantly reduced. The question, then, arises what is the optimum level of strengthening from the financial point of view, and what is the optimum design level for new buildings (Whitman et al. 1974, Ferrito 1984). Also, building owners and administrators have to decide on the priority in the order and in the distribution of the available funds for strengthening of a group of buildings, a university campus, for example, to minimize possible future losses from earthquakes. One of the key motivations for the work presented in this report has been to develop a method, based on a detailed analysis, that could help guide such decisions and answer the related questions.

I.2 Vulnerability of Existing Buildings

There are, typically, three approaches to estimate the damage of existing buildings caused by earthquakes: 1) using theoretical analysis, 2) using analyses of empirical data, and 3) using judgment of experts. The theoretical approach consists of estimating the structural response to the prescribed ground motion first, and, then, correlating it with the damage of the individual elements (Blejwas and Bresler 1979, McCabe and Hall 1987). The second method consists of developing vulnerability matrices or indices for selected types of buildings using actual earthquake damage data (Whitman 1973, Benedetti et al. 1988, Petrovski and Milutinović 1987, Coburn et al. 1987). By the third method, damage probability matrices are developed on the basis of iterated expert opinion (ATC, 1985). The theoretical models can be used to calculate the structural response to any level of loading. However, these are limited in the sense that they represent idealized image of the real structure and cannot handle all possible details and real life situations. The second approach is conceptually the most appropriate, but it is not sufficient. The compiled damage data is incomplete (empirical data is missing for some ranges of the input ground motion and is insufficient for some types of structures). Also, results from one part of the world are not directly applicable to another part of the world, because of the differences in the construction technology and in the prevailing type of structures, and because of the differences in the code provisions. Therefore, the other two approaches have to be used to fill in the regions of missing or insufficient data. The third method could be used as a compliment of the first method. Expert opinions are, however, often biased and limited by the experience and by the imagination of the experts.

At present, a fairly complete set of damage probability matrices (including physical damage of the structure and of its contents, as well as indirect losses), that is applicable to buildings in the United States, can be found in the Applied Technology Council Report No. 13 (ATC, 1985). These have been constructed on the basis of iterated expert opinions, and can be used by engineers to estimate the generic loss for types of buildings and of lifelines. An expert system has been constructed (Shah et al. 1987) that uses these damage probability matrices as input. Even though this is premature at present, this expert system is meant by the authors to be used for insurance and investment risk assessment.

I.3 The Aim of this Work

Generic losses estimated using presently available damage probability matrices (ATC 1985, Petrovski et al. 1987, Benedetti et al. 1988) are helpful for emergency planning and decision making that affect an entire region. For example, regions with higher risk for earthquake damage can be determined, and the appropriate measures to mitigate the consequences of a future catastrophic earthquake can be taken. However, these damage probability matrices cannot be used to decide on the optimum level of investment in strengthening of a particular building, or to decide which buildings of a university campus, for example, would suffer more severe losses and must, therefore, be strengthened first, because of the large scatter of the data. For the purpose of such a detailed planning, a more detailed and custom-made analysis has to be performed. The purpose of the work in this report is to establish a method and to write a computer program for a more detailed estimation of the losses of a particular building. This computer program, interfaced with an appropriate data base, is meant to be used as a decision making tool, by building owners and executives, for optimum long range planning of investment in strengthening and rehabilitation of existing buildings, and on the design level (above the one recommended by the code) for new buildings.

I.4 Organization of this Report

The material in this report is presented in four chapters. Chapter I contains the introduction. In Chapter II, the suggested model for assessment of the losses of a system exposed to some natural or man-made hazard is described, with emphasis on the losses of a single building exposed to earthquake ground motion. Some analytical probability distribution functions for the physical damage of the elements of the building are suggested, and a procedure for modeling of the indirect losses is presented. In Chapter III, the losses (expressed in some monetary units) are estimated for a hypothetical building, exposed to a given level of shaking at the site, using hypothetical damage probability distribution functions, and invented figures for the cost of strengthening of the building. Chapter IV contains the summary and the conclusions.

CHAPTER II

THE MODEL

II.1 Definitions of the Basic Concepts

In the model, the building will be referred to as the integral system (IS), which is composed of more subsystems (SS). Each of the subsystems (SS) is itself a system consisting of elements at risk (ER). The elements at risk are the finest subsystems in the decomposition. In Fig. II.1, a block diagram is shown of the integral system (IS), of the subsystems $(SS_i,\ i = 1,\ldots,n)$ and of the elements at risk for each of the subsystems $(ER_{ij},\ i = 1,\ldots,n, \quad j = 1, k_i)$, where k_i is the number of elements at risk for the i-th subsystem).

The subsystems could be physical divisions of the integral system, such as floors of a multi-story building, or functional units that run throughout the whole building such as, e.g., electrical installations, telephone lines, heating and air-conditioning systems. A subsystem could be a laboratory with expensive equipment and, maybe, toxic materials that could be released as a direct or indirect consequence of the shaking, and which can represent additional hazard and, possibly, cause additional losses. The elements at risk are those that suffer physical damage, and contribute directly and indirectly to the physical damage of the subsystem to which they belong. Elements at risk are, for example, structural elements, such as columns, beams and shear walls, or particular pieces of laboratory equipment.

The input ground motion at the site of the building is described by the shaking parameter Y. Y is a random variable which can be a scalar or a vector, depending on the level of sophistication of the description of the ground motion. Y can be or can have as components the earthquake intensity at the site, the peak acceleration, the uniform risk spectrum (URS), the duration of shaking e.t.c.. The damage of the elements at risk depends on the level of their input hazard. The input hazard level (H) for a subsystem is the level of some parameter of the response of the integral system (to the level of shaking Y) that is best correlated with the damage of the elements at risk of the subsystem. In the model, it represents the input excitation that can cause damage to the elements at risk. For example, the inter-story drift at the floor can be used as the input hazard level for the structural and nonstructural elements of a particular floor. The equipment may be sensitive to the absolute floor acceleration. The input hazard level is a random variable and it is a function of the shaking parameter Y. In simplified analyses, for assessment of generic losses for example, the shaking parameter Y would be used as the input hazard level.

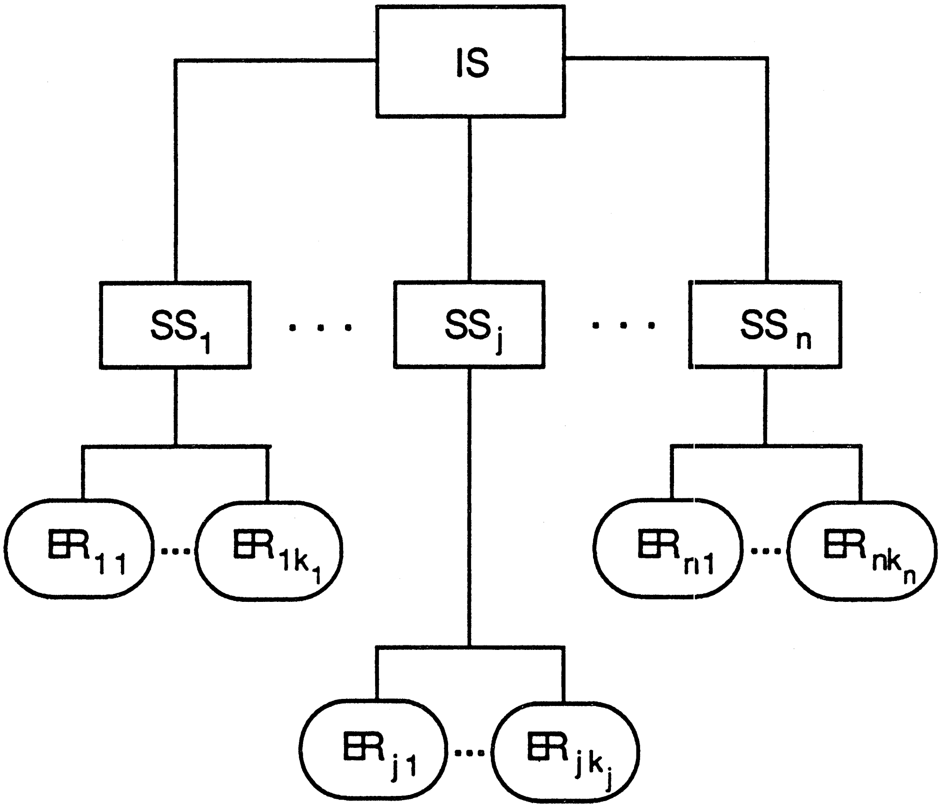


Fig.II.1 A block diagram of the integral system, IS, the subsystems, SS_j, and the elements at risk, ER_{jk_j}.

II.2 Probability Distribution Functions of the ER's, the SS's, and of the IS

II.2.1 Notation

The following convention in the notation will be followed in the mathematical representation in this chapter. F_V and f_V will indicate the cumulative and the density probability distribution functions of the random variable V, and $P\{\cdot\}$ will indicate probability of the event in the brackets. $\mathrm{E}[V]$ and $\mathrm{Var}[V]$ will indicate the expected value and the variance of the random variable V. All the random variables will be denoted by capital letters and the values that they can take by lower case letters.

II.2.2 The Loss Associated with an Element at Risk

The loss LER associated with the physical damage of an element at risk ER, is a continuous random variable that depends on the input hazard level. It has a conditional cumulative probability distribution function (dependent upon the input hazard level, H)

$$F_{LER|H}(\ell|h) = P\{LER \leq \ell|H = h\} \qquad (II.1a)$$

and a density probability distribution function

$$f_{LER|H}(\ell|h) = \frac{d}{d\ell}F_{LER|H}(\ell|h). \qquad (II.1b)$$

The input hazard level, H, for en element at risk depends on the level of the site shaking parameter, Y. Let

$$F_{H|Y}(h|y) = P\{H \leq h|Y = y\} \qquad (II.2a)$$

and

$$f_{H|Y}(h|y) = \frac{d}{dh}F_{H|Y}(h|y). \qquad (II.2b)$$

be the conditional cumulative and conditional density probability distribution functions (dependent upon the input shaking parameter, Y) of H. Then, the total density probability function of the loss of the element at risk, LER, conditioned upon the level of shaking at the site, Y, is

$$f_{LER|Y}(l|y) = \int_0^\infty f_{LER|H}(l|h) \cdot f_{H|Y}(h|y) \cdot dh. \qquad (II.3)$$

Further in the text, for the purpose of brevity, the condition upon Y will be omitted in the notation. It should be implicitly understood until stated otherwise.

II.2.3 The Loss Associated with a Subsystem

The loss LSS associated with the physical damage of a subsystem SS is some function g of the losses associated with the damage of its elements at risk ER_i, $i = 1, \ldots, n$

$$LSS = g(LER_1,\ LER_2, \ldots, LER_n) \qquad (II.4)$$

This functional relationship, in the real life situation, is not a simple function such as summation. For example, it would cost less to repair a group of elements all at one time, than to repair them one by one, separately.

Let the element losses, LER_i $i = 1, \ldots, n$, be jointly continuous with joint density function $f_{LER_1,\ldots,LER_n}(\ell_1, \ \ell_2, \ldots, \ell_n)$. Then, the probability that the subsystem loss will be less or equal to ℓ is

$$P\{LSS \leq \ell\} = P\{\ g(LER_1, \ldots, LER_n) \leq \ell\} \\ = \int\int \cdots \int_{g(LER_1,\ldots,LER_n)\leq \ell} f_{LER_1,\ldots,LER_n}(\ell_1, \ \ell_2, \ldots, \ell_n) d\ell_1 d\ell_2 \cdots d\ell_n. \tag{II.5}$$

If the element losses LER_i $i = 1, \ldots, n$ are independent, then their joint probability distribution function is a product of the individual probability distribution functions of the element losses, f_{LER_i} $i = 1, \ldots, n$,

$$f_{LER_1,LER_2,\ldots,LER_n} = f_{LER_1} \cdot f_{LER_2} \cdots f_{LER_n}. \tag{II.6}$$

Recalling that by definition

$$P\{LSS \leq \ell\} = F_{LSS}(\ell) \tag{II.7}$$

where $F_{LSS}(\ell)$ is the cumulative distribution function of the subsystem loss LSS, from Eqs. (II.5) and (II.6) if follows that

$$F_{LSS}(\ell) = \int\int \cdots \int_{g(LER_1,LER_2,\ldots,LER_n)\leq \ell} f_{LER_1}(\ell_1) \cdots f_{LER_n}(\ell_n) d\ell_1 \cdots d\ell_n. \tag{II.8}$$

Then the density distribution function of the subsystem losses can be calculated as

$$f_{LSS}(\ell) = \frac{d}{d\ell} F_{LSS}(\ell). \tag{II.9}$$

The simplest form of the function g is a simple summation. Until g is more precisely defined, the simplest form can be assumed.

II.2.4 Losses of the Integral System

The probability distribution function of the total loss due to physical damage of the integral system can be derived similarly, from the probability distribution function of the subsystems. If the system loss LS is a function G of the subsystem losses $LSSj$ $j = 1, \ldots, N$

$$LIS = G(LSS_1, \ LSS_2, \ldots, LSS_N), \tag{II.10}$$

then the cumulative distribution function of LS, $F_{LIS}(s)$, and the corresponding density function, $f_{LIS}(s)$, are

$$F_{LIS}(s) = \int\int\cdots\int_{G(LSS_1,\ldots,LSS_N)\leq s} f_{LSS_1,LSS_2,\ldots,LSS_N}(\ell_1,\ell_2,\ldots,\ell_N)d\ell_1 d\ell_2,\cdots,d\ell_N \qquad (II.11a)$$

and

$$f_{LIS}(s) = \frac{d}{ds}F_{LIS}(s) \qquad (II.11b)$$

where $f_{LSS_1,\ LSS_2,\ldots,LSS_N}(\ell_1,\ell_2,\ldots,\ell_N)$ is the joint distribution function of all the subsystem losses.

The subsystem losses are, in general, not independent of each other. For example, if the subsystems represent different stories in a building, then extensive damage at the first floor can cause interruption of work at the other floors which will induce indirect losses at these floors. At this time, neither the function G nor the joint probability density function $f_{LSS_1,\ LSS_2,\ldots,LSS_N}(\ell_1,\ \ell_2,\ldots,\ell_N)$ are known for buildings subjected to damaging earthquakes, and, therefore, assumptions have to be made in order to develop further the model. Suppose that the interaction of the subsystem losses with each other is negligible (the subsystem losses are independent), and that the total loss of the integral system is a sum of the losses of the subsystems. The assumption of the independence implies

$$f_{LSS_1,\ LSS_2,\ldots,LSS_N}(\ell_1,\ \ell_2,\ldots,\ell_N) = f_{LSS_1}(\ell_1)\cdot f_{LSS_2}(\ell_2)\cdots f_{LSS_N}(\ell_N), \qquad (II.12)$$

and the additional assumption that $G(LSS_1,\ LSS_2,\ldots,LSS_N)$ is a summation of the $LSS_i\ i = 1,\ldots,N$ implies that the integral on the right hand side of Eq. (II.8) is a convolution of the losses of the subsystems.

II.3 Identification of the Integral System and of the Subsystems

In the previous section, Eqs. (II.1) through (II.12) are applicable to any integral system, subsystems and their elements at risk, regardless of what they actually are. This way, in the implementation of the theory, flexibility is allowed in the selection of those elements. Also, the theory can be further generalized so that the integral system defined here is one of the subsystems of some higher order integral system.

In this study, the integral system is the whole building. The subsystems can be selected so that they represent either logical physical units of the system or functional units. In this study the subsystems are the individual floors and the basement of the building. This choice of the subsystems seems logical, because the shear and moment envelopes and the building response (relative displacement, absolute acceleration), which would be used as input hazard levels for the elements at risk, are normally estimated at the floor levels. Also, the direct and indirect losses, such as loss of equipment and interruption of work, heavily depend on the type of occupants of the subsystem and on the type of activities. The fact that different type of residents of the building usually occupy different floors supports this choice.

The elements at risk of a given floor are then grouped into classes according to the following general criteria:

1. they belong to the same functional class, and

2. they respond and are vulnerable to the same input hazard parameters.

In the examples in this study, it is assumed that the losses associated with different elements and with different floors are not correlated, so that Eqs. (II.8) and (II.12) hold.

II.4 The Input to the Model

The input to the model, in general, consists of: 1) the conditional probability distribution functions, $F_{H|Y}$, of the input hazard level H for different elements at risk, 2) the conditional probability distribution functions of the element losses, $F_{LER|H}$, 3) the joint probability distribution function of the losses of all the elements at risk in a subsystem, for all the subsystems $F_{LER_1,LER_2,...,LER_n}$, and 4) the functions g and G in Eqs. (II.4) and (II.10).

In the examples in this study it is assumed that the functions g and G are simple summations, i.e.

$$LSS = \sum_{i=1}^{n} LER_i \tag{II.13}$$

and

$$LIS = \sum_{j=1}^{N} LSS_j. \tag{II.14}$$

It is also assumed that the losses associated with different elements in a subsystem, and with the different subsystems in the integral system, are independent, so that Eq. (II.8) and (II.12) hold. Then, from Eqs. (II.8), (II.11a) and (II.12), and from Eqs. (II.13) and (II.14) it follows that

$$F_{LSS}(\ell) = f_{LER_1} * f_{LER_2} * \cdots * f_{LER_n} \tag{II.15}$$

and

$$F_{LIS}(s) = f_{LSS_1} * f_{LSS_2} * \cdots * f_{LSS_N}, \tag{II.16}$$

where the symbol $*$ indicates convolution.

II.4.1 Determination of $F_{H|Y}$

The conditional distribution functions $F_{H|Y}$ of the input hazard level H for different groups of elements, and the conditional distribution function $F_{LER|H}$ of the losses for the elements at risk, can be determined by statistical regression analysis applied to

1. empirical data, such as compiled data on losses after particular earthquakes,
2. results of theoretical analyses involving evaluation of linear and non-linear response of buildings, and simulation, and
3. expert opinions.

Empirical data on losses gathered after earthquakes are often incomplete. For example, the damage probability matrices obtained by regression of data on structural and nonstructural damage are incomplete. The expert opinions and the theoretical data are also not equally reliable for all values of H and Y. In addition to this, determining the probability distribution functions for all the possible values of the conditional variable is time consuming, and implementing these in the analysis is memory demanding. Therefore, another approach is recommended and used in this report.

Often, in the engineering analyses, a theoretical distribution function is chosen that would best fit the data, and that would not violate the physical properties of the process. The theoretical distribution functions are often defined by two parameters: the expected value (the mean) and the variance (the standard derivation). Those are evaluated by fitting the theoretical distribution function to the data. Then, various tests are performed, such as the Kolmogorov-Smirnov test, to determine the "goodness of fit". For example, in the case of $F_{LER|H}$, the functions u_1 and u_2 have to be determined such that

$$u_1(h) = \mathrm{E}[LER|H = h] \qquad (II.17)$$

and

$$u_2(h) = \mathrm{Var}[LER|H = h]. \qquad (II.18)$$

Similarly, for $F_{H|Y}$, the functions v_1 and v_2 have to be determined such that

$$v_1(y) = \mathrm{E}[H|Y = y] \qquad (II.19)$$

and

$$v_2(y) = \mathrm{Var}[H|Y = y]. \qquad (II.20)$$

In Eqs. (II.17) through (II.20), $\mathrm{E}[\cdot]$ indicates expected value and $\mathrm{Var}[\cdot]$ indicates variance. The advantage of this procedure is that it makes it possible to fill-in the no-data regions within the interval of the data. The reliability of the results strongly depends on the quantity and quality of the available data and on the smoothness of u_1, u_2, v_1 and v_2. In this respect, u_1 and v_1 are smoother than u_2 and v_2 because of being nondecreasing.

In this study, the Beta probability distribution function is used to model the element losses probability distribution function, i.e.

$$f_{LER|H}(\ell|h) = \frac{1}{(b-a)^{r+p+1}} \frac{(\ell-a)^{r-1}(b-\ell)^{p-1}}{B(r,p)} \tag{II.21a}$$

where

$$B(r,p) = \int_0^1 x^{r-1}(1-x)^{p-1}dx \tag{II.21b}$$

is the Beta-function, a and b are the lowest and the highest values that the element loss can take, and r and p are parameters that define the slenderness and skewness of the density function. r and p are related to the expected value and to the variance by

$$\mathrm{E}[LER|H=h] = \frac{br+pa}{r+p} = u_1(h) \tag{II.22a}$$

and

$$\mathrm{Var}[LER|H=h] = \frac{pr(b-a)^2}{(p+r)^2(p+r+1)} = u_2(h). \tag{II.22b}$$

In Fig. II.2, examples of Beta probability distribution function $f(x)$ are shown for different values of r and p. In curve (1), $r=0$ and $p >> 1$; in curve (2), $r,p \neq 0$ and $p >> r$ and $f(x)$ is skewed to the left; in curve (3), $r=p>>1$ and $f(x)$ is symmetric; in curve (4), $r >> p \neq 0$ and $f(x)$ is skewed to the right; in curve (5) $r=p=1$, and $f(x)$ is constant.

A desirable property of the Beta probability distribution function is that it is nonzero in a closed interval $[a,b]$, and with adequate choice of r and p different weight can be assigned to smaller or higher values of the losses. The minimum loss, a, is usually equal to 0 and the maximum loss, b, is usually equal to the replacement value of the element.

Examples of $u_1(h)$ and $u_2(h)$

In the hypothetical example in this paper, the functions $u_1(h)$ and $u_2(h)$ appearing in Eqs. (II.17) and (II.18) are assumed to be the following

$$u_1(h) = \mathrm{E}[LER|H=h] = b(1-e^{-qh}) \tag{II.23a}$$

and

$$u_2(h) = \mathrm{Var}[LER|H=h] = b(1-e^{-qh})e^{-qh}, \tag{II.23b}$$

where q is some constant. The graphical representations of $u_1(h)$ and $u_2(h)$ are in Figs. II.3 and II.4. These forms of $u_1(h)$ and $u_2(h)$ are physically admissible hypothetical functions, and are used only to illustrate the model. Even though, in reality, the damage of the structural components is not necessarily a continuous function of the building response, but may have jumps (components of the element suddenly break when certain level of h is reached), $u_1(h)$ in Eq. (II.23a), as a monotonically increasing function of the input

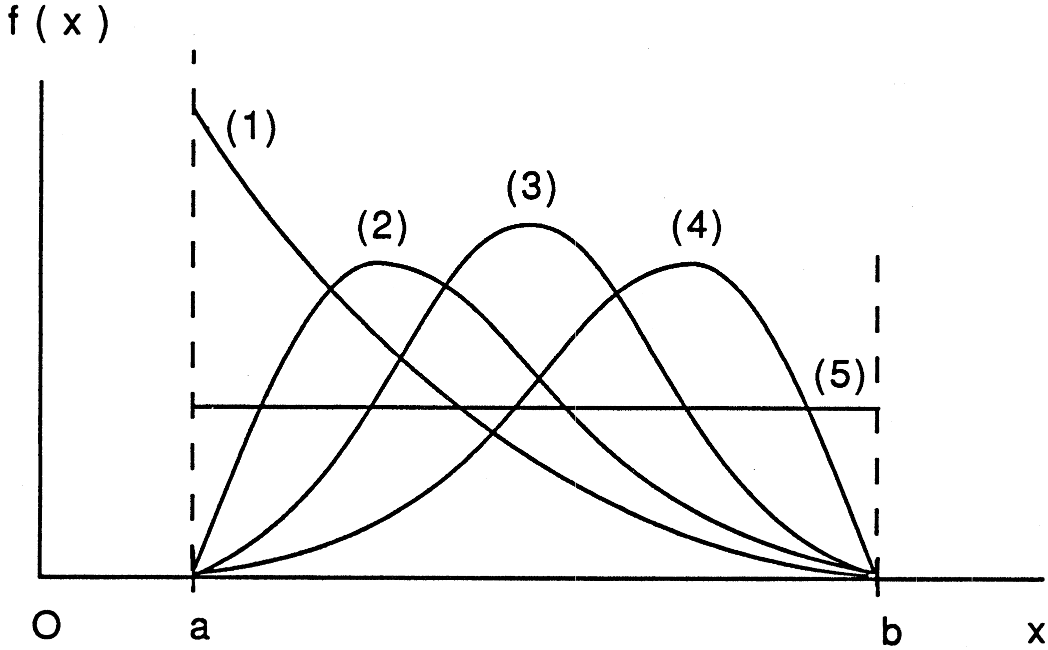


Fig. II.2 Examples of Beta-probability distrubution function, $f(x)$.

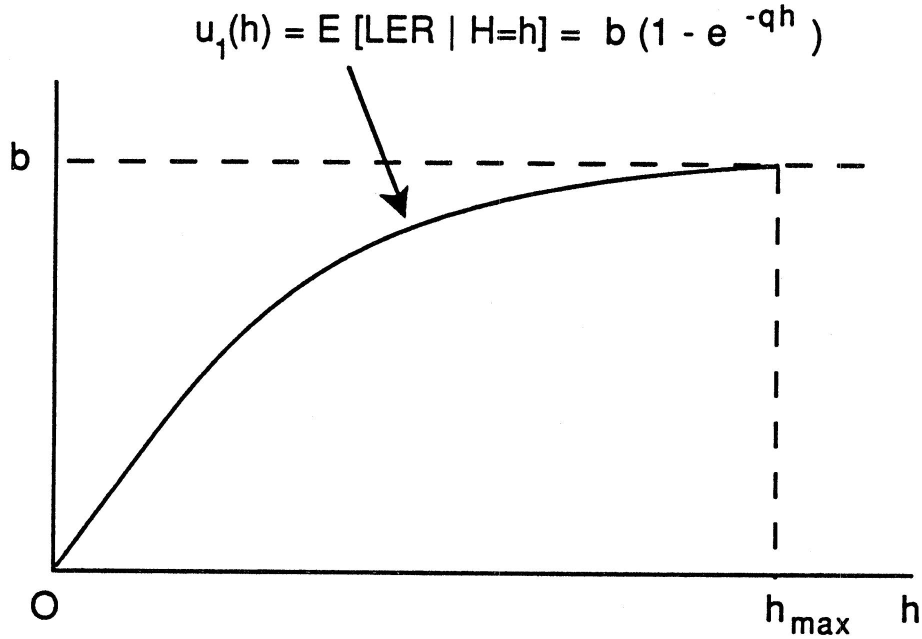


Fig. II.3

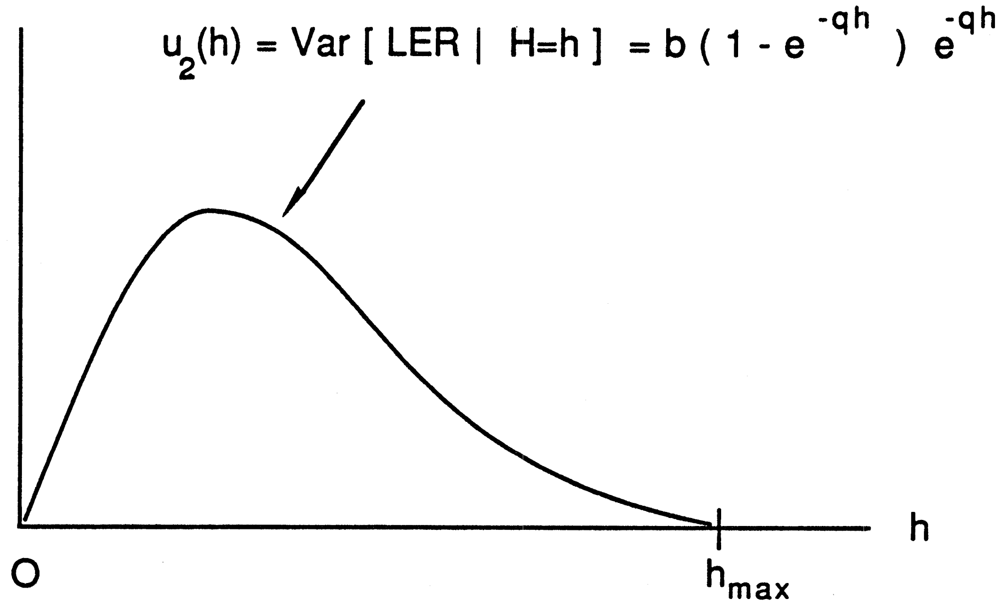


Fig. II.4

hazard level, does not violate the relationship between the damage of the element at risk and the input hazard level. From Eq. (II.23b), it follows that the scatter of the data, $\mathrm{Var}[LER|H = h]$, is small when the input hazard level and the damage are small, and $\mathrm{Var}[LER|H = h] \to 0$ as $h \to 0$. When $h \to h_{\max}$ and the loss due to the physical damage approaches the maximum loss, then $\mathrm{Var}[LER|H = h] \to 0$ also. For intermediate values of h, $\mathrm{Var}[LER|H = h] \neq 0$. Then, larger $\mathrm{Var}[LER|H = h]$ means that the loss can take comparable values in a larger interval about the mean value. The form of $u_2(h)$ in Eq. (II.23b) is also physically admissible.

II.5 Resistance Classes

The structural elements of a building sometimes may not have the design strength, because of the human factor involved in the construction process. Elements of the same kind may have different vulnerability in different subsystems. Three possibilities can be suggested to account for this difference:

1. different distribution functions have to be defined for different elements or groups of elements,

2. one distribution function can be used for all the elements of a given kind, but with a larger standard deviation, and

3. same analytical representation of $u_1(h)$ can be used (as in Eq. (II.23a), e.g.) for all the elements of the kind, but the values of some parameters of u_1 (e.g., q) should be different for elements belonging to different vulnerability classes.

In the hypothetical example that follows, the third possibility is employed.

First, three resistance classes are defined:

a) poor resistance class,

b) fair resistance class, and

c) good resistance class.

q defines the rate of growth of $u_1(h)$. Quantitatively, it is defined for each of these classes in terms of the value of h for which the expected value of the loss equals 90% of the maximum loss, b. In mathematical forms this could be expressed as

$$u_1(h) = 0.9b. \qquad (II.24)$$

Then, from Eqs. (II.23a) and (II.24) it follows

$$q = \frac{-\ln 0.1}{h}. \qquad (II.25)$$

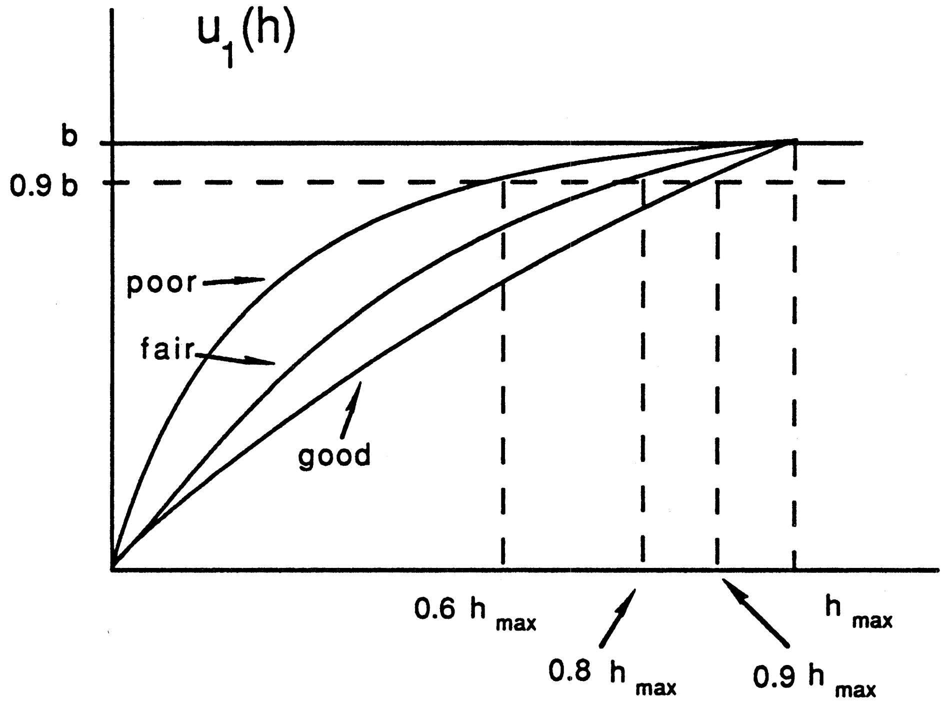


Fig. II.5

It is assumed in the examples that for a good resistance class $h = 0.9\ h_{\max}$, for a fair resistance class $h = 0.8h_{\max}$, and for the poor resistance class $h = 0.6h_{\max}$. In Fig. II.5, $u_1(h)$ are illustrated for the three resistance classes.

Accounting for the difference in the vulnerability of the elements of a given kind by assigning it to different resistance classes is physically more reasonable than by increasing the variance, because through the resistance classes the variance of the overall distribution function of the elements (including the distribution functions for the classes) is increased at all values of h, uniformly. This would not be the case if a standard shape, as in Eq. (II.23b) e.g., is assumed.

In determining the function $u_1(h) = E[LER|H = h]$ by a regression analysis of empirical data, it may happen that $u_1(h)$ in Eq. (II.23a) does not fit the data. Consequently, conditions other then Eqs. (II.24) and (II.25), have to be defined to determine the distribution function and to define the criteria for the resistance classes. In a general case, $u_1(h)$ can be defined with the help of the mean and the standard deviation, $\tilde{u}_1(h)$ and $\tilde{\sigma}(h)$, of the distribution function determined by a regression analysis of all the data for that kind. For example,

1) $u_1(h) = \tilde{u}_1(h)$ for a good resistance class,

2) $u_1(h) = \tilde{u}_1(h) - \tilde{\sigma}(h)$ for a fair resistance class, and

3) $u_1(h) = \tilde{u}_1(h) - 2\tilde{\sigma}(h)$ for a poor resistance class.

Assigning an element to a lower or to a higher resistance class may also express the confidence of the individual performing the analysis that the element will in reality perform as it was initially designed.

II.6 Modeling of the Indirect Losses

So far, in the description of the model only the losses (in monetary units) due to physical damage of the elements at risk have been considered. Those losses may include structural and nonstructural damage of the building, loss or damage of stock and equipment e.t.c., and are referred to in the text as primary or direct losses. The losses because of interruption of work, legal fees, renting temporary space, lost opportunities, disability premiums, medical expenses to treat injury, e.t.c., are called indirect or secondary losses. The loss of life has not been included so far in the model, because of the difficulty in transforming it into monetary units (this task rises many ethical questions). We suggest that the loss of life should be treated, separately, rather than together with the monetary losses.

The indirect losses are correlated with the direct losses, but also depend on other factors of local or regional nature. For example, the loss due to interruption of work depends on

1. the type of activities that are interrupted and the amount of income that they generate, and

2. how soon the facilities can be repaired.

The time required to repair the building depends on the degree and on the distribution of damage, but also on the availability of construction companies and required materials and equipment at the time immediately after the earthquake, which depends on the extent of the overall damage in the region. Because of this complexity, the indirect losses must also be treated as random variables and their probability distribution functions have to be defined.

It would be most appropriate if the probability distribution functions for the indirect losses are defined by regression analyses of empirical data. Unfortunately, so far only limitted post – earthquake data on indirect losses is available. Damage probability matrices for the indirect losses for several ranges of values of the Modified Mercalli Intensity have been developed for different classes of buildings only on the basis of iterated expert opinions (ATC 1985), and, so far, it has not been possible to verify those. Because the available damage probability matrices for the indirect losses have been developed for large classes of buildings, the estimated indirect losses are very sparse and can be used only for very general studies, to estimate regional losses, for example.

Collecting data on indirect losses and making it available to the whole engineering community is a very difficult if not an impossible task, mainly because of the fact that most of the valuable information is confidential and is not disclosed even to the engineers performing the assessment. Therefore, for practical purposes it would be convenient if some simple procedure could be developed which could be used by the building owners directly without the need to disclose confidential information. The following procedure has been suggested.

II.6.1 Indirect Loss Proportionality Factor

The indirect losses of a subsystem, ILSS, can be expressed as a product of a factor $ILF \geq 0$ and the direct losses LSS, i.e.

$$ILSS = ILF \cdot LSS$$

where the factor ILF can be a given number or a random variable. ILF (or its expected value, if it is a random variable) should be larger for a floor with expensive laboratory equipment and multi-million-dollar projects going on, than for some other floors. ILF could be called the Indirect Loss Proportionality Factor, and it should be assigned by the building owner or by his representative.

The Indirect Loss Proportionality Factor may significantly influence the total loss of the building and, therefore, its nature should be carefully studied using actual post earthquake damage data or through simulation. In general, ILF is a function of the direct loss of the subsystem. However, in the examples that follow, it is assumed that ILF is a uniformly distributed random variable over the interval of losses. For the user, the ILF can be defined descriptively. For example, three classes could be defined:

1) low indirect loss proportionality class with $ILF \in [0, 1]$,

2) average indirect loss proportionality class with $ILF \in (1, 2]$ and

3) high indirect loss proportionality class with $ILF \in (2, 3]$.

The density probability distribution functions for these three classes could be, for example, $f_{ILF} = \frac{1}{1-0}$, $f_{ILF} = \frac{1}{2-1}$ and $f_{ILF} = \frac{1}{3-2}$, respectively. In general, ILF needs not to be uniformly distributed, and it can be defined on any closed interval. This approach leaves open the possibility to introduce the fuzzy sets method in the further development of the model.

II.7 The Total System Loss

II.7.1 The Total Direct and Indirect Losses

The total loss of the integral system, $TLIS$, is a sum of the total direct loss, LIS, and the total indirect loss, $ILIS$. Assuming that it is a simple sum of the subsystem losses, it can be written that

$$TLIS = \sum_{j=1}^{N}(1 + ILF_j)LSSj \qquad (II.26)$$

The total integral loss of the system can have values in the interval $(\ell_{\text{min}}, \ell_{\text{max}})$ where

$$\ell_{\text{min}} = \sum_{j=1}^{N}[1 + r_{j,\text{min}}]\ell_{j,\text{min}} \qquad (II.27a)$$

and

$$\ell_{\text{max}} = \sum_{j=1}^{N}[1 + r_{j,\text{max}}]\ell_{j,\text{max}}, \qquad (II.27b)$$

with $r_{j,\text{min}}$ and $\ell_{j,\text{min}}$ being the lowest values that ILF and the direct loss LSS can take for the $j-$th subsystem, and with $r_{j,\text{max}}$ and $\ell_{j,\text{min}}$ being the highest values of the indirect loss factor, ILF, and of the direct losses LSS, for the j-th subsystem. Rearranging the terms on the RHS of Eq. (II.26), it follows that

$$TLIS = LIS + ILIS \qquad (II.28)$$

where

$$ILIS = \sum_{j=1}^{N} ILSS_j \qquad (II.29)$$

is the indirect loss of the integral system, and where

$$ILSS_j = ILF_j \cdot LSS_j \qquad (II.30)$$

is the indirect loss of the j-th subsystem. The cumulative probability distribution function of $ILSS_j$, $F_{ILSS_j}(s)$, then is

$$\begin{aligned} F_{ILSS_j}(s) &= P\{ILSS_j \leq s\} = \\ &= P\{ILF_j \cdot LSS_j \leq s\} \\ &= \int\int_{r \cdot \ell \leq s} f_{ILF_j,LSS_j}(r,\ell) \cdot dr \cdot d\ell, \end{aligned} \qquad (II.31a)$$

where $f_{ILF_j,LSS_j}(r,\ell)$ is the joint density function of ILF and LSS for the j-the subsystem. If ILF_j and LSS_j are not correlated, then

$$F_{ILSS_j}(s) = \int\int_{r \cdot \ell \leq s} f_{ILF_j}(r) \cdot f_{LSS_j}(\ell) \cdot dr \cdot d\ell. \qquad (II.31b)$$

The cumulative distribution function of the indirect losses of the integral system, given in Eq. (II.29), can be evaluated in a similar manner as for the direct losses, i.e. by convolution

$$F_{ILIS} = f_{ILSS_1} * f_{ILSS_2} * \cdots * f_{ILSS_N}. \qquad (II.32)$$

Similarly, the cumulative distribution function of the total integral system loss, $TLIS$, defined in Eq. (II.28), can be calculated as

$$F_{TLIS} = f_{ILIS} * f_{LIS}. \qquad (II.33)$$

In Eq. (II.32),

$$f_{ILSS_j}(s) = \frac{dF_{ILSS_j}(s)}{ds} \qquad (II.34a)$$

is the density probability function of the indirect losses of the j-th subsystem, and in Eq. (II.33)

$$f_{ILIS}(s) = \frac{dF_{ILIS}(s)}{ds} \qquad (II.34b)$$

and

$$f_{LIS}(s) = \frac{dF_{LIS}(s)}{ds} \qquad (II.34c)$$

are the density probability functions of the indirect and direct loss, respectively, of the integral system.

II.7.2 Total System Losses for Exposure time T

We recall that the probability distribution function F_{TLIS} of the total losses of the integral system and the previously defined subsystem losses distribution functions are, in fact, conditioned on the value of the site response parameter Y, but "$|Y = y$" has been omitted for the purpose of brevity.

The losses caused by earthquakes are usually assessed for a limited time interval, T, called exposure time, which is usually the expected service time for the building, e.g. $T =$ 40, 50 or 100 years. This requires the probability of occurrence of Y to be determined for that exposure time. Let

$$F_{Y|T}(y|t) = P\{Y \leq y | t_0 \leq T < t_0 + t\} \tag{II.35}$$

be the cumulative distribution function of Y for a given exposure time, and let

$$f_{Y|T}(y|t) = \frac{d}{dy} F_{Y|T}(y|t) \tag{II.36}$$

be the corresponding density function. Then the probability distribution function of the total losses for that time interval is

$$f_{TLIS|T}(\ell|t) = \int f_{TLIS|Y}(s|Y = y) f_{Y|T}(y|t) dy. \tag{II.37}$$

For decision making in optimum seismic design, optimum investment in strengthening, emergency planning and other related areas the following two quantities are usually calculated

1. The expected value of the total system losses for the exposure time t

$$E[TLIS|t] = \int_0^\infty \ell f_{TLIS|T}(\ell|t) d\ell, \tag{II.38}$$

2. The value of the losses, ℓ_β, that will not be exceeded with confidence level β during the exposure time, calculated from

$$\beta = \int_0^{\ell_\beta} f_{TLIS|T}(\ell|t) d\ell. \tag{II.39}$$

CHAPTER III

A HYPOTHETICAL EXAMPLE

To illustrate the model described in Chapter II, the computer program ESTIMATE was written and applied to a hypothetical building, exposed to a given earthquake ground motion described by a single parameter. Hypothetical analytical probability distribution functions for the damage of the elements at risk were used, as described in Chapter II. The total loss was assessed for several states of the building, each state corresponding to a different level of strengthening. In this chapter, the results for the loses corresponding to each of these states are presented, and optimum configuration is found for which the sum of the total loss and the investment in strengthening is at a minimum.

III.1 Description of the Building

The hypothetical building is a two-story moment resisting frame building. It belongs to a university campus and it is used for lecturing, as an office building, and for research. The classrooms are on the first floor. On the second floor, the X-department has faculty and administrative offices and several computer laboratories. In the basement there are several experimental laboratories. The total cost of the building, including all the equipment, has been estimated to be equal to B monetary units (m.u.). The X-department is involved in several projects which bring income of B_X m.u./year to the university, and the lectures that take place in this building generate B_L m.u./year profit to the university. The experimental laboratories are also engaged in ambitious projects whose interruption may have long term impact on the university finances.

III.1.1 Choice of the Subsystems and of the Elements at Risk

The subsystems are chosen to be the different levels of the building, i.e.

1. SS_1 : the basement,
2. SS_2 : the first floor, and
3. SS_3 : the second floor.

The considered elements at risk for each of the subsystems are the following.

<u>Basement</u>:

B.1 Structural elements (columns, beams, shear walls ...)

B.2 Non-structural elements (ceilings, partitioning walls, stairs, facade ...)

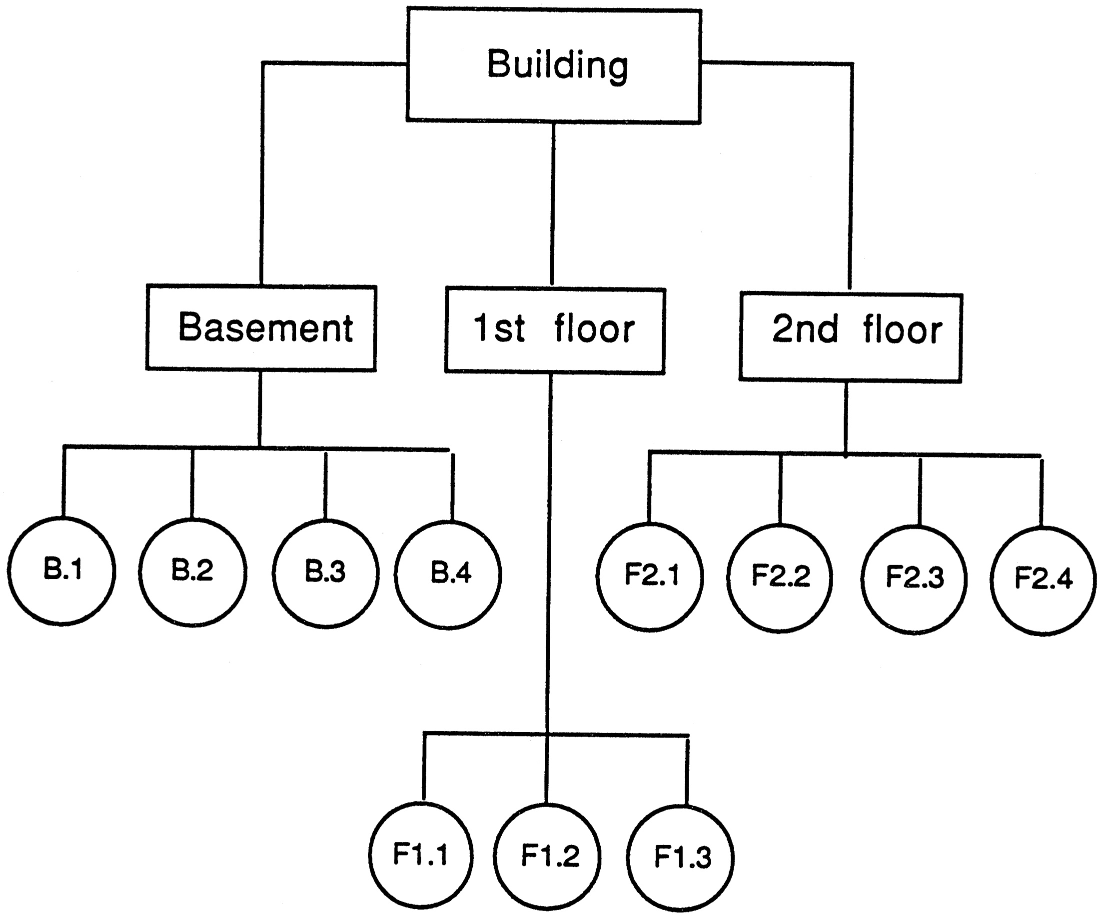


Fig. III.1 Representation of the building as an integral system, its subsystems, and the elements at risk.

B.3 Installations (telephone lines, electrical lines, air conditioning ducts, lights, elevators ...)

B.4 Laboratory equipment (electronic microscope, optical lasers ...)

First Floor:

F1.1 Structural elements (columns, beams, shear walls ...)

F1.2 Non-structural elements (ceilings, partitioning walls, stairs, facade ...)

F1.3 Installations (telephone lines, electrical lines, air conditioning ducts, lights, elevators ...)

Second Floor:

F2.1 Structural elements (columns, beams, shear walls ...)

F2.2 Non-structural elements (ceiling, partitioning walls, stairs, facade, roof ...)

F2.3 Installations (telephone lines, electrical lines, air conditioning ducts, lights, elevators ...)

F2.4 Equipment (two main-frame computers, 20 personal computers, 8 laserjet printers, 3 xerox and 3 FAX machines ...)

A block diagram of the integral system, the subsystems, and the elements at risk is shown in Fig. III.1

III.2 The Input

III.2.1 The Shaking Parameter

The shaking parameter, Y, could be the MMI intensity of shaking, the peak ground acceleration, or the response spectrum at the building site, for example. The site shaking parameter is a random variable, and a proper interface between the computer program ESTIMATE and a program that evaluates probabilistically the ground response at the building site to motion generated at the surrounding faults (NEQRISK is an example of such a computer program, Lee and Trifunac 1985) is necessary. For the purpose of demonstrating the program ESTIMATE alone, the losses for the hypothetical building are estimated for a given value of the shaking parameter, (for example the maximum value expected to occur for exposure time of 80 years). This maximum value is assumed to be equal to 8 units of the shaking parameter.

III.2.2 Input Parameters for the Elements at Risk

For each of the elements at risk, the following parameters are defined:

(i) the input hazard parameter, ihp, (the floor response parameter to which the damage of the element is best correlated with)

$ihp = d$: interstory drift

$ihp = v$: peak velocity

$ihp = a$: peak acceleration

$ihp = s$: maximum shear force

$ihp = m$: maximum bending moment,

(ii) the input hazard level, H, as a function of the ground shaking at the site,

(iii) minimum and maximum losses for the element, L_0 and L_m, in monetary units,

(iv) probability distribution function for the element losses, as functions of the input hazard level h (the Beta probability distribution function is used, defined on the interval $[L_0, L_m]$),

(v) resistance class parameter, rc,

$rc = g$: good resistance class

$rc = f$: fair resistance class

$rc = p$: poor resistance class.

Since the subsystems are the story levels, the input hazard level is assumed to depend only on the story height. For all the elements of the story, the input hazard level is assumed to be normally distributed with mean μ and standard deviation σ

$$\mu(y) = \mathrm{E}[H|Y = y] = k(y - 6)m^2 \qquad (III.4)$$

and

$$\sigma^2 = \mathrm{Var}[H|Y = y] = 0.15\mu(y) \qquad (III.5)$$

where $m = 1$ for the basement, $m = 2$ for the first floor and $m = 3$ for the second floor, and k is a proportionality factor. It follows from Eq. (III.4) that the input hazard level is larger at higher levels of the building. The standard deviation is also larger at the higher floors, where the mean of the input hazard level is larger.

Quantitatively, the resistance classes are defined as in Section II.5. Then, the expected value, and the variance of the Beta probability distribution function for the losses are defined as described in Section II.4. In Table III.2.1, the values of the input parameters for all the elements at risk are summarized. It can be seen from this table that the damage of

Table III.2.1

Input parameters for the subsystems
and for the elements at risk corresponding to
the present state of the building

Floor	Element	Input Hazard Parameter	Resistance Class	Minimum Direct Loss [m.u.]	Maximum Direct Loss [m.u.]	Indirect Loss Class
Basement	B.1	d	p	0	300	h
	B.2	d	p	0	100	
	B.3	d	p	0	400	
	B.4	a	p	0	1,000	
First Floor	F1.1	d	p	0	300	h
	F1.2	d	p	0	200	
	F1.3	d	p	0	400	
Second Floor	F2.1	d	p	0	300	h
	F2.2	d	p	0	300	
	F2.3	d	p	0	400	
	F.2.4	a	p	0	600	

all the first three elements at risk at the basement is correlated with the floor displacement, and of the fourth element, to the floor acceleration. At the first floor, the damage of all the elements at risk is correlated with the interstory drift. At the second floor, the damage of the structural and nonstructural elements, and the installations is correlated with the interstory drift, and of the equipment, with the floor accelerations.

The resistance class indicates how well the element is expected to perform during an earthquake, as compared with the average performance calculated from statistical data, or as compared with some expected performance. It reflects the past experience of the element (e.g., if the structural element has some cracks from past earthquake, then it is assigned to a lower resistance class). Also, equipment which is not bolted properly to the floor or to the wall, or which is placed where there is a higher probability that a heavy object can fall onto it and damage it, is assigned to a lower resistance class.

Because the example building is an older building, it is assumed that, for the present state, all the elements at risk belong to the poor residence class.

III.2.3 The Indirect Loss Proportionality Factors for the Present State of the Building

The Indirect Loss Proportionality Factors, $ilpf$, for the floors are assumed to take one of the following values:

$ifpf = l$: low indirect loss proportionality class,

$ifpf = a$: average indirect loss proportionality class,

$ifpf = h$: high indirect loss proportionality class.

It is assumed that the indirect losses can exceed at most three times the direct losses. The subsystems are assigned to one of the three indirect loss proportionality classes (low, average and high), defined in Section II.6. All the three subsystem are assigned to the high indirect loss proportionality class.

III.3 Numerical Results for the Present State of the Building

The minimum loss for all the elements is zero. Adding up the maximum direct losses, it follows that the maximum direct loss for the basement is $1,800$ m.u., for the first floor 900 m.u., for the third floor 1,600 m.u., and for the whole building, 4,300 m.u..

The maximum indirect losses are three times larger than the maximum direct losses, and the maximum total losses are four times larger than the maximum direct losses. In Table III.3.1, for each floor and for the whole building, the maximum direct, indirect and total losses, the expected value of the losses for exposure time of 80 years, and the

Table III.3.1

A summary of the values of the maximum direct loss,
the maximum indirect loss, the expected loss and the dispersion,
for the individual stories and for the whole building

Floor	Maximum Direct Loss [m.u.]	Maximum Indirect Loss [m.u.]	Maximum Total Loss [m.u.]	Expected Total Loss [m.u.]	Dispersion [m.u.]
1	1,800	5,400	7,200	4,126	535
2	900	2,700	3,600	2,847	287
3	1,600	4,800	6,400	5,010	486
Total	4,300	12,900	17,200	11,900	811

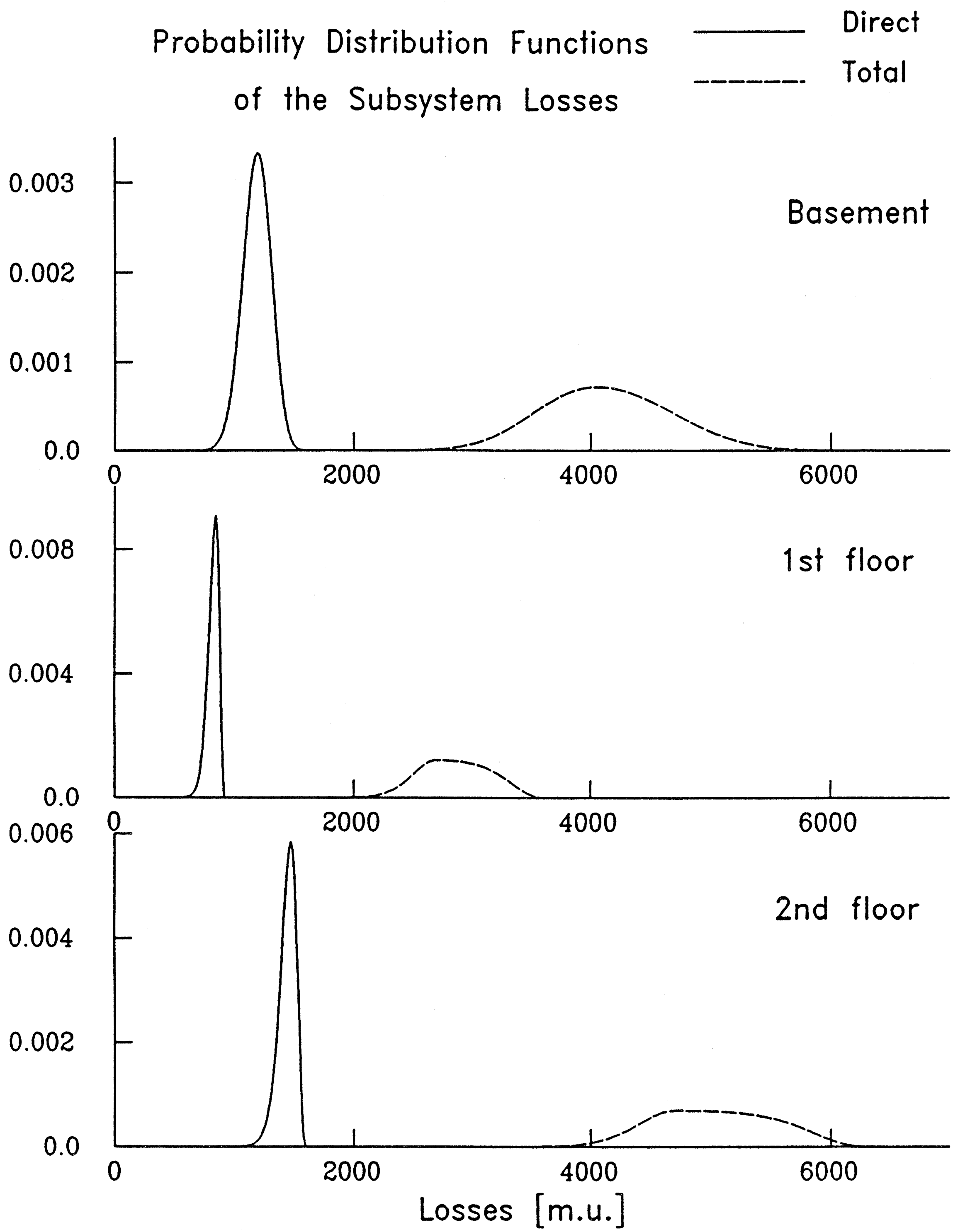

Probability Distribution Functions
of the Subsystem Losses
Direct
Total
Basement
1st floor
2nd floor
0.003
0.002
0.001
0.0
0.008
0.004
0.0
0.006
0.004
0.002
0.0
0
2000
4000
6000
Losses [m.u.]

Fig. III.2

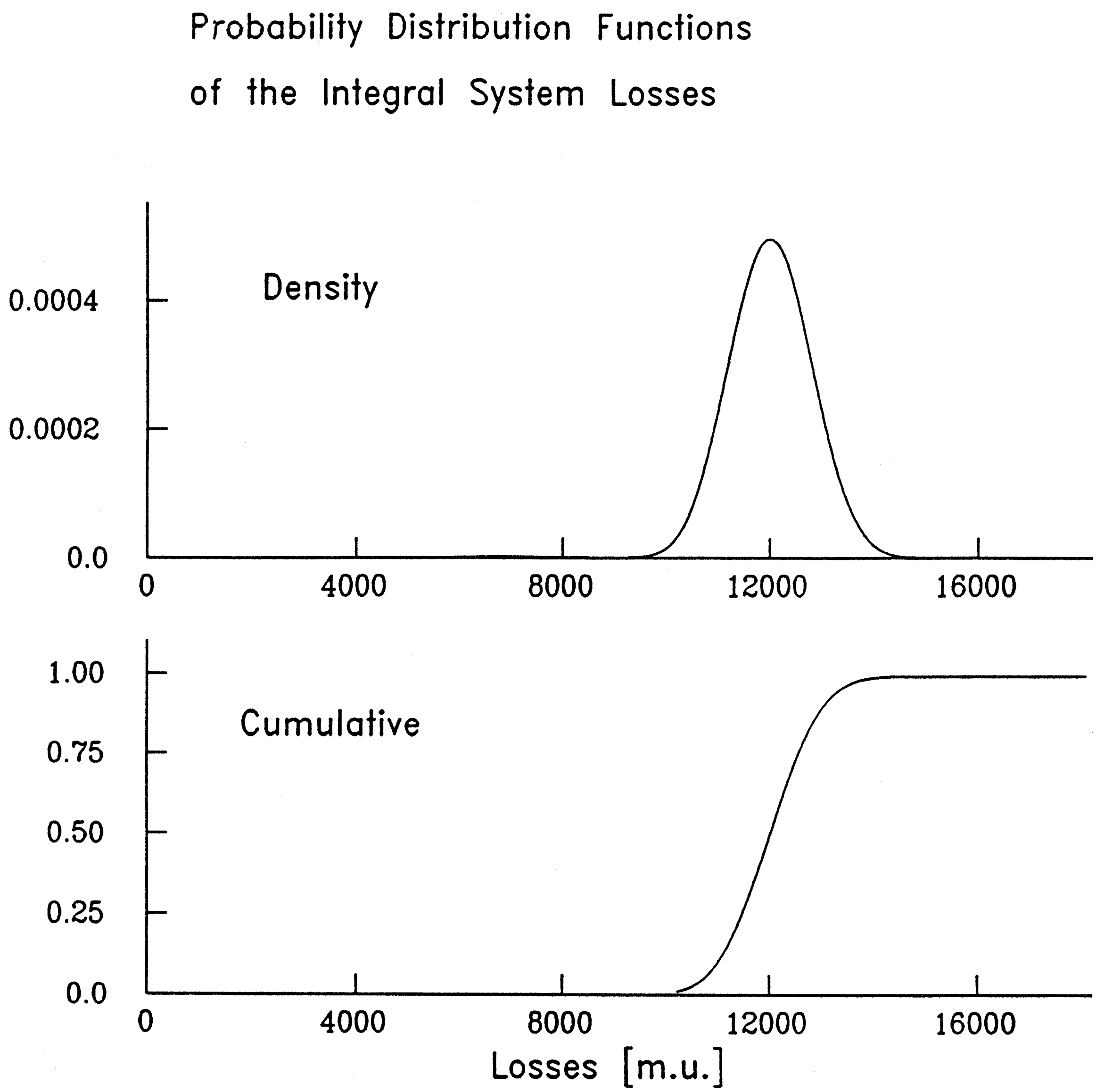

Probability Distribution Functions
of the Integral System Losses
Density
0.0004
0.0002
0.0
0
4000
8000
12000
16000
Cumulative
1.00
0.75
0.50
0.25
0.0
0
4000
8000
12000
16000
Losses [m.u.]

Fig. III.3

dispersion are shown. It can be seen that, for example, the maximum direct loss for the whole building (the replacement value) is 4,300 m.u., the maximum indirect loss is 12,900 m.u. and the maximum total loss is 17,200 m.u. The expected value of the total loss for the whole building is 11,900 m.u. and the dispersion is 811 m.u.

Let us define the mean damage ratio, MDR, as the ratio of the expected value of the total losses and the replacement value of the building. Then, it follows that, for the initial state MDR=2.77.

In Fig. III.2 the probability density distribution functions of the direct and total loss are shown for each floor, and, in Fig. III.3, the cumulative and the density probability distribution functions of the losses for the whole building are shown. From Fig. III.3, it can be seen that, given that the shaking parameter $Y = 8$, the most probable total loss is about 12,000 m.u. and the loss that will not be exceeded with confidence level of 90 % is about 13,000 m.u.

III.4 Optimization of the Total Cost

To reduce the physical damage of the building and of its contents and, consequently, all of the direct and indirect monetary losses to the building owner, it is necessary to strengthen the structural elements and their connections, as well as to revise and make necessary modifications to the configuration of the equipment inside (for example, to bolt equipment and furniture to the floor or to the wall). A more radical improvement (and more costly) of the succeptibility of the building to damage would be by base isolation of the whole structure, or base isolation of expensive equipment inside the building, for example. The improvements of the quality of the elements at risk and reduction of their vulnerability to the earthquake hazard require investment, and a proper balance between the investment and the reduction of the losses should be made. The optimization process of the investment in rehabilitation consists of finding the state for which the total cost to the building owner, equal to the sum of the investment in rehabilitation and the expected total losses (or the losses that will happen with some given level of confidence) is at a minimum.

To optimize the investment in rehabilitation of the building, the minimum of the utility function $\Phi(\alpha) = \mathrm{E}[TLIS|\alpha] + B(\alpha)$ has to be found over all possible values of α, where α is a vector whose components are the input parameters for the building (the resistance class and the indirect loss proportionality class for the elements at risk), $\mathrm{E}[TLIS|\alpha]$ is the expected value of the total loss, and $B(\alpha)$ is the investment in rehabilitation. The solution of the optimization problem is a vector α^* such that

$$\Phi(\alpha^*) \leq \Phi(\alpha), \qquad \text{for all } \alpha \in A \qquad (III.7)$$

where A is the set of admissible values of α.

Table III.4.1

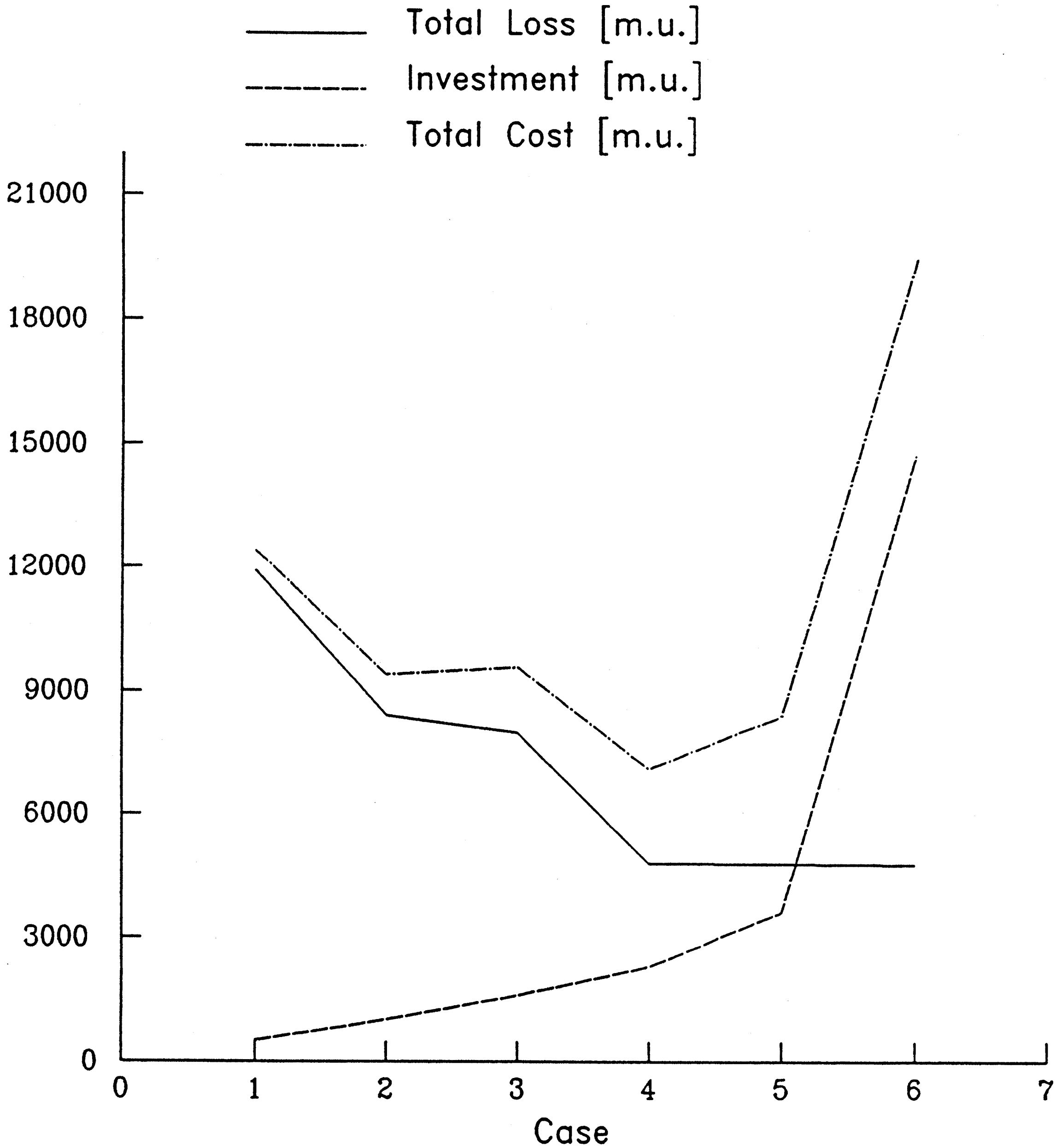
A summary of the values of the input parameters
corresponding to 6 states of the building

Type of Parameter	Sybsystem/ Elem. at Risk	Case					
		1	2	3	4	5	6
ilpf	Basement	h	a	a	l	l	l
Resistance Class	B.1	p	f	f	g	g	g
	B.2	p	f	f	f	f	g
	B.3	p	p	f	f	f	g
	B.4	p	p	g	f	g	g
ilpf	1st floor	h	a	a	l	l	l
Resistance Class	F1.1	p	f	f	g	g	g
	F1.2	p	f	f	f	f	g
	F1.3	p	p	g	f	g	g
ilpf	2nd floor	h	a	a	l	l	l
Resistance Class	F2.1	p	f	f	g	g	g
	F2.2	p	f	f	f	f	g
	F2.3	p	p	f	f	f	g
	F2.4	p	p	g	f	g	g

TABLE III.4.2

Summary of the additional investment in strengthening (broken into three parts: (a) initial cost, (b) cost of improving the resistance of the building itself, and (c) cost of improving the resistance of the equipment), the expected value of the total loss, and the mean damage ratio, MDR, for the six states of the building

Case	1	2	3	4	5	6
Initial Cost [m.u.]	0	500	500	600	600	700
Build. Resist. [m.u.]	0	500	600	1,000	2,000	9,000
Equip. Resist. [m.u.]	0	0	500	700	1,000	5,000
Total Investment [m.u.]	0	1,000	1,600	2,300	3,600	14,700
Expected Loss [m.u.]	11,900	8,400	7,965	4,790	4,770	4,750
MDR	2.767	1.953	1.852	1.114	1.109	1.104



Total Loss [m.u.]
Investment [m.u.]
Total Cost [m.u.]
21000
18000
15000
12000
9000
6000
3000
0
0
1
2
3
4
5
6
7
Case

Fig. III.4

To demonstrate the effects of the strengthening, the total loss is calculated for several variations of the state of the subsystems and of the elements at risk of the example building. In general, as a result of the strengthening the following input parameters change: the input hazard level for the elements at risk for the given level of shaking (this is because the building stiffness, and, consequently, the response amplitudes at different story levels change as a result of the strengthening), the resistance class of the elements at risk and the indirect loss proportionality class. The effect of the rehabilitation on the indirect loss proportionality factor is not known at this time. However, it is assumed in the calculations that it decreases as the level of strengthening increases. It is also assumed that the building response, and, consequently, the input hazard level for the elements at risk, do not change with the strengthening. The total loss has been calculated for five improved states of the building which are referred to as Case 2, Case 3, ..., Case 6. The initial state corresponds to Case 1.

The input parameters for Cases 1 through 6 are shown in Table III.4.1. The expected value of the total losses, the investment in the strengthening, and the total cost to the building owner are summarized in Table III.4.2. The investment in strengthening is itemized into three groups: (a) initial cost, associated with evacuation of the building, (b) cost of improving the resistance of the structural and non-structural elements, and (c) cost of improving the resistance of the equipment.

It is assumed that the minimum initial cost is 500 m.u.. The total investment for Cases 1 through 6 is: 0 m.u.; 1,000 m.u.; 1,600 m.u.; 2,300 m.u.; 3,600 m.u. and 14,700 m.u., respectively. The expected losses for the respective cases are: 11,900 m.u.; 8,400 m.u.; 7,965 m.u.; 4,790 m.u.; 4,770 m.u. and 4,750 m.u..

In Fig. III.4, the expected losses, the total investment, and the total cost to the building owner are shown in graphical form. It can be seen from this figure that, going from Case 1 to Case 6, the total loss decreases but the investment increases. The total cost to the owner, equal to the sum of the investment in strengthening and the expected loss, has a minimum at Case 4. This implies that Case 4 corresponds to the optimum level of strengthening.

CHAPTER IV

SUMMARY AND CONCLUSIONS

As a result of the advancements in the construction technology and of the more strict code provisions for the design forces, the human casualties and the material damage caused by earthquakes in a modern society have been reduced significantly. However, in spite of this, the modern society is still vulnerable, even to moderate earthquakes, because of the large losses that may result from interruption of work, legal fees, loss of important equipment e.t.c.. To abate the damaging consequences of earthquakes in the long run, adequate preparedness and planning are required. To accomplish this, a tool (consisting of a methodology, computer programs, and a data base) is needed that would estimate the possible losses and assist in the decision making. Initial investment in strengthening of existing buildings will reduce future losses. However, the long range financial gain is not a linear function of the initial investment and the optimum investment has to be determined.

The decision making tool for prediction of the losses should consists of a user-friendly computer program, a database on the building, probabilistic description of the earthquake hazard at the site, and damage probability distribution functions for given levels of the ground shaking. The computer program should be interactive and easy to use not only by earthquake engineering professionals, but also by the building owner or by an executive, which would secure the confidentiality of the gathered information and of the prediction. The database on the building should contain information on the structural properties and on the properties of the soil on which the building has been founded (so that the response to earthquake motion can be estimated), the inventory and the various functions of the structure, so that the indirect losses can be predicted. The description of the earthquake hazard consists of the probability of occurrence of ground motion with given intensity (MMI, peak acceleration or uniform risk response or Fourier spectrum) at the site during the service time of the structure. This probability of occurrence can be calculated from geological data and/or from data on the seismic activity in the past. A methodology and a computer program have been developed over the past 15 years at the University of Southern California to calculate uniform risk spectra and Modified Mercali Intensity at a site with given confidence that those will not be exceeded during a given exposure time. This methodology has been applied to microzonation of the Los Angeles Metropolitan Area (Lee and Trifunac 1987b, Trifunac 1990a). The damage probability functions can be determined from post earthquake damage data, by simulation, or from expert opinions. Damage probability matrices have been constructed for structural and non-structural damage of high-rise buildings for given range of MMI at the site, from damage data gathered after the 1971 San Fernando, California, earthquake. Such damage probability matrices are directly applicable to damage assessment in California. However these are incomplete and do not include the indirect losses (no empirical data on indirect losses has been gathered so far). Damage probability matrices have been constructed for the direct and indirect losses of different types of buildings, life-lines and other type of structures, based on expert opinion. Those are presently used by the practicing engineers as the most complete set to estimate the losses of given type of buildings (the buildings have been classified according to structural type and size, and according to their function). However, these can be used to estimate only roughly the generic losses for given type of buildings and there is a large uncertainty associated with these estimates.

In this report a method has been developed to estimate in more detail the total loss of a specific building exposed to given level of hazard. The hazard to which the building is exposed could be an earthquake, fire, tsunami, wind or other natural and man-caused hazards. The unit for which the losses are assessed is called an integral system, and it could be a building, a group of a buildings, a whole community, a life-line or any other vulnerable system. The integral system is made of subsystems which consist of elements at risk. The damage probability distribution functions for the physical damage of the elements at risk must be given, and also the input hazard level for the elements. The input hazard level is the level of a response parameter of the system to which the damage of the element is correlated with. The input hazard level is a function of the level of shaking at the site. To distinguish between different quality of the elements at risk of a given kind and their susceptibility to damage, resistance classes have been defined. The resistance class of an element may be a function of the level of the forces for which the element has been designed, of the past experience of the element, of its relation to the other elements at risk e.t.c.. The indirect losses for the subsystems are calculated from the direct losses, given a proportionality factor. The proportionality factor can be a fixed number or a random variable specified by a probability distribution function. This factor depends on the importance of the function of the subsystem, but also on the overall damage in the region which affects the time required to restore all the functions of the subsystem. The total loss of the integral system is some function of the subsystem losses.

The method is illustrated for a hypothetical building of a university campus, using hypothetical analytical probability distribution functions for the losses of the elements at risk. For that purpose, the Beta probability distribution function is used as a convenient physically admissible probability distribution function. (The expected value and the variance have to be specified for the particular elements at risk, as functions of the input hazard level.) The example building is a two story moment resisting frame building housing offices, laboratories and classrooms. The subsystems are the two stories and the basement. The elements at risk are the structural and nonstructural elements, the installations and the laboratory and office equipment, for example. Three resistance classes (good, fair and poor) are defined both rigorously and descriptively. The indirect losses proportionality factor is assumed to be uniformly distributed over the interval of the losses. Three classes of indirect losses proportionality factor are defined (low, average and high), both exactly and descriptively. The losses of the subsystems are assumed to be a sum of the losses of the elements at risk, and the losses of the integral system (the building) to be a simple sum of the subsystem losses.

The losses are estimated for the maximum possible value of the site response parameter in the next (for example) 80 years, for different scenarios of the building state. Each scenario is an improved state of the building as a result of some investment. Then, from these states, the optimum state is chosen for which the total cost to the owner (sum of the expected value of the losses and the investment in the improvement) is minimum.

An interactive computer program EQLOSS has been written to estimate the earthquake losses for a community of buildings, for example, a university campus. This program can be interfaced with the bank of data on all the buildings on the campus, which can be easily updated by the user. It also allows graphical representation of the damage probability functions for the integral system. Such a computer program can be used by the owner or by an executive as a decision making tool for mitigation of the losses caused by future earthquakes. By executing the program for different scenarios, the optimum steps for future action can be determined. At present the program estimates the losses for given level of shaking at the site. However, it can be easily interfaced with the computer program NEQRISK (Lee and Trifunac 1985) so that, then, the expected value of the losses or the losses that will not be exceeded with a given level of confidence during the service time of the building can be estimated.

What is missing at present are the probability distribution functions (or matrices) of the direct losses associated with damage for the elements at risk, and probability distribution functions for the indirect loss proportionality factors for the subsystems. This task requires at least several years of extensive research and data gathering, and is left for future work.

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