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Multi-Dimensional Fragility of Structures: Formulation and Evaluation

by

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NOTICE

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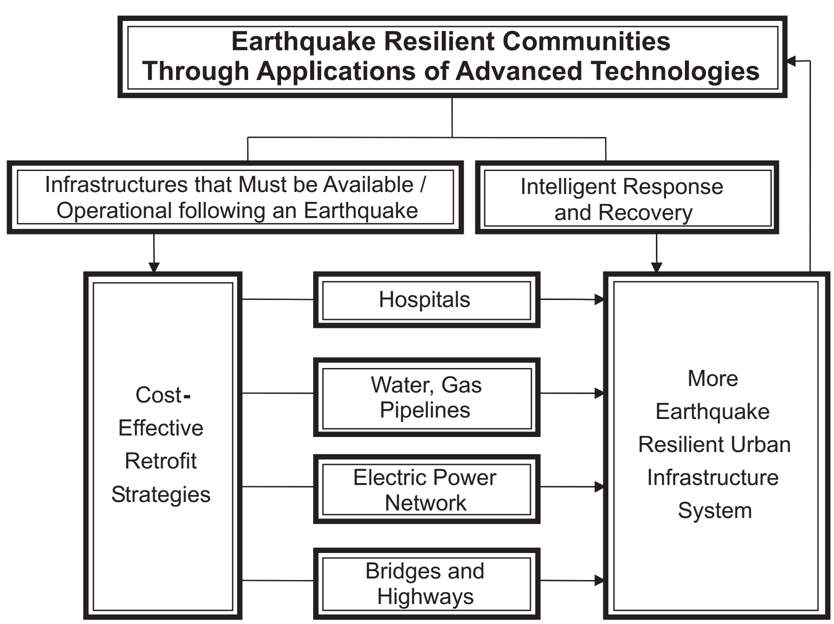
Preface

The Multidisciplinary Center for Earthquake Engineering Research (MCEER) is a national center of excellence in advanced technology applications that is dedicated to the reduction of earthquake losses nationwide. Headquartered at the University at Buffalo, State University of New York, the Center was originally established by the National Science Foundation in 1986, as the National Center for Earthquake Engineering Research (NCEER).

Comprising a consortium of researchers from numerous disciplines and institutions throughout the United States, the Center's mission is to reduce earthquake losses through research and the application of advanced technologies that improve engineering, pre-earthquake planning and post-earthquake recovery strategies. Toward this end, the Center coordinates a nationwide program of multidisciplinary team research, education and outreach activities.

MCEER's research is conducted under the sponsorship of two major federal agencies: the National Science Foundation (NSF) and the Federal Highway Administration (FHWA), and the State of New York. Significant support is derived from the Federal Emergency Management Agency (FEMA), other state governments, academic institutions, foreign governments and private industry.

MCEER's NSF-sponsored research objectives are twofold: to increase resilience by developing seismic evaluation and rehabilitation strategies for the post-disaster facilities and systems (hospitals, electrical and water lifelines, and bridges and highways) that society expects to be operational following an earthquake; and to further enhance resilience by developing improved emergency management capabilities to ensure an effective response and recovery following the earthquake (see the figure below).



A cross-program activity focuses on the establishment of an effective experimental and analytical network to facilitate the exchange of information between researchers located in various institutions across the country. These are complemented by, and integrated with, other MCEER activities in education, outreach, technology transfer, and industry partnerships.

This report presents a method of developing fragility curves of buildings (for health care facilities) on the basis of structural and statistical analyses. This research is part of MCEER's Thrust Area 2 project on improving the seismic resilience of hospitals. A generalized formula is proposed for evaluating the fragility of structures with respect to multiple control parameters using multiple thresholds limit states. Various options have been considered to exemplify the sensitivity of this formulation. A case study of the MCEER west coast Demonstration Hospital [W70], located in the San Fernando Valley in Southern California, is considered to show the applicability of this technique.

ABSTRACT

A multi-dimensional definition of fragility is developed considering multiple parameters, including structural response variables such as floor accelerations and interstory drifts. Limit states are defined based on these multiple variables, considered as random variables in the calculation of fragility. A probabilistic description of the limit state has been adopted to calculate fragility.

A generalized formula for multidimensional threshold limit states is proposed, and various cases are considered to illustrate the formulation.

The MCEER west coast Demonstration Hospital located in the San Fernando Valley in Southern California was considered to show the applicability of this technique. The development of fragility for different cases shows the importance of correct evaluation of the limit states for comparison of different techniques. The MCEER generated ground motion series, as well as those developed for the well-known SAC (SEAOC-ATC-CUREE) project are used as input for the illustration and comparison of fragility calculations.

The study investigates the sensitivity of fragility curves when uncertainties in limit states, usually defined from consensus of engineering and functionality criteria, are considered. Influence of structural and response parameters, such as stiffness, acceleration and displacement thresholds, input ground motion, and uncertainties due to structural modeling, are investigated. Different structural parameters that drastically affect the fragility are also considered, such as damping, that reduce structural response (deformations in particular).

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Any opinions, findings and conclusions or recommendations expressed in this report are those of the author(s) and do not necessarily reflect those of the Multidisciplinary Center for Earthquake Engineering Research (MCEER), the National Science Foundation (NSF), the State of New York (NYS) or the University at Buffalo.

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SECTION 1

INTRODUCTION

1.1 Research Motivation

Awareness of the potential seismic hazard and the corresponding vulnerability of structures has increased following recent earthquakes in urban areas, which have caused serious economic and social impact. The prediction of structural damage is critical for the evaluation of economic losses in seismically active regions, and should be estimated with an acceptable degree of credibility in order to mitigate the potential losses that are dependent on the seismic performance of structures in that region. Two representations can be used to describe the structural damage distribution in a given region:

1. Fragility curves
2. Damage probability matrix (DPM) (Whitman, 1973)

The damage probability matrix is a tabular representation of the distribution of damage (Table 1-1). Each column represents an intensity of ground shaking and the numbers in the columns represent the fractions of buildings experiencing different damage states. The sum of the numbers in each column is 1. The DPM specifies the discrete probabilities of reaching a given damage state at different ground motion intensities.

Table 1-1 Damage Probability Matrix

Limit State	Modified Mercalli Intensity						
	VI	VII	VIII	IX	X	XI	XII
NONE	20.4						
SLIGHT	70.3	15.5					
LIGHT	9.3	84.5	88.4	28.9	1.4		
MODERATE			11.6	71.1	81.6	38.7	3.8
HEAVY					17.0	61.3	88.7
MAJOR							7.5
DESTROYED	--						

On the other hand, fragility curves provide graphic information on the distribution of damage (Figure 1-1). The same information is provided by fragility curves and DPM. The only difference is that fragility represents the cumulative distribution of damage, which specifies the continuous probability that the indicated damage-state has been reached or exceeded.

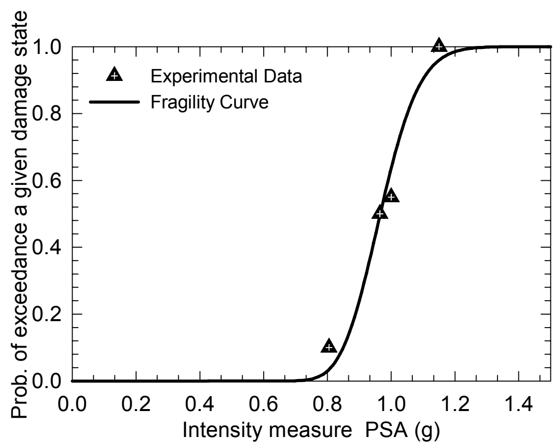

Figure 1-1 Fragility Curve

Fragility curves can either be empirical or analytical, based on the source of the data and type of analysis**.**

Empirical fragility curves are based on test or field data interpretation and engineering judgment. They are usually based on the damage data reported from past earthquakes. For example, Shinozuka (2000b) used the maximum likelihood method to generate empirical fragility curves from bridge damage observed in the 1995 Kobe earthquake.

Analytical fragility curves are developed from seismic response data obtained through analysis of the structure using simulated ground motions. The seismic response data can be obtained from nonlinear time history analysis (Shinozuka et al. 2000b), elastic spectra analysis, and nonlinear static analysis (Shinozuka et al, 2000a). Engineers usually make their recommendations using fragility curves based on deterministic performance limit states obtained from design provisions, public policies documents, engineering judgment, experimentation, etc. The rationale for using crisp (deterministic) quantities derives from the uncertainties in the earthquake loads that are larger than the uncertainties in the performance limit states.

In several case studies on fragility, a California hospital, which was damaged during the Northridge Earthquake (1994), was selected. The hospital was selected since it is a complex structure with impact and implications related to various levels of functionality of services and structural safety. The selection of this particular hospital for the case study was in part motivated by a survey conducted in 1998 with a random group of residents in Alameda County in California (Tierney et al. 1998). They were asked to identify the five most important structures or systems that must remain functional and operational during and following an earthquake. In that survey, 76% of residents indicated that hospitals were the most critical systems that should remain functional. Following several surveys and studies, the state of California enacted legislation that made it mandatory for health care facilities to evaluate the seismic adequacy of their buildings by January 2001, and to upgrade these facilities to ensure life safety by 2008, and full operationality following earthquakes by 2030 (Tierney et al., 1998). Full operation of a hospital following a major earthquake is a stringent performance requirement, and an engineer must be able to formulate his recommendations on structural and nonstructural performance in a format manageable by the key decision makers. Advanced technologies are already being considered the only way to achieve these stringent seismic rehabilitation projects. MCEER is studying advanced technologies for the rehabilitation of hospitals to meet or exceed the high level of performance expected of these facilities. Even though the initial costs of these technologies are currently high, increasing demand and implementation are expected to reduce future costs to the point where overall costs would be less than for conventional retrofitting. Different structural (passive) control techniques (using viscous or hysteretic dampers, base isolation, steel shear walls, etc.) have been proposed and analyzed for various risk levels and compared in term of structural fragility (Viti et al. 2006). This study indicates that a probabilistic approach is best suited for analytical evaluation and comparison of rehabilitation alternatives. Fragility curves can provide the necessary framework to cast the problem in the desired format.

1.2 Research Objectives

The main objective of this research is to show that the performance limit states, that are compared with the seismic response parameters in the calculation of fragility, should be properly modeled as random variables instead of deterministic quantities. If uncertainties in performance limit states are not considered, the results may be non-conservative, and wrong decisions may result. A multidimensional definition of performance limit state is formulated and a generalized formula is proposed, while different options are considered as particular cases of the main general one. A case study, the MCEER west coast Demonstration Hospital located in the San Fernando Valley in Southern California, is presented to show the applicability of this technique.

The ground motions used are from the synthetic series developed by MCEER (Wanitkorkul and Filiatrault, 2005), by SAC (Somerville *et al.* 1997) and the series generated from the Modified Kanai Tajimi power spectrum (Clough and Penzien, 1993). Their effects are compared in terms of inelastic structural response. A parametric analysis is performed to show the sensitivity of fragility to different characteristics. The multidimensional limit state fragility evaluation was programmed, and is included as a post process to the inelastic analysis program IDARC2D (Reinhorn et al., 2004).

1.3 Report Organization

Following this introduction, Section 2 defines the concept of multidimensional performance limit state. Section 3 describes different sources of uncertainties in the performance limit threshold, and a generalized formula for multidimensional definition of performance limit states is presented. All cases analyzed are shown to be particular instances of this general formula. Section 4 describes the analytical procedure to evaluate the exceedance probability of a given performance limit state. Section 5 describes the structure of the two programs developed using the described technique. Section 6 and 7 describe the case study model and the input ground motions considered, while Section 8 reports the results of the parametric analysis.

1.4 State-of-the-Art Survey

Multiple efforts were made in defining and evaluating the fragility of structures, following different strategies and approaches, showing that a unified approach for evaluating fragility is not available. Casciati and Faravelli (1991) summarized several approaches to develop fragility curves that are outlined below, but also proposed other original methods. Various recent studies used Monte Carlo simulations to calculate fragility related to a specified structural model, such as Hwang and Huo (1994), Fukushima et al. (1996), Kai and Fukushima (1996), Shinozuka et al. (2000a), Karim and Yamazaki(2001).

Shinozuka, Hwang, Reinhorn and others in the early 1990's developed analytical methods for generating fragility curves based on numerical simulation of specific structures at the National Center of Earthquake Engineering Research (NCEER). The parameters considered in the system were modeled as random variables in order to quantify the uncertainties in the structural system.

Singhal and Kiremidjian (1998) have developed fragility estimates by Bayesian analysis of observed damage data for subclasses of structural systems, and have used the Park and Ang damage index (1985) to quantify damage to a structure as a function of structural capacity and demand. The fragility was defined as the conditional probability that the damage index exceeds a certain threshold for a given ground motion. They represented the uncertainties in the damage index at a specified ground motion level with a lognormal distribution with unknown mean and a given constant standard deviation.

Shinozuka et al. (2000a) have examined the fragility curves of a bridge in Memphis by Monte Carlo simulations, in which structural response is computed by two different approaches: (1) using time history analyses and (2) using the capacity spectrum method (Barron-Corverra, 2000). Uncertainties in the ground motion and structure are considered using a sample of 10 "nominally identical, but statistically different" bridges and 80 ground motion time histories.

Other studies have used records of damage resulting from past earthquakes to develop empirical fragility curves. Basoz and Kiremidjian (1997), using observations on bridge damage after the Northridge earthquake, developed empirical fragility curves by logistic regression. Bridges were grouped into 11 classes, and empirical fragility curves were developed for each group. They were classified based on substructure material (concrete, steel, timber, masonry, etc.) and superstructure material and type (concrete girder, steel girder, concrete truss, arch, etc.). Shinozuka et al. (2000b) developed empirical fragility curves assuming that curves can be expressed in the form of two-parameter lognormal distribution functions. The location and scale parameters of the distribution have been estimated by maximizing the likelihood of observing the damage data from the 1995 Hyogo-ken Nambu (Kobe) earthquake.

Other studies have also developed analytical fragility curves on the basis of nonlinear dynamic analysis of a numerical model of a bridge in the Memphis area that has random material properties. Fragility curves were estimated by fitting a lognormal distribution to the failure/no failure data obtained from numerical simulations (Hwang and Huo, 1994).

Tanaka et al. (2000), instead of using a cumulative lognormal distribution to fit the fragility curve, used a two-parameter normal distribution function. A total of 3683 bridges were grouped into five structure types, and the extent of damage was ranked into five levels. These field data have been used to determine the two unknown parameters of the distribution.

Karim and Yamakazi (2001) developed an analytical approach to constructing fragility curves of piers of specific bridges which do not have enough earthquake experience, using the nonlinear dynamic response of an equivalent single degree of freedom model of the pier obtained by static pushover analysis. They considered the variation of input ground motion that is usually not accounted for in empirical fragility curves. Using damage index and ground motion indices, the analytical fragility curves of bridges piers were compared with empirical ones showing good agreement.

Dimova and Hirata (2000) utilize a simplified method of fragility estimation based on the concept of “mean seismic excitation” and linear regression of the seismic response parameters on seismic intensity parameter allowing a considerable reduction in the computational time. The technique has been applied to a structure with two types of friction devices.

Recently, Tekie and Ellingwood (2003) presented a methodology to develop fragility curves for concrete gravity dams to assess their seismic performance. Lupoi et al. (2005) investigated the effects of spatial variability of ground motion on the response of bridge structures using a statistical approach in terms of fragility curves showing that spatial variability affects the response. Lu et al. (2005) investigated, by mean of statistical simulation, the probabilistic drifts limits of reinforced concrete column for three distinctive performance levels. The performance reliability of different reinforced concrete columns was then evaluated by constructing the fragility curves based on the probabilistic displacement response spectra.

Disadvantages related to all these approaches are that their fragility curves are related to specific structural models and cannot be used to assess the fragility of other structures of the same type, unless in a very crude way. Another disadvantage is that these models cannot be verified by laboratory testing, since this requires multiple physical models be brought to failure, which is too expensive and time consuming. Also, none of these models consider all the uncertainties involved in fragility analyses. For example, the performance limit threshold is usually considered as a crisp quantity, whereas it should be modeled as a random variable as well.

While this literature survey is by no means comprehensive, it is presented here to highlight several distinct techniques, and set the stage for future developments in this work.

SECTION 2

DEFINITION OF MULTIDIMENSIONAL PERFORMANCE LIMIT STATE

Fragility curves are functions that represent the conditional probability that a given structure's response to various seismic excitations exceeds given performance limit states. Theoretically, fragility represents the probability that the response R of a specific structure (or family of structures) exceeds a given threshold $r_{\lim}$, associated with a given limit state, conditional on earthquake intensity parameter I. In mathematical form, this simply is a conditional probability (Barron-Corvera, 2000, Reinhorn et al, 2001):

$$Fragility = P\left\{R \geq r_{\lim} / I\right\} \tag{2-1}$$

where:

R = Response parameter (deformation, force, velocity, etc.),

$r_{\lim}$ = Response threshold parameter that is correlated with damage,

I = Earthquake intensity (Return period, PGA, Modified Mercalli Intensities, etc.).

This definition can be extended to N-dimensional parameters where the number of parameters to be checked is N. So, the general definition can be written in the following form:

$$Fragility = P\left\{R_1 \geq r_{\lim 1} \cup R_2 \geq r_{\lim 2} \ldots \cup R_N \geq r_{\lim N} / I\right\} = P\left\{\bigcup_{i=1}^{N} R_i \geq r_{\lim i} / I\right\} \tag{2-2}$$

where:

R_i = Response parameter related to a certain quantity (deformation, force, velocity, etc.),

$r_{i,lim}$ = Response threshold parameter related to a certain quantity that is correlated with damage.

when the problem is reduced to a bi-dimensional case considering for instance, displacements and accelerations of a building story, the fragility can be written in the following form:

$$Fragility = P\left\{\Delta \geq D_{\lim} \cup Z \geq A_{\lim} / I\right\} \tag{2-3}$$

where:

Δ = Random variable representing the displacement response,

Z = Random variable representing the acceleration response,

$D_{\lim}$ = Given displacement threshold,

$A_{\lim}$ = Given acceleration threshold.

In this case, the response can be visualized and represented by a "bell surface" in the pseudo spectral acceleration (PSA) – spectral displacement (S_d) plane and the limit thresholds in these cases can be expressed in term of accelerations, displacements, or velocity (Bruneau & Reinhorn*,* 2004) as shown in Figure 2-1) and represented in the plane by straight lines. In Figure 2-2 a multidimensional deterministic limit state is shown for simplicity even though random limit states can be considered in the analysis. In the most general case, it is also possible to describe different shapes of limit thresholds like circles, ellipses etc. In both cases, the probability of failure is determined by the volume underneath the "bell surface" beyond the surface limit state, typically- the grey area in Figures 2-2 and 2-3. In order to reduce the probability that the response exceeds a specific limit state, two methods can be used (Bruneau & Reinhorn, 2004). For a given structural response of the building, the retrofit of only the nonstructural components would allow them to resist greater floor accelerations or displacements, resulting in a shift of the limit state to the right (Figure 2-1) and a reduction in the volume under the probability distribution surface, hence a smaller probability of exceedance of the limit state. The second method consists of modifying the structural system resulting in a modified structural response, which slides the multidimensional bell curve to the left, thereby reducing the volume under the probability distribution surface. For example, stiffening the structural system moves the response surface to the left whereas structural damage during an earthquake moves the response surface to the right, resulting in greater intersection with drift-controlled limit states. Once the probability of exceeding the limit states is calculated, it can be represented by fragility curves.

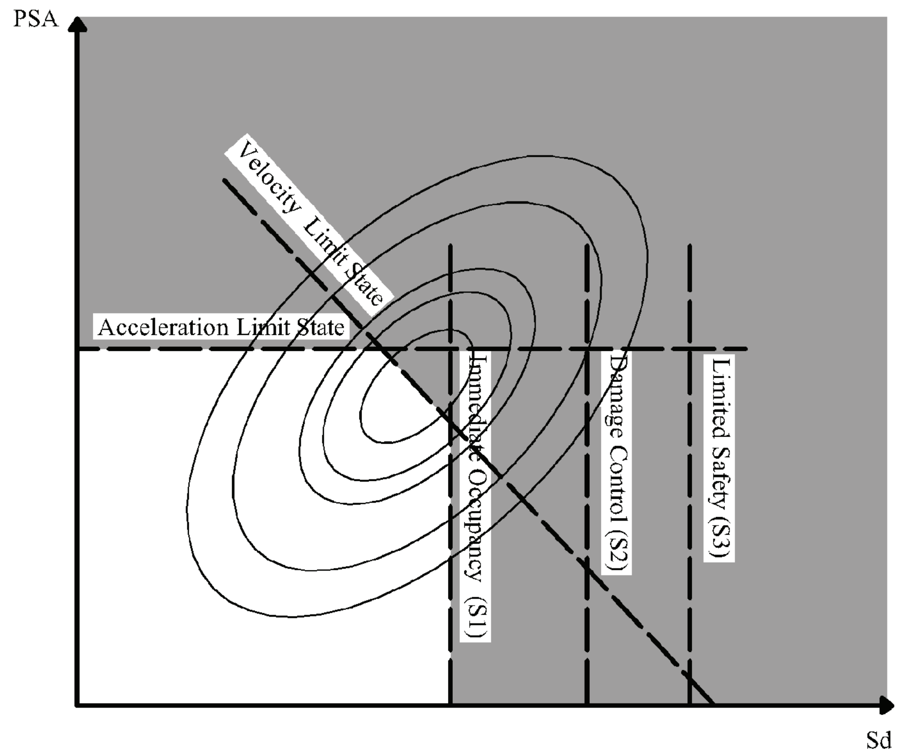

Figure 2-1 Performance Limit State by a Surface Relating Independent Accelerations, Velocity and Interstory Drift Limit States

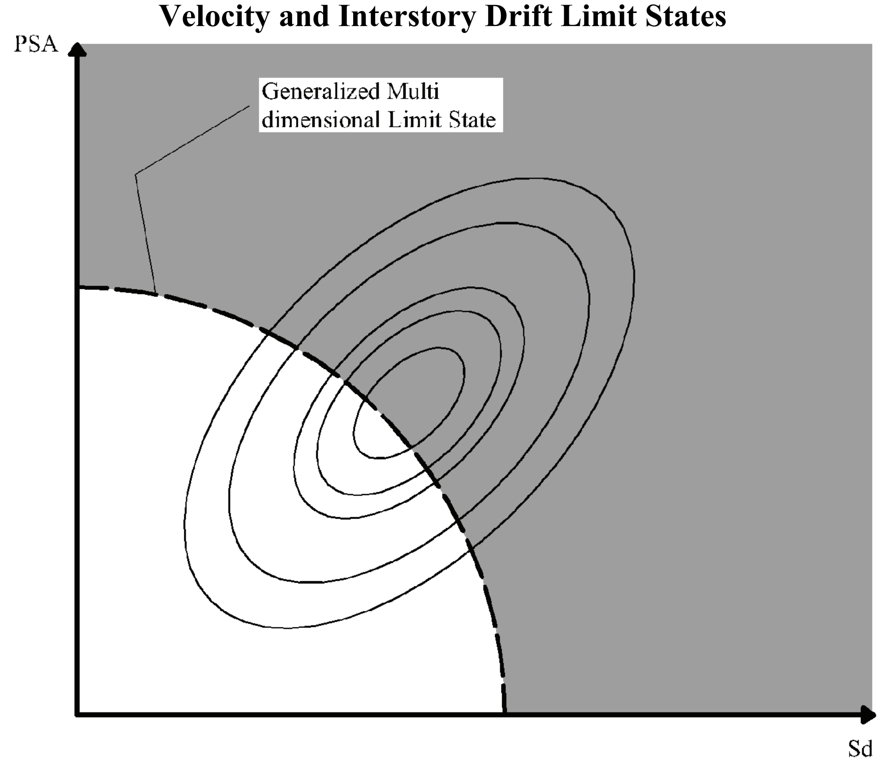

Figure 2-2 Generalized Performance Limit State by a Surface Relating Implicitly Accelerations and Interstory Drift Limit States

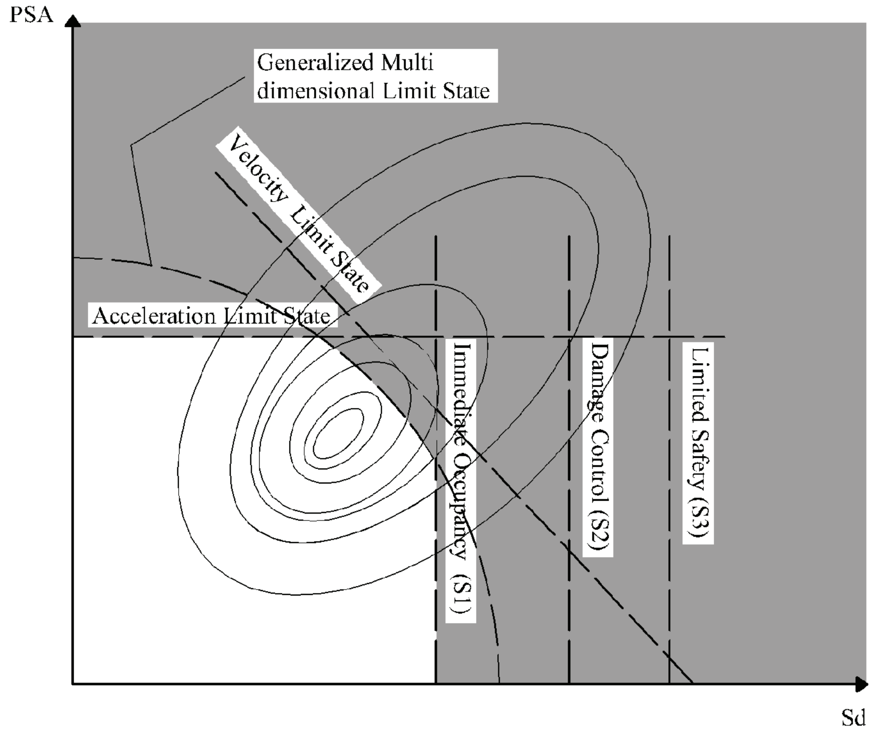

Figure 2-3 Multidimensional Performance Limit States and Generalized Function Relating Accelerations and Interstory Drift Limit States

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SECTION 3

PROPOSED GENERALIZED FORMULATION FOR MULTIDIMENSIONAL DEFINITION OF PERFORMANCE LIMIT STATES

3.1 Multidimensional Probability Distribution Response

The response of the structure in the plane spectral acceleration-spectral displacement can be represented through the so called "Bell-curve" response (Bruneau & Reinhorn, 2004), that is the joint probability density function of the response expressed in term of two variables -the maximum spectral displacement and the maximum spectral acceleration that are assumed to be lognormally distributed.

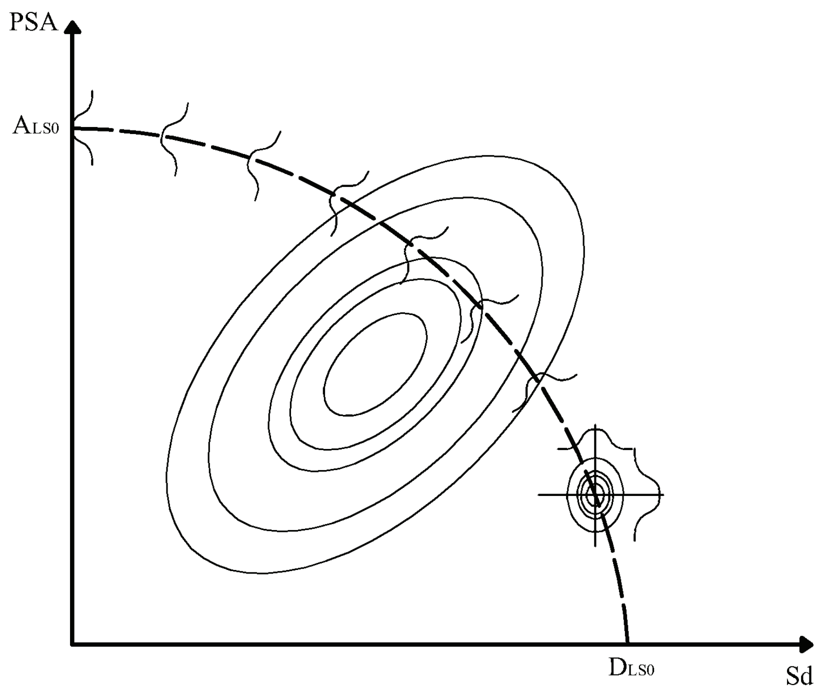


Figure 3-1 Generalized Formula for Multidimensional Threshold Limit State (MTLS)

Figure 3-1 shows a contour plot of the response in the form of an ellipse, since the maximum responses in terms of interstory drift and peak floor acceleration are considered as random variables.

3.2 Proposed Generalized Formula for Multidimensional Definition of Performance Limit States

The generalized formula for performance limit states is a tool that allows considering multiple limit states related to different quantities in the same formulation. The relationship among different limit states can be determined by chosing parameters that allow different shapes of performance threshold, and can be estimated using probabilistic analysis and engineering judgment.

This model can be used to build the fragility curve of a single nonstructural component, or also to obtain the global (overall) fragility curve for the entire building structure including the nonstructural components, because it allows different response parameters (forces, displacements, velocities, accelerations, etc.) to be controlled and combined in a unique fragility curve.

Limit states can either be linear or nonlinear, dependent or independent. All these options can be formulated as particular cases of the main general one with a suitable choice of the parameters involved.

A generalized formula for multidimensional performance limit threshold can be formulated as:

$$L\left(R_1,\ldots R_n\right)=\left(\frac{R_1}{r_{1\lim}}\right)^{N_1}+\left(\frac{R_2}{r_{2\lim}}\right)^{N_2}+\ldots+\left(\frac{R_n}{r_{n\lim}}\right)^{N_n}-1=0 \tag{3-1}$$

Or in a more compact form:

$$L\left(R_1,\ldots R_n\right)=\sum_{i=1}^{n}\left(\frac{R_i}{r_{i\lim}}\right)^{Ni}-1 \tag{3-2}$$

where:

R_i = Response parameter (deformation, force, velocity, etc.),

$r_{i\lim}$ = Response threshold parameter that is correlated with damage,

N_i = Interaction factors determining the shape of n-dimensional surface.

In a non-dimensional space considering only three parameters, Equation 3-1 or 3-2 assumes the shape shown in Figure 3-2.

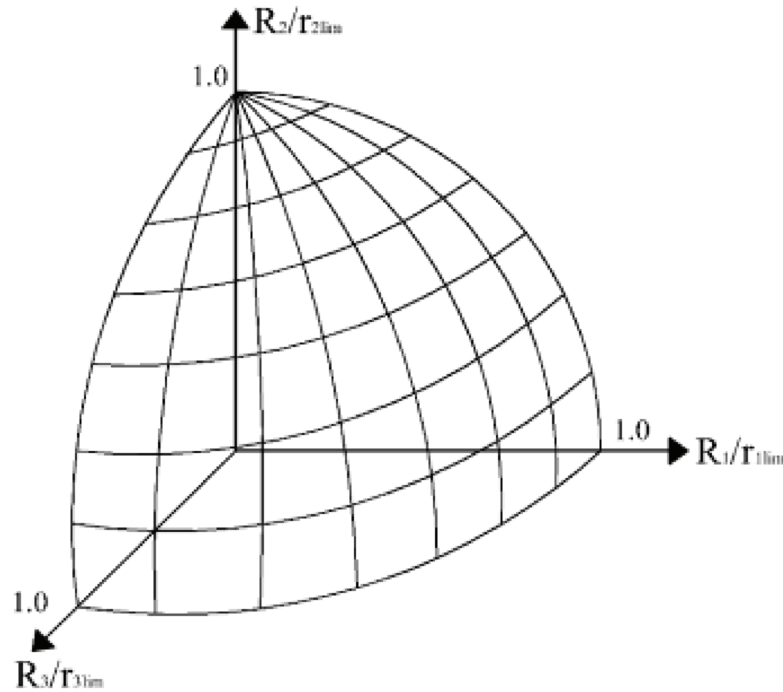


Figure 3-2 Three-Dimensional Performance Threshold

In the bi-dimensional case, the proposed multidimensional threshold limit state can be expressed by the following equation:

$$\left(\frac{A_{LS}}{A_{LS0}}\right)^{N_a} + \left(\frac{D_{LS}}{D_{LS0}}\right)^{N_d} - 1 = 0 \qquad (3\text{-}3)$$

Where

A_{LS0} = Independent peak floor acceleration limit state

D_{LS0} = Independent peak floor interstory drift limit state

A_{LS} = Dependent peak floor acceleration limit state

D_{LS} = Dependent peak floor interstory drift limit state

N_a, N_d = Interaction factors determining the shape of limit state surface

In the bi-dimensional case, the curve of performance limit threshold can be visualized as in Figure 3-1.

A simpler expression is obtained assuming $N_a=1$ resulting in:

$$\frac{A_{LS}}{A_{LS0}}+\left(\frac{D_{LS}}{D_{LS0}}\right)^N-1=0 \tag{3-4}$$

A_{LS0} and D_{LS0} are independent quantities and usually are calculated from:

1. Field data after an earthquake
2. Experimental laboratory tests.

The first procedure consists of collecting past earthquake field data. Damage data are related to drift as determined by field observation, while acceleration threshold can be determined in the field only when the building is monitored using accelerometers.

The second procedure provides damage information from laboratory experiments. The advantage of this procedure is that for the structure of interest, the range of earthquake intensities can be controlled as required, and both interstory drifts and accelerations can be monitored and measured more accurately than in the field, but the amount of damage data is limited due to financial constraints.

A_{LS} and D_{LS} are dependent quantities through Equation 3-4, in which the only parameter to be estimated is N, through comparison with experimental data.

Equation 3-4 describes a two-dimensional threshold limit state (*2DTLS*), while the response of the structure is defined by a point (D_γ, A_γ) in the plane *PSA- Sd*, meaning that when this point is located to the right of the *2DTLS,* the performance limit state has been exceeded. In analytical form, this can be expressed by the following equation:

$$\frac{A}{A_{LS0}}+\left(\frac{D}{D_{LS0}}\right)^N-1\geq 0 \tag{3-5a}$$

$$A\geq A_{LS0}\left[1-\left(\frac{D}{D_{LS0}}\right)^N\right] \tag{3-5b}$$

in which:

A = Peak floor acceleration response

D = Peak floor interstory drift response

A_{LS} and D_{LS} can either be considered as random variables or crisp quantities without the need to modify Equation 3-5. All other cases can be considered as particular realizations of the general Equation 3-3. The power N dictates the dependency of the random variables describing the limit state.

3.3 Specific Cases

For example, the simplest case where only drift is considered as the performance limit state can be determined using Equation 3-4 assuming:

$$\left.\begin{array}{c} A_{LS0} = \infty \\ N = 1 \end{array}\right\} \Rightarrow D_r \leq D_{LS} \tag{3-6}$$

and is shown in Figure 3-3.

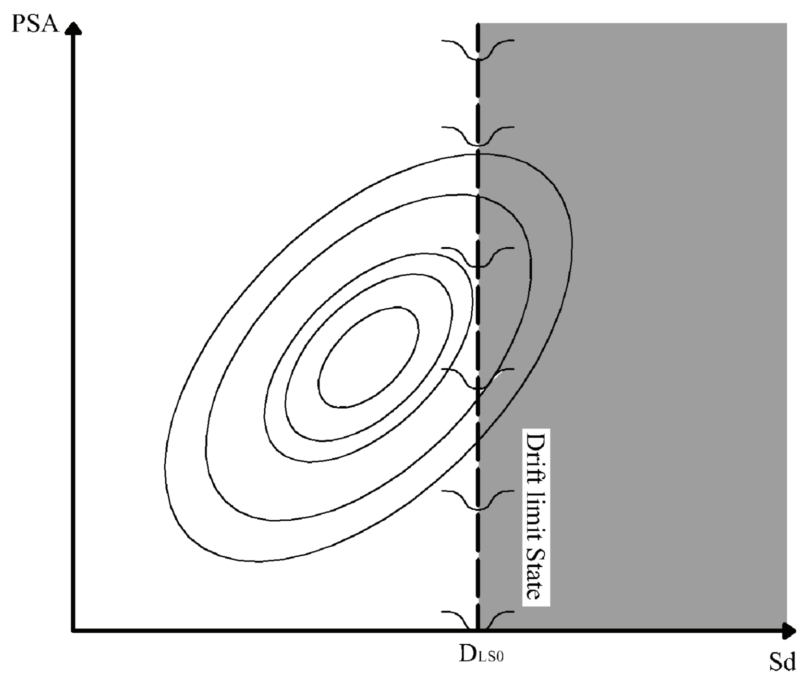


Figure 3-3 Drift Threshold Limit State

This is the more common case, with D_{LS} either taken as a crisp quantity or a random variable.

Alternatively, if an acceleration limit state is given, then this can be determined assuming:

$$\left.\begin{array}{c} D_{LS0} = \infty \\ N = 1 \end{array}\right\} \Rightarrow A_r \leq A_{LS} \tag{3-7}$$

as shown in Figure 3-4.

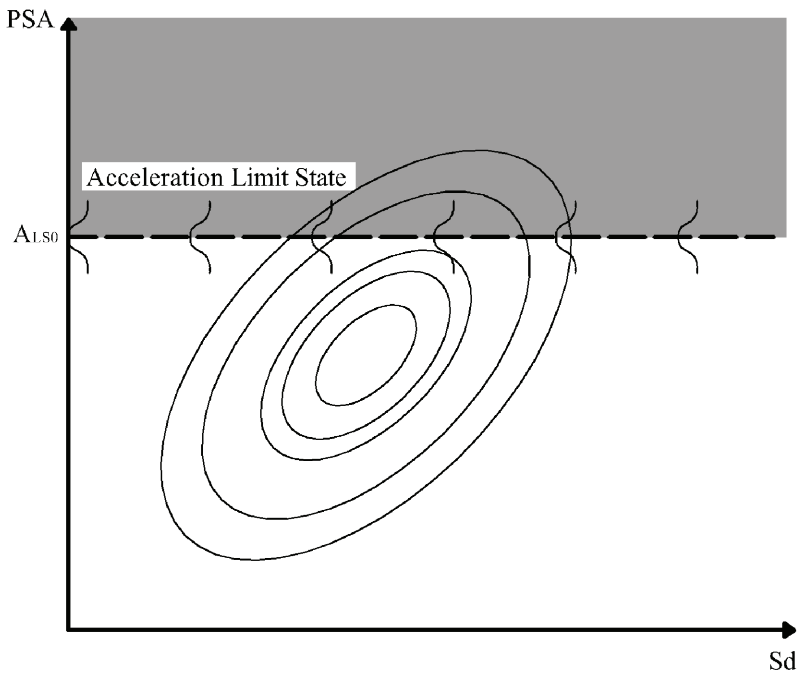


Figure 3-4 Acceleration Threshold Limit State

A_{LS0} can also be considered as either a crisp quantity or a random variable. This TLS is mainly applicable to nonstructural components such as computer hardware and medical equipment, which are usually acceleration sensitive.

The case in which both acceleration and interstory drift are considered, but as unrelated quantities, can be determined by assuming:

$$N = \infty \Rightarrow \frac{A}{A_{LS0}} + \left(\frac{D}{D_{LS0}}\right)^{\infty} - 1 \leq 0 \tag{3-8}$$

Therefore, Equation 3-5 leads to the following two cases shown in Figure 3-5:

$$\left(\frac{D}{D_{LS0}}\right)^{\infty} \Rightarrow 0 \quad \text{if} \quad \left(\frac{D}{D_{LS0}}\right)^{\infty} \langle 1 \quad \text{so} \quad \frac{A}{A_{LS}} - 1 \leq 0 \tag{3-9}$$

and

$$\left(\frac{D}{D_{LS0}}\right) \leq \left[1 - \frac{A}{A_{LS0}}\right]^{\frac{1}{\infty}} \Rightarrow 1 \qquad \text{so} \quad \frac{D}{D_{LS}} - 1 \leq 0 \tag{3-10}$$

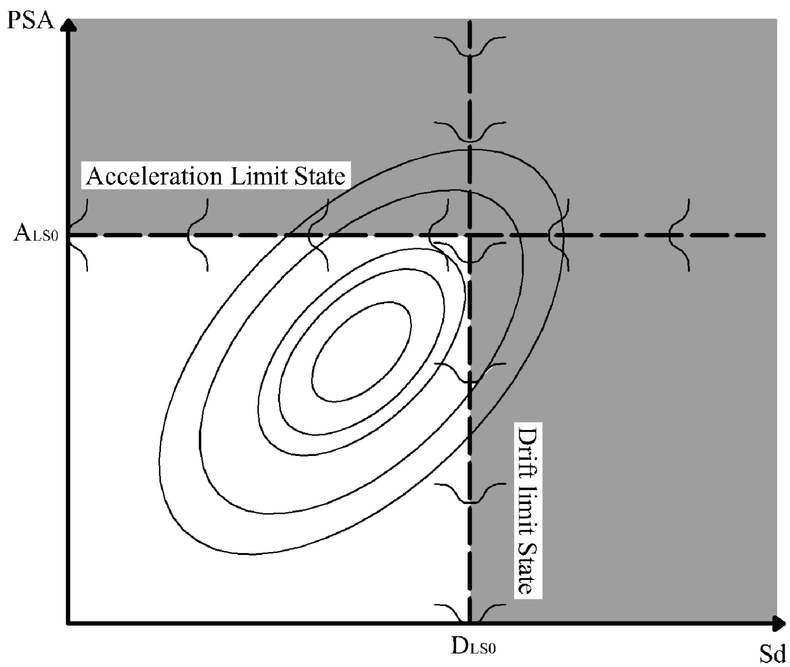


Figure 3-5 Unrelated Acceleration Threshold and Interstory Drift Limit State

On the other hand, assuming a linear relationship between acceleration and interstory drift limit states it is possible to determine the dependent velocity limit state as shown in Figure 3-6:

$$N = 1 \Rightarrow \frac{A}{A_{LS0}} + \left(\frac{D}{D_{LS0}}\right)^{1} - 1 \leq 0 \tag{3-11}$$

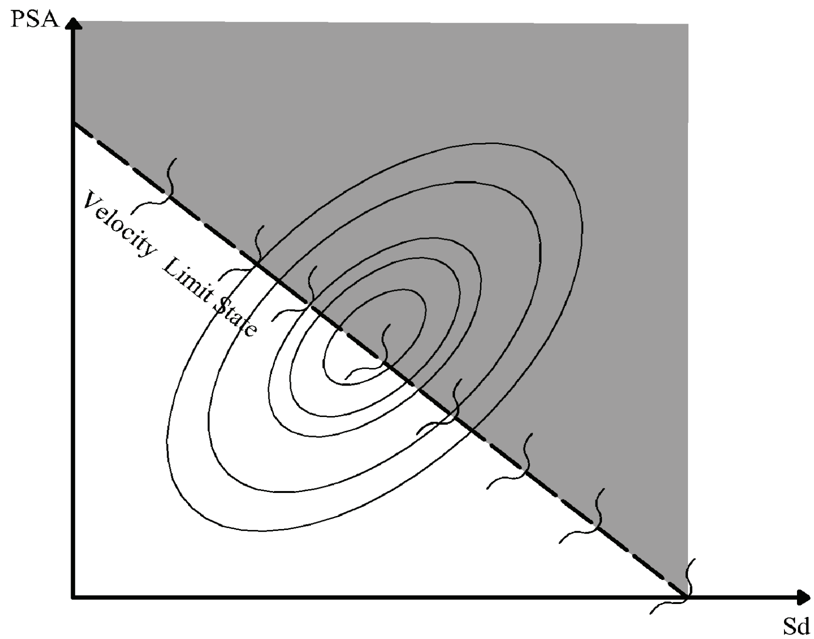


Figure 3-6 Velocity Threshold Limit State

SECTION 4

FRAGILITY EVALUATION PROCEDURE

4.1 Methodology for Generating Fragility Curves

The procedure to determine fragility curves using different global performance limit states of the structure is presented in this section. First, the local responses in terms of displacement and acceleration (or other parameters) of each member in every story are obtained. While the structural system is sensitive to several structural parameters (such as displacements, story drifts, yielding forces), the building contents and the nonstructural components are also sensitive to other parameters (such as accelerations, velocities, shear forces, etc). In a preliminary study, nonstructural components are also considered and assumed rigid and rigidly connected to the structure. Hence, the response of nonstructural components is well defined. For simplicity, only story drifts (or displacements) and accelerations are discussed here. The limit state in term of displacements and accelerations, partly dictated by structural safety (displacements) and functionality (accelerations) at each floor level, is taken as the "story performance limit state." The "floor fragility curve" (FFC) is then constructed as shown subsequently, and this procedure is repeated for each story level. Then, the performance level of the most critical story is defined as the global performance limit state for the structure.

The development of fragility curves is illustrated in the following steps:

Step 1: Compute the maximum pseudo spectral acceleration (PSA) response and the maximum spectral displacement (Sd) for each earthquake record consistent with a given hazard level;

Step 2: Estimate the probability density function of the response distribution -assumed lognormal - from the values of the mean and the standard deviation.

Step 3: Generate a larger ensemble of random numbers lognormally distributed;

Step 4: Count the number of times N_f that the maximum PSA and the maximum Sd exceed a given performance threshold and divide by the total number of trials N related to the respective hazard level, so the probability P_f of reaching or exceeding the performance limit state as:

$$P_f = \frac{N_f}{N} \tag{4-1}$$

As N approaches infinity, P_f approaches the true probability of reaching or exceeding a limit state;

Step 5: The probability P_f of exceeding the limit state is evaluated for different hazard levels, so in the plane probability of exceedance vs. earthquake intensity as many points as the number of considered hazard levels can be located;

Step 6: The fragility curves in this report are plotted showing the probability of reaching or exceeding a limit state versus the corresponding return period. Experimental data points corresponding to the different hazard levels in the probability of exceedance vs. earthquake intensity plane are transformed into a fragility curve by assuming that the response of the structural system is lognormally distributed as per Equation 4-2:

$$F_Y(y) = P(Y \le y) = \int_{-\infty}^{y} f_Y(y)\,dy = \int_{-\infty}^{y} \frac{1}{y \cdot \beta \cdot \sqrt{2\pi}} \cdot e^{\left[-\frac{1}{2\beta^2} \cdot \ln^2\left(\frac{y}{\theta_y}\right)\right]} dy \quad y \ge 0 \tag{4-2}$$

in which f_y is the probability density function, or in its more compact form:

$$F_Y(y) = \Phi\left[\frac{1}{\beta}\ln\left(y/\theta_Y\right)\right] \quad y \ge 0 \tag{4-3}$$

where Φ is the standardized cumulative normal distribution function , θ_y is the median of y, and β is the standard deviation of the natural logarithm of y (Soong, 2004). A chi-squared $\chi 2$ goodness-of-fit test was used to select the optimal values of the parameters of the lognormal distribution (θ_y and β).

4.2 Methodology for Generation of Fragility Curves Based on Maximum Likelihood Method (MLE)

This method also assumes that the fragility curves are expressed by the cumulative lognormal distribution function of Equation 4-2 or -4-3. However, the two parameters that characterize the curve, i.e., the median θ_y and the log-standard deviation β, are determined by the method of maximum likelihood (MLE) (Soong, 2004; Shinozuka et al. 2003). This method can only be applied to large samples. The likelihood function L for the present purpose is expressed as:

$$L = \prod_{j=1}^{k} \left[F_Y\left(a_j\right) \right]^{x_j} \left[1 - F_Y\left(a_j\right) \right]^{1-x_j} \tag{4-4}$$

Where $F_Y()$ represents the fragility curve for a specific state of damage; $a_j = PGA$ value to which the building is subjected; $x_j = 1$ or 0 depending on whether or not the structure sustains the state of damage under $PGA = a_j$; and k=total number of earthquake records considered. The two parameters θ_y and β are computed to satisfy the following equation that maximizes $ln(L)$, and hence L:

$$\frac{d \ln L}{d\theta_y} = \frac{d \ln L}{d\beta} = 0 \tag{4-5}$$

Fragility curves generated using the methodology proposed in Section 4.1 are compared with the maximum likelihood method. The same set of 100 earthquakes (designated later as the MCEER series), divided in four subsets of 25 records associated with a given hazard level, are used for comparison. The first story interstory drift of the MCEER demonstration hospital (W70) is taken as the response considered for comparison. Details of the building and the ground motions are given, respectively, in Sections 6 and 7. A drift performance threshold D_{LS0} of 0.9% is adopted.

Fragility curves obtained with the Maximum Likelihood method (MLE) and with the curve fitting method (FIT) are illustrated in Figure 4-1. It can be seen that whereas the median θ_y values are comparable, the log-standard deviation β are quite different. In other words, the fragility curves obtained with the MLE have larger dispersion than the fragility curve obtained with FIT.

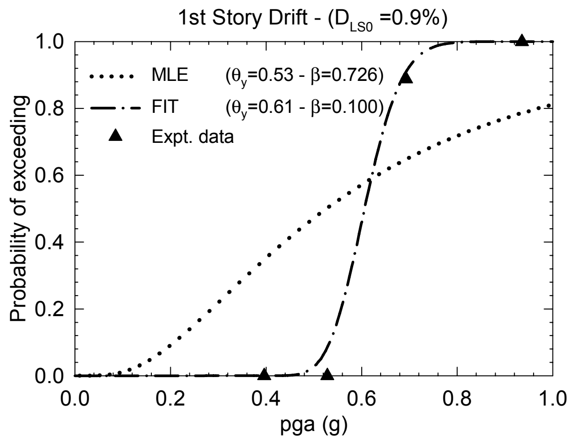


Figure 4-1 Probability of Exceeding a Given Threshold

Fragility curves can also use return period T_r as a measure of earthquake intensity. However, the transition from PGA to return period T_r is possible when using probability measures, but there is not a unique correspondence between these two quantities (e.g., for a given return period, there are several possible values of PGA). The number of return periods or hazard levels available for design in the USGS website (USGS, 2002) is usually four. If fragility curves are to be plotted vs. return period, the number of points available to determine the curve is that of the hazard levels. Since each hazard level includes ranges of PGA, the fragility curve based on hazard levels has a lesser deviation than that related to PGA (see Fig 4-1). In this case, the MLE method needs a larger number of points to provide reasonable results.

4.3 Sources of Uncertainties in Limit States

The definition of performance limit states (PLSs) plays an important role in the construction of fragility curves because their values have a direct effect. The performance limit state represents the level of response at which some harmful damage or loss of functionality occurs in the structure, however, for this to be useful, a description of the post-earthquake condition of the building is required. Damage states of structural and nonstructural components depend on mechanical properties such as strength and deformability, which are in themselves uncertain. Therefore, a crisp description of PLSs can be inappropriate. Instead, PLSs should be modeled as random variables although they are often described by crisp quantities (because the uncertainty in the earthquake load is considerably larger than the uncertainty in the PLSs themselves). For fragility evaluations, however, the uncertainties are significant. In this study, the performance limit states are considered as random variables, and both are defined in terms of interstory drifts and accelerations, since the behavior and failure modes of the hospital structure and its equipment are governed by both.

Several cases have been considered to estimate the probability of exceeding a certain PLS assuming that the limit thresholds are random variables. Two different types of responses were considered: interstory drift and floor acceleration. Both response peaks are assumed to be lognormally distributed. This assumption is reasonable, since the maximum of the response is always taken as positive. Also, the PLSs for the cases considered as random are assumed to be lognormally distributed. For each case, the responses in the linear and nonlinear ranges have been separated, and different assumptions have been made regarding the random variables considered. In the following paragraphs, for each case analyzed, an analytical solution has been formulated to calculate the probability of exceeding a certain performance limit state, given the probability distribution function of the response and of the limit states. The case of several random variables is also considered.

4.3.1 Case 1 - Interstory Drift Only: Crisp Threshold

Case 1 is the simplest, where the interstory drift threshold *D* is considered as a crisp quantity and compared with the random variable *Δ* of the interstory drift response, which is assumed to be lognormally distributed:

$$f_\Delta(\delta) = \begin{cases} \dfrac{1}{\delta \sigma_\Delta \sqrt{2\pi}} \cdot e^{-\frac{\left(\ln(\delta)-m_\Delta\right)^2}{2\sigma_\Delta{}^2}} & \delta \geq 0 \\ 0 & elsewhere \end{cases} \tag{4-6}$$

Hence, the probability of exceeding a given performance limit state is obtained from Equation 4-7, as shown in Figure 4-2.

$$P(\Delta \geq D) = 1 - F_{\Delta}(D) = 1 - \int_{0}^{D} f_{\Delta}(\delta) d\delta \qquad (4\text{-}7)$$

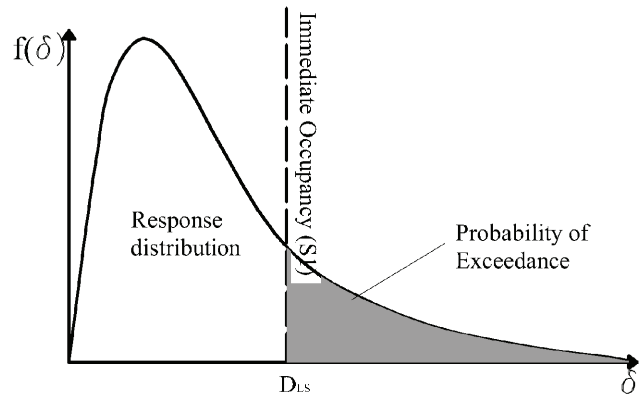


Figure 4-2 Case 1: Probability of Exceeding a Given Threshold

4.3.2 Case 2 – Interstory Drift Only: Random Thresholds

Case 2 is similar to Case 1, but here the interstory drift D and the peak interstory drift response threshold Δ are considered as lognormally distributed random variables. A new random variable $Y=\Delta/D$ is defined. The two random variables Δ and D can be considered independent, because the response random variable Δ and the process defining the limit state D are not related. The probability of exceeding the given threshold is the following:

$$P(\Delta \geq D) = P(\underbrace{\frac{\Delta}{D}}_{Y} \geq 1) = P(Y \geq 1) = 1 - F_{Y}(1);$$

Where:

$$F_{y}(y) = \int_{0}^{\infty}\int_{0}^{yd} f_{\Delta}(\delta) f_{D}(d) d\delta dd = \int_{0}^{\infty} f_{D}(d) \int_{0}^{yd} f_{\Delta}(\delta) d\delta dd = \int_{0}^{\infty} f_{D}(d) F_{\Delta}(yd) dd;$$

So finally:

$$P(\Delta \geq D) = P(Y \geq 1) = 1 - F_{Y}(1) = 1 - \int_{0}^{\infty} f_{D}(d) F_{\Delta}(d) dd; \qquad (4\text{-}8)$$

4.3.3 Case 3: Interstory Drift and Acceleration: Crisp Drift and Acceleration Thresholds

Case 3 considers performance limit states both in terms of accelerations and interstory drift, but as crisp quantities. The response is described by two random variables log-normally distributed, corresponding to the interstory drift response *Δ* and to the acceleration response *Z*.

$$f_\Delta(\delta) = \begin{cases} \dfrac{1}{\delta\sigma_\Delta\sqrt{2\pi}} \cdot e^{-\frac{\left(\ln(\delta)-m_\Delta\right)^2}{2\sigma_\Delta^{\,2}}} & \delta \geq 0 \\ 0 & elsewhere \end{cases} \tag{4-9}$$

$$f_Z(\zeta) = \begin{cases} \dfrac{1}{\zeta\sigma_Z\sqrt{2\pi}} \cdot e^{-\frac{\left(\ln(\zeta)-m_Z\right)^2}{2\sigma_Z^{\,2}}} & \zeta \geq 0 \\ 0 & elsewhere \end{cases} \tag{4-10}$$

Random variables are compared with the corresponding interstory drift performance limit state *D* and acceleration performance limit state *A*. To obtain fragility information, it is assumed that the two random variables are lognormally distributed, and the elastic and inelastic ranges are treated separately. In the elastic range, it is assumed that if *Z* is the pseudo-acceleration and *Δ* is the related displacement, then the following relationship exists:

$$\frac{Z}{\omega^2} = \Delta \tag{4-11}$$

a) In the **elastic case**, for every type of structure, there is always a relationship between accelerations and displacements, so the two random variables cannot be considered independent. In view of this general relationship, a problem with two random variables is reduced to one with only a single random variable. Since the problem is reduced from two-dimensional to one-dimensional, the probability of exceedance is the following:

$$P\{\Delta \geq D \cup Z \geq A\} = P\{\Delta \geq D \cup \Delta\omega^2 \geq A\} = P\{\Delta \geq \min(D, A/\omega^2)\} =$$

$$= 1 - F_\Delta(\min(D, A/\omega^2)) = 1 - \int_0^{\min(D, A/\omega^2)} f_\Delta(\delta)\, d\delta; \tag{4-12}$$

Figure 4-3 shows this case.

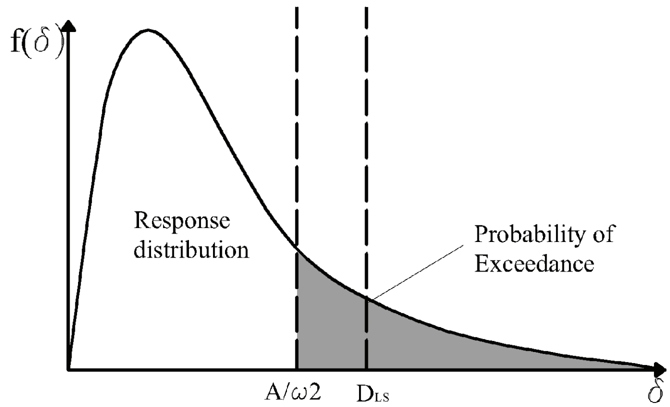


Figure 4-3 Case 3: Probability of Exceeding a Given Threshold

b) When the structure is in the **inelastic range,** it can reasonably be assumed that there is no relationship between interstory drift and acceleration, so the random variables can be considered independent. In this case, the joint probability density function is the product of the density functions of each single random variable. Therefore:

$$P(\Delta \geq D \cup Z \geq A) = \int_A^\infty \int_D^\infty f_\Delta(\delta) f_Z(\zeta)\, d\delta d\zeta =$$

$$= \int_A^\infty f_Z(\zeta)[1 - F_\Delta(D)]\, d\zeta = 1 - F_Z(A) - F_\Delta(D)[1 - F_Z(A)] = \tag{4-13}$$

$$= 1 + F_Z(A) F_\Delta(D) - F_Z(A) - F_\Delta(D);$$

Therefore, the probability of exceeding the limit space can be evaluated when cumulative distribution functions of both the acceleration response and interstory drift response are known. Both parameters of the density functions can be calculated using the maximum likelihood method.

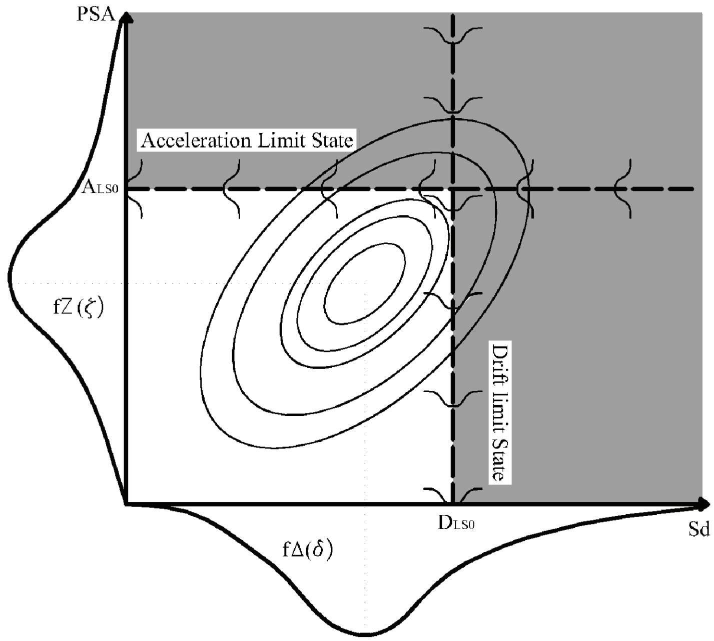


Figure 4-4 Probability of Two Random Variables to Exceed Two Deterministic Performance Limit States [Two-dimensional Case]

4.3.4 Case 4: Interstory Drift and Acceleration: Random Drift and Acceleration Thresholds

Case 4 is similar to Case 3, but the interstory drift performance limit state *D* and the acceleration performance limit state *A* are also random variables. It is assumed that the two response random variables are lognormally distributed (Figure 4-4) and the probability density functions are expressed by the following formulas:

$$f_{\Delta}(\delta) = \begin{cases} \dfrac{1}{\delta \sigma_{\Delta} \sqrt{2\pi}} \cdot e^{-\frac{\left(\ln(\delta) - m_{\Delta}\right)^2}{2\sigma_{\Delta}^{2}}} & \delta \geq 0 \\ 0 & elsewhere \end{cases} \tag{4-14}$$

$$f_Z(\zeta)=\begin{cases}\dfrac{1}{\zeta\sigma_Z\sqrt{2\pi}}\cdot e^{-\frac{(\ln(\zeta)-m_Z)^2}{2\sigma_Z^{\,2}}} & \zeta\geq 0\\[2ex] 0 & elsewhere\end{cases} \tag{4-15}$$

It is also assumed that the two performance limit states are random variables lognormally distributed:

$$f_D(d)=\begin{cases}\dfrac{1}{d\sigma_D\sqrt{2\pi}}\cdot e^{-\frac{(\ln(d)-m_D)^2}{2\sigma_D^{\,2}}} & d\geq 0\\[2ex] 0 & elsewhere\end{cases} \tag{4-16}$$

$$f_A(a)=\begin{cases}\dfrac{1}{a\cdot\sigma_A\sqrt{2\pi}}\cdot e^{-\frac{(\ln(a)-m_A)^2}{2\sigma_A^{\,2}}} & a\geq 0\\[2ex] 0 & elsewhere\end{cases} \tag{4-17}$$

Again, a distinction is made between the elastic and the inelastic cases. In the elastic range, it is assumed that the acceleration response Z and the displacement response Δ are related, so that the relation $\Delta=Z/\omega^2$ holds. In general, between interstory drift and acceleration threshold, there is no relationship because, for example, nonstructural components such as electronic devices (computers, etc.) that are acceleration sensitive cannot be related to the building PLSs that are typically displacement sensitive. Therefore, the two PLSs can be considered independent. Two new random variables can be defined: $X=\Delta/D$ and $Y=Z/A$ so Case 4 reduces to Case 2, and the problem with four random variables reduces to a problem with only two random variables, which in the elastic range are also dependent:

$$P\{\Delta \geq D \cup Z \geq A\} = P\left\{\underbrace{\frac{\Delta}{D}}_{X} \geq 1 \cup \underbrace{\frac{Z}{A}}_{Y} \geq 1\right\} = P\left\{\underbrace{\frac{\Delta}{D}}_{X} \geq 1 \cup \frac{\Delta}{\frac{A}{\omega^2}} \geq 1\right\} =$$

$$= P\left\{\underbrace{\frac{\Delta}{D}}_{X} \geq 1 \cup \left(\frac{\omega^2 D}{A}\right) \cdot \underbrace{\frac{\Delta}{D}}_{X} \geq 1\right\} = P\left\{\underbrace{\frac{\Delta}{D}}_{X} \geq 1 \cup \underbrace{\frac{\Delta}{D}}_{X} \geq \frac{A}{\omega^2 D}\right\} = \qquad (4\text{-}18a)$$

$$= P\left\{X \geq \min\left(1, \frac{A}{\omega^2 D}\right)\right\} = 1 - F_X\left[\min\left(1, \frac{A}{\omega^2 D}\right)\right] =$$

$$= 1 - \int_0^\infty f_D(d) F_\Delta\left(\min\left(1, \frac{A}{\omega^2 D}\right) \bullet d\right) dd;$$

or:

$$P\{\Delta \geq D \cup Z \geq A\} = 1 - \int_0^\infty f_D(d) F_\Delta\left(\min\left(1, \frac{A}{\omega^2 D}\right) \bullet d\right) dd; \qquad (4\text{-}18b)$$

Hence, for the evaluation of the exceedance probability in this case, only the probability density function of interstory drift and the probability density function of the interstory drift limit states are required.

When the structure is in the **inelastic range,** it can reasonably be assumed that between interstory drift and acceleration there is no relationship, so the random variables can be considered independently and the joint density function is the product of the density functions of two random variables. Two new random variables are defined: $X=\Delta/D$ and $Y=Z/A$, hence:

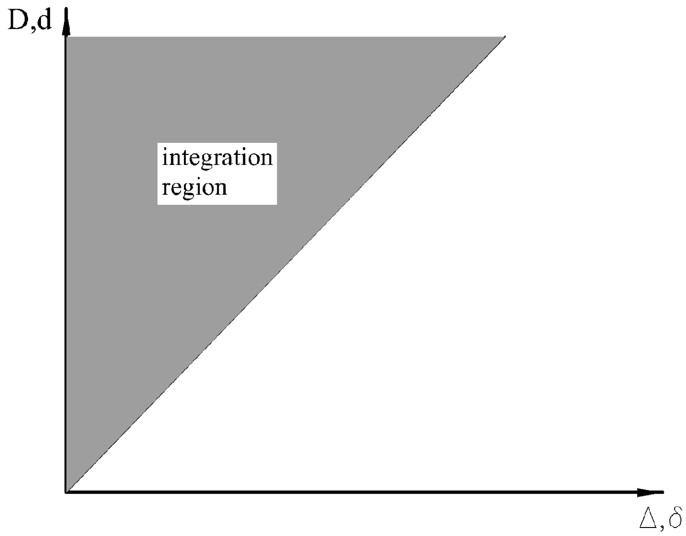


Figure 4-5 Integration Region Related to the Two Random Variables

$$P\{\Delta \geq D \cup Z \geq A\} = P\left\{\frac{\Delta}{D} \geq 1 \cup \frac{Z}{A} \geq 1\right\} = P\left\{\underbrace{\frac{\Delta}{D}}_{X} \geq 1\right\} + P\left\{\underbrace{\frac{Z}{A}}_{Y} \geq 1\right\} +$$

$$-P\left\{\underbrace{\frac{\Delta}{D}}_{X} \geq 1\right\} \cdot P\left\{\underbrace{\frac{Z}{A}}_{Y} \geq 1\right\} = P\{X \geq 1\} + P\{Y \geq 1\} - P\{X \geq 1\} \cdot P\{Y \geq 1\} =$$

$$= 1 - F_X(1) + 1 - F_Y(1) - \left[1 - F_X(1)\right] \cdot \left[1 - F_Y(1)\right] = \left[1 - \int_0^\infty f_D(d) F_\Delta(d)\, dd\right] +$$

$$+\left[1 - \int_0^\infty f_A(a) F_Z(a)\, da\right] - \left[1 - \int_0^\infty f_D(d) F_\Delta(d)\, dd\right] \cdot \left[1 - \int_0^\infty f_A(a) F_Z(a)\, da\right] =$$

$$= 2 - \int_0^\infty f_D(d) F_\Delta(d)\, dd - \int_0^\infty f_A(a) F_Z(a)\, da - 1 - \int_0^\infty f_D(d) F_\Delta(d)\, dd \cdot \int_0^\infty f_A(a) F_Z(a)\, da +$$

$$+\int_0^\infty f_D(d) F_\Delta(d)\, dd + \int_0^\infty f_A(a) F_Z(a)\, da = 1 - \int_0^\infty f_D(d) F_\Delta(d)\, dd \cdot \int_0^\infty f_A(a) F_Z(a)\, da;$$

Finally, the probability of exceeding the PLS in this case is obtained from integration of region shown in Figure 4-5:

$$P\{\Delta \geq D \cup Z \geq A\} = 1 - \int_0^\infty f_D(d) F_\Delta(d)\, dd \cdot \int_0^\infty f_A(a) F_Z(a)\, da; \tag{4-19}$$

4.3.5 Case 5: Interstory Drift and Acceleration: Randomly Interdependent Drift and Acceleration Thresholds

Case 5 only considers that the structure is in the inelastic range. Here, it can reasonably be assumed that there is no relationship between displacement and acceleration response, so the random variables can be considered independent, and the joint density function is the product of the densities function of each single random variable. Instead, it is assumed that the drift limit state *D* and acceleration limit state *A* are dependent quantities with a relationship such as:

$$\frac{A}{A_{LS0}}+\left(\frac{D}{D_{LS0}}\right)^{N}-1=0 \tag{4-20}$$

Where A_{LS0}, D_{LS0} and N are parameters determined through laboratory tests. From Equation 4-20, it is possible to express one limit state as function of the other:

$$A=A_{LS0}\left[1-\left(\frac{D}{D_{LS0}}\right)^{N}\right] \tag{4-21}$$

Therefore, on the basis of the assumptions made, the probability of exceeding the performance limit state can be calculated for the main general case, namely:

$$\begin{aligned}
&P(\Delta \geq D \cup Z \geq A)=\int_{A}^{\infty}\int_{D}^{\infty} f_{\Delta}(\delta)\, f_{Z}(\zeta)\, d\delta d\zeta=\int_{A}^{\infty} f_{Z}(\zeta)[1-F_{\Delta}(D)]\, d\zeta= \\
&=1-F_{Z}(A)-F_{\Delta}(D)\left[1-F_{Z}(A)\right]=1+F_{Z}(A)F_{\Delta}(D)-F_{Z}(A)-F_{\Delta}(D)= \\
&=1+F_{Z}\left(A_{LS0}\left[1-\left(\frac{D}{D_{LS0}}\right)^{N}\right]\right)F_{\Delta}(D)-F_{Z}\left(A_{LS0}\left[1-\left(\frac{D}{D_{LS0}}\right)^{N}\right]\right)-F_{\Delta}(D);
\end{aligned}$$

The final analytical expression for the probability of exceedance is:

$$
\begin{aligned}
P(\Delta \geq D \cup Z \geq A) = 1 + F_Z\left(A_{LS0}\left[1 - \left(\frac{D}{D_{LS0}} \right)^N \right] \right) F_\Delta\left(D\right) + \\
- F_Z\left(A_{LS0}\left[1 - \left(\frac{D}{D_{LS0}} \right)^N \right] \right) - F_\Delta\left(D\right)
\end{aligned}
\qquad (4\text{-}22)
$$

The advantage of this case is that a given limit state can be expressed as function of the other, once the parameters of the model have been identified; hence, only a single parameter is needed to limit both displacement and acceleration.

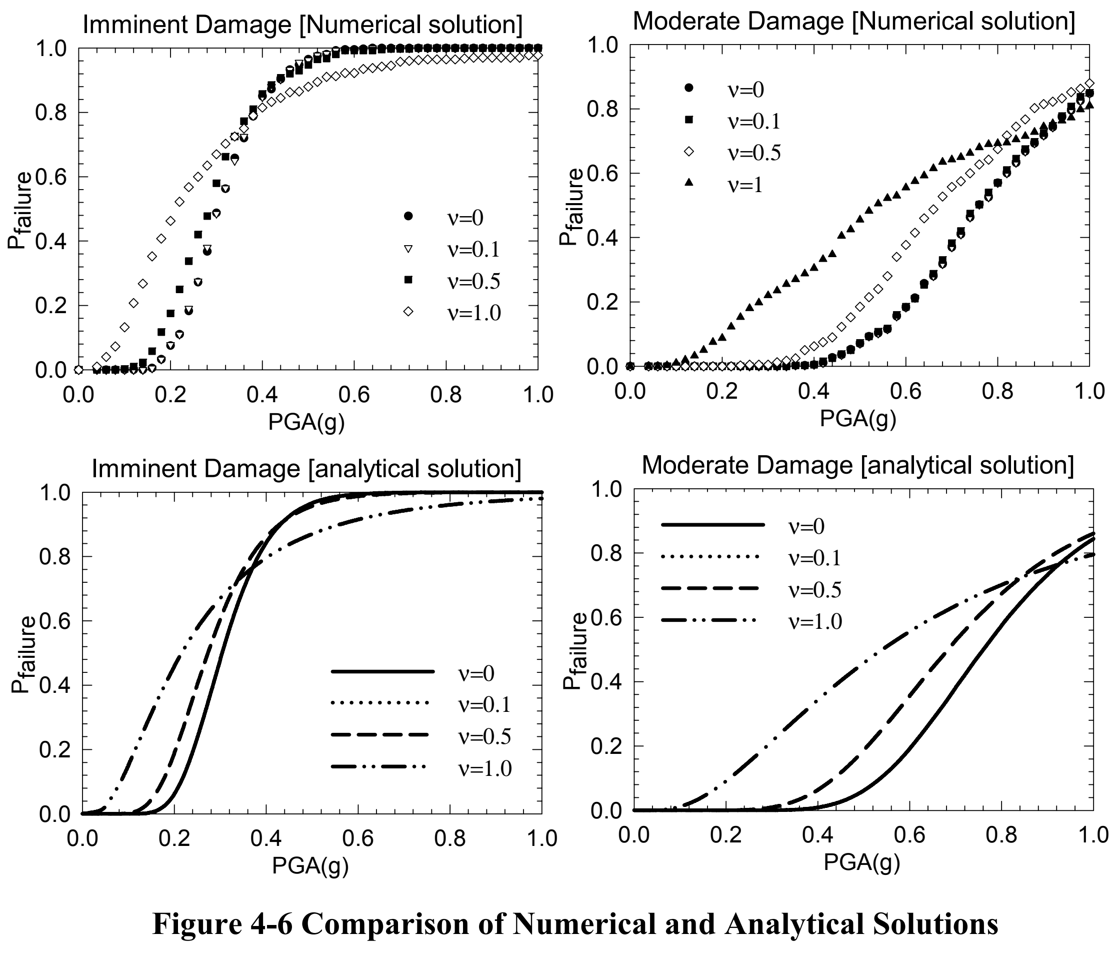
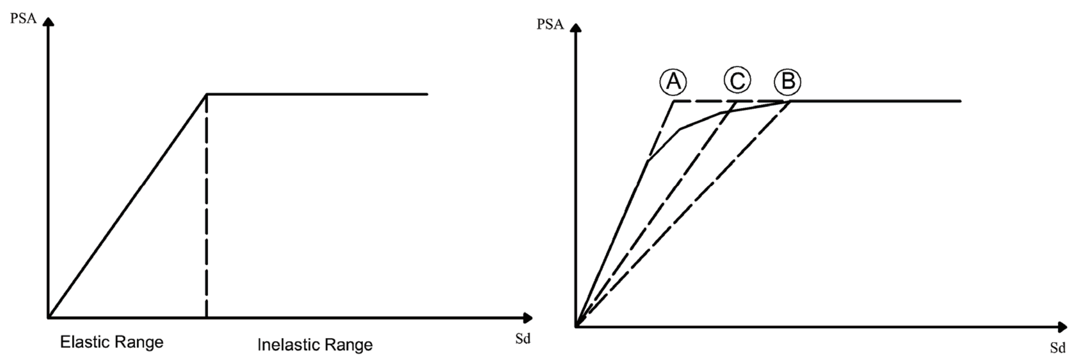


Figure 4-6 Comparison of Numerical and Analytical Solutions

The analytical solution obtained by the previous equations is compared in Figure 4-6 with the numerical solution obtained from Monte Carlo simulations. The fragility curves are built for different values of the coefficient of variation related to the limit thresholds and the adopted model is a nonlinear SDOF system equivalent to the case study analyzed. The good agreements demonstrate the validity of the analytical solution.

4.3.6 Extension to MDOF Systems

The analytical solutions proposed in Cases 3, 4 and 5 are strictly valid for SDOF systems with elastic-perfectly plastic force displacement relationships, and they distinguish between the elastic and the inelastic ranges (Figure 4-7a).



(a) (b)

Figure 4-7 Extension to MDOF Systems

The solutions obtained can easily be extended to MDOF systems using different types of approximations. Figure 4-7b shows the pushover curve of a MDOF structure with three approximations compared to an equivalent SDOF. These can take the form of tangential stiffness (A), secant stiffness (B) obtained by the intersection with the maximum yield force, or equal energy (C), where the curve is obtained by equalizing the areas under the two curves.

SECTION 5

PROGRAM EXTENSION OF IDARC 2D

The two programs, implemented in FORTRAN and working in conjunction with IDARC 2D 6.0 (Reinhorn *et al.,* 2004), are described in this section and shown in Figure 5-1.

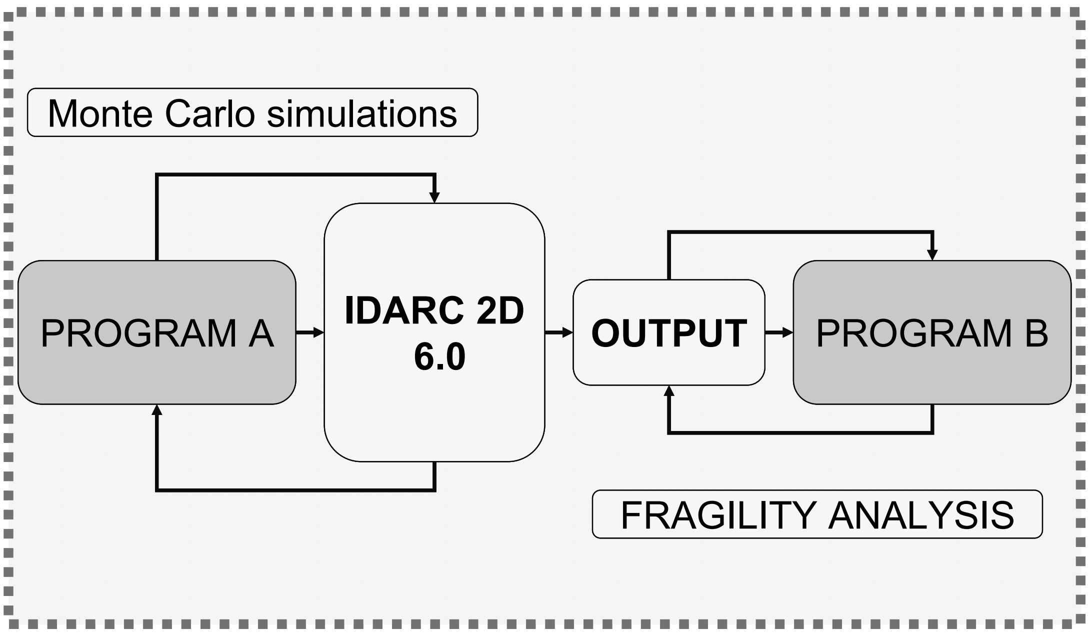


Figure 5-1 Flowchart

The first program, **PROGRAM A (**multiple inelastic dynamic analysis of reinforced concrete**),** realizes multiple nonlinear dynamic runs using IDARC2D vers.6.0 as a processor, and stores the data obtained for each story level in different self-created directories. PROGRAM B uses the data stored in the different directories to calculate the fragility curves of the building for multidimensional limit states, and plot the curves for either peak ground acceleration or return period.

5.1 Computer Program for Monte Carlo Simulations (Multiple Program Executions)

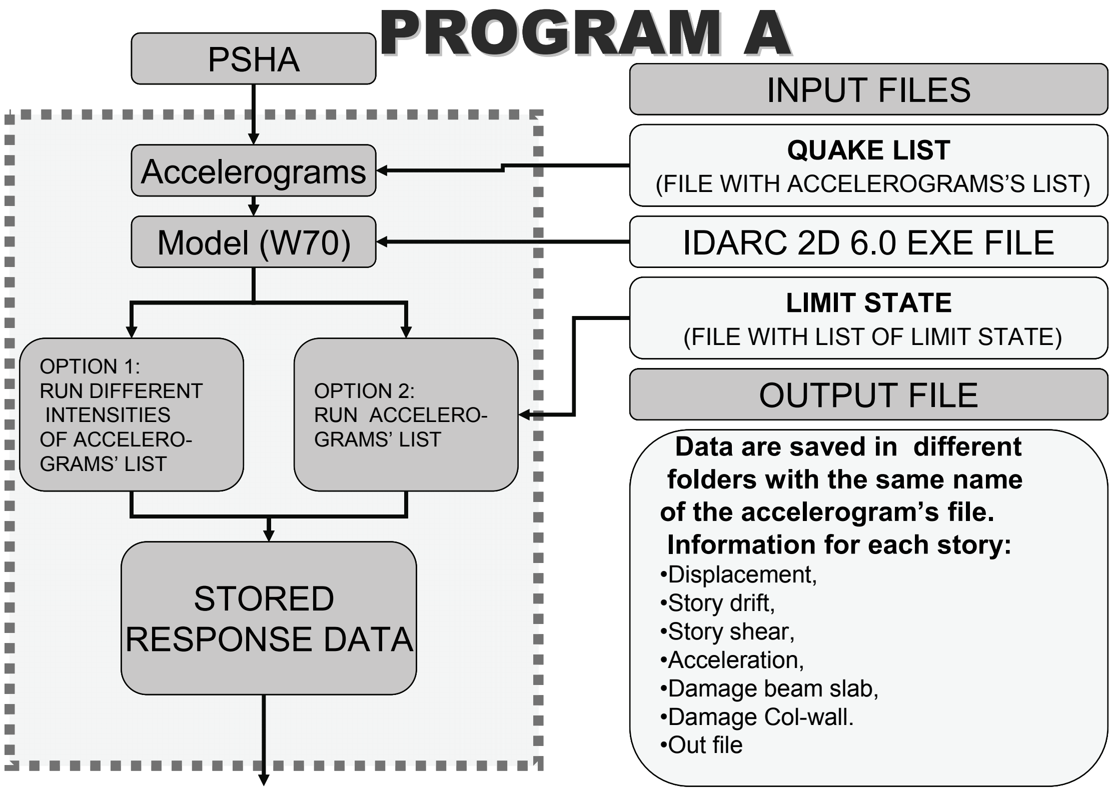


Figure 5-2 Flowchart of PROGRAM A

The basic structure of the program A is explained in the flowchart in Figure 5-2. Some of the basic features of the program follow.

The input accelerograms are listed in a file called "**quake list,**" where all data related to each single record necessary for running IDARC 2D are listed. An example of the earthquake list ("quake list") file is shown in Figure 5-3.

```
C WHFILE  ,IWV,NDATA,  DTINP   ,GMAX      ,GMAXV      ,  DTCAL   , TDUR     ,   DAMP    ,ITDMP,
ba01.acc  ,0, 8192  ,  0.005   ,0.3566    , 0.0       ,  0.005   , 40.96    ,   5.0     , 3 ,
ba02.acc  ,0, 8192  ,  0.005   ,0.4109    , 0.0       ,  0.005   , 40.96    ,   5.0     , 3 ,
ba03.acc  ,0, 8192  ,  0.005   ,0.3401    , 0.0       ,  0.005   , 40.96    ,   5.0     , 3 ,
ba04.acc  ,0, 8192  ,  0.005   ,0.4516    , 0.0       ,  0.005   , 40.96    ,   5.0     , 3 ,
ba05.acc  ,0, 8192  ,  0.005   ,0.4088    , 0.0       ,  0.005   , 40.96    ,   5.0     , 3 ,
ba06.acc  ,0, 8192  ,  0.005   ,0.3288    , 0.0       ,  0.005   , 40.96    ,   5.0     , 3 ,
ba07.acc  ,0, 8192  ,  0.005   ,0.6505    , 0.0       ,  0.005   , 40.96    ,   5.0     , 3 ,
ba08.acc  ,0, 8192  ,  0.005   ,0.4853    , 0.0       ,  0.005   , 40.96    ,   5.0     , 3 ,
ba09.acc  ,0, 8192  ,  0.005   ,0.3361    , 0.0       ,  0.005   , 40.96    ,   5.0     , 3 ,
ba10.acc  ,0, 8192  ,  0.005   ,0.3537    , 0.0       ,  0.005   , 40.96    ,   5.0     , 3 ,
ba11.acc  ,0, 8192  ,  0.005   ,0.4240    , 0.0       ,  0.005   , 40.96    ,   5.0     , 3 ,
ba12.acc  ,0, 8192  ,  0.005   ,0.4240    , 0.0       ,  0.005   , 40.96    ,   5.0     , 3 ,
ba12.acc  ,0, 8192  ,  0.005   ,0.4145    , 0.0       ,  0.005   , 40.96    ,   5.0     , 3 ,
ba14.acc  ,0, 8192  ,  0.005   ,0.5535    , 0.0       ,  0.005   , 40.96    ,   5.0     , 3 ,
ba15.acc  ,0, 8192  ,  0.005   ,0.3712    , 0.0       ,  0.005   , 40.96    ,   5.0     , 3 ,
ba16.acc  ,0, 8192  ,  0.005   ,0.4927    , 0.0       ,  0.005   , 40.96    ,   5.0     , 3 ,
ba17.acc  ,0, 8192  ,  0.005   ,0.4820    , 0.0       ,  0.005   , 40.96    ,   5.0     , 3 ,
ba18.acc  ,0, 8192  ,  0.005   ,0.5453    , 0.0       ,  0.005   , 40.96    ,   5.0     , 3 ,
```

Figure 5-3 Example of the Quake List File

The variables in the list shown in Figure 5-3 are as follows:

WHFILE	=Name of file with extension from which to read horizontal component of earthquake
IWV	= 0 for vertical component of acceleration not included, 1 for vertical component of acceleration included.
NDATA	= number of points in earthquake wave files.
DTINP	= time interval of input wave
GMAXH	= Peak horizontal acceleration (g)
GMAXV	= Peak vertical acceleration (g)
DTCAL	= Time step for response analysis (sec)
TDUR	= Total duration of analysis (sec)
DAMP	= Damping coefficient (% of critical)
ITDMP	= Type of structural damping: 1 for Mass proportional; 2 for Stiffness proportional; 3 for Rayleigh proportional damping;

For each record (row) in the list, a single run is performed until the end of the list is reached. Multiple runs can also be set for each single record scaling values of peak ground acceleration. Data are stored for each single run in different folders with the same name of the accelerograms file (e.g. “Ba01”).

Data stored for each story level are as follows:

1. Displacement
2. Story drift
3. Story shear
4. Acceleration
5. Damage beam slab
6. Damage Col-wall
7. Out file

The files in the computer program for Monte Carlo simulations include the following:

MIDARC:	The main program opens the "quake_list" and it substitutes the names in the input text file of IDARC2D iteratively and runs the program. It saves data in different directories with the same name of the accelerograms.
GET PATH	This subroutine saves the path of the current directory, so the program can be run in every directory in the computer.
MAKE DIR	This subroutine creates new directories according to the name of the accelerograms and save output files in these directories.
PGA	This subroutine does the dynamic pushover analysis for different values of pga defined by the user for every accelerograms in the quake list.

5.2 Computer Program for Multidimensional Fragility Analysis

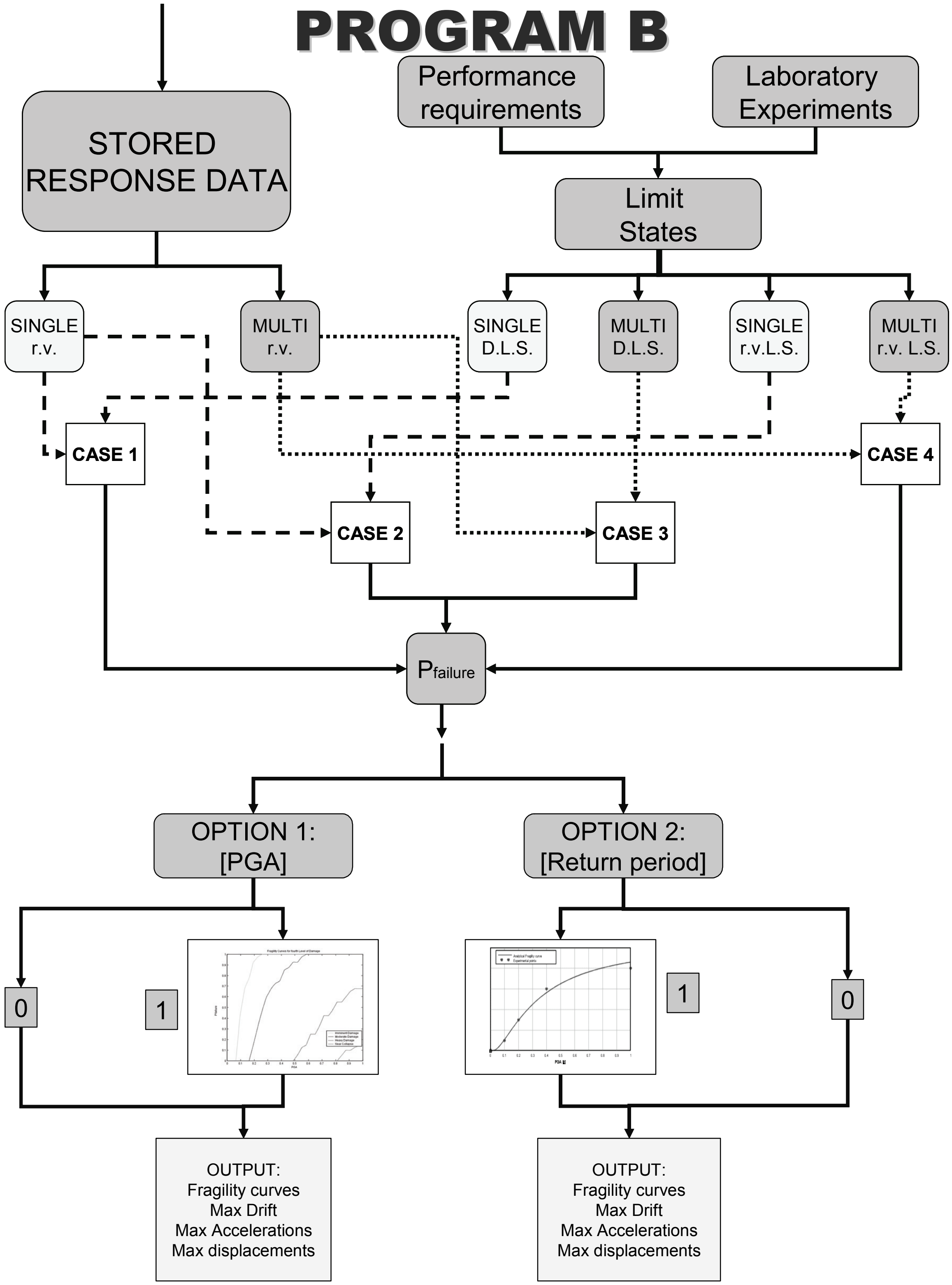


Figure 5-4 Flowchart of PROGRAM B (r.v. –random variable)

PROGRAM B uses the data stored in the different directories by PROGRAM A (Figure 5-2) as shown in Figure 5-4. It extracts the peak floor interstory drifts and the peak floor accelerations at each story level and compares them with the performance limit states that are stored in another file called "limit states." Different cases can be chosen by the user of the program to calculate the fragility curves (see Section 4). A single response random variable (e.g., interstory drift) or two response random variables (e.g., interstory drift and accelerations) can be used to calculate fragility. The limit states can also be considered as crisp or random variables, and single or multidimensional limit states can be considered using the proposed generalized formula (Equation 3-3) that shows the relationship between acceleration limit states and interstory drift limit states.

The information about the limit states is contained in an input file shown in Figure 5-5.

```
OPTION  CASE_Number  [n1].INT.PGA  [n2]tot.TH  n_points  [a1]NUM.Tr1 [a2]NUM.Tr2 [a3]NUM.Tr3 [a4]NUM.
|2|     |5|             |4  |        |100|       |10000 |  | 25|       | 25|       | 25|       | 25|
LIMIT STATES               DRIFT                          ACCELERATION
                     mean[%]    c.var.[%mean]      mean[%g]    c.var.[%mean]
imminent damage   0.700000000     80.000000       1.100000    10.0000000
moderate damage   1.500000000     80.000000       1.100000    10.0000000
heavy    damage   2.500000000     80.000000       1.100000    10.0000000
near   collapse   5.000000000     80.000000       1.100000    10.0000000
```

Figure 5-5 Example of the Limit State File

The variables in the list shown in Figure 5-5 are as follows:

OPTION	= 1 the fragility curves are plotted as function of the PGA; 2 the fragility curves are plotted as function of the return period;
CASE_number	= 1,2,3,4 according to the flowchart of figure 5-4.
[n1]. INT.PGA	= number of discrete points between 0 and 1 PGA. If it is chosen option 2 it represents the number of return periods considered.
[n2]tot.TH	= total number of time histories considered in the analysis.
n_points	= number of points inside a time history
[a1]NUM.Tr1	= number of accelerograms for the first return period
[a2]NUM.Tr2	= number of accelerograms for the second return period
[a3]NUM.Tr3	= number of accelerograms for the third return period
[a4]NUM.Tr4	= number of accelerograms for the fourth return period

In the example file, four performance limit states (imminent damage, moderate damage, heavy damage and near collapse) are reported. These are expressed in terms of drift and acceleration, using the mean and the coefficient of variation (COV) expressed as % of the mean.

Once the probability of exceeding the limit state has been determined, fragility curves can be fitted to the calculated discrete points. The final fitted fragility curves can be plotted with peak ground acceleration and return period on the X-axis. The final output files contain the fragility curves for each limit state, and the maximum interstory drift at each story level, the maximum floor accelerations and displacements. The files in the computer program for fragility analysis are described in the following paragraphs.

PROGRAM B (*Fragility inelastic dynamic analysis of Reinforced Concrete***)**: The main program opens the output files in different directories, collects information ordered by different return periods, calculates the fragility for different limit states, and saves the data in a txt file called "FRAG_CURVE_OUTPUT." The fragility curves are calculated according to the different cases chosen by the user. Fragility curves are calculated for each story level.

The program contains the following subroutines:

MEAN_STDEV	Calculates mean and standard dev. of the drift log response that is normal distributed.
MEAN_STDEV_ACC	Calculates mean and standard dev. of the acceleration log response that is normal distributed.
RNLNL	Generates random lognormal number (IMSL library)
FIT_LOG	Fits the lognormal distribution to the given data points.
DISCR_LOG	Generates the discrete number of points of the fitted lognormal distribution.
PLOT	Plots the fitted fragility curve together with the given data points using a program called DplotJr.

SECTION 6

CASE STUDY: WEST COAST HOSPITAL W70

6.1 Introduction

The previous sections described an analytical procedure to evaluate the fragility curve of a structure when functionality is represented by multiple parameters. In this and the following sections, a case study of a hospital building is considered to show the applicability of the method. Section 6 (this section) describes the adopted structural models. Section 7 describes the ground motion input for the case study and Section 8 reports the results of the parametric analysis.

6.2 Description of the Structural Model and Assumptions

The facility chosen as the MCEER west coast Demonstration Hospital is an existing structure in the San Fernando Valley in Southern California. The hospital was constructed in the early 1970s to meet the seismic requirements of the 1970 Uniform Building Code (ICBO, 1970) (Yang et al., 2003).

It is a four-story steel framed building with plan dimensions of *275×56.5 ft*. The height of the building, from grade level to the roof, is *51 ft*. The lateral force resisting system is comprised of four moment-resisting frames in the north-south direction and two perimeter moment-resisting frames in the east-west direction. The four-bay north-south moment frames are located on Lines B, F, J, and N of Figure 6-1, Figure 6-2 and Figure 6-3. The east-west moment frames are located on Lines 2 and 5.

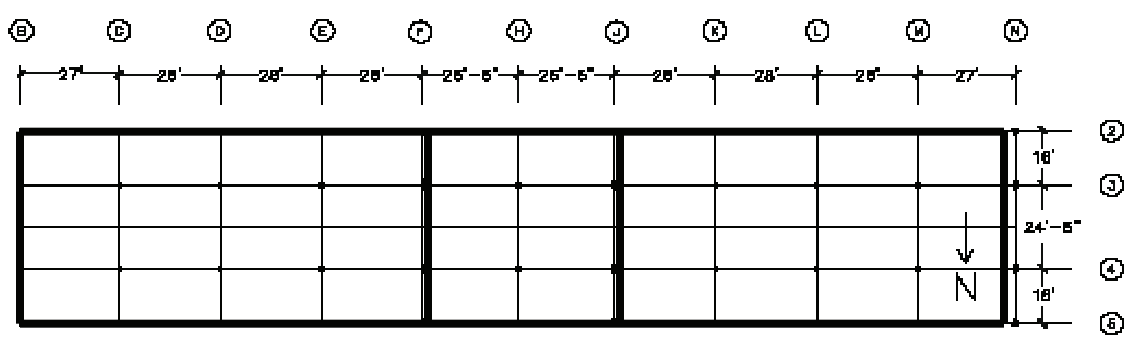


Figure 6-1 Plan View of the Existing Facilities

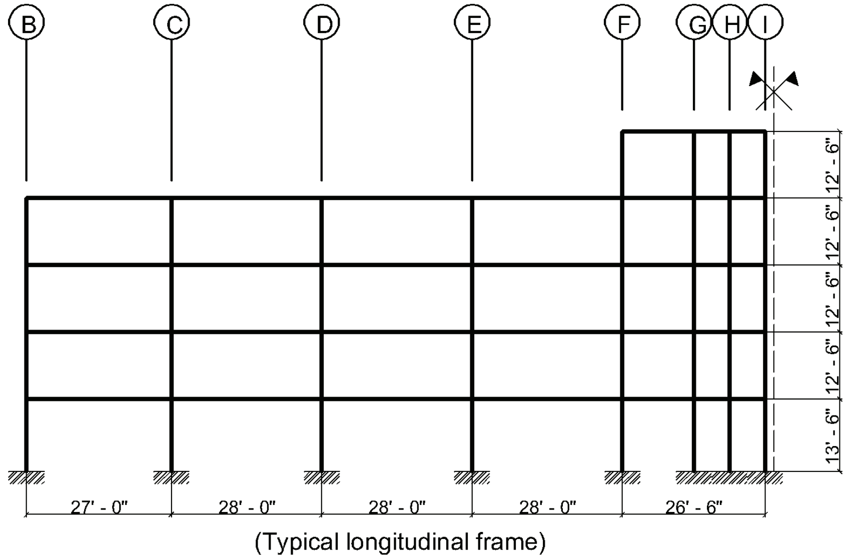


Figure 6-2 Typical Longitudinal Frame (Half view) of the Model of W70

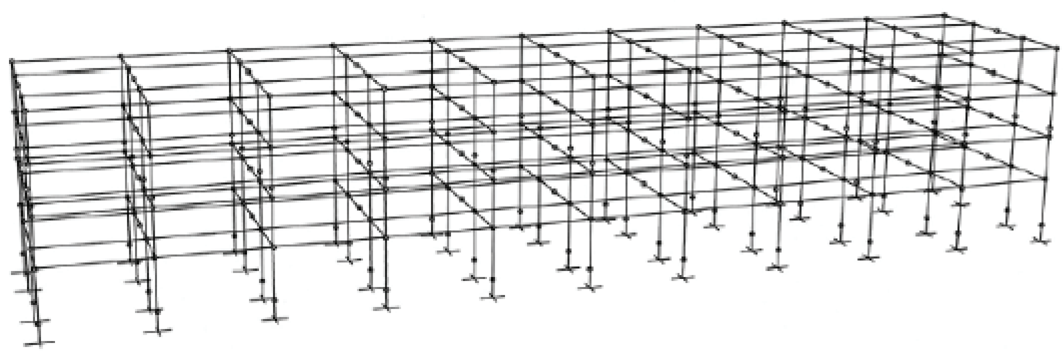


Figure 6-3 Wire Computational Model of W70 (Yang and Whittaker, 2003)

The moment frames were constructed with *ASTM A572* and *A588 Grade 50* steel. ASTM A36 steel was used for the remaining steel beams, girders, and columns. The modal properties of the building are reported in Table 6-1.

Table 6-1 Translational Modal Frequencies

			Cumulative % Mass	
Mode	**Period (secs)**	**Frequency (Hz)**	**E-W direction**	**N-S direction**
1	0.87	1.15	82.7	0.00
2	0.82	1.22	82.7	82.9
4	0.30	3.34	94.6	82.9
5	0.27	3.66	94.6	94.6
7	0.17	5. 95	98.6	94.6
9	0.15	6.55	98.6	98.6

6.3 Nonlinear SDOF Structural Model

The mass, the stiffness and the damping coefficient used for the SDOF model are respectively $m=20.98\ kips \cdot sec^2/in$, $k=1094.27\ kips/in$ and $c=2\zeta\sqrt{k \cdot m}=15.151\ kips \cdot sec/in$.

The SDOF system has been modeled as elastic-perfectly plastic model with a yield shear strength $V_Y=0.62W$ calculated by nonlinear static pushover analysis. A simple plastic analysis ("shake down") in the east-west and north-south direction has been performed (Yang et al., 2003) using two mechanisms and two lateral load profiles: (1) a normalized first mode load profile, and (2) a constant acceleration profile. The collapse loads, V_m, for the building frame were, respectively, *6040 kips* (*0.62W*) and *7389 kips* (*0.75W*) in the north-south and east-west directions.

6.4 Nonlinear MDOF Structural Model

The computer program IDARC2D (Reinhorn et al. 2004) was used to perform the nonlinear time history analysis of the hospital. It is a two dimensional model where all moment resisting frames are modeled with rigid beam-column connections and other beam-column connections were assumed to be pinned (non-resisting model). For comparison, two other models were built to consider the uncertainties in the structural model. In the second model, all the beam-column connections in all non-moment resisting frame were modeled as semi rigid (they can transfer some moment), while in the third model, these connections were taken as rigid fully (transferring all the moment). The models analyzed by MATLAB and three models analyzed by IDARC 2D are listed in Table 6-2.

Table 6-2 Building Structural Models

SDOF model in MATLAB
• Model 0 - Elastic-perfectly plastic model [Vy= 0.62W]
MDOF models in IDARC2D 6.0
• Model 1 - Non resisting model – ideal hinge in every non MRF • Model 2 - Partial resisting model – Plastic hinges in every non MRF • Model 3 - Resisting model – fixed hinges in every non MRF

SECTION 7

CHARACTERIZATION OF INPUT GROUND MOTION

7.1 Source of Uncertainties in Earthquake Ground Motions

The seismic input is one of the most uncertain quantities involved in the evaluation of the structural response under seismic excitation. The magnitude of the ground motion, its frequency content and duration are very difficult to predict. These parameters are usually evaluated statistically, and are characterized by a relevant dispersion.

Three different types of ground motions have been used for the case study:

1. Numerical realizations of suitably defined stochastic excitation process.
2. SAC series (Somerville, 1997)
3. MCEER series (Wanitkorkul and Filiatrault, 2005)

In the first case, the ground motion frequency content is characterized by the Kanai Tajimi process (e.g., Clough and Penzien, 1993) power spectral density that has been determined empirically. On this basis, a series of numerical ground motions were generated and scaled for different values of PGA.

The second case corresponds to a series of recorded accelerograms in California with modified amplitude and frequency content in order to adapt to the target spectrum. The third case corresponds to a series of synthetic near fault ground motions that were generated using the so called “Barrier model” (Papargeogiu and Aki, 1983a, 1983b), calibrated using actual near fault records.

7.2 SAC Series

For this study, a series of 60 ground motion recorded in California on stiff soil were selected from a collection of ground motions used in a national program on steel connections (Somerville, 1997). Three return periods were considered (100, 500 and 2500 years) corresponding to 50%, 10% and 2% probability of exceedance in 50 years. The two horizontal components originally provided were resolved into fault-normal and fault-parallel orientations. The records were adjusted in the frequency domain to have characteristics appropriate for NEHRP SO soil sites (Somerville, 1997). The records were amplitude scaled so that the averages of the two horizontal spectra matched the target spectrum. Tables 7-1, 7-2 and 7-3 list the details.

Table 7-1 Records with 10% Probability of Exceedance in 50 Years in Los Angeles

LA 10 in 50

EQ code	Description	Earthquake Magnitude	Distance (km)	Scale Factor	Number of Points	Time Step (sec)	PGA (cm/sec^2)	PGA (g's)
la01	fn Imperial Valley, 1940, El Centro	6.9	10.0	2.01	2674	0.020	452.03	0.46
la02	fp Imperial Valley, 1940, El Centro	6.9	10.0	2.01	2674	0.020	662.88	0.68
la03	fn Imperial Valley, 1979, Array #05	6.5	4.1	1.01	3939	0.010	386.04	0.39
la04	fp Imperial Valley, 1979, Array #05	6.5	4.1	1.01	3939	0.010	478.65	0.49
la05	fn Imperial Valley, 1979, Array #06	6.5	1.2	0.84	3909	0.010	295.69	0.30
la06	fp Imperial Valley, 1979, Array #06	6.5	1.2	0.84	3909	0.010	230.08	0.23
la07	fn Landers, 1992, Barstow	7.3	36.0	3.20	4000	0.020	412.98	0.42
la08	fp Landers, 1992, Barstow	7.3	36.0	3.20	4000	0.020	417.49	0.43
la09	fn Landers, 1992, Yermo	7.3	25.0	2.17	4000	0.020	509.70	0.52
la10	fp Landers, 1992, Yermo	7.3	25.0	2.17	4000	0.020	353.35	0.36
la11	fn Loma Prieta, 1989, Gilroy	7.0	12.0	1.79	2000	0.020	652.49	0.67
la12	fp Loma Prieta, 1989, Gilroy	7.0	12.0	1.79	2000	0.020	950.93	0.97
la13	fn Northridge, 1994, Newhall	6.7	6.7	1.03	3000	0.020	664.93	0.68
la14	fp Northridge, 1994, Newhall	6.7	6.7	1.03	3000	0.020	644.49	0.66
la15	fn Northridge, 1994, Rinaldi RS	6.7	7.5	0.79	2990	0.005	523.30	0.53
la16	fp Northridge, 1994, Rinaldi RS	6.7	7.5	0.79	2990	0.005	568.58	0.58
la17	fn Northridge, 1994, Sylmar	6.7	6.4	0.99	3000	0.020	558.43	0.57
la18	fp Northridge, 1994, Sylmar	6.7	6.4	0.99	3000	0.020	801.44	0.82
la19	fn North Palm Springs, 1986	6.0	6.7	2.97	3000	0.020	999.43	1.02
la20	fp North Palm Springs, 1986	6.0	6.7	2.97	3000	0.020	967.61	0.99

Table 7-2 Records with 2% Probability of Exceedance in 50 Years in Los Angeles

EQ code	Description	Earthquake Magnitude	Distance (km)	Scale Factor	Number of Points	Time Step (sec)	PGA (cm/sec^2)	PGA (g's)
la21	fn 1995 Kobe	6.9	3.4	1.15	3000	0.020	1258.00	1.28
la22	fp 1995 Kobe	6.9	3.4	1.15	3000	0.020	902.75	0.92
la23	fn 1989 Loma Prieta	7.0	3.5	0.82	2500	0.010	409.95	0.42
la24	fp 1989 Loma Prieta	7.0	3.5	0.82	2500	0.010	463.76	0.47
la25	fn 1994 Northridge	6.7	7.5	1.29	2990	0.005	851.62	0.87
la26	fp 1994 Northridge	6.7	7.5	1.29	2990	0.005	925.29	0.94
la27	fn 1994 Northridge	6.7	6.4	1.61	3000	0.020	908.70	0.93
la28	fp 1994 Northridge	6.7	6.4	1.61	3000	0.020	1304.10	1.33
la29	fn 1974 Tabas	7.4	1.2	1.08	2500	0.020	793.45	0.81
la30	fp 1974 Tabas	7.4	1.2	1.08	2500	0.020	972.58	0.99
la31	fn Elysian Park (simulated)	7.1	17.5	1.43	3000	0.010	1271.20	1.30
la32	fp Elysian Park (simulated)	7.1	17.5	1.43	3000	0.010	1163.50	1.19
la33	fn Elysian Park (simulated)	7.1	10.7	0.97	3000	0.010	767.26	0.78
la34	fp Elysian Park (simulated)	7.1	10.7	0.97	3000	0.010	667.59	0.68
la35	fn Elysian Park (simulated)	7.1	11.2	1.10	3000	0.010	973.16	0.99
la36	fp Elysian Park (simulated)	7.1	11.2	1.10	3000	0.010	1079.30	1.10
la37	fn Palos Verdes (simulated)	7.1	1.5	0.90	3000	0.020	697.84	0.71
la38	fp Palos Verdes (simulated)	7.1	1.5	0.90	3000	0.020	761.31	0.78
la39	fn Palos Verdes (simulated)	7.1	1.5	0.88	3000	0.020	490.58	0.50
la40	fp Palos Verdes (simulated)	7.1	1.5	0.88	3000	0.020	613.28	0.63

Table 7-3 Records with 50% Probability of Exceedance in 50 Years in Los Angeles

EQ code	Description	Earthquake Magnitude	Distance (km)	Scale Factor	Number of Points	Time Step (sec)	PGA (cm/sec^2)	PGA (g's)
la41	fn Coyote Lake, 1979	5.7	8.8	2.28	2686	0.010	578.34	0.59
la42	fp Coyote Lake, 1979	5.7	8.8	2.28	2686	0.010	326.81	0.33
la43	fn Imperial Valley 1979	6.5	1.2	0.40	3909	0.010	140.67	0.14
la44	fp Imperial Valley 1979	6.5	1.2	0.40	3909	0.010	109.45	0.11
la45	fn Kern, 1952	7.7	107.0	2.92	3931	0.020	141.49	0.14
la46	fp Kern, 1952	7.7	107.0	2.92	3931	0.020	156.02	0.16
la47	fn Landers, 1992	7.3	64.0	2.63	4000	0.020	331.22	0.34
la48	fp Landers, 1992	7.3	64.0	2.63	4000	0.020	301.74	0.31
la49	fn Morgan Hill, 1984	6.2	15.0	2.35	3000	0.020	312.41	0.32
la50	fp Morgan Hill, 1984	6.2	15.0	2.35	3000	0.020	535.88	0.55
la51	fn Parkfield, 1966, Cholame 5W	6.1	3.7	1.81	2197	0.020	765.65	0.78
la52	fp Parkfield, 1966, Cholame 5W	6.1	3.7	1.81	2197	0.020	619.36	0.63
la53	fn Parkfield, 1966, Cholame 8W	6.1	8.0	2.92	1308	0.020	680.01	0.69
la54	fp Parkfield, 1966, Cholame 8W	6.1	8.0	2.92	1308	0.020	775.05	0.79
la55	fn North Palm Springs, 1986	6.0	9.6	2.75	3000	0.020	507.58	0.52
la56	fp North Palm Springs, 1986	6.0	9.6	2.75	3000	0.020	371.66	0.38
la57	fn San Fernando, 1971	6.5	1.0	1.30	3974	0.020	248.14	0.25
la58	fp San Fernando, 1971	6.5	1.0	1.30	3974	0.020	226.54	0.23
la59	fn Whittier, 1987	6.0	17.0	3.62	2000	0.020	753.70	0.77
la60	fp Whittier, 1987	6.0	17.0	3.62	2000	0.020	469.07	0.48

7.3 MCEER Series

The "MCEER series" (Wanitkorkul and Filiatrault, 2005) consists of 100 synthetic accelerograms considered as white noise generated from a spectrum that is based on the "Specific Barrier model" (Papageorgiou and Aki, 1983). This kinematics modeling approach was developed by seismologists, and involves the prediction of ground motions from a fault having specific dimensions and orientation in a given geologic setting. The rupture process inside the fault is modeled by postulating a slip function on a fault plane and then using the elasto-dynamics representation theorem to compute the motion (Papageorgiou and Aki, 1983a). According to the specific Barrier model, the seismic source consists of an aggregate of circular cracks of equal diameter $2\rho_0$ filling up a rectangular fault plane of length L and width W, as shown in Figure 7-1. The rupture progresses with each crack developing in a statistically independent manner.

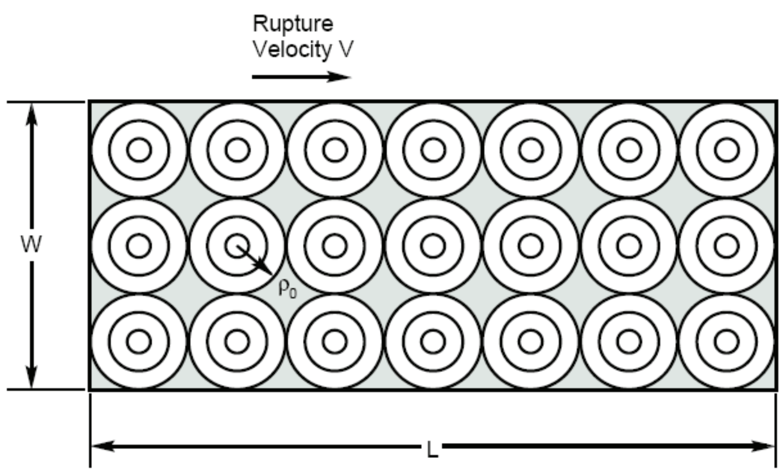


Figure 7-1 The Specific Barrier Model (Papageorgiou and Aki, 1983a; 1983b)

A series of 100 accelerograms was generated using this model corresponding, respectively, to four different return periods: 250, 500, 1000 and 2500 years, so that for each return period, 25 accelerograms were available. In Figure 7-2, the pseudo acceleration spectra corresponding to 2% probability of exceedance in 50 years for the fault-normal condition are plotted.

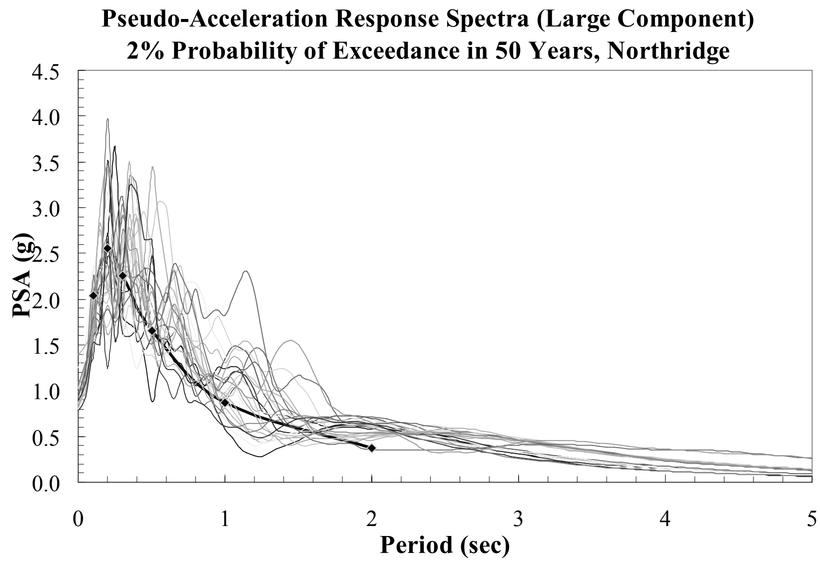


Figure 7-2 Pseudo Acceleration Response Spectra (Fault-normal) for 2% Probability of Exceedance in 50 Years

7.4 Random Generation of Ground Motion

The ground motion is modeled as a random function $\ddot{y}_g(t)$, which is characterized by a Power Spectral density (*PSD*) function and an equivalent duration of strong shaking t_d. The Kanai-Tajimi process (e.g., Clough and Penzien, 1993) spectral density function has been adopted for the generation of ground acceleration $\ddot{y}_g(t)$. The Kanai-Tajimi spectral density function has the following form:

$$S_g(\omega) = \frac{1 + 4\zeta_g^2 \left(\dfrac{\omega}{\omega_g}\right)^2}{\left[1 - \left(\dfrac{\omega}{\omega_g}\right)^2\right]^2 + 4\zeta_g^2 \left(\dfrac{\omega}{\omega_g}\right)^2} S_0 \tag{7-1}$$

where ω_g and ζ_g are the characteristics of frequency and damping. S_0 is the intensity of an earthquake in a particular geological location. In this study, the modified Kanai-Tajimi spectral density function is also used to study the effect on the spectral response of the excitation spectral density function in the low frequency range. The modified Kanai-Tajimi spectral density function has the form (Clough and Penzien, 1993):

$$S_g(\omega) = \frac{\left[1+4\zeta_g^2\left(\frac{\omega}{\omega_g}\right)^2\right]\cdot S_0}{\left[1-\left(\frac{\omega}{\omega_g}\right)^2\right]^2+4\zeta_g^2\left(\frac{\omega}{\omega_g}\right)^2} \times \frac{\left(\frac{\omega}{\omega_k}\right)^4}{\left[1-\left(\frac{\omega}{\omega_k}\right)^2\right]^2+4\zeta_k^2\left(\frac{\omega}{\omega_k}\right)^2} \tag{7-2}$$

Where the parameters ω_k, and ζ_k are introduced to produce the desired filtering of the very low frequencies. The parameters in the ground acceleration spectral density functions expressed by equations (7-1) and (7-2) are $\omega_g = 15.0\, rad/s$, $\zeta_g = 0.6$, $\omega_k = 1.5\, rad/s$ and $\zeta_k = 0.6$. Figure 7-3 shows a typical modified Kanai-Tajimi PSD.

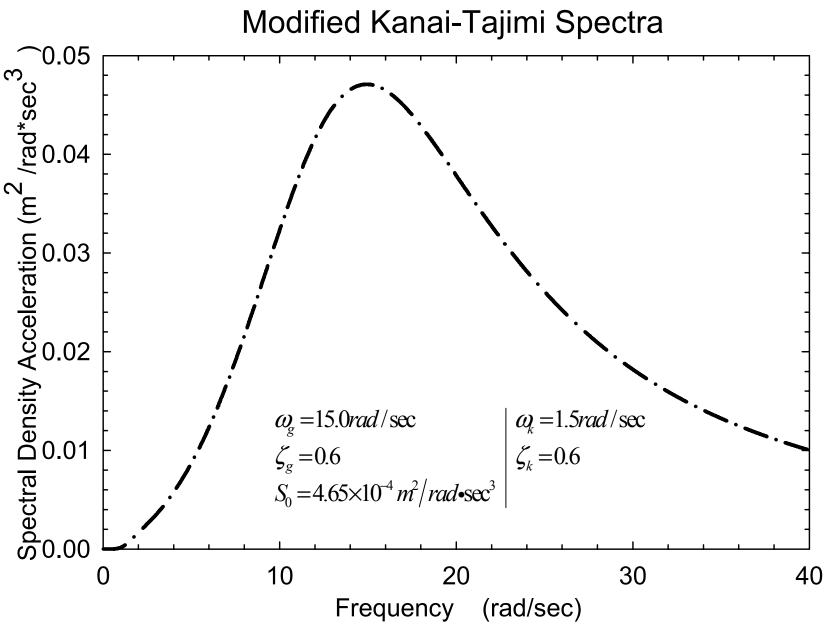


Figure 7-3 Power Spectral Density Function of Ground Acceleration (Firm Soil Condition)

These parameters have been used to reflect firm-soil conditions in some publication (e.g., Heredia-Zavoni et al., 1994). S_0 is taken as $4.65\times10^{-4}\ m^2/rad\ s^3$, which is compatible with that of the Housner average response spectra (Housner et al., 1970).

7.4.1 Generating Samples of Univariate and Multivariate Random Parameters

There are numerous techniques for generating samples of univariate and multivariate random parameters. Most of these techniques use random number generators producing independent realizations that are uniformly distributed over the range (0, 1). Considering a zero-mean, real valued, stationary Gaussian process *Y(t)* with covariance function $R(\tau)=E\{Y(t)Y(t+\tau)\}$ and the one-side power spectral density $G(\omega)$, the process has the following spectral representation:

$$Y(t) = \int_0^\infty \left[\cos \omega t dU(\omega) + \sin \omega t dV(\omega)\right] \tag{7-3}$$

In which $U(\omega)$ and $V(\omega)$ are real-valued, zero-mean, independent Gaussian processes with orthogonal increments and increment variances $E\{dU^2(\omega)\}= E\{dV^2(\omega)\}=G(\omega)d\omega$.

It is not possible to generate samples of *Y(t)* from equation (7-3), because it involves an uncountable set of random variables in the processes $U(\omega)$ and $V(\omega)$. Simulation is usually based on approximations of *Y(t)* involving a finite number of random variables in any bounded time interval. The simulation technique used is based on an approximate spectral representation of *Y(t)*. First consider a frequency $\tilde{\omega}$ chosen so that:

$$\int_0^{\tilde{\omega}} G(\omega)d\omega = \int_0^\infty G(\omega)d\omega.$$

Let $\tilde{Y}(t)$ be a zero-mean Gaussian process with one sided-power spectral density:

$$\begin{aligned} \tilde{G}(\omega) &= G(\omega), \quad 0 \le \omega \le \tilde{\omega} \\ &= 0, \qquad\quad \omega \ge \tilde{\omega} \end{aligned} \tag{7-4}$$

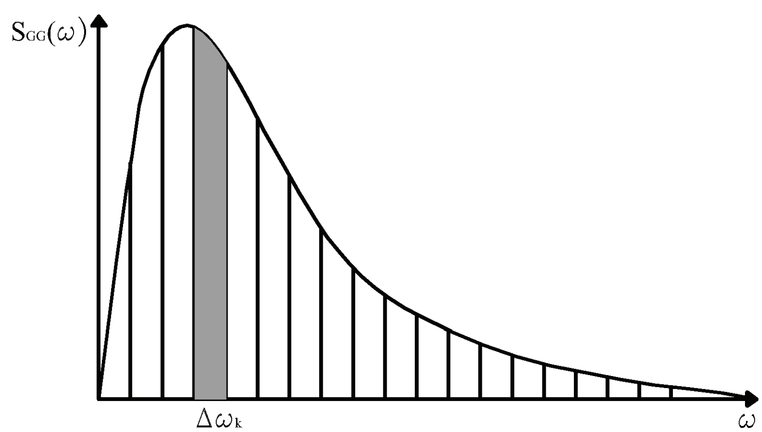


Figure 7-4 Discrete Description of the PSD

Figure 7-4 shows this spectrum and a partition of the frequency range $(0,\tilde{\omega})$ into m non-overlapping intervals I_k of width $\Delta\omega_k$ and midpoints ω_k, $k=1,\dots,m$. $\tilde{G}(\omega)$ is approximated by the discrete spectrum:

$$G_m(\omega)=\sum_{k=1}^{m}\sigma_k^2\delta(\omega-\omega_k) \tag{7-5}$$

in which

$$\sigma_k^2=\int_{I_k}G(\omega)\,d\omega\simeq G(\omega_k)\Delta\omega_k$$

constitutes the contribution of the power in interval I_k to the total variance of the process $\tilde{Y}(t)$, and δ is the delta function (equal to 1 for $\omega=\omega_k$ and 0 for $\omega\neq\omega_k$). Let $Y_m(t)$ be the process associated with the one sided power spectral density $G_m(\omega)$. It is seen from the previous equations that $Y_m(t)$ are the spectral representation

$$Y_m(t)=\sum_{k=1}^{m}\sigma_k\left(V_k\cos\omega_k t+W_k\sin\omega_k t\right) \tag{7-6}$$

In which V_k and W_k are independent Gaussian random variables with zero means and unit variances.

7.4.2 Envelope Function

The realization is subsequently windowed using the envelope function of Saragoni and Hart (Saragoni and Hart, 1974):

$$w(t)=a\cdot t^b\cdot e^{-ct}H(t) \tag{7-7}$$

Where $H(t)$ is the Heaviside step function, and

$$b = \frac{-\varepsilon \ln \eta}{1 + \varepsilon(\ln \varepsilon - 1)} \tag{7-8}$$

$$c = \frac{b}{\varepsilon T_W} \tag{7-9}$$

$$a = \left(\frac{e^1}{\varepsilon T_W}\right)^b \tag{7-10}$$

The other parameters are $\varepsilon=0.2$, $\eta=0.05$ (Boore, 1983). Equation 7-7 represents an envelope function with maximum value of one (Figure 7-5).

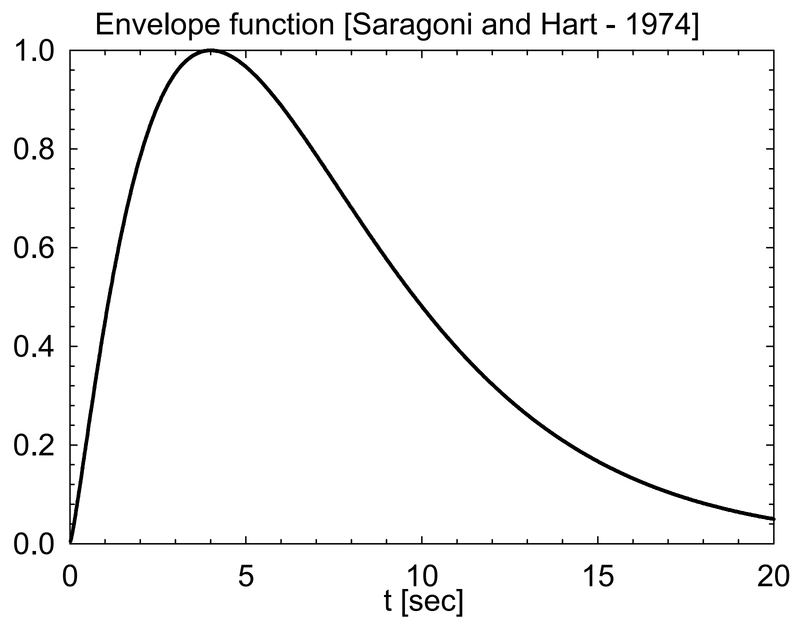


Figure 7-5 Saragoni and Hart Function (1974)

Therefore, the ground acceleration is modeled by a non-stationary Gaussian shot noise with $X''_0(t)=W(t) \cdot Y(t)$, in which $Y(t)$ is a zero mean Gaussian white noise and $W(t)$ is a deterministic modulating function, the Saragoni function. One sample of the synthetically generated ground motion is shown in Figure 7-6.

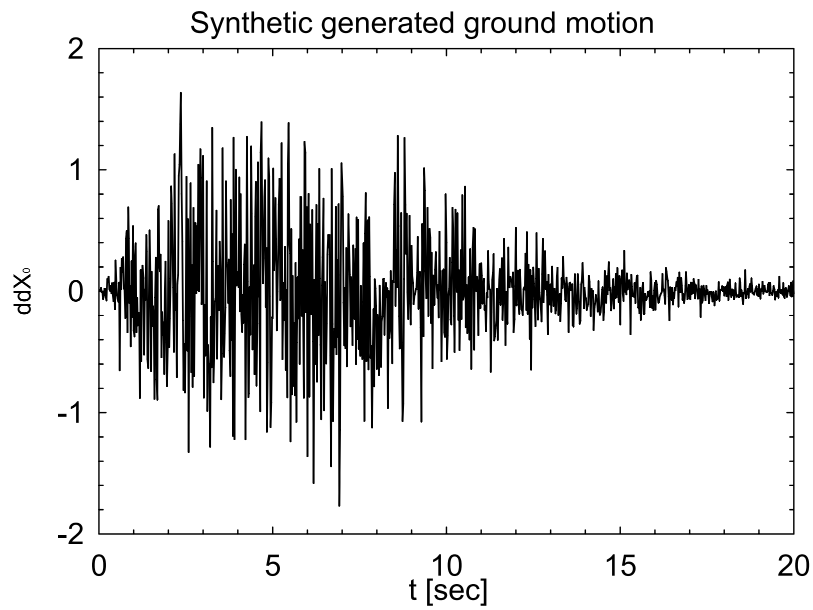


Figure 7-6 Synthetic Ground Motion Sample

When samples have been generated, they need to be scaled to obtain different peak ground accelerations. Two techniques can be used:

1. Each sample $\tilde{X}''_0(t)$ can be normalized to the respective peak ground acceleration;
2. Each sample $\tilde{X}''_0(t)$ can be normalized to the mean of the *PGA* of all the samples;

In the first case, the peak ground acceleration related to each sample is computed:

$$PGA_i = MAX\left(\left|\ddot{X}_{0i}(t)\right|\right) \quad i = 1\ldots 400 \tag{7-11}$$

where 400 is the total number of generated samples and then each sample is scaled to the respective PGA_i so:

$$\ddot{X}_{0i}(t) = \frac{\ddot{\tilde{X}}_{0i}(t)}{PGA_i} \quad i = 1\ldots 400 \tag{7-12}$$

In the second case, once the peak ground acceleration of each sample is computed, the mean of the peak ground acceleration is estimated from:

$$\overline{PGA} = MEAN\left(PGA_i\right) \quad i = 1\ldots 400 \tag{7-13}$$

And then each sample is normalized with the mean of the peak ground acceleration of all samples:

$$\ddot{X}_{0i}(t) = \frac{\tilde{\ddot{X}}_{0i}(t)}{\overline{PGA}} \quad i = 1 \ldots 400 \tag{7-14}$$

The two techniques for scaling the synthetically generated ground motions lead to practically the same results, as shown in Figure 7-7.

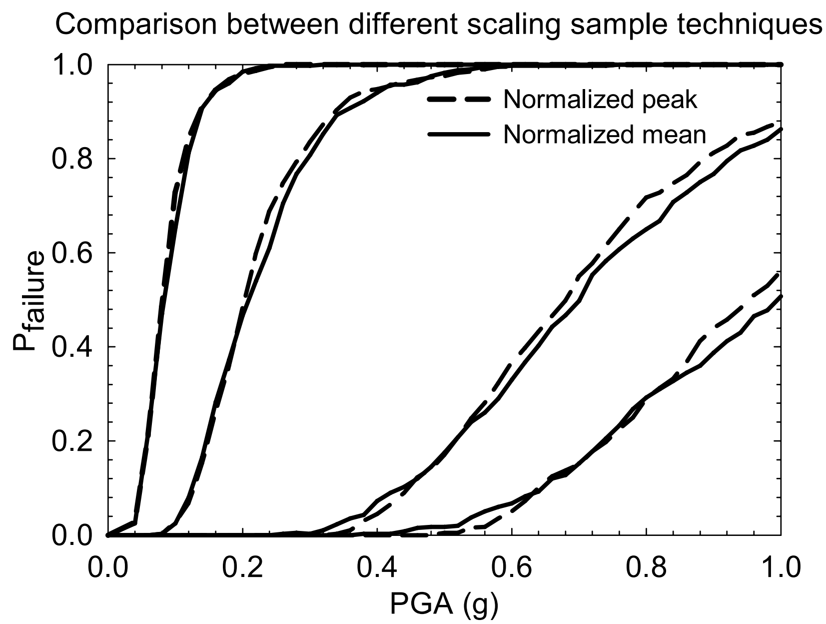


Figure 7-7 Comparison of Fragility Curves with Mean PGA and Maximum PGA

7.5 Comparison of Characteristics of Ground Motions

In order to develop fragility curves for the hospital, it is necessary to collect response values from a limited number of nonlinear dynamics analyses. These analyses are then used to determine the distribution of the response random variables that can be expressed by two parameters: the mean and the standard deviation. Running several nonlinear dynamics analyses on complex structural systems is computationally expensive, so it is useful to explore the possibility of obtaining the same type of response distribution using a reduced number of nonlinear time history analyses, both for the *MCEER series* and the *SAC series*. From each set of the SAC series composed of 20 records, it is possible to choose two random records and obtain the mean of the response μ_{2by2}. The value of the mean in this case is affected by the choice of the two records, so when all the possible combinations are considered, μ_{2by2} is a random variable for which it is possible to calculate the coefficient of variation ν :

$$\nu = \frac{\sigma_{\mu_{2by2}}}{m_{\mu_{2by2}}} \tag{7-15}$$

Where σ is the standard deviation and m is the mean value. The coefficient of variation is the expected error of the mean when only two records instead of 20 are used. It is possible to repeat the same procedure for 3, 4, 5 records and so on until 20 records. The number of all the possible combinations inside each series is given by the binomial formula

$$\binom{n}{k} = \frac{n!}{k!(n-k)!} \qquad n = 20 \quad k = 1 \ldots 20 \tag{7-16}$$

For each of the 20 series of mean values, it is possible to calculate the variance and plot as function of the number of records.

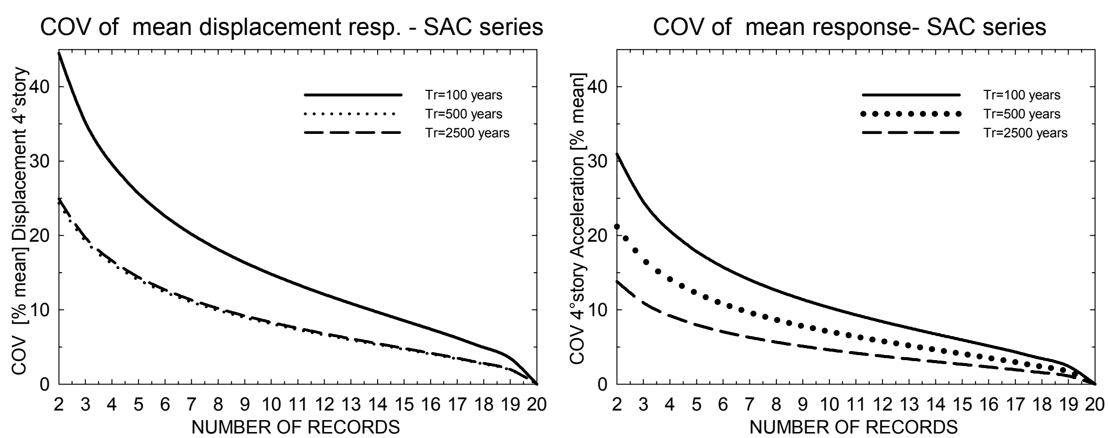


Figure 7-8 Mean Displacement and Acceleration COV for SAC Series

In this case, the percent of error will reduce with increasing number of records as shown in Figure 7-8 for two different responses: displacement and acceleration at the 4th story level. For example, with an earthquake with a return period of 500 years, the mean displacement response can be calculated with an error of 10% using only seven records instead of 20. From Figure 7-8, it is possible to conclude that as the intensity of the earthquake increases, the errors of the mean reduce to the same number of records. In addition, the percent of errors are larger in displacements than in accelerations. The same procedure can be used for the MCEER series, where the number of events (25 records in total) related to each return period are chosen in such a way so as to be proportional to the more probable scenario. In fact, the probabilistic seismic hazard deaggregation map related to the location of the hospital indicates four more probable scenarios corresponding to a given magnitude and distance, so the number of sub-events related to each scenario are chosen proportional to these four additional probable scenarios. Therefore, for scenario 1, there are 11 events; for scenario 2, there are 10 events; and for scenarios 3 and 4, there are two events each. According to this assembling of the series, the minimum number of records are eight, two for each of the four scenarios considered inside the set of 25 records. The same procedure applied to the SAC series can be applied inside each scenario of the MCEER series, so it is possible to calculate the variance of the mean as a function of the number of records for each scenario. Different variances can be combined using their respective weight factors w_i that are determined from the probabilistic seismic hazard analysis using the following formula:

$$\sigma_m^2(n) = w_1 \cdot \sigma_{m,SET1}^2(n_1) + w_2 \cdot \sigma_{m,SET2}^2(n_2) + w_3 \cdot \sigma_{m,SET4}^2(n_3) + w_4 \cdot \sigma_{m,SET4}^2(n_4) \qquad (7\text{-}17)$$

The variance calculated according to Equation 7-17 can also be plotted as a function of the number of records. Figure 7-9 shows the evolution of the error of the mean as the number of records increases. The percent of error of the mean is reduced when compared to the SAC series; in fact, it is possible to reduce the error of the mean below 10% using eight records for all earthquake intensities. It is important to remember that the records cannot be chosen randomly, but they must be two each from each of the four possible scenarios considered.

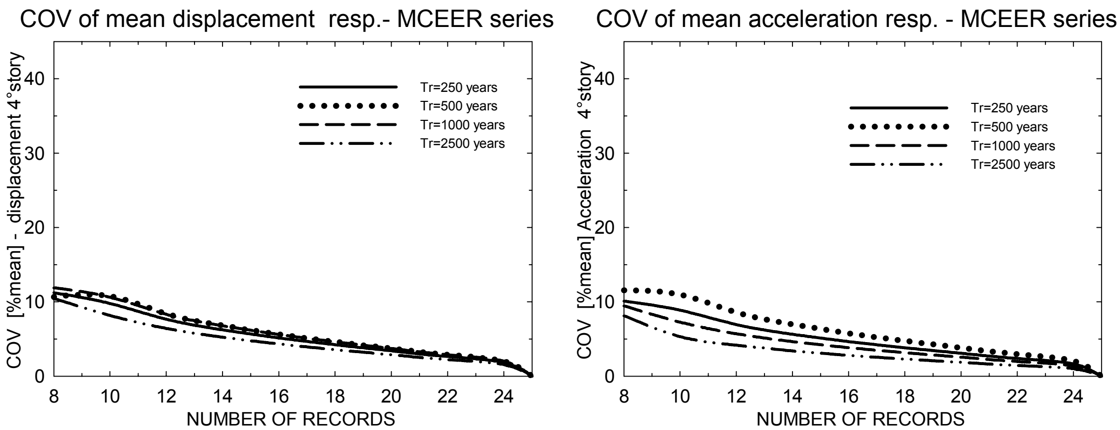


Figure 7-9 Mean Displacement and Acceleration COV for MCEER Series

By comparing the two series it is possible to see that the SAC series is characterized by more variability than the MCEER series, and in conclusion, if an error of 10 % is acceptable, it is possible to use eight records chosen randomly from the SAC series and eight records chosen judiciously from the MCEER series.

SECTION 8

EVALUATION OF FRAGILITY: PARAMETRIC ANALYSIS

8.1 Analytical Fragility Curves

Traditionally, a two parameter lognormal distribution function was used for the construction of fragility curves. The lognormal assumption was made in the development of probabilistic risk assessment methodology for nuclear power plants in the 1970's and in the early 1980's (U.S. Nuclear Regulatory Commission, 1983) and was derived from the observation that the actual structural strength and the design strength are related through an overall factor of safety which is assumed to be factored into a number of multiplicative safety factors, each associated with a specific source of uncertainty. Therefore, when the lognormal assumption is made for each of these factors, the overall safety factor is also distributed lognormally due to the multiplicative nature of the lognormal variables.

Therefore, it is assumed in this study that the fragility curves can be expressed in the form of two parameter lognormal distribution functions, and the estimation of the two parameters is obtained by a straightforward optimization algorithm based on the least square method.

The peak ground acceleration (PGA) is usually used to represent the intensity of the seismic ground motion in the X-axis of the fragility curves even though the use of other intensity measures such as peak ground velocity, spectral acceleration, spectral intensity, modified Mercalli intensity, return period or others can be used.

In this study, fragility curves, developed using scaled synthetic accelerograms as input, are plotted as functions of PGA, while fragility curves developed using the two other time history series are plotted as functions of the return period.

A sample of 450 accelerograms were synthetically generated from the Kanai Tajimi PSD, and used to develop the fragility curves.

A sample of 100 and 60 accelerograms, respectively, from the MCEER and SAC series were used to generate fragility curves. Each series is composed of sub groups of accelerograms corresponding to different return periods. The given return periods leads to only four points for the MCEER series and three points for SAC series, each one corresponding to a given return period.

Fragility curves are affected by several parameters that can be grouped into four types:

1. Performance Limit Threshold considered both as random and multidimensional
2. Input ground motion
3. Structural modeling
4. Structural parameters (damping ratio, stiffness)

The results of this investigation are discussed in the following subsections.

8.2 Influence of Multidimensional Limit States on Fragility

The definition of the limit threshold using the generalized Equation 3-1 has a significant effect on fragility curves, so a parametric analysis has been performed to understand the sensitivity of different parameters. Different deterministic limit states for interstory drift in steel moment resisting frames according to FEMA 356: 0.7% - 2.5% - 5% of interstory height and SEAOC:0.2% - 0.5% - 1.5% - 2.5% of interstory height have been considered.

In Figure 8-1, the fragility curves for the SDOF model of the W70 hospital presented in Section 6 are plotted as function of PGA for the limit state of “Imminent Damage” (0.7% of interstory height) and “Moderate Damage” (2.5% of interstory height).

Different values of the coefficient of variation ν of the limit threshold (ν=0,0.1, 0.51), have been considered, and their respective fragility curves are plotted in Figure 8-1. The legend shows the median value θ_y of the fragility curves.

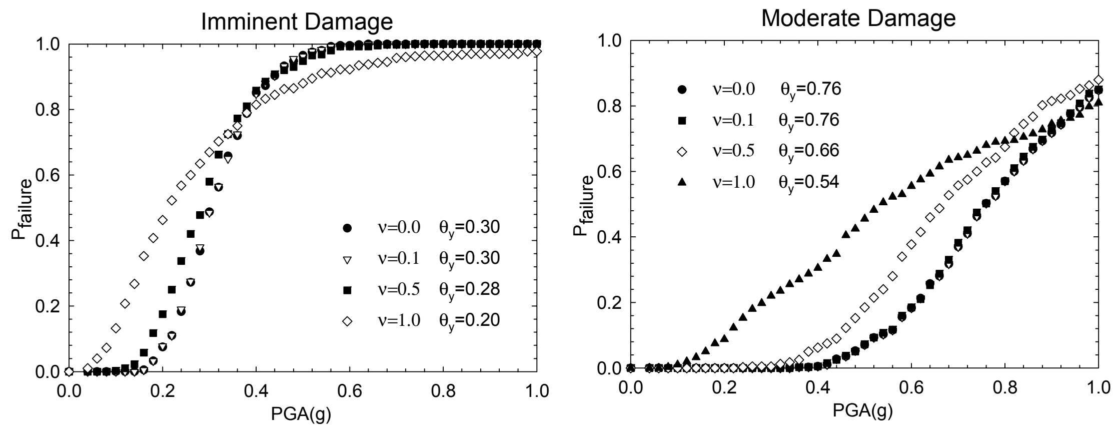


Figure 8-1 Influence on Global Fragility of Limit Threshold Uncertainties for COV Different Values ν

From the fragility curve of imminent damage it can be observed that when uncertainties in the performance limit states are ignored, fragility values are not conservative for PGA below $0.4g$, but are conservative for upper values of PGA. However, for the moderate damage performance limit state, the fragility curves are always not conservative when uncertainties are considered in the threshold.

Fragility curves are influenced by different parameters of the generalized formulation of the multidimensional threshold limit state, which is repeated in Equation 8-1 for simplicity:

$$\frac{A_{LS}}{A_{LS0}}+\left(\frac{D_{LS}}{D_{LS0}}\right)^{N}-1=0 \tag{8-1}$$

In particular, the effects of the parameter *N* and the effect of the acceleration threshold A_{LS0} are also considered.

For different values of *N* it is possible to change the shape of the curve as required, as shown in Figure 8-2. For *N=1,* the limit state becomes a straight line, while for *N=∞,* acceleration and interstory drift PLSs are unrelated. The sensitivity of fragility curves to *N* is shown in Figure 8-3, where the fragility curves related to the first story level of the hospital are plotted for different *N* values. The parameter N describes the interdependence between the acceleration threshold and the drift threshold, and as N increases, the two thresholds become uncorrelated. Increasing the value of *N* moves the fragility curves to the right and the exceedance probability decreases, as shown in Figure 8-3.

The adopted structural model is a nonlinear model of the hospital developed in IDARC2D, and details about the model are provided in Section 6. The fragility curves are developed for the first story level with the interstotory drift as a performance limit state, using the FEMA 356 values for immediate occupancy and damage control. The acceleration limit state values are chosen arbitrarily, due lack of information. However, to show the sensitivity of fragility curves to acceleration thresholds, trial values are given, ranging from 1g to 1.5g. Fragility curves are very sensitive to the acceleration threshold as shown in Figure 8-4, where the fragility curves related to the fourth story level of the hospital are plotted for the FEMA 356 immediate occupancy interstory drift limit state and for different values of acceleration thresholds. Figure 8-4 clearly shows that ignoring the acceleration threshold A_{LS} can lead to unconservative results.

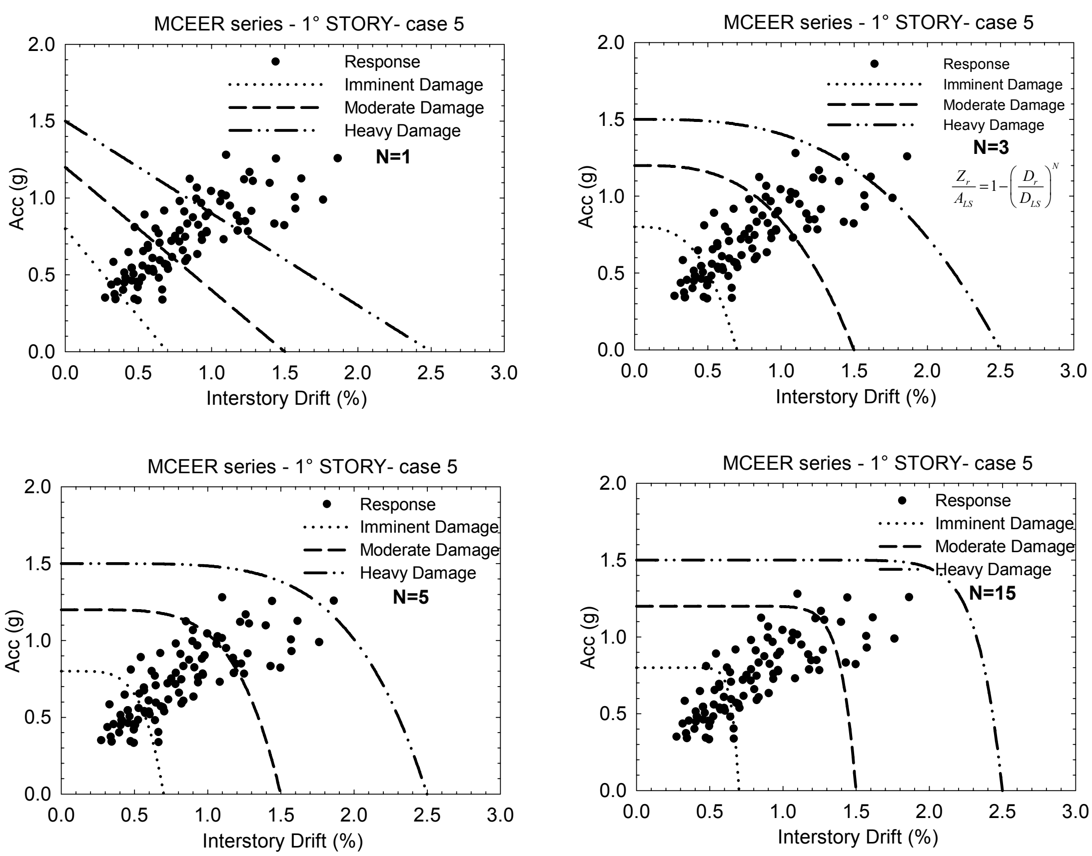


Figure 8-2 Influence of the Parameter "N" on Multidimensional Limit Thresholds

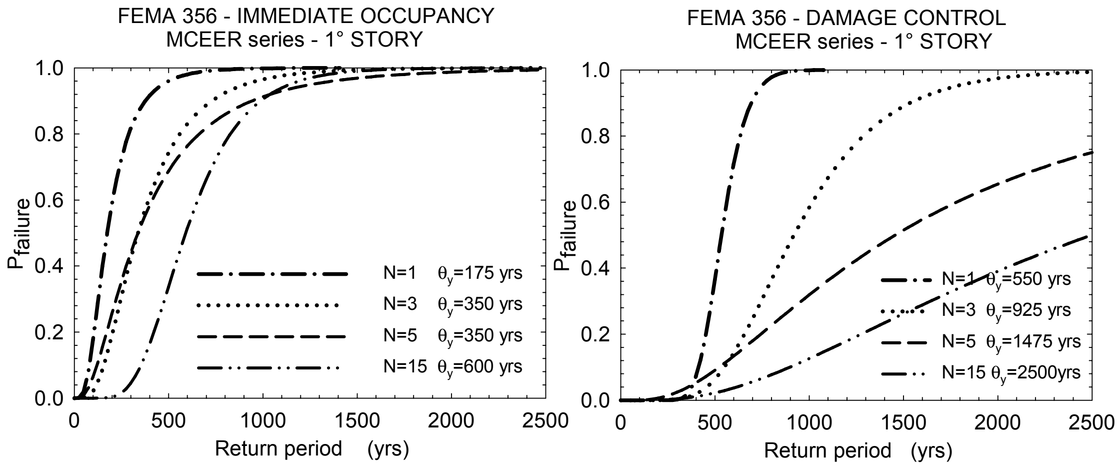


Figure 8-3 Sensitivity of Fragility Curves to Interaction of Drifts and Accelerations, "N"

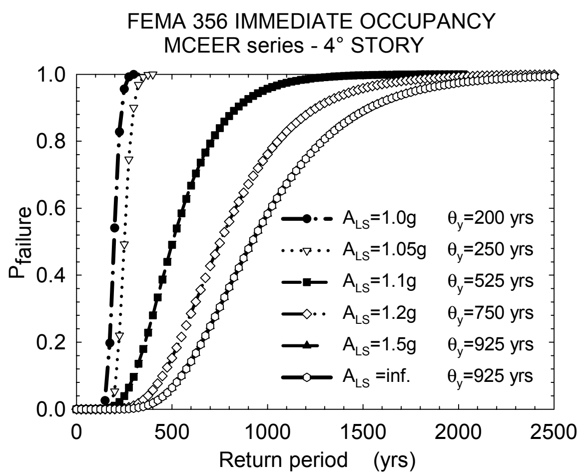


Figure 8-4 Influence of Acceleration Threshold A_{LS} on Fragility Curves

8.3 Uncertainties of Structural Model (Ensemble of Structures)

Development of fragility curves for a class of buildings or for an individual building is always related to the choice of the structural model, and the structural parameters involved in modeling the structure which are inherently uncertain.

The uncertainty is both in the mechanical properties, such as yield strength and stiffness, and geometric properties, such the modeling of the beam-column connections and so on.

A rational approach to fragility should consider these quantities as random variables that can be defined in terms of probability distribution functions, as, for example, lognormal PDF.

The effect of the structural model on fragility has been studied by comparing the fragility curves at different story levels of three different models of the MCCER Demonstration Hospital where the modeling of the beam-column connection is considered as a random variable, as described in the following paragraphs.

In all the three models developed at UB, the moment resisting frame connections are modeled as fully fixed (Figure 8-5a), while the difference among the three is in modeling the beam-column connections of all the non moment-resisting frames (MRF). The first model has ideal hinges (Figure 8-5c) in every non-MRF. The second model is partially moment resisting with plastic hinges (Figure 8-5b) in every non-MRF. The third model has full fixity in every non-MRF beam to column connection (Figure 8-5a).

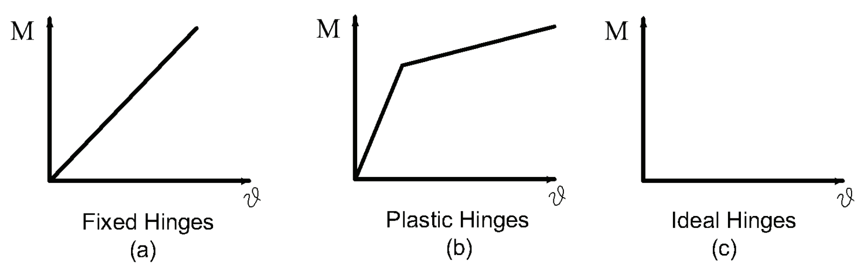


Figure 8-5 Moment-Rotation Relationship for Non-Moment Resisting Frames

Comparing the three models in terms of fragility curves in Figure 8-7, it is observed that there is no difference between the models at the second and third story levels, while there are differences between models at the first and fourth story levels. This result is clearly the consequence of the behavior of the building, which is always a combination of a shear type and flexural type behavior (Figure 8-6). In fact, the fixed-end model (Figure 8-5a) behaves more as a shear type system with larger displacements at the bottom, and in fact the fragility curve at that level is more severe. On the other hand, the ideal hinge model (Figure 8-5c) behaves more as a flexural model, so larger displacements are expected at the top; and in this case the fragility curve is more severe at the fourth story level (Figure 8-7).

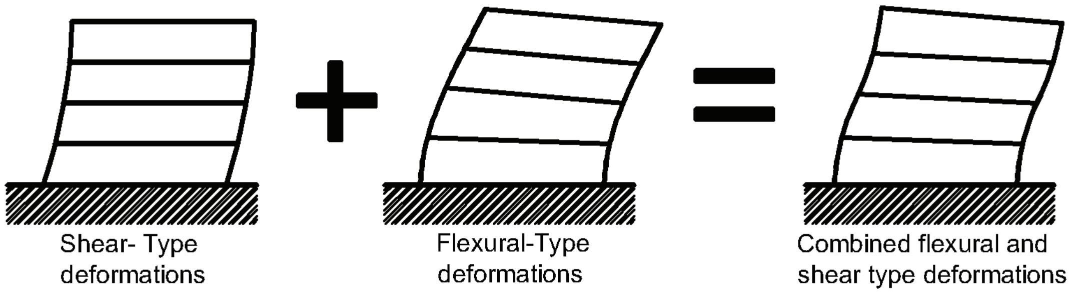


Figure 8-6 Structural Behavior of the Model

This behavior can also be seen in Figure 8-8, where the roof drift is plotted as a function of the interstory drift distribution at various story levels.

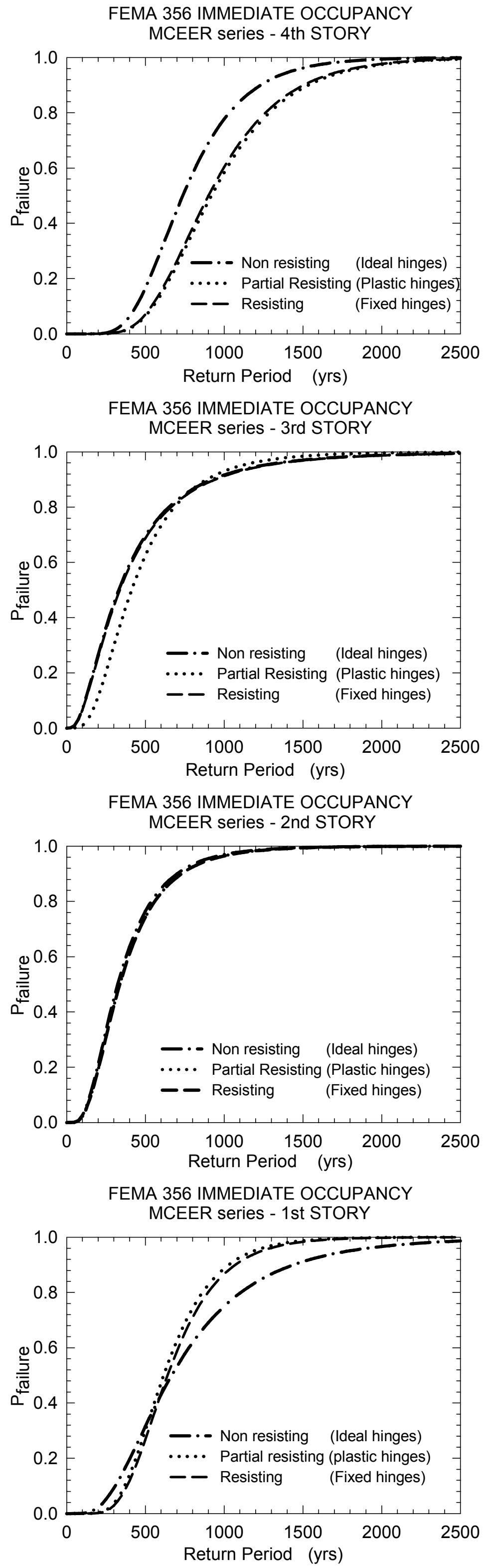


Figure 8-7 Comparison – Fragility Curves for Different Structural Models at the 1st 2nd 3rd & 4th Story Levels

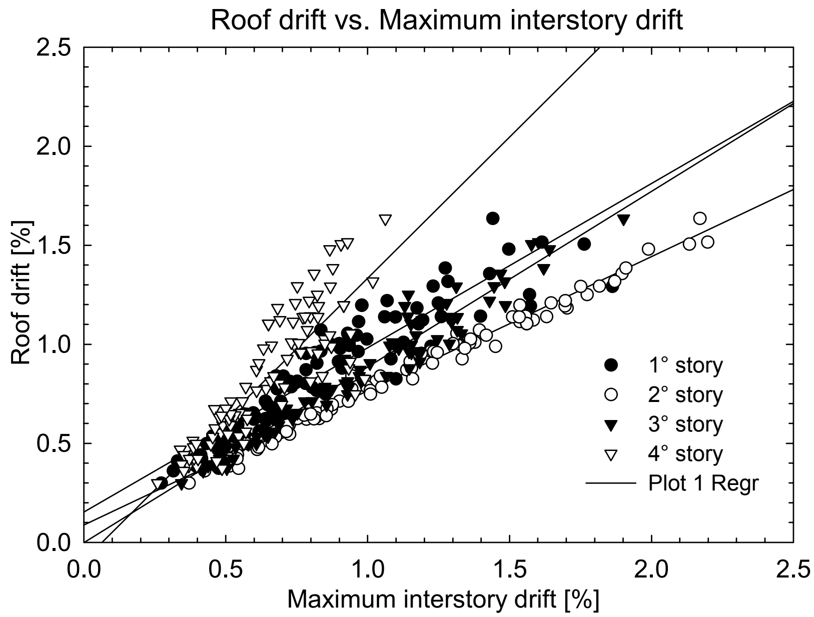


Figure 8-8 Relationship between Maximum Interstory Drift and Roof Drift of Well Designed MRF Subjected to Several Ground Motion Records

The roof drift is a useful measure of the overall structural deformation, but it does not reflect the distribution of damage along the height of the structure, and it does not identify weak elements or soft stories. Instead, interstory drift can be directly correlated with damage at a given story level. A MRF structure well designed per current seismic code provisions would have an almost uniform interstory drift distribution along its height. In this case, the relationship between the roof drift and the maximum interstory drift is linear with a slope close to 45°. For existing non-ductile structures and poorly designed frames such as those with soft story, the maximum interstory drift of the soft story may indicate collapse while the roof drift may still correspond to a lower damage level. Therefore, the damage to MRF is affected by two drift parameters:

1. Interstory drift
2. Distribution along the height of the structure

8.4 Uncertainties of Failure Modes

A structural system usually has many possible failures modes. For example, a system may fail due to cracking, yielding, crushing or buckling. In fragility analysis, it is essential to specify the failure modes for the structural system considered, because the purpose of fragility curves is to predict which component will fail and how, and with what probability. A refined fragility analysis requires a good description of failure modes and their uncertainties. In the fragility studies in this report, the definitions of failures modes are presently only described in broad general terms, so further studies are necessary in this direction.

8.5 Effect of Uncertainties of Input Ground Motion on Fragility

Not only the structural model, but also the type of input ground motion, influences the fragility curves. Figure 8-9 shows the fragility curves obtained using the MCEER series as input and then comparing them with those obtained using the SAC series.

These curves are plotted for each story level of the hospital and according to the FEMA 356 performance limit states for “Immediate Occupancy” and “Damage Control.”

From Figure 8-9 it is seen that for the Immediate Occupancy limit state, there is a large variability especially at the first and fourth story levels. In particular, the SAC series is always more conservative than the MCEER series for earthquakes with return periods less than 1000 years, while for earthquakes with a longer return period, the MCEER series is more conservative.

On the other hand, the curves for the second and third story levels do not change too much with the ground motion, even though the SAC series is always more conservative.

For the Damage Control limit state, there is a large variability at all stories, but the SAC series is always conservative compared to the MCEER series.

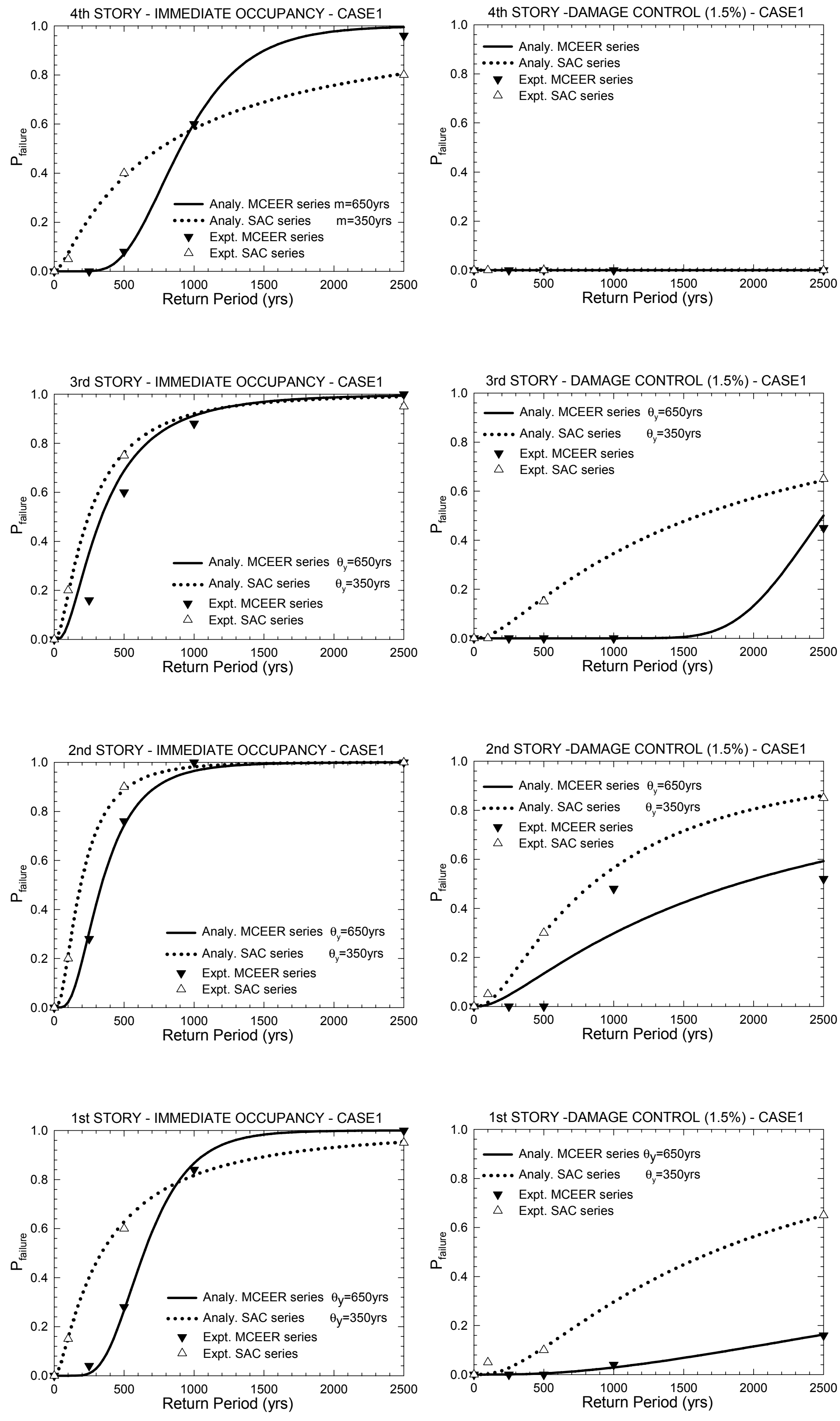


Figure 8-9 Comparison of SAC and MCEER Series at 1st -2nd -3rd - 4th Story Levels

8.6 Fragility Sensitivity to Structural Parameters

Fragility curves can be used for decisions regarding the desired performance of high risk buildings, and for this purpose it is necessary to estimate the effects on fragility of different structural parameters such as strength, stiffness, and damping. Figure 8-10 shows the influence of stiffness on fragility, and how stiffness increments reduce fragility. This is due to the reduction in displacements when stiffness is increased. It can be seen that the uncertainties in the limit states (LS) generate larger increases in the probability of exceeding the threshold compared with the reduction in exceedance probability due to the stiffening of the structure. This shows how much a correct evaluation of the LS is important for a comparison among different retrofit techniques.

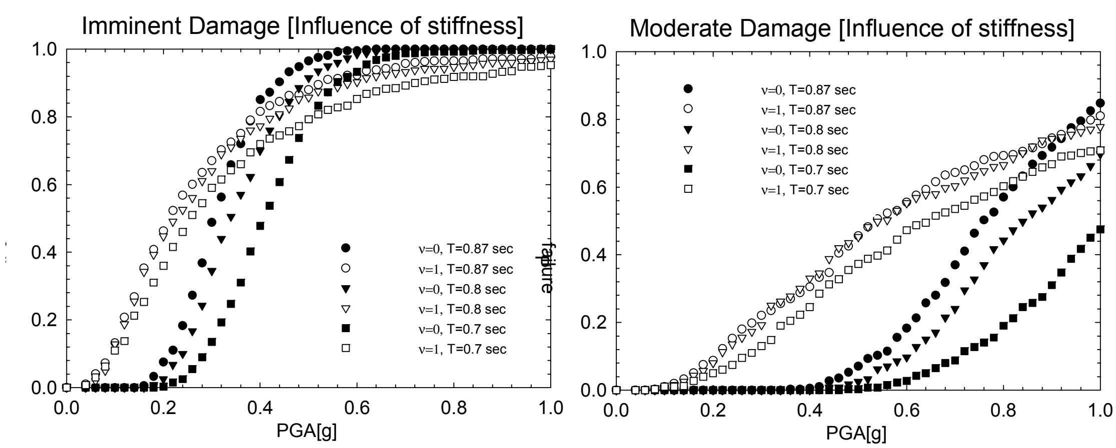


Figure 8-10 Comparison of Different Values of L.S. Dispersion and Different Values of Stiffness

One of the advanced technologies for retrofitting structures studied by MCEER consists of adding damping to reduce displacements. Therefore, it is desirable to know the effect of added damping on fragility (Barron, 2000; Reinhorn and Barron 2001). In Figure 8-11, the fragility curves are plotted for the Imminent Damage State and Moderate Damage State for three different values of damping ratios: 5%, 15% and 25%. It can be seen that a considerable reduction of fragility is obtained when damping is added. However, this reduction is not proportional to the added damping. It is seen in Figure 8-11 that not considering uncertainties in the performance limit state can be non-conservative for PGA values below a range varying between *0.4g* and *0.6g*, depending on the level of damping considered, and conservative for higher values of PGA.

From Figure 8-11 it is also seen that ignoring uncertainties in the performance limit state is always non conservative for all values of damping and PGA.

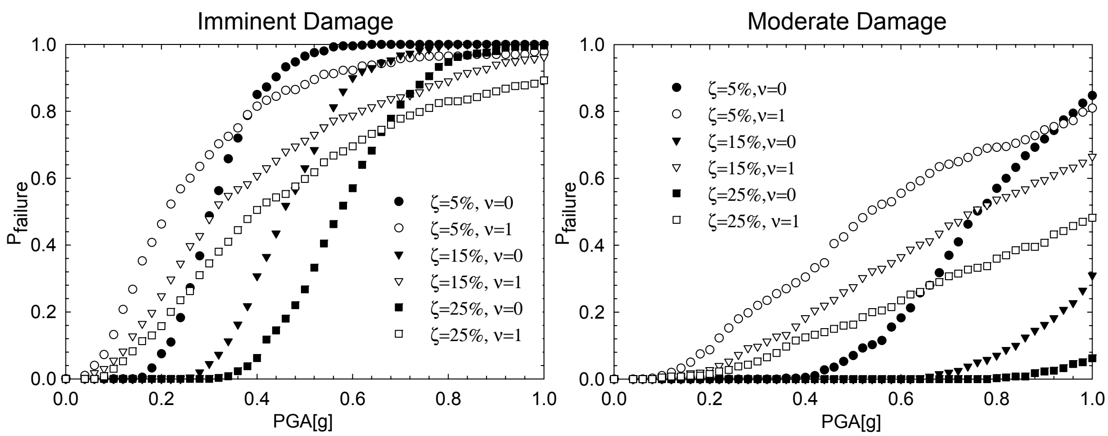


Figure 8-11 Influence of Increased Damping on Fragility for Moderate and Imminent Damage State

Other parameters, such as strength, have also been considered, but increments of strength do not produce significant improvements in fragility, and this is probably due to the fact that changes in strength do not affect displacement in the inelastic range.

SECTION 9

CONCLUSION

9.1 Summary and Conclusions

The report presents an analytical procedure to obtain the fragility function for cases when functionality and safety are described by multiple parameters. A multidimensional definition of the performance limit state has been presented, and exemplified considering two variables that define the limit threshold: effective peak ground acceleration (PGA) and interstory drifts. A generalized formula has been proposed, and different specific cases have been considered. A random description of the limit threshold has been adopted to evalulate fragility.

The procedure to evaluate fragility was programmed and implemented in the pre- and post-processors of IDARC2D (Reinhorn *et al*. 2004), an inelastic analysis program. Appendices A and B, respectively, present the Fortran code and the users manual for the two programs developed for this purpose.

A case study, the MCEER west coast Demonstration Hospital located in the San Fernando Valley in Southern California, has been used to demonstrate the applicability of this technique. The MCEER series and SAC series as well as the Modified Kanai Tajimi power spectrum were used as input ground motions, and their structural response compared.

The development of fragility for different cases shows how important a correct evaluation of the limit threshold is, e.g., for comparing different retrofit techniques. Moreover, if uncertainties in the limit state are not considered unconservative estimates may result.

Parametric analyses using the proposed technique have been performed to show the sensitivity of fragility curves to different parameters. Among the different parameters that influence fragility, damping has a considerable effect on reducing displacements. Therefore, it clearly produces changes in fragility even when the changes in damping are small. The influence of stiffness and acceleration threshold as well as uncertainties due to the structural model and input ground motion were also investigated and quantified. The influence of the hysteretic behavior of components and the structure, including deterioration and fracture that can substantially affect the fragility curves, was not investigated in this report and may be the subject of a future study. Fragility curves are related to a specific structural system and to its specific functionality requirements, so these cannot be used to assess the fragility of other structures, except in a very crude way. Another limitation of calculated fragility curves is that these curves cannot be easily verified by laboratory tests, because of financial constraints.

9.2 Recommendations

Historically, fragility analysis was often based on a single deterministic (crisp) limit state. However, in order to be realistic, fragility analysis should include not only a single response random variable, but should consider multi-response random variables, especially when nonstructural components play an important role in the global fragility evaluation of the building.

The multidimensional limit threshold is a powerful tool to calculate fragility, but in order to determine the proper limit state function and to evaluate fragility when using multidimensional random variables, well-defined values of acceleration thresholds in conjunction with interstory drift thresholds are necessary.

Values of acceleration threshold that are typically related to nonstructural components can be evaluated by laboratory tests. Limit states related to accelerations most often represent the functionality thresholds of buildings contents and nonstructural systems. There is a need for determining each limit states through either analysis or experiment. Without such quantification, the fragility limit states may not accurately reflect the performance of a building (e.g. such as hospitals) and may lead to incorrect decisions.

The quantitative results in this study were based on an elastic-perfectly plastic response relationship. It would be interesting to study the effect of other realistic types of hysteretic behavior on the shape of fragility curves.

CHAPTER 10

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APPENDIX A:

USER'S GUIDE – PROGRAM A

Standard FORTRAN variable format is used to distinguish integers and floating point numbers. Input data must, therefore, conform to specified variable type.

Notes: 1. the required input files for running the program are:

"quake_list.tx"t
"limit_states.txt"
"IDARC2D 6.0.exe (and related files)"

They must run in the same directory.

SET A: SET OF INPUT FILE "quake_list.txt".

```
WHFILE,IWV,NDATA,DTINP ,GMAXH ,GMAXV ,  DTCAL , TDUR , DAMP ,ITDMP,
```

Description:

WHFILE: Name of file (with extension) from which to read horizontal component of earthquake record. Note: Filename should not exceed 10 characters including the extension.(max 10chrs)

IWV: 0 for Vertical component of acceleration not included,
or
1 for Vertical component of acceleration included. (1chrs)

NDATA: Number of points in earthquake wave files. (max 7 chrs)

DTINP: Time interval of input wave. (max 10 chrs)

GMAXH: Peak horizontal acceleration (g's). (max 10 chrs)

GMAXV: Peak vertical acceleration (g's). (max 10 chrs)

DTCAL: Time step for response analysis (secs). (max 10 chrs)

TDUR: Total duration of analysis (secs). (max 10 chrs)

DAMP: Damping coefficient (% of critical). (max 10 chrs)

ITDMP: Type of structural damping: (max 3 chrs)
1 for Mass proportional (default),
2 for Stiffness proportional, or
3 for Rayleigh proportional damping.

*Notes: 1. Each parameter in the input file called, "**quake_list**"(the name must not be changed) has a fixed number of characters that must not be changed. Each space available for each parameter is delimited by a comma. This is an example of how the file looks like:*

```
C WHFILE  ,IWV,NDATA,  DTINP   ,GMAX      ,GMAXV     ,  DTCAL   , TDUR     ,  DAMP    ,ITDMP,
Gian.acc  ,0, 8192  ,  0.005   ,0.3566    , 0.0      ,  0.005   , 40.96    ,  5.0     , 3 ,
Paolo.acc ,0, 8192  ,  0.005   ,0.4109    , 0.0      ,  0.005   , 40.96    ,  5.0     , 3 ,
Cimell.acc,0, 8192  ,  0.005   ,0.3401    , 0.0      ,  0.005   , 40.96    ,  5.0     , 3 ,
the.acc   ,0, 8192  ,  0.005   ,0.4516    , 0.0      ,  0.005   , 40.96    ,  5.0     , 3 ,
best.acc  ,0, 8192  ,  0.005   ,0.4088    , 0.0      ,  0.005   , 40.96    ,  5.0     , 3 ,
```

2. *No blank lines are to be in input otherwise the multiple running stops.*
3. *Every parameter has to be given a value because no program default values are furnished.*
4. *The input accelerogram is scaled uniformly to achieve the specified peak acceleration. DTCAL should not exceed the time interval of the input wave, DTINP. The nonlinear analysis of the structure is often very sensitive to the choice for DTCAL, a value of 0.005 is suggested for typical buildings, however, a smaller value may be necessary if drastic changes in the stiffness ot the elements are expected, or if the structure consists of only a few elements. Larger values can be used for smoother transitions in the stiffness of the elements. Often an inadequate choice of this parameter will yield large unbalanced forces, that may cause numerical instabilities, and stop the execution of the program, or report extremely large values in the damage indices (DI>>3) of some or all elements.*
5. *The ratio (DTINP/DTCAL) must yield an integer number.*
6. *TDUR may be less than the total duration of the earthquake. If TDUR is greater than the total time duration of the input wave, a free vibration analysis of the system will result for the remaining time.*
7. *Each accelerogram Time history must be furnished in a different file in txt format and the file name must coincide with the one in the list of the earthquakes.*
8. *The input file of IDARC related to the model has to have inside the sentence "CONTROL DATA FOR DYNAMIC ANALYSIS", like in the example file furnished.*
9. *Information data saved in different directories depends on the output information given in the input file of the main program IDARC2D 6.0. In the example furnished the output related to 4 story levels are furnished.*

APPENDIX B:

USER'S GUIDE - PROGRAM B

Notes: 1. the required files to run this program are:

quake_list.txt
limit_states.txt
IDARC2D 6.0.exe (and related files.).

They must run in the same directory.

2. Every parameter has to be given a value because no program default values are furnished.

SET A: SET OF INPUT FILE "limit_states.txt".

```
OPTION, CASE_Number, [n1].INT.PGA, [n2]tot.TH, n_points, [a1]NUM.Tr1,
[a2]NUM.Tr2 [a3]NUM.Tr3, [a4]NUM.Tr4, Tr1, Tr2, Tr3, Tr4
```

Description:

OPTION: =1: Dynamic pushover analysis. Calculate fragility curves scaling up and down the intensity of accelerograms listed in the quake list and running different time history.
=2: Calculate fragility curves using accelerograms listed in the quake list without scaling.

CASE_Number: =1: Calculate probability of failure using only a deterministic drift limit state
=2: Calculate probability of failure using only a random drift limit state lognormally distributed and defined in term of mean and st.dev.
=3: Calculate probability of failure using 2 dereministic limit states defined in term of interstorydrift and acceleration.
=4: Calculate probability of failure using 2 random limit states defined in term of interstorydrift and accelerations(both lognormally distributed and defined in term of mean and st. dev).
=5: Calculate probability of failure using a generalized formula that describe the nonlinear interaction between interstory-drift and accelerations deterministic variables.
=6: Calculate probability of failure using a generalized formula that describe the nonlinear interaction between interstory-drift and accelerations random variables.

[n1].INT.PGA :	if OPTION =1 it describes the nummber of intervals you divide the PGA between o and 1 g. if OPTION =2 it describes the number of different return periods considered in the analysis.
[n2]tot.TH :	Total number of accelerograms considered in the "quake_list.txt".
n_points :	number of point associated with each time history.
[a1]NUM.Tr1:	number of accelerograms related to the first return period.
[a2]NUM.Tr2:	number of accelerograms related to the second return period.
[a3]NUM.Tr3:	number of accelerograms related to the third return period.
[a4]NUM.Tr4:	number of accelerograms related to the fourth return period.
Tr1:	value of the first return period.
Tr2:	value of the second return period.
Tr3:	value of the third return period.
Tr4:	value of the fourth return period.

Four different limit state thresoholds have been defined as:

1. **Imminent damage**
2. **Moderate damage**
3. **Heavy damage**
4. **Near Collapse**

For each limit state 4 different parameters can be assigned related to interstory-drift and accelerations expressed in term of mean and coefficient of variation (% of st.dev/mean).
The fragility curves (assumed log-normally distributed) are based on the data points determined from different return periods and they are curve fitted and plotted in a program called Dplot Jr that need to be installed in the machine where the program is running.

Notes: 1: The return period have to be ordered in crescent order inside the quake list not for running the multiple running, but for extracting the values by the folders.
2: The number of limit states considered in the program is fixed equal to 4 and it can not be changed.

APPENDIX C:

COMPUTER PROGRAM LISTING

```
PROGRAM A !MULTIPLE INELASTIC DYNAMIC ANALYSIS REINFORCE CONCRETE

!**************************************************************
!MAIN PROGRAM
!the program openS the quake_list and it substitutes the names
!in the input text file iterately and run the program idarc.
!save the data in different  directories with the same name of
!the accelerograms.
!**************************************************************
USE MSFLIB
IMPLICIT NONE

!==========================
!declaration of the variables
!==========================
INTEGER (2) result
INTEGER:: IWV,NDATA,j,n,OPTION, CASE_Number, n1, n2
LOGICAL (4) status
REAL DTINP,GMAXH,GMAXV,DTCAL,TDUR,DAMP
CHARACTER*100 TextLine,TextLine2,TextLine3, WHFILE*10, ITDMP*3,namefile*15, out*15
CHARACTER(150) dir
INTEGER :: OpenStatus,IOStatus

!HEAD TEXT
WRITE(*,*)'*******************************************************************'
WRITE(*,*)'                                    '
WRITE(*,*)'                                    '
WRITE(*,*)'                                    '
WRITE(*,*)'                 M I D A R C    2 D            '
WRITE(*,*)'                  MULTIPLE RUNNING             '
WRITE(*,*)'                   Version 1.0                 '
WRITE(*,*)'                                    '
WRITE(*,*)'                                    '
WRITE(*,*)'*******************************************************************'
!====================================
!open the file list of the accelerograms
!====================================
OPEN(UNIT=1,FILE='quake_list.DAT',STATUS='UNKNOWN',ACTION="READ",IOSTAT =
OpenStatus)
READ(1, "(A)") TextLine
OPEN(UNIT=7,FILE='idarc.DAT',STATUS='UNKNOWN',ACTION="READWRITE",IOSTAT =
OpenStatus)
READ(7,"(A)",IOSTAT=IOStatus) namefile !read the name of the input file
READ(7,"(A)") out                  !read the name of the output file
```

```
CLOSE(7)
CALL getpath  !save the path of the directory in the parameter dir.
!OPEN limit states and read which cases to run

          !OPTION = [1]   !Dynamic pushover analysis of all quake list.
          !OPTION = [2]   !Dynamic analysis of accelerograms in the quake-list.
OPEN(UNIT=107,FILE='limit_states.DAT',STATUS='UNKNOWN',ACTION="READWRITE",IOSTA
T = OpenStatus)
READ(107,'(/,1X,I1,7X,I1,14X,I3,9X,I3)',IOSTAT=IOStatus) OPTION, CASE_Number, n1, n2
WRITE(*,*) 'OPTION=',OPTION,'CASE Number=', CASE_Number, n1, n2
CLOSE(107)
!=====================================================================
!It sobstitutes the parameters in the quake list in the input file
!=====================================================================

DO
          status = CHANGEDIRQQ(dir)

OPEN(UNIT=2,FILE=TRIM(namefile),STATUS='UNKNOWN',ACTION="READWRITE",IOSTAT =
OpenStatus)
OPEN(UNIT=3,FILE=TRIM(namefile)//'_temp',STATUS='UNKNOWN',ACTION="READWRITE",IO
STAT = OpenStatus)
          READ(1,
'(A10,1X,I1,1X,I7,1X,F10.3,1X,F10.3,1X,F10.3,1X,F10.3,1X,F10.3,1X,F10.3,1X,A3)',IOSTAT=IOStatu
s) WHFILE,IWV,NDATA,DTINP,GMAXH,GMAXV,DTCAL,TDUR,DAMP,ITDMP
          IF (IOStatus  > 0) STOP "***Input error***"
          IF (IOStatus  < 0) EXIT
          IF (OPTION==1) THEN   !Dynamic pushover analysis
                  CALL
PGA(WHFILE,IWV,NDATA,DTINP,GMAXH,GMAXV,DTCAL,TDUR,DAMP,namefile,n1,ITDMP)
      status = CHANGEDIRQQ(dir)
OPEN(UNIT=2,FILE=TRIM(namefile),STATUS='UNKNOWN',ACTION="READWRITE",IOSTAT =
OpenStatus)

OPEN(UNIT=3,FILE=TRIM(namefile)//'_temp',STATUS='UNKNOWN',ACTION="READWRITE",IO
STAT = OpenStatus)
         ELSEIF  (OPTION==2) THEN
   !OPTION = [2]   !Dynamic analysis of accelerograms in the quake-list.
                DO
                READ(2,"(A)",IOSTAT=IOStatus) TextLine
                IF (IOStatus  > 0) STOP "***Input error***"
                IF (IOStatus  < 0) EXIT
                IF (TextLine=='CONTROL DATA FOR DYNAMIC ANALYSIS
')THEN
                WRITE (3,"(A)") TextLine
                READ(2,"(A)",IOSTAT=IOStatus) TextLine
                WRITE
(3,"(F10.3,F10.3,F10.3,F10.3,F10.3,A3)")GMAXH,GMAXV,DTCAL,TDUR,DAMP,ITDMP
                READ(2,"(A)",IOSTAT=IOStatus) TextLine
                WRITE (3,"(A)") TextLine
                READ(2,"(A)",IOSTAT=IOStatus) TextLine
```

```
                    WRITE (3,"(I1,I7,F10.3)")IWV,NDATA,DTINP
                    READ(2,"(A)",IOSTAT=IOStatus) TextLine
                    WRITE (3,"(A)") TextLine
                    READ(2,"(A)",IOSTAT=IOStatus) TextLine
                    WRITE (3,"(A10)") WHFILE
                    ELSE
                    WRITE (3,"(A)") TextLine
                    END IF
          END DO
   CLOSE (2)
   CLOSE (3)
   OPEN(UNIT=4,FILE=TRIM(namefile)//'_temp',STATUS='UNKNOWN',ACTION="READ",IOSTAT
= OpenStatus)
OPEN(UNIT=5,FILE=TRIM(namefile),STATUS='UNKNOWN',ACTION="WRITE",IOSTAT =
OpenStatus)
DO
          READ (4,"(A)",IOSTAT=IOStatus) TextLine2
          IF (IOStatus  > 0) STOP "***Input error***"
          IF (IOStatus  < 0) EXIT
          WRITE (5,"(A)") TextLine2
END DO
CLOSE (4)
CLOSE (5)
!===================
!run IDARC2d program
!===================
result=RUNQQ('idarc2d_60.EXE','')
CALL makedir(WHFILE,dir,out)
END IF
END DO
CLOSE (1)
WRITE (*,*) "END OF MULTIPLE RUNNING"
END PROGRAM MIDARC
```

```
SUBROUTINE getpath
!**********************************************************
!the subroutine save the path of the current directory in
! the parameter dir
!**********************************************************
USE DFLIB      !module to save the path of the directory
CHARACTER($MAXPATH) dir
INTEGER(4) length
!It get current directory
dir = FILE$CURDRIVE
length = GETDRIVEDIRQQ(dir)
IF (length .GT. 0) THEN
  WRITE (*,*) 'Current directory is: '
  WRITE (*,*) dir
ELSE
  WRITE (*,*) 'Failed to get current directory'
```

```
END IF
END SUBROUTINE getpath
```

```
SUBROUTINE makedir (WHFILE,dir,out)

!*************************************************************
!crate new directories acoording to the name of the accelerograms
! and save output files in these directories
!*************************************************************
USE DFLIB
LOGICAL(4) status
INTEGER (2) result
INTEGER :: OpenStatus,IOStatus
CHARACTER(5), INTENT(IN) :: WHFILE
CHARACTER($MAXPATH) dir
INTEGER (4) length
CHARACTER*10 TextLine*150,namefile*15, out*15
OPEN(UNIT=6,FILE=out,STATUS='UNKNOWN',ACTION="READWRITE",IOSTAT = OpenStatus)
OPEN(UNIT=8,FILE='story_1.OUT',STATUS='UNKNOWN',ACTION="READWRITE",IOSTAT =
OpenStatus)
OPEN(UNIT=10,FILE='story_2.OUT',STATUS='UNKNOWN',ACTION="READWRITE",IOSTAT =
OpenStatus)
OPEN(UNIT=12,FILE='story_3.OUT',STATUS='UNKNOWN',ACTION="READWRITE",IOSTAT =
OpenStatus)
OPEN(UNIT=14,FILE='story_4.OUT',STATUS='UNKNOWN',ACTION="READWRITE",IOSTAT =
OpenStatus)
result = MAKEDIRQQ(WHFILE)
dir = FILE$CURDRIVE
length = GETDRIVEDIRQQ(dir)
WRITE(*,*) TRIM(dir)//"\"//WHFILE
        DO
                READ(6,"(A)",IOSTAT=IOStatus) TextLine
                IF (IOStatus  > 0) STOP "***Input error***"
                IF (IOStatus  < 0) EXIT
                status = CHANGEDIRQQ(TRIM(dir)//"\"//WHFILE)

OPEN(UNIT=7,FILE=out,STATUS='UNKNOWN',ACTION="READWRITE",IOSTAT = OpenStatus)
                WRITE(7,"(A)",IOSTAT=IOStatus) TextLine
        END DO
 status = CHANGEDIRQQ(TRIM(dir))

        DO
                READ(8,"(A)",IOSTAT=IOStatus) TextLine
                IF (IOStatus  > 0) STOP "***Input error***"
                IF (IOStatus  < 0) EXIT
                status = CHANGEDIRQQ(TRIM(dir)//"\"//WHFILE)

OPEN(UNIT=9,FILE='story_1.OUT',STATUS='UNKNOWN',ACTION="READWRITE",IOSTAT =
OpenStatus)
                WRITE(9,"(A)",IOSTAT=IOStatus) TextLine
```

```
            END DO
  status = CHANGEDIRQQ(TRIM(dir))
            DO
                        READ(10,"(A)",IOSTAT=IOStatus) TextLine
                        IF (IOStatus  > 0) STOP "***Input error***"
                        IF (IOStatus  < 0) EXIT
                        status = CHANGEDIRQQ(TRIM(dir)//"\"//WHFILE)

OPEN(UNIT=11,FILE='story_2.OUT',STATUS='UNKNOWN',ACTION="READWRITE",IOSTAT =
OpenStatus)
                        WRITE(11,"(A)",IOSTAT=IOStatus) TextLine
            END DO
 status = CHANGEDIRQQ(TRIM(dir))
            DO
                        READ(12,"(A)",IOSTAT=IOStatus) TextLine
                        IF (IOStatus  > 0) STOP "***Input error***"
                        IF (IOStatus  < 0) EXIT
                        status = CHANGEDIRQQ(TRIM(dir)//"\"//WHFILE)

OPEN(UNIT=13,FILE='story_3.OUT',STATUS='UNKNOWN',ACTION="READWRITE",IOSTAT =
OpenStatus)
                        WRITE(13,"(A)",IOSTAT=IOStatus) TextLine
            END DO
 status = CHANGEDIRQQ(TRIM(dir))
            DO
                        READ(14,"(A)",IOSTAT=IOStatus) TextLine
                        IF (IOStatus  > 0) STOP "***Input error***"
                        IF (IOStatus  < 0) EXIT
                        status = CHANGEDIRQQ(TRIM(dir)//"\"//WHFILE)

OPEN(UNIT=15,FILE='story_4.OUT',STATUS='UNKNOWN',ACTION="READWRITE",IOSTAT =
OpenStatus)
                        WRITE(15,"(A)",IOSTAT=IOStatus) TextLine
            END DO
CLOSE(6)
CLOSE(7)
CLOSE(8)
CLOSE(9)
CLOSE(10)
CLOSE(11)
CLOSE(12)
CLOSE(13)
CLOSE(14)
CLOSE(15)
END SUBROUTINE makedir
```

```
SUBROUTINE makedir2 (WHFILE,dir)

!****************************************************************
!it create new directories acoording to the name of the accelerograms
```

```
! and save output files in these directories
!******************************************************************
USE DFLIB
LOGICAL(4) status
INTEGER (2) result
INTEGER :: OpenStatus,IOStatus
CHARACTER(5), INTENT(IN) :: WHFILE
CHARACTER($MAXPATH) dir
INTEGER (4) length
CHARACTER*10 TextLine*150,k*2
OPEN(UNIT=6,FILE='prova.OUT',STATUS='UNKNOWN',ACTION="READWRITE",IOSTAT =
OpenStatus)
OPEN(UNIT=8,FILE='story_1.OUT',STATUS='UNKNOWN',ACTION="READWRITE",IOSTAT =
OpenStatus)
OPEN(UNIT=10,FILE='story_2.OUT',STATUS='UNKNOWN',ACTION="READWRITE",IOSTAT =
OpenStatus)
OPEN(UNIT=12,FILE='story_3.OUT',STATUS='UNKNOWN',ACTION="READWRITE",IOSTAT =
OpenStatus)
OPEN(UNIT=14,FILE='story_4.OUT',STATUS='UNKNOWN',ACTION="READWRITE",IOSTAT =
OpenStatus)
OPEN(UNIT=100,FILE="n_int_pga.DAT",STATUS='UNKNOWN',ACTION="READWRITE",IOSTA
T = OpenStatus)
READ(100,"(3X,A2)") k
result = MAKEDIRQQ(WHFILE//"-"//ADJUSTL(k))
dir = FILE$CURDRIVE
length = GETDRIVEDIRQQ(dir)
WRITE(*,*) TRIM(dir)//"\"//WHFILE//"-"//ADJUSTL(k)

        DO
                READ(6,"(A)",IOSTAT=IOStatus) TextLine
                IF (IOStatus  > 0) STOP "***Input error***"
                IF (IOStatus  < 0) EXIT
                status = CHANGEDIRQQ(TRIM(dir)//"\"//WHFILE//"-"//ADJUSTL(k))

OPEN(UNIT=7,FILE='prova.OUT',STATUS='UNKNOWN',ACTION="READWRITE",IOSTAT =
OpenStatus)
                WRITE(7,"(A)",IOSTAT=IOStatus) TextLine
        END DO
 status = CHANGEDIRQQ(TRIM(dir))
        DO
                READ(8,"(A)",IOSTAT=IOStatus) TextLine
                IF (IOStatus  > 0) STOP "***Input error***"
                IF (IOStatus  < 0) EXIT
                status = CHANGEDIRQQ(TRIM(dir)//"\"//WHFILE//"-"//ADJUSTL(k))

OPEN(UNIT=9,FILE='story_1.OUT',STATUS='UNKNOWN',ACTION="READWRITE",IOSTAT =
OpenStatus)
                WRITE(9,"(A)",IOSTAT=IOStatus) TextLine
        END DO
 status = CHANGEDIRQQ(TRIM(dir))
        DO
```

```
            READ(10,"(A)",IOSTAT=IOStatus) TextLine
            IF (IOStatus  > 0) STOP "***Input error***"
            IF (IOStatus  < 0) EXIT
            status = CHANGEDIRQQ(TRIM(dir)//"\"//WHFILE//"-"//ADJUSTL(k))

OPEN(UNIT=11,FILE='story_2.OUT',STATUS='UNKNOWN',ACTION="READWRITE",IOSTAT =
OpenStatus)
            WRITE(11,"(A)",IOSTAT=IOStatus) TextLine
      END DO
 status = CHANGEDIRQQ(TRIM(dir))
      DO
            READ(12,"(A)",IOSTAT=IOStatus) TextLine
            IF (IOStatus  > 0) STOP "***Input error***"
            IF (IOStatus  < 0) EXIT
            status = CHANGEDIRQQ(TRIM(dir)//"\"//WHFILE//"-"//ADJUSTL(k))

OPEN(UNIT=13,FILE='story_3.OUT',STATUS='UNKNOWN',ACTION="READWRITE",IOSTAT =
OpenStatus)
            WRITE(13,"(A)",IOSTAT=IOStatus) TextLine
      END DO
 status = CHANGEDIRQQ(TRIM(dir))
      DO
            READ(14,"(A)",IOSTAT=IOStatus) TextLine
            IF (IOStatus  > 0) STOP "***Input error***"
            IF (IOStatus  < 0) EXIT
            status = CHANGEDIRQQ(TRIM(dir)//"\"//WHFILE//"-"//ADJUSTL(k))
OPEN(UNIT=15,FILE='story_4.OUT',STATUS='UNKNOWN',ACTION="READWRITE",IOSTAT =
OpenStatus)
            WRITE(15,"(A)",IOSTAT=IOStatus) TextLine
      END DO
CLOSE(6)
CLOSE(7)
CLOSE(8)
CLOSE(9)
CLOSE(10)
CLOSE(11)
CLOSE(12)
CLOSE(13)
CLOSE(14)
CLOSE(15)
END SUBROUTINE makedir2
```

```
SUBROUTINE
PGA(WHFILE,IWV,NDATA,DTINP,GMAXH,GMAXV,DTCAL,TDUR,DAMP,namefile,n1,ITDMP)
!=============================================================================
==============
!This subroutine does the dynamic pushover analysis of all accelerograms in the quake list.
!=============================================================================
==============
USE MSFLIB
IMPLICIT NONE
```

```
INTEGER (2) result
LOGICAL (4) status
REAL GMAXV,DTCAL,TDUR,DAMP,j,r
CHARACTER*100 TextLine,TextLine2,TextLine3,namefile,k*2
CHARACTER(3), INTENT(INOUT) :: ITDMP
CHARACTER(10), INTENT(INOUT) :: WHFILE
INTEGER, INTENT(INOUT) :: IWV,n1
INTEGER, INTENT(INOUT) :: NDATA
REAL, INTENT(INOUT) :: GMAXH
REAL, INTENT(INOUT) :: DTINP
CHARACTER(150) dir
INTEGER :: OpenStatus,IOStatus

!n1:number of intervals between 0 and 1 PGA.

r=1.0
OPEN(UNIT=100,FILE="n_int_pga.DAT",STATUS='UNKNOWN',ACTION="READWRITE",IOSTA
T = OpenStatus)
DO WHILE (r .LT. n1+1)
WRITE (100,*) r         !write the number of intervals in pga
r=r+1.0
END DO
CLOSE(100)
CLOSE(2)
CLOSE(3)
j=1
DO WHILE (GMAXH <=1)
          GMAXH =j/n1
   IF (GMAXH <=1) THEN
      WRITE(*,*) j
                 WRITE(*,*) n1
           GMAXH =j/n1
                 WRITE(*,*) GMAXH
                 DO
                    status = CHANGEDIRQQ(dir)
OPEN(UNIT=2,FILE=namefile,STATUS='UNKNOWN',ACTION="READWRITE",IOSTAT =
OpenStatus)

OPEN(UNIT=3,FILE='prova2.DAT',STATUS='UNKNOWN',ACTION="READWRITE",IOSTAT =
OpenStatus)
                          READ(2,"(A)",IOSTAT=IOStatus) TextLine
                          IF (IOStatus  > 0) STOP "***Input error***"
                          IF (IOStatus  < 0) EXIT

          !=======================================================
                          !All the parameters remain the same. Only GMAXH changes
                          !=======================================================

                          IF (TextLine=='CONTROL DATA FOR DYNAMIC ANALYSIS
')THEN
                          WRITE (3,"(A)") TextLine
```

```
                    READ(2,"(A)",IOSTAT=IOStatus) TextLine
                    WRITE
(3,"(F10.3,F10.3,F10.3,F10.3,F10.3,A3)")GMAXH,GMAXV,DTCAL,TDUR,DAMP,ITDMP
                    READ(2,"(A)",IOSTAT=IOStatus) TextLine
                    WRITE (3,"(A)") TextLine
                    READ(2,"(A)",IOSTAT=IOStatus) TextLine
                    WRITE (3,"(I1,I7,F10.3)")IWV,NDATA,DTINP
                    READ(2,"(A)",IOSTAT=IOStatus) TextLine
                    WRITE (3,"(A)") TextLine
                    READ(2,"(A)",IOSTAT=IOStatus) TextLine
                    WRITE (3,"(A10)") WHFILE
                    ELSE
                    WRITE (3,"(A)") TextLine
                    END IF
              END DO
         CLOSE (2)
         CLOSE (3)
         OPEN(UNIT=4,FILE='prova2.DAT',STATUS='UNKNOWN',ACTION="READ",IOSTAT =
OpenStatus)
         OPEN(UNIT=5,FILE=namefile,STATUS='UNKNOWN',ACTION="WRITE",IOSTAT =
OpenStatus)
      DO
              READ (4,"(A)",IOSTAT=IOStatus) TextLine2
              IF (IOStatus  > 0) STOP "***Input error***"
              IF (IOStatus  < 0) EXIT
              WRITE (5,"(A)") TextLine2
      END DO
      CLOSE (4)
      CLOSE (5)
      result=RUNQQ('idarc2d_60.EXE','')
      CALL makedir2(WHFILE,dir)
      j=j+1
   END IF
END DO
status = CHANGEDIRQQ(dir)  !Go back to the main working directory.

END SUBROUTINE PGA
```

```
PROGRAM FIDARC2D !Fragility inelastic dynamic analysis Reinforced Concrete

!*************
!MAIN PROGRAM*
!*************

!*******************************************************************
!The program opens the output files in different  directories and
!It collects information dividing by return period and calculate
!the fragility for different limit states saving the data in a
!file txt called FRAG_CURVE_OUTPUT.It can runs separately one time
!the data have been collected.
!*******************************************************************

USE DFLIB
USE AVDEF
USE numerical_libraries
IMPLICIT NONE
INTEGER (2) result
INTEGER :: OpenStatus,IOStatus
INTEGER::
IWV,NDATA,i,j,st,row,OPTION,CASE_Number,n1,n2,NR,ls,a2,a3,a4,m,t,n_points,NSOUT,FC,nrn,pot
INTEGER (4) length
LOGICAL (4) status
REAL
DTINP,GMAXH,GMAXV,DTCAL,TDUR,DAMP,DISP,ACC,Dmax,Amax,DELTAmax,h1,h2,DM,AM
REAL meanDLS,sigmaDLS,meanALS,sigmaALS,niDLS,niALS,S,XM,Tr1,Tr2,Tr3,Tr4,a1
CHARACTER*100 TextLine,TextLine2,TextLine3, WHFILE*10, ITDMP*3, k*2,namefile*15
CHARACTER($MAXPATH) dir
REAL, ALLOCATABLE :: B(:,:),R(:,:),DLS(:,:),ALS(:,:), X(:,:),TR(:,:),mean_Resp(:,:),std_Resp(:,:)
REAL, ALLOCATABLE :: A(:,:),D(:,:),DELTA(:,:),DELTA_RESP(:,:,:),A_RESP(:,:,:)
REAL, ALLOCATABLE :: P(:,:),
AMAXIMUM(:,:),DMAXIMUM(:,:),DELTAMAXIMUM(:,:),OUT2(:,:) !to define the dimension as a
function of a parameter.
REAL, ALLOCATABLE ::
AMAXIM(:,:,:),DMAXIM(:,:,:),DELTAMAXIM(:,:,:),LOGDELTAMAXIM(:,:,:),OUT(:,:,:) !to define
the dimension as a function of a parameter.
REAL, ALLOCATABLE ::BOOL(:,:),BOOL2(:,:),BOOL3(:,:)  !to define the dimension as a function of
a parameter.
CHARACTER*20, ALLOCATABLE :: stories(:,:)

!head text
WRITE(*,*)'                                    '
WRITE(*,*)'                                    '
WRITE(*,*)'*************************************************************************'
WRITE(*,*)'                                    '
WRITE(*,*)'                                    '
WRITE(*,*)'                                    '
WRITE(*,*)'                    F I D A R C 2 D                '
WRITE(*,*)'                     [FRAGILITY]          '
WRITE(*,*)'                     Version 2.1                   '
```

```
WRITE(*,*)'                                        '
WRITE(*,*)'                                        '
WRITE(*,*)'*******************************************************************'
WRITE(*,*)'                                        '

!=============================================================================
===============
!Open the file 'limit states' that defines the type of commands for calculating fragility.
!=============================================================================
===============
!n1=4   !number of return period considered

OPEN(UNIT=7,FILE='limit_states.DAT',STATUS='UNKNOWN',ACTION="READWRITE",IOSTAT
= OpenStatus)
READ(7,'(/1X,I1,7X,I1,14X,I3,9X,I3,9X,I6,4X,F3.0,9X,I3,9X,I3,9X,I3,9X,F4.0,9X,F4.0,9X,F4.0,9X,F4.
0)',IOSTAT=IOStatus) OPTION, CASE_Number,n1, n2,n_points,a1,a2,a3,a4,Tr1,Tr2,Tr3,Tr4
CLOSE(7)
WRITE(*,*) "Return period", Tr1,Tr2,Tr3,Tr4
nrn=2000      !number of random number to generate

!------------------------------------------------------------------------------------------------
!OPTION:      [1]method for calculating fragility using scale of intensity of accelerograms or
!            [2]method to calculate fragility using accelerograms divide by return period Tr.
!CASE_Number:    different type for calculating the probability of failure.
!n1:             number of return period considered.
!n2:             number of TH.
!------------------------------------------------------------------------------------------------

ALLOCATE (B(n_points,1),R(nrn,1),DLS(a2,1),ALS(a2,1))
!ALLOCATE(
P(n1+1,1),OUT(5,n1+1),AMAXIM(a2,4),DMAXIM(a2,4),AMAXIMUM(n2,1),DMAXIMUM(n2,1))
!the dim is equal to the number of point fixed to plot the FC.
ALLOCATE(BOOL(nrn,1),BOOL2(nrn,1),BOOL3(nrn,1)) !the dim is equal to the number of point fixed
to plot the FC.

!Open the input file and it store the name of the output file

OPEN(UNIT=207,FILE='idarc.DAT',STATUS='UNKNOWN',ACTION="READWRITE",IOSTAT =
OpenStatus)
READ(207,"(A)",IOSTAT=IOStatus) namefile !read the name of the input file
CLOSE(207)
OPEN(UNIT=202,FILE=TRIM(namefile),STATUS='UNKNOWN',ACTION="READWRITE",IOSTAT
= OpenStatus)
DO
READ(202,"(A)",IOSTAT=IOStatus) TextLine
                        IF (IOStatus  > 0) STOP "***Input error***"
                        IF (IOStatus  < 0) EXIT
        IF (TextLine=='OUTPUT CONTROL')THEN
                        READ(202,"(I2)",IOSTAT=IOStatus) NSOUT !read the number of stories

ALLOCATE (stories(NSOUT,1),X(n1+1,1),TR(n1,1),mean_Resp(NSOUT,n1),std_Resp(NSOUT,n1))
```

```
ALLOCATE(
AMAXIM(a2,n1,NSOUT),DMAXIM(a2,n1,NSOUT),DELTAMAXIM(a2,n1,NSOUT),LOGDELTAMA
XIM(a2,n1,NSOUT))
ALLOCATE( OUT(5,n1+1,NSOUT)) !the dim is equal to the number of point fixed to plot the FC.
ALLOCATE(OUT2(5,n1+1),DELTA_RESP(nrn,n1,NSOUT),A_RESP(nrn,n1,NSOUT))
ALLOCATE (A(n_points,NSOUT),D(n_points,NSOUT),DELTA(n_points,NSOUT))
ALLOCATE(
AMAXIMUM(n2,NSOUT),DMAXIMUM(n2,NSOUT),DELTAMAXIMUM(n2,NSOUT)) !the dim is
equal to the number of point fixed to plot the FC.
ALLOCATE( P(n1+1,1)) !the dim is equal to the number of point fixed to plot the FC.

TR(1,1)=Tr1/Tr4
TR(2,1)=Tr2/Tr4
TR(3,1)=Tr3/Tr4
TR(4,1)=Tr4/Tr4

!store all the names of the output story file.

DO i=1,NSOUT
        READ(202,"(A)",IOSTAT=IOStatus) stories(i,1)
END DO
END IF
END DO
CLOSE(202)


WRITE(*,*) NSOUT
WRITE(*,*) stories(1,1)
WRITE(*,*) stories(2,1)
WRITE(*,*) stories(3,1)
WRITE(*,*) stories(4,1)

!*********************************************************************************
****
!Open the quake_list and save parameters related to each directories.

WRITE(*,*) ' '
WRITE(*,*) 'Enter 1 to calculate the quake list'
WRITE(*,*) '     2 to not calculate the quake list'
WRITE(*,*) '? '
READ(*,*) FC

!*****************************************
!FC=1  !calculate the quake list
!FC=2  !jump to calculate the quake list
!*****************************************

!FC=2

IF (FC==1) THEN
```

```
        WRITE(*,*) "START OF EXTRACTION"

        OPEN(UNIT=1,FILE='quake_list.DAT',STATUS='UNKNOWN',ACTION="READ",IOSTAT =
OpenStatus)
        READ(1, "(A)") TextLine
        dir = FILE$CURDRIVE
        length = GETDRIVEDIRQQ(dir)

        j=1   !Counter for number of TH in the quake list.
        m=1   !Counter of the number of return period considered.
        DO    !

        !read quake list file

        !-------------------------------------------
        !Save maximum values in different directories
        !-------------------------------------------

                READ(1,
'(A10,1X,I1,1X,I7,1X,F10.3,1X,F10.3,1X,F10.3,1X,F10.3,1X,F10.3,1X,F10.3,1X,A3)',IOSTAT=IOStatu
s) WHFILE,IWV,NDATA,DTINP,GMAXH,GMAXV,DTCAL,TDUR,DAMP,ITDMP

                IF (IOStatus  > 0) STOP "***Input error***"

                IF (IOStatus  < 0) EXIT


                        DO st=1,NSOUT
                         WRITE(*,*)'st=',st

                        status = CHANGEDIRQQ(TRIM(dir)//"\"//ADJUSTL(WHFILE(:5)))
                WRITE(*,*)WHFILE

                        OPEN(UNIT=2,
FILE=TRIM(stories(st,1)),STATUS='UNKNOWN',ACTION="READ",IOSTAT = OpenStatus)
                        READ(2,'(9/)')
                        i = 1
                        DO
                                READ(2,'(12X,E11.5,34X,E11.5)',IOSTAT=IOStatus) DISP,ACC
                                IF (IOStatus  > 0) STOP "***Input error***"
                                IF (IOStatus  < 0) EXIT
                                D(i,st)= DISP            !displacement vector
                                A(i,st)= ACC
                                i=i+1
                        END DO

        h1=4114.8   ![mm]
        h2=3810     ![mm]

        IF (st==1) THEN
        DELTA(:,st)=(D(:,st)/h1)*100  !drift first story
```

```
        ELSE IF (st>1) THEN

        DELTA(:,st)=((D(:,st)-D(:,(st-1)))/h2)*100  !drift first story
        END IF

                    Amax = MAXVAL(ABS(A(:,st)))
                    Dmax = MAXVAL(ABS(D(:,st)))
                    DELTAmax = MAXVAL(ABS(DELTA(:,st))) !maximum interstory drift.

                    AMAXIMUM(j,st)=Amax
                    DMAXIMUM(j,st)=Dmax
                    DELTAMAXIMUM(j,st)=DELTAmax        !maximum for each TH.

                    !save the TH of disp and acc in a TXT file

        OPEN(UNIT=3,FILE='DISP_'//TRIM(stories(st,1)),STATUS='UNKNOWN',ACTION="READ
WRITE",IOSTAT = OpenStatus)
                    WRITE(3,'(E11.5)') D
                    CLOSE(3)
                    OPEN(UNIT=4,FILE='ACC_'//TRIM(stories(st,1))
,STATUS='UNKNOWN',ACTION="READWRITE",IOSTAT = OpenStatus)
                    WRITE(4,'(E11.5)') A
                    CLOSE(4)
                    status = CHANGEDIRQQ(TRIM(dir))

                    !Save the max disp and acc for all TH.

        END DO   ! Associated with the number of stories [st]

        DO st=1,NSOUT

        OPEN(UNIT=5,FILE='AMAX_'//TRIM(stories(st,1)),STATUS='UNKNOWN',ACTION="REA
DWRITE",IOSTAT = OpenStatus)
                    WRITE(5,'(E11.5)') AMAXIMUM(1:j,st)

        OPEN(UNIT=6,FILE='DMAX_'//TRIM(stories(st,1)),STATUS='UNKNOWN',ACTION="REA
DWRITE",IOSTAT = OpenStatus)
                    WRITE(6,'(E11.5)') DMAXIMUM(1:j,st)

        OPEN(UNIT=606,FILE='DELTAMAX_'//TRIM(stories(st,1)),STATUS='UNKNOWN',ACTIO
N="READWRITE",IOSTAT = OpenStatus)
                    WRITE(606,'(E11.5)') DELTAMAXIMUM(1:j,st)
        END DO
        CLOSE(100)
        j=j+1
        END DO

        !Redistribution of the matrix
        j=1
        m=1
```

```
!The number of accelerograms for each return period must be the same.

ELSE IF (FC==2.or.FC==1) THEN
WRITE(*,*) "LOAD DELTAMAX files"

!Load drift displacement from file

DO st=1,NSOUT
j=1
DO
	OPEN(UNIT=607,FILE='DELTAMAX_'//TRIM(stories(st,1)),STATUS='UNKNOWN',ACTIO
N="READWRITE",IOSTAT = OpenStatus)
	READ(607,'(E11.5)',IOSTAT=IOStatus) DM
	IF (IOStatus  > 0) STOP "***Input error***"
	IF (IOStatus  < 0) EXIT
	DELTAMAXIMUM(j,st)=DM
j=j+1
END DO
CLOSE(607)
END DO

!Load max acceleration from file

DO st=1,NSOUT
j=1
DO
	OPEN(UNIT=608,FILE='AMAX_'//TRIM(stories(st,1)),STATUS='UNKNOWN',ACTION="RE
ADWRITE",IOSTAT = OpenStatus)
	READ(608,'(E11.5)',IOSTAT=IOStatus) AM
	IF (IOStatus  > 0) STOP "***Input error***"
	IF (IOStatus  < 0) EXIT
	AMAXIMUM(j,st)=AM
j=j+1
END DO
CLOSE(608)
END DO

	DO st=1,NSOUT
DO i=1,n1

	DO j=1,a1

	AMAXIM(j,i,st)=AMAXIMUM(j+(i-1)*a1,st)

	DMAXIM(j,i,st)=DMAXIMUM(j+(i-1)*a1,st)

	DELTAMAXIM(j,i,st)=DELTAMAXIMUM(j+(i-1)*a1,st)

	LOGDELTAMAXIM(j,i,st)=ALOG(DELTAMAXIM(j,i,st))

	END DO
```

```
END DO

        END DO  !Associated with number of stories
        CLOSE(1)
        CLOSE(2)
        CLOSE(5)
        CLOSE(6)
        CLOSE(606)

        WRITE(*,*) 'disp st1'
        WRITE(*,*) LOGDELTAMAXIM(:,:,1)
        WRITE(*,*) 'disp st2'
        WRITE(*,*) LOGDELTAMAXIM(:,:,2)
        WRITE(*,*) 'disp st3'
        WRITE(*,*) LOGDELTAMAXIM(:,:,3)
        WRITE(*,*) 'disp st4'
        WRITE(*,*) LOGDELTAMAXIM(:,:,4)

        WRITE(*,*) "END OF EXTRACTION"
        WRITE(*,*) "START CALCULATING FRAGILITY CURVES"

        !Until here option 1 and 2 are common
        !Until here the program extracts dispalcements and accelerations and
        !it saves the maximum values in 2 files for dispalcements and accelerations.
        !Open again the file limit state, but only to read the limit states.

        st=1
        DO st=1,NSOUT  !counter for different stories

        OPEN(UNIT=7,FILE='limit_states.DAT',STATUS='UNKNOWN',ACTION="READWRITE",I
OSTAT = OpenStatus)
        READ(7,'(/,1X,I1,7X,I1,14X,I3,9X,I3)',IOSTAT=IOStatus) OPTION, CASE_Number, n1, n2
        READ(7,"(1/)")
        WRITE(*,*) '   OPTION=', OPTION,' CASE Num=', CASE_Number,'Num. points=', n1,'Num
TH', n2

        !st=1
        !DO st=1,NSOUT  !counter for different stories

        ls=1 !counter for different limit states
        DO
                READ(7, '(18X,F10.3,3X,F10.3,3X,F10.3,3X,F10.3)',IOSTAT=IOStatus)
meanDLS,niDLS,meanALS,niALS
                IF (IOStatus  > 0) STOP "***Input error***"
                IF (IOStatus  < 0) EXIT

        !The coefficient of variation is espressed as percentage of the mean.


        meanALS=9810*meanALS          ![mm/sec*sec]
```

```
	sigmaDLS=meanDLS*niDLS/100    !Multiply the coefficient of variation by the mean.
	sigmaALS=meanALS*niALS/100    !St. Dev. as percentage of story height.


!	WRITE(*,*) "START OF CALCULATION OF 4 PROBABILITIES OF FAILURE"
	!------------------------------------------------
	!start 4 different CASES for calculating fragility
	!------------------------------------------------

	!******
	!CASE 1
	!******

	IF (CASE_Number==1) THEN
	j=1
	m=1
	P(1,1)=0.0
	X(1,1)=0.0
	!OUT(1,1,st)=0.0
	OUT2(1,1)=0.0

	DO m=1,n1			!number of return periods Tr.It is fixed to four.
		DO  j=1,a2		!till the total number of TH related to one return period Tr.
			IF (DELTAMAXIM(j,m,st) > meanDLS) THEN
				BOOL(j,1)=1
			ELSE IF (DELTAMAXIM(j,m,st) < meanDLS) THEN
				BOOL(j,1)=0
			END IF
		END DO
		P(m+1,1)=SUM(BOOL)/a1			!probability of failure: ratio of 2 real
numbers.
		X(m+1,1)=TR(m,1)			!x axis parameter

		!OUT(1,m+1,st)=X(m+1,1)
		!OUT(m+1,1,st)=0.0			! the probability at time has to be zero.
		!OUT(ls+1,m+1,st)=P(m+1,1)
		OUT2(1,m+1)=X(m+1,1)
		OUT2(m+1,1)=0.0				! the probability at time has to be zero.
		OUT2(ls+1,m+1)=P(m+1,1)
	END DO

	WRITE(*,*) 'P=',P

	!******
	!CASE 2
	!********************
	!STATISTIC LIMIT STATE
	!********************

	ELSEIF (CASE_Number==2) THEN
```

```
   !SUBROUTINE that calculate mean and standard dev. of the log response
          !that is normal distributed.

   CALL MEAN_STDEV(a2,n1,st,DELTAMAXIM,NSOUT,mean_Resp,std_Resp)

          WRITE(*,*) 'mean_Resp=',mean_Resp
          WRITE(*,*) 'std_Resp=',std_Resp

!*************************
!RESPONSE

NR=nrn                    !Number of random numbers to generate.
DO m=1,n1

          XM=ALOG((mean_Resp(st,m))**2/sqrt((mean_Resp(st,m))**2+(std_Resp(st,m))**2)) !Mean of
the underlying normal distribution.   (Input)
          S=sqrt(ALOG((mean_Resp(st,m)**2+std_Resp(st,m)**2)/mean_Resp(st,m)**2))      !Standard
deviation of the underlying normal distribution.   (Input)


          !XM=mean_Resp(st,m)
          !S=std_Resp(st,m)

          CALL RNLNL (NR, XM, S, R)      !it generate random lognormal number at each return period.
   DELTA_RESP(:,m,st)=R(:,1)      !random generation of drift response log-normal distributed
END DO

!*************************
!Limit state

          XM=ALOG((meanDLS)**2/sqrt((meanDLS)**2+(sigmaDLS)**2))  !Mean of the underlying
normal distribution.   (Input)
          S=sqrt(ALOG((meanDLS**2+sigmaDLS**2)/meanDLS**2))       !Standard deviation of the
underlying normal distribution.   (Input)

!         XM=exp(meanDLS+((sigmaDLS)**2)/2)

!         S=sqrt(exp(2*meanDLS+sigmaDLS**2)*(exp(sigmaDLS**2)-1)) !Standard deviation of the
underlying normal distribution.   (Input)

!         XM=meanDLS
!         S=sigmaDLS

  WRITE(*,*) 'XM=',XM
  WRITE(*,*) 'S=',S

          !command to use in external subroutine called RNLNL
!         NR=a2 !number of random number to generate = equal to the total number of accelerograms.

          !CALL RNLNL (NR, XM, S, R)    !subroutine to generate random lognormal number
          ![NR]:Number of random numbers to generate.   (Input)
```

```
	![XM]:Mean of the underlying normal distribution.   (Input)
	![S] :Standard deviation of the underlying normal distribution.   (Input)
	! S must be positive.
	![R] :Vector of length NR containing the random lognormal deviates.   (Output)
	!The log of each element of R has a normal distribution with mean XM and standard deviation S.


	CALL RNLNL (NR, XM, S, R)	!it generate random lognormal number at each return period.
	j=1
	m=1
	P(1,1)=0.0
	X(1,1)=0.0
	OUT2(1,1)=0.0
DO m=1,n1			!number of return periods.it is fixed to four.

		DO  j=1,nrn
			IF (DELTA_RESP(j,m,st) > R(j,1)) THEN
				BOOL(j,1)=1
			ELSE IF (DELTA_RESP(j,m,st) < R(j,1)) THEN
				BOOL(j,1)=0
			END IF
		END DO
		P(m+1,1)=(SUM(BOOL))/nrn	!probability of failure
		X(m+1,1)=TR(m,1)
		OUT2(1,m+1)=X(m+1,1)
		OUT2(m+1,1)=0.0		! the probability at time has to be zero.
		OUT2(ls+1,m+1)=P(m+1,1)
	END DO

	!******
	!CASE 3
	!*****************
	!2 random variables
	!*****************

	ELSEIF (CASE_Number==3) THEN

		!MEAN OF DISPL. RESPONSE

   CALL MEAN_STDEV(a2,n1,st,DELTAMAXIM,NSOUT,mean_Resp,std_Resp)

	WRITE(*,*) 'mean_Resp=',mean_Resp
	WRITE(*,*) 'std_Resp=',std_Resp

	!DISPL. RESPONSES

	NR=nrn			!Number of random numbers to generate.
	DO m=1,n1

		XM=ALOG((mean_Resp(st,m))**2/sqrt((mean_Resp(st,m))**2+(std_Resp(st,m))**2))
!Mean of the underlying normal distribution.   (Input)
```

```
                    S=sqrt(ALOG((mean_Resp(st,m)**2+std_Resp(st,m)**2)/mean_Resp(st,m)**2))
!Standard deviation of the underlying normal distribution.   (Input)


                    !XM=mean_Resp(st,m)
                    !S=std_Resp(st,m)

                    CALL RNLNL (NR, XM, S, R)      !it generate random lognormal number at each return
period.
                    DELTA_RESP(:,m,st)=R(:,1)      !random generation of drift response log-normal
distributed
          END DO

          !MEAN OF ACC. RESPONSE

          CALL MEAN_STDEV_ACC(a2,n1,st,AMAXIM,NSOUT,mean_Resp,std_Resp)

          WRITE(*,*) 'mean_Resp=',mean_Resp
          WRITE(*,*) 'std_Resp=',std_Resp

          !ACC. RESPONSE

          DO m=1,n1

                    XM=ALOG((mean_Resp(st,m))**2/sqrt((mean_Resp(st,m))**2+(std_Resp(st,m))**2))
!Mean of the underlying normal distribution.   (Input)
                    S=sqrt(ALOG((mean_Resp(st,m)**2+std_Resp(st,m)**2)/mean_Resp(st,m)**2))
!Standard deviation of the underlying normal distribution.   (Input)

                    !XM=mean_Resp(st,m)
                    !S=std_Resp(st,m)

                    CALL RNLNL (NR, XM, S, R)   !it generate random lognormal number at each return
period.
                    A_RESP(:,m,st)=R(:,1)       !random generation of drift response log-normal distributed
          END DO

          j=1
          m=1
          P(1,1)=0.0
          X(1,1)=0.0
          OUT2(1,1)=0.0
          DO m=1,n1                          !number of return periods.it is fixed to four.
                    DO  j=1,nrn
                              IF (DELTA_RESP(j,m,st) > meanDLS) THEN
                                        BOOL(j,1)=1
                              ELSE IF (DELTA_RESP(j,m,st) < meanDLS) THEN
                                        BOOL(j,1)=0
                              END IF

                              IF (A_RESP(j,m,st) > meanALS) THEN
```

```
                BOOL2(j,1)=1
            ELSE IF (A_RESP(j,m,st) < meanALS) THEN
                BOOL2(j,1)=0
            END IF
        END DO

        DO j=1,nrn
            BOOL3(j,1)=BOOL2(j,1)+BOOL(j,1)
            IF (BOOL3(j,1)==2) THEN
              BOOL3(j,1)=1
            END IF
        END DO
        P(m+1,1)=(SUM(BOOL3))/nrn       !probability of failure
        X(m+1,1)=TR(m,1)
        OUT2(1,m+1)=X(m+1,1)
        OUT2(m+1,1)=0.0               ! the probability at time has to be zero.
        OUT2(ls+1,m+1)=P(m+1,1)
    END DO
    !PLOT in the plane X-P the fragility curves

    !******
    !CASE 4
    !*****************
    !2 random variables
    !********************
    !STATISTIC LIMIT STATE
    !********************

    ELSEIF (CASE_Number==4) THEN

    !MEAN OF DISPL. RESPONSE

  CALL MEAN_STDEV(a2,n1,st,DELTAMAXIM,NSOUT,mean_Resp,std_Resp)

    WRITE(*,*) 'mean_Resp=',mean_Resp
    WRITE(*,*) 'std_Resp=',std_Resp

    !DISPL. RESPONSES

    NR=nrn                  !Number of random numbers to generate.
    DO m=1,n1
        XM=ALOG((mean_Resp(st,m))**2/sqrt((mean_Resp(st,m))**2+(std_Resp(st,m))**2))
!Mean of the underlying normal distribution.   (Input)
        S=sqrt(ALOG((mean_Resp(st,m)**2+std_Resp(st,m)**2)/mean_Resp(st,m)**2))
!Standard deviation of the underlying normal distribution.   (Input)

        !XM=mean_Resp(st,m)
        !S=std_Resp(st,m)

        CALL RNLNL (NR, XM, S, R)  !it generate random lognormal number at each return
period.
```

```
            DELTA_RESP(:,m,st)=R(:,1)  !random generation of drift response log-normal
distributed
        END DO
        !MEAN OF ACC. RESPONSE
        CALL MEAN_STDEV_ACC(a2,n1,st,AMAXIM,NSOUT,mean_Resp,std_Resp)

        WRITE(*,*) 'mean_Resp=',mean_Resp
        WRITE(*,*) 'std_Resp=',std_Resp

        !ACC. RESPONSE

        DO m=1,n1

            XM=ALOG((mean_Resp(st,m))**2/sqrt((mean_Resp(st,m))**2+(std_Resp(st,m))**2))
!Mean of the underlying normal distribution.   (Input)
            S=sqrt(ALOG((mean_Resp(st,m)**2+std_Resp(st,m)**2)/mean_Resp(st,m)**2))
!Standard deviation of the underlying normal distribution.   (Input)

            !XM=mean_Resp(st,m)
            !S=std_Resp(st,m)

            CALL RNLNL (NR, XM, S, R)     !it generate random lognormal number at each return
period.
            A_RESP(:,m,st)=R(:,1)         !random generation of drift response log-normal distributed
        END DO

        j=1
        m=1
        P(1,1)=0.0
        X(1,1)=0.0
        OUT2(1,1)=0.0
        DO m=1,n1                                  !number of return periods.it is fixed to four.
            !R.GEN. OF DISPL. LIMIT STATE

            XM=ALOG((sigmaDLS)**2/sqrt((meanDLS)**2+(sigmaDLS)**2))  !Mean of the
underlying normal distribution.   (Input)
            S=ALOG((meanDLS**2+sigmaDLS**2)/meanDLS**2)            !Standard deviation of
the underlying normal distribution.   (Input)
            CALL RNLNL (NR, XM, S, R)
            DLS=R                                    !Displacement limit state lognormal distributed

            !R. GEN. OF ACC. LIMIT STATE

            XM=ALOG((sigmaALS)**2/sqrt((meanALS)**2+(sigmaALS)**2))  !Mean of the
underlying normal distribution.   (Input)
            S=ALOG((meanALS**2+sigmaALS**2)/meanALS**2)            !Standard deviation of
the underlying normal distribution.   (Input)
            CALL RNLNL (NR, XM, S, R)
            ALS=R                                    !Acceleration limit state lognormal distributed

                DO  j=1,nrn                          !
```

```
IF (DELTA_RESP(j,m,st) > DLS(j,1)) THEN
                    BOOL(j,1)=1
                ELSE IF (DELTA_RESP(j,m,st) < DLS(j,1)) THEN
                    BOOL(j,1)=0
                END IF
                IF (A_RESP(j,m,st) > ALS(j,1)) THEN
                    BOOL2(j,1)=1
                ELSE IF (A_RESP(j,m,st) < ALS(j,1)) THEN
                    BOOL2(j,1)=0
                END IF
            END DO
            DO j=1,nrn
                BOOL3(j,1)=BOOL2(j,1)+BOOL(j,1)
                IF (BOOL3(j,1)==2) THEN
                 BOOL3(j,1)=1
                END IF
            END DO
            P(m+1,1)=(SUM(BOOL3))/nrn        !probability of failure
            X(m+1,1)=TR(m,1)
            OUT2(1,m+1)=X(m+1,1)
            OUT2(m+1,1)=0.0                  ! the probability at time has to be zero.
            OUT2(ls+1,m+1)=P(m+1,1)
    END DO


    !******
    !CASE 5
    !*****************
    !2 determined limit states related
    !********************
    !STATISTIC LIMIT STATE
    !********************

    ELSEIF (CASE_Number==5) THEN

    pot=15

    !MEAN OF DISPL. RESPONSE

  CALL MEAN_STDEV(a2,n1,st,DELTAMAXIM,NSOUT,mean_Resp,std_Resp)

    WRITE(*,*) 'mean_Resp=',mean_Resp
    WRITE(*,*) 'std_Resp=',std_Resp

    !DISPL. RESPONSES

    NR=nrn               !Number of random numbers to generate.
    DO m=1,n1

        XM=ALOG((mean_Resp(st,m))**2/sqrt((mean_Resp(st,m))**2+(std_Resp(st,m))**2))
!Mean of the underlying normal distribution.   (Input)
```

```
                S=sqrt(ALOG((mean_Resp(st,m)**2+std_Resp(st,m)**2)/mean_Resp(st,m)**2))
!Standard deviation of the underlying normal distribution.   (Input)


                !XM=mean_Resp(st,m)
                !S=std_Resp(st,m)

                CALL RNLNL (NR, XM, S, R)      !it generate random lognormal number at each return
period.
                DELTA_RESP(:,m,st)=R(:,1)           !random generation of drift response log-normal
distributed
        END DO

        !MEAN OF ACC. RESPONSE

        CALL MEAN_STDEV_ACC(a2,n1,st,AMAXIM,NSOUT,mean_Resp,std_Resp)

        WRITE(*,*) 'mean_Resp=',mean_Resp
        WRITE(*,*) 'std_Resp=',std_Resp

        !ACC. RESPONSE

        DO m=1,n1

                XM=ALOG((mean_Resp(st,m))**2/sqrt((mean_Resp(st,m))**2+(std_Resp(st,m))**2))
!Mean of the underlying normal distribution.   (Input)
                S=sqrt(ALOG((mean_Resp(st,m)**2+std_Resp(st,m)**2)/mean_Resp(st,m)**2))
!Standard deviation of the underlying normal distribution.   (Input)

                !XM=mean_Resp(st,m)
                !S=std_Resp(st,m)

                CALL RNLNL (NR, XM, S, R)      !it generate random lognormal number at each return
period.
                A_RESP(:,m,st)=R(:,1)           !random generation of drift response log-normal distributed
        END DO

        j=1
        m=1
        P(1,1)=0.0
        X(1,1)=0.0
        OUT2(1,1)=0.0
        DO m=1,n1                      !number of return periods.it is fixed to four.
                DO  j=1,nrn                    !

                        IF ((A_RESP(j,m,st)/meanALS)+(DELTA_RESP(j,m,st)/meanDLS)**pot-1> 0)
THEN
                                BOOL(j,1)=1
                        ELSE IF ((A_RESP(j,m,st)/meanALS)+(DELTA_RESP(j,m,st)/meanDLS)**pot-
1< 0) THEN
                                BOOL(j,1)=0
```

```
                END IF
            END DO

            P(m+1,1)=(SUM(BOOL))/nrn        !probability of failure
            X(m+1,1)=TR(m,1)
            OUT2(1,m+1)=X(m+1,1)
            OUT2(m+1,1)=0.0              ! the probability at time has to be zero.
            OUT2(ls+1,m+1)=P(m+1,1)
        END DO

        !******
        !CASE 6
        !*****************
        !2 random limit states related.
        !********************
        !STATISTIC LIMIT STATE
        !********************

        ELSEIF (CASE_Number==6) THEN

        !MEAN OF DISPL. RESPONSE

   CALL MEAN_STDEV(a2,n1,st,DELTAMAXIM,NSOUT,mean_Resp,std_Resp)

        WRITE(*,*) 'mean_Resp=',mean_Resp
        WRITE(*,*) 'std_Resp=',std_Resp

        !DISPL. RESPONSES

        NR=nrn                  !Number of random numbers to generate.
        DO m=1,n1

            XM=ALOG((mean_Resp(st,m))**2/sqrt((mean_Resp(st,m))**2+(std_Resp(st,m))**2))
!Mean of the underlying normal distribution.   (Input)
            S=sqrt(ALOG((mean_Resp(st,m)**2+std_Resp(st,m)**2)/mean_Resp(st,m)**2))
!Standard deviation of the underlying normal distribution.   (Input)

            !XM=mean_Resp(st,m)
            !S=std_Resp(st,m)

            CALL RNLNL (NR, XM, S, R)      !it generate random lognormal number at each return
period.
            DELTA_RESP(:,m,st)=R(:,1)      !random generation of drift response log-normal
distributed
        END DO

        !MEAN OF ACC. RESPONSE

        CALL MEAN_STDEV_ACC(a2,n1,st,AMAXIM,NSOUT,mean_Resp,std_Resp)

        WRITE(*,*) 'mean_Resp=',mean_Resp
```

```
        WRITE(*,*) 'std_Resp=',std_Resp

        !ACC. RESPONSE

        DO m=1,n1
        XM=ALOG((mean_Resp(st,m))**2/sqrt((mean_Resp(st,m))**2+(std_Resp(st,m))**2)) !Mean of
the underlying normal distribution.   (Input)
                S=sqrt(ALOG((mean_Resp(st,m)**2+std_Resp(st,m)**2)/mean_Resp(st,m)**2))
!Standard deviation of the underlying normal distribution.   (Input)

                !XM=mean_Resp(st,m)
                !S=std_Resp(st,m)

                CALL RNLNL (NR, XM, S, R)     !it generate random lognormal number at each return
period.
                A_RESP(:,m,st)=R(:,1)        !random generation of drift response log-normal distributed
        END DO

        j=1
        m=1
        P(1,1)=0.0
        X(1,1)=0.0
        OUT2(1,1)=0.0
        DO m=1,n1                                !number of return periods.it is fixed to four.

                !R.GEN. OF DISPL. LIMIT STATE

                XM=ALOG((sigmaDLS)**2/sqrt((meanDLS)**2+(sigmaDLS)**2))  !Mean of the
underlying normal distribution.   (Input)
                S=ALOG((meanDLS**2+sigmaDLS**2)/meanDLS**2)            !Standard deviation of
the underlying normal distribution.   (Input)
                CALL RNLNL (NR, XM, S, R)
                DLS=R                                  !Displacement limit state lognormal distributed

                !R. GEN. OF ACC. LIMIT STATE

                XM=ALOG((sigmaALS)**2/sqrt((meanALS)**2+(sigmaALS)**2))  !Mean of the
underlying normal distribution.   (Input)
                S=ALOG((meanALS**2+sigmaALS**2)/meanALS**2)            !Standard deviation of
the underlying normal distribution.   (Input)
                CALL RNLNL (NR, XM, S, R)
                ALS=R                                  !Acceleration limit state lognormal distributed

                        DO  j=1,nrn                              !parametro che definisce il numero di TH

                                IF ((A_RESP(j,m,st)/ALS(j,1))+(DELTA_RESP(j,m,st)/DLS(j,1))**pot-
1> 0) THEN
                                        BOOL(j,1)=1
                                ELSE IF
((A_RESP(j,m,st)/ALS(j,1))+(DELTA_RESP(j,m,st)/DLS(j,1))**pot-1< 0) THEN
                                        BOOL(j,1)=0
```

```
                    END IF
                END DO
                P(m+1,1)=(SUM(BOOL))/nrn        !probability of failure
                X(m+1,1)=TR(m,1)
                OUT2(1,m+1)=X(m+1,1)
                OUT2(m+1,1)=0.0                ! the probability at time has to be zero.
                OUT2(ls+1,m+1)=P(m+1,1)
        END DO

        END IF
        ls=ls+1
        WRITE(*,*) 'ls=',ls
        END DO  !End do related to different limit states.
        OUT(:,:,st)=OUT2(:,:)
        CLOSE(7)

END DO  !Associated with the number of stories

        ! Write Prob. Failure

        WRITE(*,*) 'story 1'
        WRITE(*,*) OUT(:,:,1)

        WRITE(*,*) 'story 2'
        WRITE(*,*) OUT(:,:,2)

        WRITE(*,*) 'story 3'
        WRITE(*,*) OUT(:,:,3)

        WRITE(*,*) 'story 4'
        WRITE(*,*) OUT(:,:,4)

        !======
        !OUTPUT
        !======
        !
        !Save Prob. failure in a file for each story.
        !
        DO st=1,NSOUT

        OPEN(UNIT=101,FILE='PROB_FAIL'//TRIM(stories(st,1)),STATUS='UNKNOWN',ACTION=
"READWRITE",IOSTAT = OpenStatus)
            WRITE(101,'(F10.5,3X,F10.5,3X,F10.5,3X,F10.5,3X,F10.5)') OUT(:,:,st)
            CLOSE(101)
        END DO  !Associated with the number of stories
        WRITE(*,*) "END OF CALCULATION OF 4 PROBABILITIES OF FAILURE"

!ELSE IF (FC==2) THEN
        DO st=1,NSOUT
WRITE(*,*) 'story',st
```

```
                    IF (OPTION==1) THEN   !Dynamic pushover analysis
                      WRITE(*,*) 'OPTION 1 - under construction'

                      ! CALL another subroutine

                    ELSEIF  (OPTION==2) THEN   !OPTION=[2] Dynamic analysis of accelerograms in
the quake-list.
                              CALL fit_log(st,stories,NSOUT,n1)
                    END IF

          END DO  !Associated with the number of stories

END IF

END PROGRAM FIDARC2D
```

```
SUBROUTINE MEAN_STDEV(a2,n1,st,DELTAMAXIM,NSOUT,mean_Resp,std_Resp)

!***********************************************************************
!it starts procedure to calculate mean and st.dev. of response in DELTAMAXIM
!***********************************************************************

!parameters for subroutine to calculate the mean
INTEGER, INTENT(INOUT) :: a2,st,NSOUT,n1
REAL, INTENT(INOUT) ::
DELTAMAXIM(a2,n1,NSOUT),mean_Resp(NSOUT,n1),std_Resp(NSOUT,n1)
INTEGER    LDSTAT, LDX, NVAR,i,j
INTEGER    IDO, IFRQ, IPRINT, IWT, MOPT, NR, NRMISS, NROW, NV
REAL       CONPRM, CONPRV
REAL, ALLOCATABLE :: STAT(:,:),X(:,:)
LDX=a2    !parameters used for subroutine to calculate the mean of the response
NVAR=n1   !parameters used for subroutine to calculate the mean of the response
LDSTAT=15
ALLOCATE(STAT(LDSTAT,NVAR), X(LDX,NVAR))
!NVAR : Number of variables
!X    : |NROW| by NVAR + m matrix containing the data,
!LDX  : Leading dimension of X
!IWT = 0 means that all weights are 1.0.
!IFRQ = 0 means that all frequencies are 1.0.
!MOPT=0         : The exclusion is listwise. (The entire row of X is excluded
!       if any of the values of the row is equal to the missing value code.)
!CONPRM : Confidence level for two-sided interval estimate of the means
        !(assuming normality), in percent.
!                    No unequal frequencies or weights are used
IFRQ = 0
IWT  = 0
CONPRM = 95.0            !Get 95% confidence limits.
CONPRV = 95.0
MOPT = 0                 !Delete any row containing a missing value
```

```
IPRINT = 0              !print results
NROW=a2
X(:,:)=DELTAMAXIM(:,:,st)
CALL UVSTA (IDO, NROW, NVAR, X, LDX, IFRQ, IWT, MOPT, CONPRM,CONPRV, IPRINT,
STAT, LDSTAT, NRMISS)
WRITE(*,*) 'mean'
WRITE(*,*) STAT(1,:)   !mean
WRITE(*,*) 'std'
WRITE(*,*) STAT(3,:)   !st.dev.
!It stores the values of mean and std. for return periods and different stories.
DO j=1,n1
std_Resp(st,j)=STAT(3,j)
mean_Resp(st,j)=STAT(1,j)
END DO
END SUBROUTINE MEAN_STDEV
```

```
SUBROUTINE MEAN_STDEV_ACC(a2,n1,st,AMAXIM,NSOUT,mean_Resp,std_Resp)

!*****************************************************************
!start procedure to calculate mean and st.dev. of response in AAMAXIM
!*****************************************************************

!parameters for subroutine to calculate the mean
INTEGER, INTENT(INOUT) :: a2,st,NSOUT,n1
REAL, INTENT(INOUT) :: AMAXIM(a2,n1,NSOUT),mean_Resp(NSOUT,n1),std_Resp(NSOUT,n1)
INTEGER    LDSTAT, LDX, NVAR,i,j
INTEGER    IDO, IFRQ, IPRINT, IWT, MOPT, NR, NRMISS, NROW, NV
REAL       CONPRM, CONPRV
REAL, ALLOCATABLE :: STAT(:,:),X(:,:)
LDX=a2    !parameters used for subroutine to calculate the mean of the response
NVAR=n1   !parameters used for subroutine to calculate the mean of the response
LDSTAT=15
ALLOCATE(STAT(LDSTAT,NVAR), X(LDX,NVAR))
!NVAR : Number of variables
!X    : |NROW| by NVAR + m matrix containing the data,
!LDX  : Leading dimension of X
!IWT = 0 means that all weights are 1.0.
!IFRQ = 0 means that all frequencies are 1.0.
!MOPT=0        : The exclusion is listwise. (The entire row of X is excluded
!       if any of the values of the row is equal to the missing value code.)
!CONPRM : Confidence level for two-sided interval estimate of the means
        !(assuming normality), in percent.
!                     No unequal frequencies or weights are used
IFRQ = 0
IWT  = 0
CONPRM = 95.0           !Get 95% confidence limits.
CONPRV = 95.0
MOPT = 0                !Delete any row containing a missing value
IPRINT = 0              !print results
NROW=a2
```

```
X(:,:)=AMAXIM(:,:,st)
CALL UVSTA (IDO, NROW, NVAR, X, LDX, IFRQ, IWT, MOPT, CONPRM,CONPRV, IPRINT,
STAT, LDSTAT, NRMISS)
WRITE(*,*) 'mean'
WRITE(*,*) STAT(1,:)   !mean
WRITE(*,*) 'std'
WRITE(*,*) STAT(3,:)   !st.dev.
!It stores the values of mean and std. for return periods and different stories.
DO j=1,n1
std_Resp(st,j)=STAT(3,j)
mean_Resp(st,j)=STAT(1,j)
END DO
END SUBROUTINE MEAN_STDEV_ACC
```

```
SUBROUTINE fit_log(st,stories,NSOUT,n1)

!*****************************************************************
!The subroutine fits the lognormal distribution to the 4 data points.
!*****************************************************************

!********
!OPTION 2
!********

IMPLICIT NONE
!declaration of variables
REAL:: A,DeltaX,X,Y,sum,B,j,s,s_es,mu,mu_es,min,err,TR,ID,MD,HD,NC
INTEGER, ALLOCATABLE :: ms(:)
REAL, DIMENSION(5,1):: C,E
REAL, DIMENSION(5,4):: Y1
REAL, DIMENSION(101,1):: X1
REAL, DIMENSION(101,4):: P
INTEGER, INTENT(INOUT) :: st,NSOUT,n1
INTEGER::N,I,k,t,d,r,rq,m,w,OpenStatus,IOStatus
CHARACTER*20, INTENT(INOUT):: stories(NSOUT,1)
real*4 l,l2

!3 parameters to define the discretization of mean and sd.

parameter (rq=50,l=0.02,l2=0.2)  !Num points, interval mean, interval std.
REAL, DIMENSION(rq,1):: s1,mu1
REAL, DIMENSION(rq,rq):: Q
d = SIZE(SHAPE(Q))       !Get the number of dimensions in array
ALLOCATE (ms (d) )

i=1

!open the outfile with four data points.
```

```
OPEN(UNIT=101,FILE='PROB_FAIL'//TRIM(stories(st,1)),STATUS='UNKNOWN',ACTION="READ
WRITE",IOSTAT = OpenStatus)
DO
        READ (101,'(F10.5,3X,F10.5,3X,F10.5,3X,F10.5,3X,F10.5)',IOSTAT=IOStatus)
TR,ID,MD,HD,NC
        IF (IOStatus  > 0) STOP "***Input error***"
        IF (IOStatus  < 0) EXIT
        WRITE(*,*) TR,ID,MD,HD,NC
                C(i,1)=TR
          Y1(i,1)=ID
          Y1(i,2)=MD
          Y1(i,3)=HD
          Y1(i,4)=NC
i=i+1
write(*,*)'i=', i

END DO
CLOSE(101)

w=1
DO w=1,4            !limit states
!3 parameters to adapt to do the estimation
!maximum error permitted
err=0.1
m=-4
min=1
DO WHILE (min.GT. err)
IF (m>0) STOP "***NOT CONVERGE - change limit of ERF***" !to stop the program when not
converge.
        m=m+1
        WRITE(*,*) 'Calculating Curve Fitting...'
        WRITE(*,*) 'mean=',m
!generate different values of mean and st.dev.
DO k=1,rq
        s1(k,1)=l2*k
        mu1(k,1)=l*k+m
END DO

        DO k=1,rq       !sd of lognorm.
                DO t=1,rq    !mean of lognorm.
                        DO j=1,n1 !return period    Piazzo i 4 punti e faccio il fitting.
                        A=0.001   !lower limit of integral. It must be close to zero [fixed]
                        N=1000   !number of sub intervals to calculate the integral [fixed]
                        i=1
                        !Calculate subinterval length
                        !and initialize the approximating Sum and X

                        B=C(j+1,1)    !upper limit of integral corresponding to each return period
                        s=s1(k,1)     !sd
                        mu=mu1(t,1)   !mean
                        DeltaX=(B - A)/Real(N)
```

```
                    X=A
                    Sum=0.0
                    DO I=1,N-1
                              X=X+DeltaX
                              Y=F(X)
                              Sum=Sum+Y
                    END DO
                    Sum=DeltaX*((F(A)+F(B))/2.0+Sum)
                    E(j,1)=(Sum-Y1(j+1,w))                    !square of error function
                    END DO

                    IF (n1==4) THEN
                    Q(k,t)=E(1,1)**2+E(2,1)**2+E(3,1)**2+E(4,1)**2   !function to minimize
                    ELSE IF(n1==3) THEN
                    Q(k,t)=E(1,1)**2+E(2,1)**2+E(3,1)**2           !function to minimize
                    END IF

          END DO
     END DO

min=MINVAL(Q)
ms = MINLOC (Q)
 s_es=(l2)*ms(1)
mu_es=(l)*ms(2)+m
END DO
WRITE(*,*) 'estimated error function is:',min
WRITE(*,*) ms
WRITE(*,*) 'estimated standard deviation is:', s_es
WRITE(*,*) 'estimated mean is:', mu_es
CALL DISCR_LOG(s_es,mu_es,C,Y1,w,X1,P,n1)
END DO  ! associated with w and limit states

!***********************************
!Save fragility curves in a txt file.
!***********************************

OPEN(UNIT=1,FILE='FRAG_CURVES'//TRIM(stories(st,1)),STATUS='UNKNOWN',ACTION="REA
DWRITE",IOSTAT = OpenStatus)
DO j=1,101
     WRITE(1,'(F10.5,3X,F10.5,3X,F10.5,3X,F10.5,3X,F10.5)') X1(j,1),P(j,1),P(j,2),P(j,3),P(j,4)
END DO
CLOSE(1)

CONTAINS

! - F(X)--------------------------------------------------
!The integrand - Cumulative lognormal distribution function
!--------------------------------------------------------

FUNCTION F(X)
REAL :: F
```

```
REAL,INTENT(IN)::X
F=(1/(X*s*sqrt(2*3.14)))*EXP(-(log(X)-mu)**2/(2*s**2))
END FUNCTION F

END SUBROUTINE fit_log
```

```
subroutine DISCR_LOG(s_es,mu_es,C,Y1,w,X1,P,n1)

!*****************************************************************************
!The subroutine generate the discrete number of the fitted lognormal distribution
!*****************************************************************************

IMPLICIT NONE
!declaration
REAL, INTENT(IN) :: s_es,mu_es
INTEGER, INTENT(INOUT) :: w,n1
REAL:: A,DeltaX,X,Y,sum,B,j,s,mu,min
REAL,INTENT(INOUT)::C(n1+1,1),Y1(n1+1,4)
REAL,INTENT(INOUT), DIMENSION(101,1):: X1
REAL,INTENT(INOUT), DIMENSION(101,4):: P
INTEGER::N,I,t,d,r
INTEGER :: OpenStatus,IOStatus
!fragility curve with 100 points.
j=1
DO j=1,100  !number of points on each fragility curve

            A=0.001  !lower limit. It must be close to zero
            N=1000  !number of sub intervals to calculate the integral
            i=1

            !Value on the x axis of the four points
            !fixed according to the return period

            !Calculate subinterval length
            !and initialize the approximating Sum and X

            !B=C(j,1)
            B=0.01*j
            s=s_es
            mu=mu_es
            DeltaX=(B - A)/Real(N)
            X=A
            Sum=0.0
            !Now calculate and display the sum
            DO I=1,N-1
                  X=X+DeltaX
                  Y=F(X)
                  Sum=Sum+Y
            END DO
```

```
                    Sum=DeltaX*((F(A)+F(B))/2.0+Sum)
X1(1,1)=0
P(1,1)=0
X1(j+1,1)=B
P(j+1,w)=Sum
END DO
CALL PLOT(X1,P,C,Y1,w,n1)       !subroutine that call the program DPLOT_JR
CONTAINS

! - F(X)--------------------------------------------------
!The integrand - Cumulative lognormal distribution function
!---------------------------------------------------------

FUNCTION F(X)
REAL :: F
REAL,INTENT(IN)::X
F=(1/(X*s*sqrt(2*3.14)))*EXP(-(log(X)-mu)**2/(2*s**2))
END FUNCTION F
END subroutine DISCR_LOG
```

```
c
c FTEST - tests DPLOTLIB.DLL with Compaq Visual Fortran 6.6
c
c This program has been tailored for Compaq Visual Fortran 6.6. Other Fortran compilers may require
c changes, particularly in the interface to DPlot_Plot.
c
c Things to watch for with other compilers and general notes:
c
c 1) By default, most Fortran compilers translate the names of all functions/subroutines to UPPERCASE.
c    The name "DPlot_Plot" in the DLL is case-specific. In other words you will most likely encounter
c    an "unresolved external" error on DPLOT_PLOT unless you take steps to tell the compiler not to
c    fold all characters to uppercase. If you are certain that you've taken the correct steps in this
c    regard and continue to get linker errors, the problem most likely lies with...
c
c 2) DPLOTLIB.LIB - The import library for DPLOTLIB.DLL. The Compaq Visual Fortran and Absoft
Fortran
c    demos use the same import library as the C demo, which was produced as a byproduct of compiling
c    DPLOTLIB.DLL by the MSVC compiler. The DPLOTLIB.LIB used by the WATCOM Fortran demo
was produced
c    with "wlib dplotlib +dplotlib.dll". This import library will almost certainly not work with other
c    compilers. If the import library does not work correctly, check your compiler's documentation for
c    the method used to produce import libraries from compiled DLL's.
c
c 3) The last parameter to DPlot_Plot is a character string containing DPlot commands. This character
c    string must be null-terminated (ends in a 0 byte). If you do NOT terminate this character string
c    with a char(0), at best DPlot will report an error in the command string; at worst DPlot and/or
c    this demo will crash. This restriction does not apply to the character string members of the DPlot
c    structure, although adding a terminating char(0) to those strings will not hurt anything.
c
      subroutine PLOT(X1,P,C,Y1,w,n1)
```

```
      implicit none
      include  'dplot.fi'

      structure /XYZ/
        real*4 x
        real*4 y
        real*4 z
      end structure
            REAL,INTENT(INOUT)::n1
            !REAL,INTENT(INOUT)::C(n1+1,1),Y1(n1+1,4)
            REAL,INTENT(INOUT), DIMENSION(5,1):: C
            REAL,INTENT(INOUT), DIMENSION(5,4):: Y1
            REAL,INTENT(INOUT), DIMENSION(101,1):: X1
            REAL,INTENT(INOUT), DIMENSION(101,4):: P
            INTEGER, INTENT(INOUT)::w

      !real*4   random

      integer*4 NP
      parameter (NP=101)

      record  /DPLOT/ DPlot
      !record  /XYZ/ Node(NZ)
      real*4  x(2*NP), y(2*NP)
      real*4  extents(4)
      !real*4  z(NX*NY)
      real*4  PI
      real*4  dummy
      integer option
      integer i, j, k
      integer ret
      !integer seed

      PI = 4.*atan(1.0) !strange way to define pi.



            !C(1,1)=0.2  !PGA associated to return period
            !C(2,1)=0.4
            !C(3,1)=0.6
            !C(4,1)=0.8

                        !Values of the four points on the y axis

            !Y1(1,1)=0.01
            !Y1(2,1)=0.1
            !Y1(3,1)=0.45
            !Y1(4,1)=0.7

100  continue
```

```
      write(*,*) 'Enter 0 to exit'
      write(*,*) '      1 for XY plot of fragility curves'
      write(*,*) '? '
      read(*,*) option

      select case(option)
      case(1)
c       Plot sin(PI*x) and cos(PI*x) from x = 0 to 4.
c       In this case we've used DATA_XYYY (one X array for one or more Y arrays).
c
c       Since the X values are evenly spaced we could also use
c       DATA_DXY  - X has only 2 elements, DX and X0
c
c       And you can ALWAYS use
c       DATA_XYXY - Each curve uses its own X array. This is the only
c                   option available if the curves have different X values or
c                   a different number of points.
        do i=1,NP
          x(i)   = X1(i,1)
                    !x(i)=(4.*i)/(NP-1)
          y(i)   = P(i,w)
      IF (i<=5) THEN
                    x(i+NP)=C(i,1)
                    y(i+NP)=Y1(i,w)
            ELSE IF (i>5) THEN
                    x(i+NP)=0
                    y(i+NP)=0
            END IF
                    !y(i)   = sin(PI*x(i))
          !y(i+NP)= cos(PI*x(i))
        end do


        DPlot.Version     = DPLOT_DDE_VERSION
        DPlot.hwnd        = 0
        DPlot.DataFormat  = DATA_XYXY
        DPlot.MaxCurves   = 2
        DPlot.MaxPoints   = NP
        DPlot.NumCurves   = 2
        DPlot.Scale       = SCALE_LINEARX_LINEARY
        DPlot.LegendX     = 0.05
        DPlot.LegendY         = 0.05
        DPlot.NP(1)       = NP
        DPlot.NP(2)       = NP
        DPlot.LineType(1) = LINESTYLE_SOLID
        DPlot.LineType(2) = LINESTYLE_NONE
        DPlot.SymbolType(1) = 0
        DPlot.SymbolType(2) = 3
            DPlot.Legend(1)   = 'Analytical Fragility curve'
c                              {\s is DPlot-speak for "use symbol font"
        DPlot.Legend(2)   = 'Experimental points'
```

```
      DPlot.Title(1)    = 'FRAGILITY CURVES'
      DPlot.XAxis       = 'Tr/Tr[MAX] - Tr[max]=2500 years'
      DPlot.YAxis       = 'P_failure'
c
c       The command string can be as complex as you like, limited to 32K characters.
c       As an alternative, if your program will be producing many similar plots then
c       you might prefer to create a preferences file, edit the file with a text
c       editor to remove unwanted entries, and use the [GetPreferences("filename")]
c       command.
c
      ret = DPlot_Plot(loc(DPlot),x(1),y(1),
     1             '[ManualScale(0,0,1,1.0)]'//
     2             '[TickInterval(1,0.1,0.2)]'//
     3             '[Caption("DPLOTLIB XY Test")]'//
     4             '[DocMaximize()]'//
     5             '[ClearEditFlag()]'//char(0))

     case(0)
      goto 9999

     end select

     goto 100
9999  continue
     END SUBROUTINE PLOT
c
c=======================================================================
c
     !real*4 function random(iseed)
     !implicit none
     !integer*4 iseed

     !iseed = mod(iseed*7141+54773,259200)
     !random = real(iseed)/259200.
     !return
     !end
```

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