International Journal of Engineering and Techniques - Volume 4 Issue 6, Nov-Dec 2018

RESEARCH ARTICLE OPEN ACCESS

An Experimental Development of Fragility Curves & Performance Analysis of Ferro-Concrete Frame under Moderate Loading Conditions

Mr.Imandi Vamsi Kiran* Mr.CH.Bhaskara Rao**

*M.Tech - Scholor, Dept. of Civil Engineering. Aditya college of engineering and technology
**Assistant Professor, Aditya college of engineering and technology Kakinada, Andhra Pradesh, INDIA.

Abstract

When earthquake loads are the functions of ground motion intensity or other design parameters, Fragility curves provide the conditional probability of structural response. Seismic fragility curves are used mainly by decision makers for the assessment of seismic losses both for pre-earthquake disaster planning as well as post-earthquake recovery programs. Generation of fragility curves in conventional methods involves development of large number of computational models that represent the inherent variation in the material properties of particular building type and its earthquake time history analyses to obtain an accurate and reliable estimate of the probability of exceedance of the chosen damage parameter. There are many Response surface methods available in the literature that is capable of representing the limit state surface depending on the problem type. High Dimensional Model Representation (HDMR) method is a type of response surface method that can express input-output relations of complex computational models. This input-output relation can reduce the number of iterations of expensive computations especially in problems like fragility curve development. Unnikrishnan *et al.* (2012) applied this technique in fragility evaluation for the first time and demonstrated its computational efficiency compared to computationally intensive Monte Carlo method. In this study, fragility curve of an RC frame is developed using HDMR response surface method. There are also other simplified approaches which are computationally easy for fragility curve development. Cornell *et.al.* (2002) proposed such a simplified method which assumes a power law model between the damage parameter and intensity measure of earthquake. This study presents Fragility curves evaluated using HDMR and its computational efficiency with reference to the one using the method suggested by Cornell *et al* (2002).

Keywords: *HDMR, Fragility Curve, Cornell's Method, Latin Hypercube Sampling, MCS, Probability of exceedance*

Introduction

Former to an earthquake, vulnerability evaluations of buildings are normally carried out for judging the requirement for strengthening vital facilities and buildings against later earthquakes. The best way to accomplish such assessments is Fragility curves. Fragility curves epitomise the conditional probability that a response of a particular structure may exceed the performance limit at a given ground motion intensity. These curves are valuable tools for the valuation of probability of structural damage due to earthquakes as a function of ground motion indices otherwise design parameters.

Fragility curves - show the probability of failure verse us peak ground acceleration. Fig 1.1 shows a typical fragility curve with PGA along the x-axis and probability of failure along y-axis. A point in the curve represents the probability of exceedance of the damage parameter, which can be lateral drift, storey drift, base shear etc., over the limiting value mentioned, at a given ground motion intensity parameter.

Earthquake engineering has evolved over the years and it is now moving towards Performance-based methods rather than the existing force based approaches. The concept of design for the force is now changing towards design for a particular performance objective required by the stake holders.

The engineers are familiar with the performance measures such as strain, drift, acceleration etc. but the stakeholders may be more familiar with cost involved for design making. To convert the performance of a particular structure to a format involving repair cost in a systematic way there are many factors to consider. Probabilistic seismic hazard (Probability of earthquake with certain intensity), Response analysis (Exceedance probability of a demand parameter of structure for a specific intensity measure of earthquake), Damage analysis (Damage of structure given a particular demand parameter), Loss analysis (Cost involved for a particular damage) are the four components of the a performance based earthquake engineering frame work introduced by Moehle and Deierlein (2004). Figure 1.2 shows the components involved in performance-based earthquake engineering frame work. The second component in this frame work is the development of fragility curves.

The intensity measure here is the spectral displacement of the earthquake. As the limiting value increases the curve shifts towards right and becomes more flat. From the figure it can be seen that at weak shaking the probability of exceedance for the limit state corresponding to slight damage is high. For strong earthquakes probability of exceedance is 100% for the first curve, which means slight damage is sure, moderate and extensive damages are likely to occur. But probability that complete damage will occur is low. Regions of various damage states such as slight, moderate, Extensive and complete damages are marked between each fragility curves. With the severity of damage, the parameter defining the limit state of damage increases, and the exceedance probability decreases. For an earthquake with spectral intensity corresponding to weak shaking, the exceedance probability for the slight damage is quite high and the levels defined by higher damage states such as moderate, Extensive, complete are very negligible. Whereas if there is an earthquake of strong intensity the building is more likely to be crossed the damage states of slight and moderate. The exceedance probability for the extensive damage state is more than that of complete damage state.

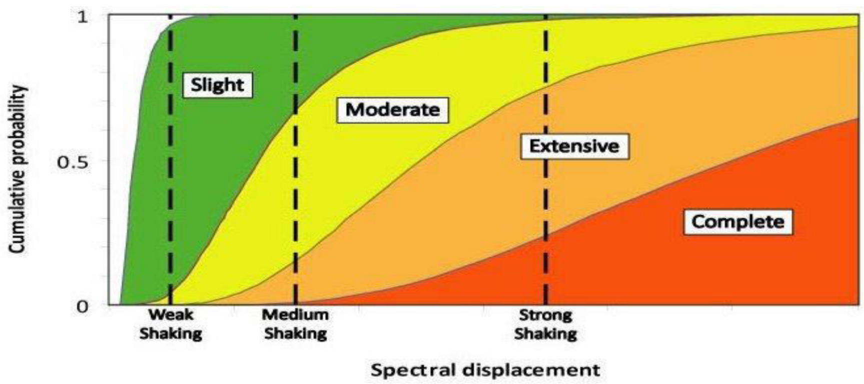

Figure 1.3 Fragility curves for 4 different limit states (Tobas and Lobo 2008)

1.2 Methods of Developments of Fragility Curves:

Conventional methods for computing building fragilities are:

- Monte Carlo simulation (MCS)
- Cornell *et al.* (2002)
- Response Surface Method
- ATC-63

The Monte Carlo simulation is a statistical simulation procedure that provides reasonably accurate solutions to problems expressed mathematically. It employs a sequence of random numbers to execute the simulation. This tactic requires fairly large number of models to obtain a satisfactorily reliable evaluation of fragilities which makes it computationally expensive and also time consuming.

The Latin hypercube sampling method is a competent sampling technique which makes sure that the complete ranges of input variables are sampled. Metamodels are a more advanced approach for fragility analysis, which is a statistical estimate of the complex and implicit occurrences, expressed by the use of response surface methods. Response is evaluated in a closed-form function of input variables thus reducing the computational effort. One of the most common metamodel used is the response surface methodology. This methodology states not simply to the use of a response surface as a multivariate function, but also to the determination of polynomial coefficients. A response surface equation is simply a polynomial representation to a data set. The process of obtaining the polynomial is more accurate by using a large data set. Cornell *et al.* (2002) proposed a methodology to characterize the fragility function as the probability of exceedance of the designated Engineering Demand Parameter (EDP) for a selected physical limit state (DS) for a particular ground motion intensity quota (IM). Fragility curve reaching a specified damage state or more is represented as a function of that particular demand.

Schotanus (2002) applied a general and urbane method for seismic fragility analysis of systems previously proposed by Veneziano *et.al* (1983) to a reinforced concrete frame. Response surface was used to switch the capacity part in an analytical limit-state function (g- function), with a categorical functional relationship which fits a second order polynomial, and is used as input for SORM analysis. Such an explicit function highly reduces the number of costly numerical analyses needed compared to classical methods that determine the failure domain.

High Dimensional Model Representation:

Two types of HDMRs were demonstrated by Rabitz H *et al.* (1999): ANOVA-HDMR which is the same as the analysis of variance (ANOVA) decomposition used in statistics, and cut-HDMR which was be shown to be computationally more efficient than the ANOVA decomposition. Application of the HDMR tools affectedly reduced the computational struggle needed in representing the input–output relationships of a physical system.

Alis and Rabitz (2001) illustrated the application of Random-sample High Dimensional Model Representation (RS-HDMR) by captivating two examples, Sensitivity analysis and an inverse problem in dynamical systems. RS-HDMR was shown to be computationally very efficient to compute sensitivity catalogues with high accuracy, and as such this method can be used to construct a data-generating dynamical system.

An illustration of High Dimensional Model Representation was carried out by Li *et al.* (2001) in financial instruments whose value derives from the value of other merchandises. They also suggested the application of this method in industrial plant or economic system performance under conditions of constrained resources, and other similar mathematical problems.

Rajib *et al.* (2009) proposed a new computational tool for forecasting failure probability of structural/mechanical systems subject to random loads, material properties, and geometry. The method involved high-dimensional model representation (HDMR) that facilitates lower-dimensional approximation of the original high dimensional implicit limit state/performance function.

Methodology of HDMR in Fragility Evaluation

The principal step in the computation of the seismic fragility curves using HDMR is the definition of the input and output variables. Seismic intensity parameter is also defined and used as an input variable. To recognize the damage states, depending upon the type of structure being considered, Base Shear, Maximum Roof displacement, Peak interstorey drift, Damage indices, Ductility ratio and Energy dissipation capacity can be used.

Various combinations of input variables were generated, which represents different earthquake-structure circumstances and the sampling points of the HDMR. Computational seismic analysis was performed on those structural models using Scaled earthquake records (20 in number) as the loading inputs. Mean and standard deviation of the response from the analysis using 20 earthquake records for each combination of input variables were calculated. Metamodels, which are polynomial functions representing the mean and standard deviation of the responses, were framed by applying HDMR technique. Metamodels are polynomial functions representing the mean and standard deviation.

Development of Fragility Curves Using HDMR:

This chapter is based on the development of the fragility curves using HDMR technique. The frame considered uncertainties in material properties and ground motion data, limit states and finally fragility evaluation is detailed here. For the study, the peak ground acceleration is taken as the seismic intensity measure and the roof displacement is considered as the engineering demand parameter for generation of fragility curves for different performance levels.

In this study an RC frame having six stories and three bays is considered. The frame is designed according to IS 456-2000 using M20 concrete and Fe415 steel. The details of the building elevation and reinforcement details of beams and columns are shown in Figure 3.1. The frame is having a storey

3.4 Modeling of Uncertainties

The uncertainties in the material properties are unavoidable in reality. The uncertainty in the material properties are modelled by considering the parameters defining the materials as random variables. Some of studies (Rajeev and Tesfamariam, 1999, Únnikrishnan *et al.,* 2012) conducted shows that the major random variables to be considered in fragility study are compressive strength of concrete ( ), yield strength of steel ( ) and Young‘s modulus of concrete ( ). The distribution characteristics and the values used in this work is taken from Ranganathan (1990) and these are specified in Table 3.1.

Table 3.1 Statistics of Random Variables‘

Material	Mean (Mpa)	COV (%)	Distribution
Concrete	19.54	21.0	Normal
Concrete	34100	20.6	Normal
Steel	469	10	Normal

Arthquake Ground Motions

Randomness in ground motion is taken into account by using 44 scaled earthquake records. The ground motion data is taken from the work done by Haselton *et al.(*2007). In this research and related work, a general far-field ground motion set was established for use in structural analyses and performance valuation. 22 pairs of motions that cover the FEMA P695 (ATC-63) far-field ground motion set details of which are given in Table 3.2. This 22 pairs (44 components) of ground motions are used in this study.Table 3.2 Details of Earthquake records considered as per FEMA P695 (ATC-63)

Sl No	Magnitude	Year	Event	Fault type	Station name	Vs_30 (m/s)
1	6.7	1994	Northridge	Blind thrust	Beverly Hills - 14145 Mulhol	356
2	6.7	1994	Northridge	Blind thrust	Canyon Country - W Lost Cany	309
3	7.1	1999	Duzce, Turkey	Strike-slip	Bolu	326
4	7.1	1999	Hector Mine	Strike-slip	Hector	685
5	6.5	1979	Imperial Valley	Strike-slip	Delta	275
6	6.5	1979	Imperial Valley	Strike-slip	El Centro Array #11	196
7	6.9	1995	Kobe, Japan	Strike-slip	Nishi-Akashi	609
8	6.9	1995	Kobe, Japan	Strike-slip	Shin-Osaka	256
9	7.5	1999	Kocaeli, Turkey	Strike-slip	Duzce	276
10	7.5	1999	Kocaeli, Turkey	Strike-slip	Arcelik	523
11	7.3	1992	Landers	Strike-slip	Yermo Fire Station	354
12	7.3	1992	Landers	Strike-slip	Coolwater	271
13	6.9	1989	Loma Prieta	Strike-slip	Capitola	289
14	6.9	1989	Loma Prieta	Strike-slip	Gilroy Array #3	350
15	7.4	1990	Manjil, Iran	Strike-slip	Abbar	724
16	6.5	1987	Superstition Hills	Strike-slip	El Centro Imp. Co. Cent	192
17	6.5	1987	Superstition Hills	Strike-slip	Poe Road (temp)	208
18	7	1992	Cape Mendocino	Thrust	Rio Dell Overpass - FF	312
19	7.6	1999	Chi-Chi, Taiwan	Thrust	CHY101	259
20	7.6	1999	Chi-Chi, Taiwan	Thrust	TCU045	705
21	6.6	1971	San Fernando	Thrust	LA - Hollywood Stor FF	316
22	6.5	1976	Friuli, Italy	Thrust-part blind	Tolmezzo	425

Failure Criteria and Performance Limits

In this study roof displacement as often preferred by many researchers is taken as the failure criteria because of the ease and convenience allied with its estimation. The limit states considered are according to Federal Emergency Management Agency (FEMA) 356. The limit states associated with various performance levels of reinforced concrete frames is given in Figure 3.2 and Table 3.3 (FEMA 356, 2000).

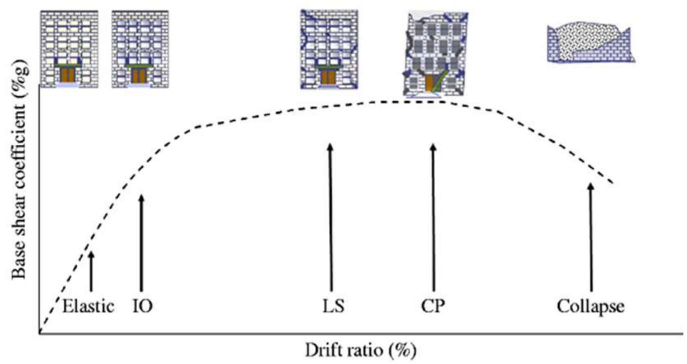

Figure 3.2 Damage states of a representative building pushed to failure (FEMA356)

Table 3.3 Limits associated with various structural performance levels

Structural performance level	Permissible top storey drift
Immediate Occupancy (IO)	1%
Life Safety (LS)	2%
Collapse Prevention (CP)	4%

Fragility Evaluation Using Cornell's Method

In this chapter a conventional method for development of fragility curve is used. The method is termed Cornell‘s method in this study which was developed by Cornell *et al.* in the year 2002. The detailed description of the method has been explained in Chapter 2. This method assumes power law to represent the input (PGA) and output (roof displacement) relation. This method uses Latin Hypercube sampling to generate the input sets. The same uncertainties in materials and ground motion, as taken in HDMR method conducted in Chapter 3, are used in this method also.

Cornell's Method

Latin Hypercube sampling is a sampling technique designed to accurately produce the input distribution through sampling in fewer repetitions when compared with the Monte Carlo method. The fundamental to Latin Hypercube sampling is stratification of the input probability distributions. Stratification divides the cumulative curve into equal interims on the cumulative probability scale (0 to 1.0). A model is then randomly taken from each interval or stratification of the input distribution. Sampling is enforced to represent values in each interval, and thus, is forced to recreate the input probability distribution. A sample is taken from every stratification.

Computational models of the frame are developed for the 30 sets of random variables. PGA values, which are used to scale the ground motion intensities, are uniformly distributed in the range of 0.1g to 1.0g to 30 values. For each set, time history analysis is done with the 44 earthquake records, scaled using the PGA values, and mean of maximum roof displacement obtained from each set is taken. The maximum roof displacements are also specified in Table 4.1.

Table 4.1 Set of input variables for Cornell's Method of Fragility evaluation

Sl No.	( )	( )	( )	()	y (mm)
1	1.60E+01	4.90E+04	5.06E+02	0.13	108.0182
2	2.00E+01	4.04E+04	4.79E+02	0.16	124.9727
3	2.20E+01	4.57E+04	4.75E+02	0.19	145.0203
4	2.80E+01	2.86E+04	4.37E+02	0.22	193.1908
5	1.80E+01	3.20E+04	5.25E+02	0.25	197.3111
6	2.10E+01	3.50E+04	4.67E+02	0.28	210.4379
7	2.00E+01	4.25E+04	4.42E+02	0.31	231.1819
8	1.40E+01	3.44E+04	5.34E+02	0.34	270.5515
9	1.90E+01	3.96E+04	4.59E+02	0.37	277.4043
10	1.50E+01	1.92E+04	4.47E+02	0.4	311.4825
11	2.30E+01	3.26E+04	4.55E+02	0.43	317.1274
12	1.70E+01	3.07E+04	4.32E+02	0.46	358.5697
13	2.00E+01	2.57E+04	4.20E+02	0.49	383.3279
14	1.80E+01	3.88E+04	5.69E+02	0.52	404.1237
15	2.10E+01	3.75E+04	5.46E+02	0.55	422.5428
16	1.80E+01	3.68E+04	4.87E+02	0.58	469.1865
17	2.20E+01	2.68E+04	4.13E+02	0.61	520.29
18	2.30E+01	4.38E+04	4.27E+02	0.64	543.7953
19	2.60E+01	3.81E+04	4.63E+02	0.67	585.1315
20	1.90E+01	3.32E+04	5.11E+02	0.7	593.7053
21	1.10E+01	3.62E+04	4.04E+02	0.73	723.4289
22	1.70E+01	3.56E+04	3.69E+02	0.76	782.3677
23	2.40E+01	2.44E+04	3.92E+02	0.79	761.3428
24	1.60E+01	3.38E+04	4.91E+02	0.82	764.4065
25	2.40E+01	3.01E+04	4.96E+02	0.85	771.214
26	2.10E+01	2.94E+04	5.01E+02	0.88	816.4072
27	2.50E+01	2.78E+04	4.71E+02	0.91	864.1148
28	1.30E+01	3.14E+04	4.83E+02	0.94	937.8056
29	1.90E+01	2.25E+04	4.51E+02	0.97	970.2053
30	1.50E+01	4.14E+04	5.18E+02	1	986.3147

Probabilistic Seismic Demand Model (PSDM)

Probabilistic seismic demand model is the relationship between maximum displacement (EDP) and the PGA (IM). Cornell (2002) assume power law model for PSDM as given by Equation 2.4. In order to find the parameters of the PSDM model, the maximum roof displacement (y) and the corresponding PGA from the set 1 to 30 is expressed in a logarithmic graph. The parameters of the power law model (a, b) are found out by regression method for the frame to form the PSDM model. Figure 4.1 shows the plot of maximum roof displacement (y) and the corresponding PGA values in logarithmic graph. The straight line is the fitted curve and the parameters of the PSDM model are obtained as a = 928.75 and b = 1.1261 which is also shown in Figure 4.1.

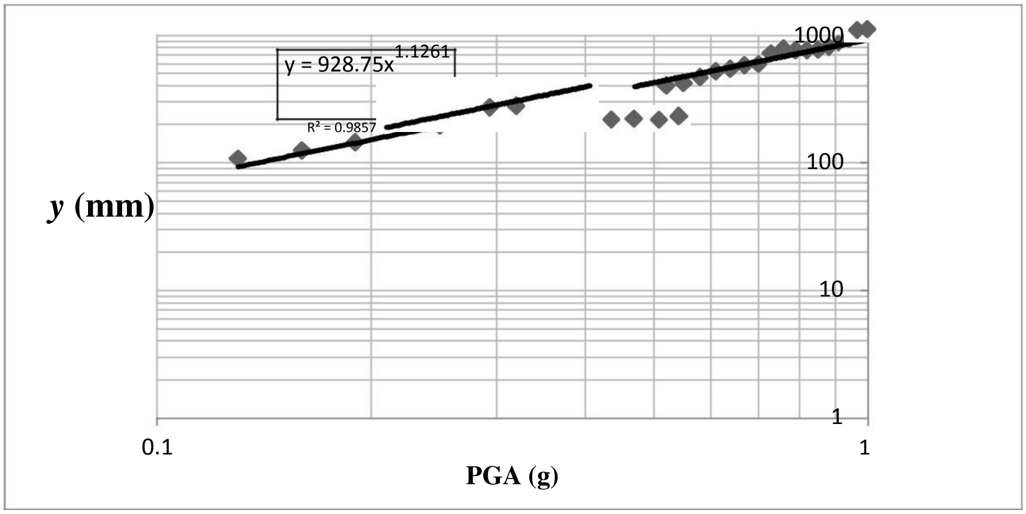

Figure 4.1 Probabilistic Seismic Demand Model (a=928.75, b= 1.1261)

Fragility Curve

The dispersion in capacity, β_c is reliant on the building type and construction excellence. For β_c, ATC 58 50% draft suggests 0.10, 0.25 and 0.40 depending on the quality of construction. In this study, dispersion in capacity has been assumed as 0.25.

Comparison of Fragility Curves Obtained Using HDMR and Cornell's Method

In this section the fragility curves developed using HDMR technique and Cornell's method is compared. Plots showing fragility curves using both the methods, taking into account each limit states, is shown in different figures. Figure 4.3 shows both curves for Immediate Occupancy, Figure 4.4 and 4.5 shows the comparison of the curves for Life Safety and Collapse Prevention limit states respectively. From the graphs showing the comparison of both methods the initial part seems to be same but the later part of the curve shows slight difference. The error in the fragility curve developed by HDMR method compared to that of Cornell method can be estimated using an error index proposed by Menjivar (2004). The error index is calculated for all the three cases and presented in the Table 3.6. This can be due to the various assumptions and approximations of the two approaches.

Comparison of Computational Efficiency

A comparison of computational efficiency between HDMR and Cornell's method is given in Table 3.7. To have a comparison with the Monte Carlo Simulation (accurate) the expected computational requirement for the same is also tabulated. Time taken for single analysis (computational model developed using a set of input variables and its time history analysis for 44 scaled earthquake records) is about 5 hours. From the table it is evident that HDMR method is fairly efficient in the computational time when compared to MCS.

Table 4.3 Computational requirements of different methods of Fragility Evaluation

Method	Number of analysis required	Estimated time if done using a single system
MCS (expected)	10000 minimum	70 months
Cornell's	35	7 days
HDMR 3-point	4	2 days
HDMR 5-point(expected)	21	4 days

Conclusions

The following are the major conclusions that are reached from the studies conducted:

HDMR method of Fragility Evaluation

- Computational efficiency with reference to Monte Carlo Simulation
  - Time History analysis of one model for 44 earthquake data takes about 5 hour for the considered plane frame.
  - If Monte Carlo simulation is used for the evaluation of fragility curve a minimum of 10,000 time history analysis is to be performed.
  - In HDMR 3-point sampling method, only 9 Time History analysis was done to obtain the metamodel, on which Monte Carlo simulation was done using the metamodel (generating 10,000 random values for the input variables), which takes only few minutes.
  - The time consumption is reduced by about 99.9% compared to MCS when HDMR is used.

References

1. Alis, O.F. and Rabitz, H. (2001) Efficient Implementation of High Dimensional Model Representations. *Journal of Mathematical Chemistry*; 29(2):127-142.
2. Ang, A.H.S, Tang, W.H. (1975) *Probability Concepts in Engineering Planning and Design: Volume 1 – Basic Principles* (Vol 1). John Wiley & Son's, Inc: New
3. ATC 63 (2007), *Recommended Methodology for Quantification of Building System Performance and Response Parameters - 75% Interim Draft Report*, Applied Technology Council, Redwood City, CA.
4. Balakrishnan, S, Ierapetritou, A.R., Marianthi, G., Flach, G.P. and Georgopoulos, P.G. (2005) A comparative assessment of efficient uncertainty analysis techniques for environmental fate and transport models: application to the FACT model. *Journal of Hydrology*; 307(1-4):204-218.