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Study on the Development of Seismic Fragility of Steel SMRF

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Abstract: Vulnerability assessment of the structure is the most important and wide area of research which requires more input from the engineers and seismologist. The seismic vulnerability assessment of the structure can be evaluated by developing Fragility curves. Fragility curves shows the conditional probability of the structure exceeding the particular performance limit of the given damage state during strong ground motions. Fragility curves can be developed for different parameters like spectral displacement (Sd), spectral acceleration (Sa) Peak ground acceleration (PGA) , Inter storey drift ratio (IDR) etc. This paper describes about the different methods used in deriving the Fragility curves like conventional methods, Nonlinear Dynamic analysis methods and Nonlinear Static analysis methods. Also the fragility analysis of 5 Storied Steel Moment Resisting Frame (SMRF) has been carried out based on the parameters suggested by HAZUS M.H 2.1. Nonlinear static pushover analysis of the frame has been carried out in ETABS2016. Fragility curves are developed based on the pushover analysis results. The damage states defined as per HAZUS are Slight damage (SD), Moderate damage (MD) Extensive damage (ED) and Complete damage (CD). After carrying out the fragility analysis for the steel SMRF, it has been found out that, as the spectral displacement increases probability of failure for the slight damage of the structure is very high and the probability of failure for the complete damage is very low. Hence the probability of failure of the structure reduces from slight damage to complete damage.
Keywords: Fragility curves, vulnerability assessment, Nonlinear static pushover analysis, HAZUS M.H 2.1.

I. INTRODUCTION

Earthquake engineering is evolved over many years and it is moving towards performance based methods rather than existing force based methods. Our Earth is vulnerable to many hazards, among these multiple hazards Earthquake may cause severe direct and indirect losses to the structure. This causes significant losses of lives and severe damage to the structure. Therefore the evaluation of seismic vulnerability of the building plays a very important role. The best way to accomplish this evaluation is by developing Fragility curves. Fragility curves shows the conditional probability that the response of the structural system exceeds the performance limits during strong ground motions. This paper mainly focuses on the study on the different methodologies for developing the Fragility curve. One of the method used in this paper for developing the fragility curves for steel SMRF is based on parameters suggested by HAZUS[1]. The damage states are classified into four categories; Slight damage (SD) , Moderate damage (MD), Extensive damage (ED), Complete damage (CD)[1]. This study first reviews different methodologies used for developing the fragility curves. Also the vulnerability assessment for steel SMRF has been carried out for different damage states[1].

II. REVIEW OF METHODS

Fragility is the probability that the structural systems exceed a critical level if subjected to seismic loading of specified intensities. Researchers mainly adopt conventional methods, empirical methods, nonlinear dynamic analysis method and nonlinear static analysis method for developing the curves.

Conventional methods used for building fragility curves are Monte Carlo simulation (MCS), Cornell et al. (2002), High Dimensional Model Representation (HDMR).

Monte Carlo simulation is a statistical simulation procedure that gives reasonably accurate solutions to problems expressed mathematically. This computerized mathematical technique performs risk analysis by developing building models of possible results by substituting range of values for any factor that has certain inherent uncertainty. The results are calculated every time using different set of random values from the probability function. With the help of probability distribution, variables may have different probablities of different outcomes occurring. Probability distribution is the realistic way of describing uncertainty in variables for analysis. Cornell et al proposed the methodology to characterize the fragility function as the probability of exceedance of designated Engineering Demand Parameter (EDP) for selected limit state (DS) for specific ground motion intensity (IM). These curves shows the conditional probability of the structure that can be damage for given damage state. Fragility curve are developed for each damage state can be obtained using the equation

.P(C_D ≤ 0/IM) = Ø ($\frac{\ln Sd/Sc}{\sqrt{\frac{\beta 2d+}{IM}}\ \beta 2c}$) (Eq 1)

Where C is drift capacity, D is drift demand Sd is median of demand and Sc is median of chosen damage state(DS), βd/IM and βc are dispersion in intensity measure and capacity respectively. The above equation is redrafted as follows (Nilson, 2005)

P(C_D ≤ 0/IM) = Ø ($\frac{\ln IM - \ln IMm}{\beta comp}$) (Eq 2)

Where IMm = exp ($\frac{\ln Sc - \ln a}{b}$) (Eq 3)

a and *b* are regression coefficient of probabilistic seismic demand model. Cornell suggested that estimate of average engineering demand parameter (EDP) can be represented by power law model using the equation

EDP = $a\ (IM)^b$ (Eq 4)

HDMR is a method expresses the input-output relations of computational models in terms of hierarchical interrelated function expansions. 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, inter storey drift, Damage indices, Ductility ratio and Energy dissipation capacity can be used. Computational seismic analysis was performed on the structural models using Scaled earthquake records as the inputs. From the earthquake records, Mean and standard deviation were calculated for each combination of input variables. By applying HDRM technique Metamodels are created which are polynomial functions representing the mean and standard deviation of the responses. Metamodels are polynomial functions representing the mean and standard deviation. The two metamodels are combined to form the overall metamodel as specified in equation

$y = y_\mu + N[0, y_\sigma]$ (Eq 5)

Where y_μ and y_σ are the mean and standard deviation of metamodels respectively, N is the normal distribution.

Emperical methods are the post-earthquake investigation method. Fragility curves are developed based on sufficient post-earthquake damage data. Nonlinear time history analysis. Some researchers[2,3] have analysed the damage data and the ground shaking data to give the estimate for fragility curve. Data from the 1994 Northridge, California and the 1999 Chi-Chi, Taiwan earthquakes are aggregated and analysed in order to develop these relationships.

Nonlinear dynamic analysis methods first define and calibrate the damage indices, functions of the maximum displacement and the cumulative energy dissipation, for structural components based on monotonic and cyclic test results. Secondly, all significant uncertain seismic and structural quantities are appropriately modelled by random variables or random processes. Finally, the simplified target structures are analysed by a sufficiently large number of nonlinear time-history analyses. The obtained fragility curves are more accurate than those obtained by most methods, but require much more modelling and computational effort.

Nonlinear static analysis methods compute the capacity curves by nonlinear static analyses (or the so-called pushover analyses) [5,6] and evaluate the fragility curves by capacity-demand spectrum methods. There are two different nonlinear static procedures that have replaced dynamic analysis in generation of fragility curves, namely Capacity Spectrum Method (CSM) and Displacement Coefficient Method (DCM). CSM was first developed by Freeman et al.(1975) and then it has been introduced in ATC-40(1996). In CSM method the nonlinear capacity curve obtained from pushover analysis in acceleration displacement response spectrum (ADRS) format with an elastic demand spectrum that is introduced to account for equivalent damping. The intersection point of capacity curve and demand curve is known as “Performance point”. DCM was introduced by FEMA-273 document (Federal Emergency Management Agency 1997). Just like CSM the results are converted into SDOF response. By using both the methods it is easier to develop the fragility curves.

III. PROPOSED METHOD AND MODEL CLASSIFICATION

The fragility functions are highly dependent on the seismic demand. The seismic behaviour of the structure is characterised by the extent of damages, and it is assumed that the inelastic deformation occurred during the strong earthquake ground motion. As such the linear static analysis cannot predict such behaviour nonlinear static or dynamic analysis is generally applied to the structure. In this study the Non- linear static pushover analysis has been carried out for the frame in ETABS. Pushover analysis is a static, nonlinear procedure. It is the procedure of pushing the structure horizontally with prescribed pattern, until failure. Pushover analysis expose the design weakness that may hidden in elastic analysis. It also identifies the location of weak points in the structure. These weak points or weak links are in the form of plastic hinges. Pushover curve helps in understanding the cracking and deformation of the structure in case of earthquake. The performance of the structure and its components is defined by the acceptance criteria to provide desirable information for evaluation or retrofit.

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Acceptance criteria for pushover analysis is being defined in ATC40 and FEMA 273. It refers to specific limiting values for the deformation controlled and loadings. Two non-linear procedure using pushover methods: (a) Capacity Spectrum method (b) Displacement coefficient method. The frame has been modelled in ETABS with the above mentioned section properties and frame configuration. For beam hinges are of M3 type steel beams and for columns hinges are of type PM2-M3 steel columns. Fig 2 shows the pushover curve of the frame. Table 4 shows the various results obtained from the nonlinear static analysis.

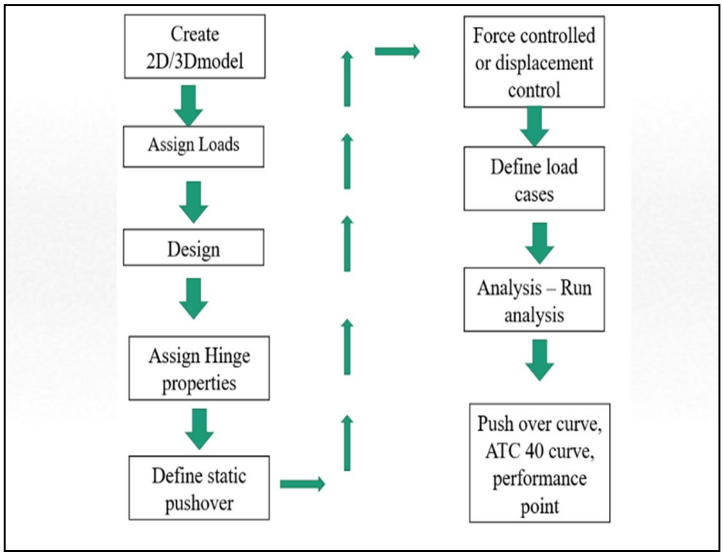

Fig. 1 Steps for Pushover Analysis

5 storied steel MRF resting on medium soil, Seismic zone 5. Live load on roof is considered as 1.5kN/m^2 and live load on floors is considered as 3.5 kN/m^2, Floor finish is taken as 1kN/m^2. Density of steel is taken 78 kN/m^3. Fe 250 grade of steel is used. Following figure shows the elevation of the frame.

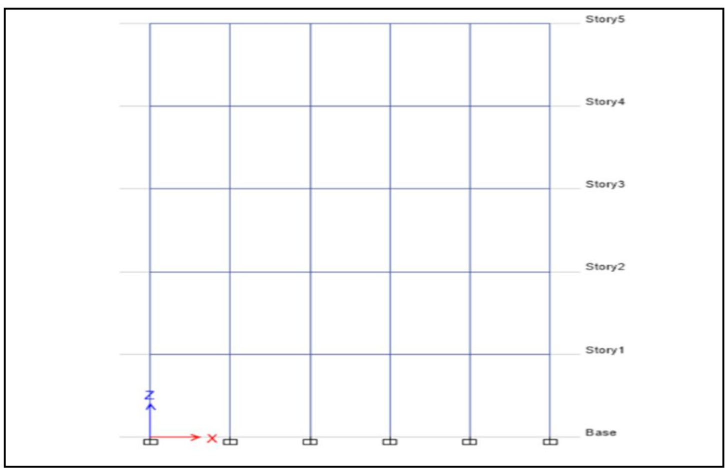

Fig. 1 Elevation of the frame

TABLE I
FEAME CONFIGURATION

1	No of stories	5
2	Height of building	10m
3	No of bays in X direction	5 bays @2m
4	No of bays in Y direction	5 bays @2m
5	On roof	345.23kN
6	On remaining floors	748.56kN

The frame has been modelled in ETABS with the following section properties:

Table 2
Section Properties

No of stories	Beam size	Column size
Roof	ISMB100	ISHB 150
4	ISMB 175	ISHB 150
3	ISMB 200	ISHB 200
2	ISMB 200	ISHB 200
1	ISMB 200	ISHB 225

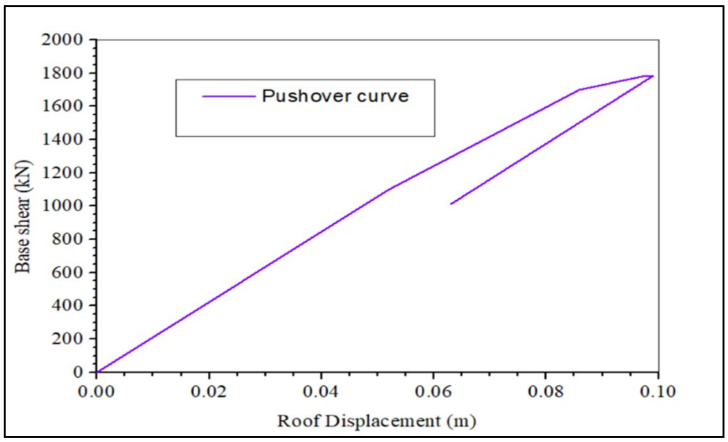

Fig. 3 Base shear vs Roof displacement

Table 3
Pushover Analysis Values

Step	Monitored displacement (m)	Base force (kN)	A-B	B-C	C-D	D-E	>E	A-IO	IO-LS	LS-CP	>CP	Total
0	4.954E-07	0	110	0	0	0	0	110	0	0	0	110
1	0.052	1101.302	105	5	0	0	0	110	0	0	0	110
2	0.086	1697.974	94	16	0	0	0	103	7	0	0	110
3	0.097	1777.2849	84	26	0	0	0	98	12	0	0	110
4	0.099	1786.3418	84	25	1	0	0	97	13	0	0	110
5	0.063	1011.8102	84	25	0	1	0	97	12	0	1	110

IV. SEISMIC DEMAND AND FRAGILITY FUNCTIONS

To obtain the fragility curves, different damage states need to be quantified in terms of spectral displacement. These curves depend on the seismic demand and its variability. The seismic behaviour of the structure is characterised by the different damage states. Nonlinear static pushover analysis is applied to predict the behaviour of the structure during strong earthquake ground motions. The probability of the exceedance of the threshold values are quantified. The statistical information of the spectral displacements corresponding to different damage states is also obtained. Evaluation of Exceedance Probability of exceedance is done by developing fragility curves for various damage states. For a given damage state, P [S | Sd], P [M| Sd], P [E | Sd], P [C | Sd] a fragility curve is well described by the following lognormal probability density function Barbat et al, (2002), HAZUS (2003).

$$P[ds/S_d]=\Phi\frac{1}{[\beta_{ds}}\frac{\ln(Sd)}{(S_{d'dsi})]} \qquad \text{(Eq 6)}$$

P [S | Sd] = probability of being in or exceeding a slight damage state, S.
P [M | Sd] = probability of being in or exceeding a moderate damage state, M.
P [E | Sd] = probability of being in or exceeding an extensive damage state, E.
P [C | Sd] = probability of being in or exceeding a complete damage state, C.
Here, P[ds/Sd] is the conditional probability of exceeding the particular damage state(ds), given the spectral displacement demand (Sd) of the performance point, Φ is the standard normal cumulative distribution function and βds is the normalized standard deviation of the natural logarithm of the displacement threshold, Sddsi indicates uncertainties in capacity curves, damage levels, modelling errors and seismic hazards. Evaluation of the uncertainty in fragility analysis is difficult due to unavailability of variable material properties of steel or masonry, different construction methods, scarcity of ground motion records of the earthquake etc. Hence preliminary the analysis of the frame is carried out using different material properties.

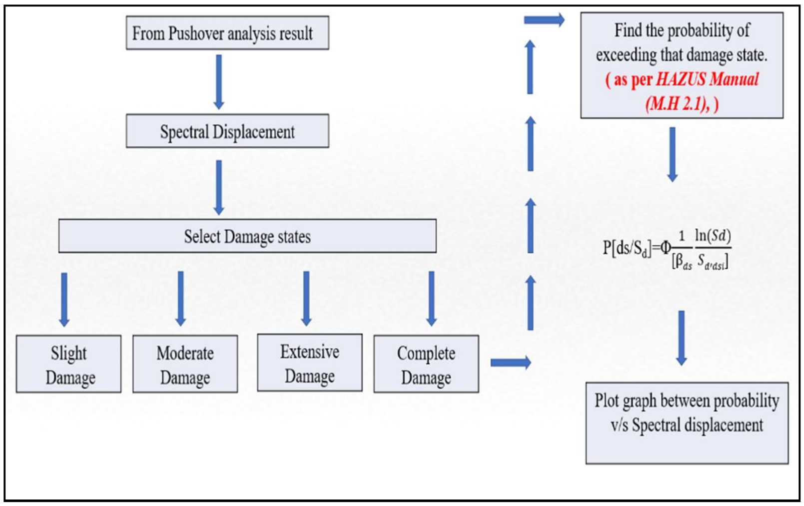

Fig. 4 Flow chart for the development of the fragility curve

From the Pushover analysis results Fragility curves are developed for various damage states and the damage threshold values are taken as per "Seismic fragility of open ground storey RC frames with wall openings for vulnerability assessment." (Trishna Choudhury, Hemant B. Kaushik) ELSEVIER, *Engineering structures, 155(2018) 345-367.*

TABLE 3
Damage States With Their Threshold Values

Damage states	Damage states threshold	Threshold values (mm)
Slight (Sd1)	$0.7 * d_y$	0.1562
Moderate (Sd2)	d_y	0.218
Extensive (Sd3)	$d_y + 0.25 (d_u - d_y)$	0.229
Complete (Sd4)	d_u	0.264

Where, Sd is spectral displacement and suffix 1, 2, 3, 4 show slight damage, moderate damage, extensive damage, and complete collapse respectively.
dy = yield spectral displacement
du = ultimate spectral displacement.
There is a good statistical correlation between the displacement of the structure due to the seismicity induced in the structure due to earthquake ground motions, and the structural damage.

For the evaluation of the damage of the structure, these damage state do not exceed given threshold values defined as damage states (DS) (e.g. slight damage, moderate damage, extensive damage, complete damage). These damage states represents the undesirable condition that has direct impact on building during and after earthquake. Well defined damage states because of their direct impact on the fragility curve parameters. The adopted damage states threshold are shown in table for the frame. From the table it is clearly seen that the threshold values are increasing from slight damage to complete damage. The probability of exceeding the damage states thresholds values are determined.

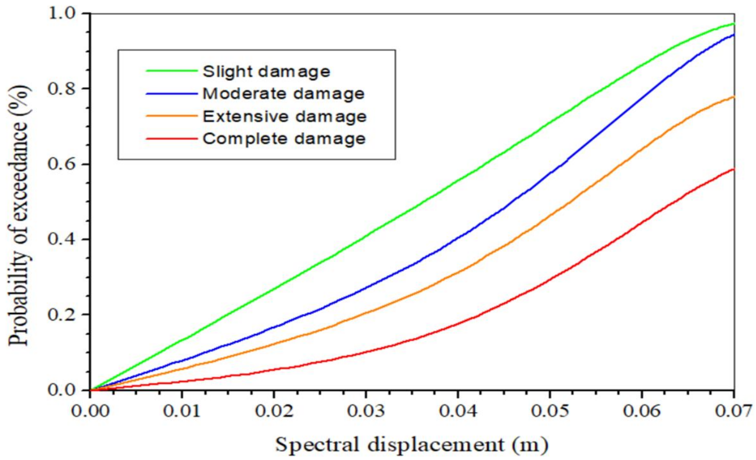

Fig. 5 Fragility curves for various damage states

From the graph it is clearly seen that the probability of damage is reducing as moving from slight damage to the complete damage. The probability of occurring slight damage is highest 0.95%, for moderate damage 0.90%, extensive damage 0.74% and for complete damage is 0.55%.

V. CONCLUSIONS

This study first reviews different methods in deriving fragility curves. One of the efficient ways to lessen the impact of earthquake on the structures is accurate risk assessment and implementation of methods ti mitigate the same.researchers adopt different methods in developing fragility curves. Also fragility curves can be developed considering different parameters like pga, inter-storey drift ratio, spectral displacement, spectral acceleration, etc. In this paper 5 storied steel mrf was analysed and designed in etabs using nonlinear static analysis method and vulnerability assessment of the frame has been carried out by developing fragility curves. After carried out the fragility analysis of the frame for various damage states and for different damage states threshold values it has been found out that the probability of damage decreases from slight damage to complete damage. Also it has been observed that the hazus showed the highest probability occurring slight damage. If there is an earthquake of strong intensity the building will more likely to crossed the damage state of slight and moderate. The exceedance probability for the extensive damage state is more than that of complete damage state. This example also shows the importance of development of the seismic fragility of the structure for the risk assessment.

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