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Development of Vulnerability Curves for Low-Rise RC Building

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***Abstract*— the damage to the buildings during recent earthquakes has demonstrated the need of seismic risk assessment of the building. This paper represents vulnerability assessment using fragility and vulnerability curves for RC buildings considering various damages states. For the development of fragility curve, guidelines given by HAZUS technical manual have been used. In this paper, RC building models have been considered as per HAZUS (only low-rise) and modeled in SAP-2000 v17. Static non-linear analysis (pushover) has been used for the present work. The results of the pushover curve in the form of spectral displacement are used to plot the fragility curve. Fragility curves are plotted considering spectral displacement as ground motion measurement parameter. Finally, after plotting fragility curves the spectral displacement values that satisfy the slight, moderate, extensive and complete damage states were estimated. Vulnerability curves are also developed for RC building models. Vulnerability curves are generated as a combined effect of fragility curves for four different damage states.**

***Keywords*- fragility curve, vulnerability curve, HAZUS, pushover, damage states**

I. INTRODUCTION

The seismic vulnerability of a structure can be described as its liability to damage by ground shaking of given intensity. Vulnerability studies are carried out prior to an earthquake for the purpose of assessing the need to strength essential facilities and structures again future earthquakes. The aim of vulnerability assessment is to obtain the probability of a given level of damage to a given building type due to a scenario earthquake. The vulnerability is usually represented in terms of either Damage Probability Matrices (DPM) or Vulnerability (Fragility) Curves.

Fragility curves are the conditional probability of exceedance of response of a structure for a given ground motion intensity. Fragility curves are used commonly for the estimation of probability damage of structural due to earthquakes as a function of ground motion indices or other design parameters. For structural damage, given the spectral displacement, Sd, the probability of being in or exceeding a damage state, ds, is modeled as:

$$P[\, ds \mid Sd\,] = \phi \left[\frac{1}{\beta ds} \left(\frac{Sd}{Sd,ds} \right) \right] \qquad (1)$$

Where, Sd, ds = is the median value of spectral displacement at which the building reaches the threshold of the damage state, ds,

βds = is the standard deviation of the natural logarithm of spectral displacement of damage state, ds, and

Φ = is the standard normal cumulative distribution function

The curve in which expected amount of damage or the expected mean damage probability is represented as a function of ground motion is called as vulnerability curve. Vulnerability functions are used to plot vulnerability curves. The HAZUS-MH developers tabulate vulnerability functions for each structure type and damage state ‗d'. Let *Ld* denote the loss ratio in a building that experiences structural damage state‗d', and let *L* denote value of expected damage due to an event. One can employ the theorem of total probability and Equation 1 to estimate *L* as a function of Sd or Sa.

$$L = \sum P[Ds = d \mid Sd/Sa = x]\, Ld \qquad (2)$$

II. METHODOLOGY

Pushover analysis can be performed in two ways either forced controlled or displacement controlled. For this study, pushover analysis is performed in SAP 2000 v17. This will include model creation, section properties, defining load Cases, defining hinge properties etc. After pushover analysis, Capacity curve in the form of Base shear vs Roof displacement will be obtained from display menu. The capacity curve is converted into ADRS (acceleration displacement response spectra) for further use. SAP2000 v17 will automatically convert pushover curve in the form of roof displacement vs base shear to ADRS (acceleration displacement response spectra) format. The results of this analysis are further used for fragility analysis.

Building fragility curves are lognormal functions that describe the probability of reaching, or exceeding, structural and nonstructural damage states, given median estimates of spectral response, for example spectral displacement. These curves take into account the variability and uncertainty associated with capacity curve properties, damage states and ground shaking. The probability of being in, or exceeding, a given damage state is modeled as a cumulative lognormal distribution 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.

$$P[\, ds \mid Sd\,] = \phi \left[\frac{1}{\beta ds} \left(\frac{Sd}{Sd,ds} \right) \right] \qquad (3)$$

Where is Sd,ds the threshold spectral displacement,Î²ds is the standard deviation of the natural logarithm of this spectral displacement Figure 3.3.1 shows how the threshold obtain from capacity spectrum, Î¦ is the standard normal cumulative distribution function and Sd is the spectral displacement of the structure.

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Where,
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.
Vulnerability curve defines a level of damage as a function of an intensity measure. Vulnerability function is required for plotting vulnerability curve. A typical equation that represents HAZUS vulnerability function is given in equation (4).

$$E[P \mid Sa] = \sum_{ds}(Loss|ds = DS) * P[DS \approx ds|Sa] \quad (4)$$

Where, E[P | Sa] = mean probability of damage for no. of ground motion parameters

$(Loss|ds = DS)$ = Loss ratio corresponding to structural damage ii)

$P[DS \approx ds|Sa]$ = Probability of damage which is equal to a predefined damage state corresponding to parameter Sa.

The vulnerability function is depending on the probability of damage which is equal to a predefined damage state and loss ratio. The value of loss ratio is taken from table 6.1 of HAZUS MH MR1. The probability of mean damage from all damage states is calculated from vulnerability curve. Table 1 shows the values of loss ratios to be taken for vulnerability functions. In this paper, the vulnerability curve is plotted for an individual building model.

Table 1: Loss Ratio Values corresponding to damage state

Damage State	Loss Ratio (Loss|ds=DS)
Slight	2%
Moderate	10%
Extensive	50%
Complete	100%

III. RESULT ANALYSIS

Earthquake damage evaluation methodology in terms of fragility, vulnerability curves and computational modeling process in SAP 2000 v17 for RCC structural systems are described. Now several RC buildings models are developed and evaluated for seismic vulnerability assessment using HAZUS procedures. In this the seismic performance of low-rise, mid-rise, and high-rise buildings using fragility iiain) d vulnerability curves is worked out. Non-linear static analysis is performed with selected 3D building frames designed as per IS 456-2000 considering bare frame. After the analysis, ground motion parameters such as spectral displacement is considered for plotting fragility and vulnerability curves.

A. Low-Rise Building Model

This building models are designed for gravity loading as per IS-456 2000 and pushover analysis is performed on these building models for vulnerability assessment.

i) Description of 3D building Model

In this a three storey RC 3D building model is considered for analysis. The building parameters are shown in following table 2.

Table 2: Description of Low-rise 3D Building Model

Parameter	value	parameter	value
No. of stories	3	No. of bays in X-direction	4
Height of each storey	3.06 m	No. of bays in Y-direction	3
Bay width (X direction)	5 m	Grade of concrete	M25
Bay width (Y direction)	3 m	Grade of Steel	HYSD 415
Beam size	0.25 x 0.4 m	Column Size	0.4 x 0.4 m
Live Load	3.5 kN/m^2		

Above building is designed for gravity loads as per IS 456-2000 and reinforcement obtained from analysis is assigned to beam and column frame elements. After the design, pushover analysis is performed considering deformation controlled analysis. Response spectra of Zone V with soil type II is considered for plotting demand spectra. The building modeled in SAP 2000 v17 is shown in figure 1. The results in the form of pushover curve, fragility curve, and vulnerability curves are generated for this building model. The parameters required for vulnerability and fragility curves are taken from HAZUS and FEMA 356.

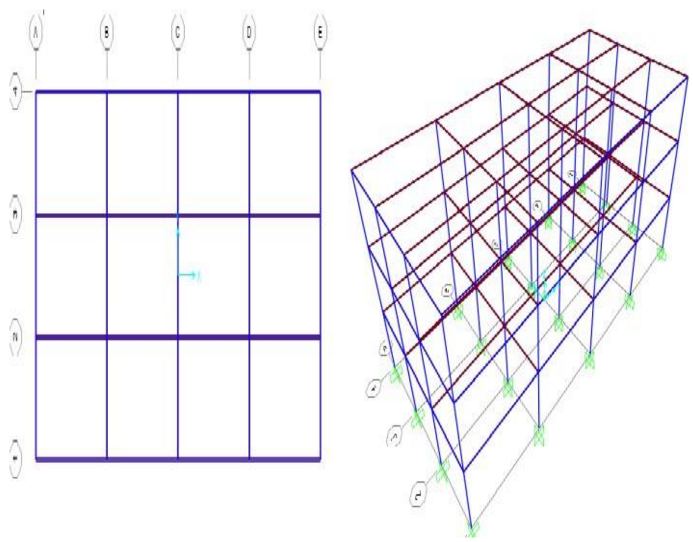

Figure 1: SAP Model for G+2 Building Frame (3D)

ii) Results of 3D Building Model

The results obtained from analysis are described below. First result obtained from SAP analysis is pushover curve in ADRS format as per ATC 40. The pushover curve is shown in figure 2. The performance point coordinate of this pushover curve is shown in figure 2. Now fragility and vulnerability curves are plotted. Figure 3 and figure 4 describes the fragility curve and vulnerability curve respectively for this low-rise 3D building in terms of spectral displacement as ground motion parameter.

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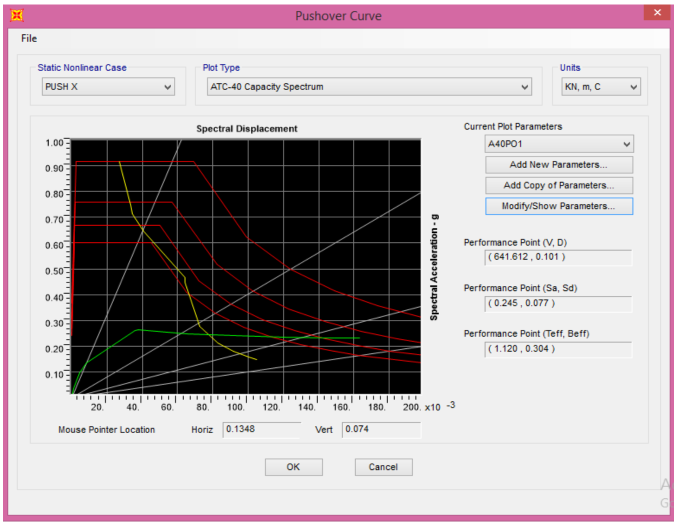

Figure 2: Pushover Curve for Low-rise 3D Building Model

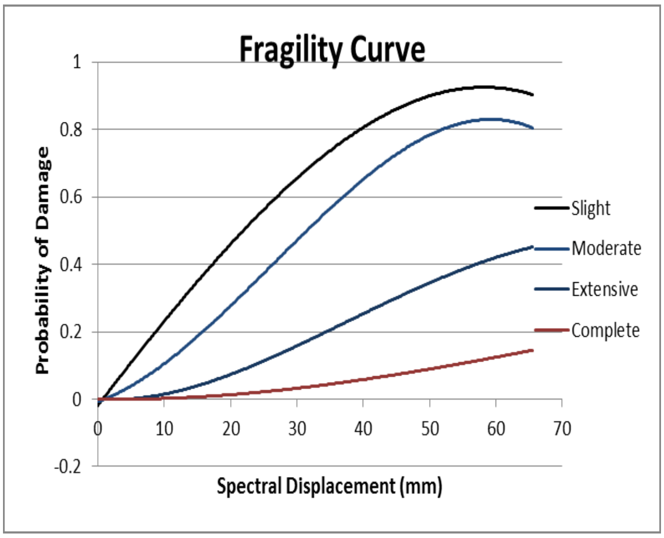

Figure 3: Fragility Curve for Low-Rise 3D Building in terms of Sd

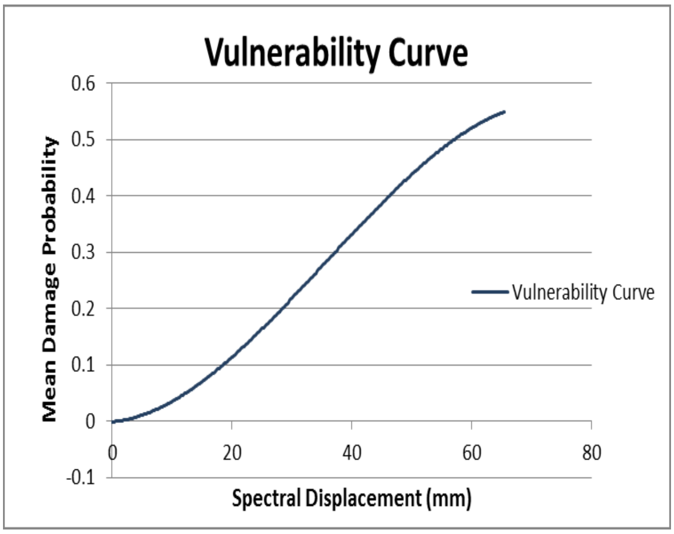

Figure 4: Vulnerability Curve for Low-Rise 3D building in terms of Sd

The mean damage probability of this low rise building is 0.57 for the value of 67 mm spectral displacement value.

iii) Description of 2D Building Model

A frame is selected from low-rise 3D building model for the analysis. Same building data is taken from table 2 for modeling in SAP 2000 v17. Figure 5 shows the frame modeled in SAP. Other analysis data remain the same which is used for low-rise 3D building model. The vulnerability study is carried out to this 2D frame for assessment of 2D and 3D behavior of building. For this purpose, the control node and the direction of lateral load applied is kept same.

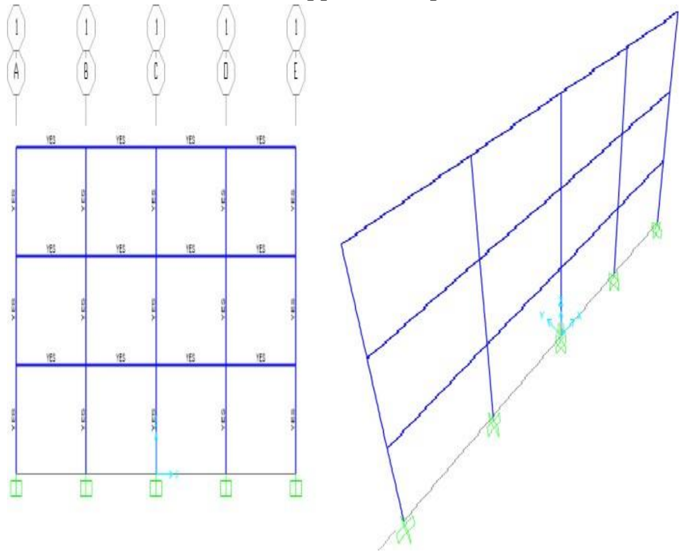

Figure 5: SAP Model for G+2 Building Frame (2D)

iv) Results of 2D Building Model

Similar to 3D low-rise 3D building model, pushover curve, fragility and vulnerability curves are generated considering two ground motion parameters. Figure 6 shows the pushover curve as per ATC 40. Figure 7 shows the fragility curves in terms of spectral displacement. Figure 8 shows the vulnerability curve in terms of spectral displacement. The mean probability of occurring damage to building is calculated from this vulnerability curve. A comparative study between 2D building model and 3D building model is done with considering ground motion parameters namely spectral displacement. This study will helps in identifying the better results of damage probability from fragility and/or vulnerability curve.

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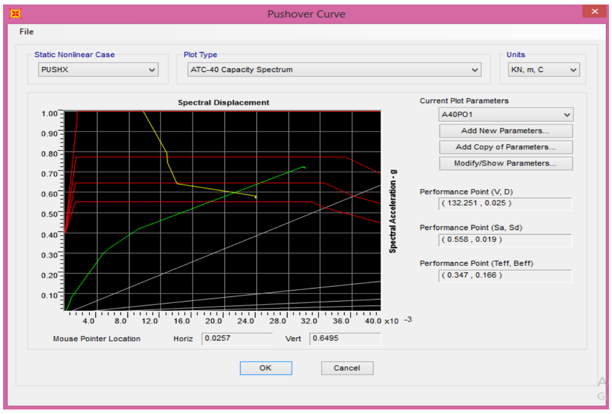

Figure 6: Pushover Curve for Low-rise 2D Building Model

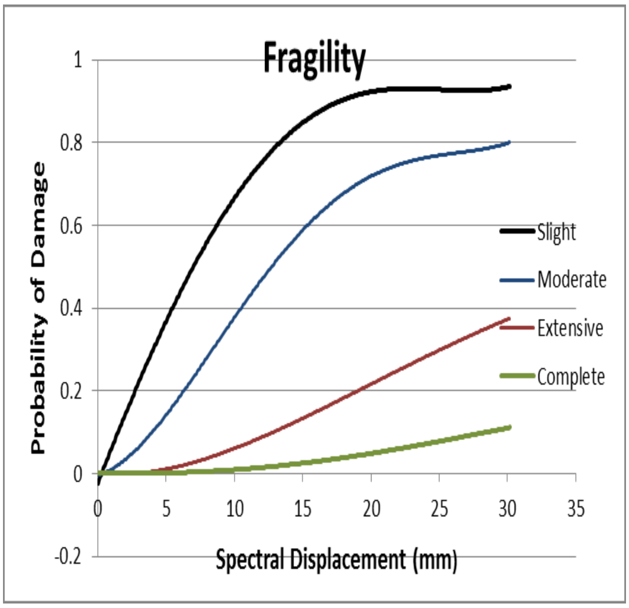

Figure 7: Fragility Curve for Low-Rise 2D Building in Terms of Sd

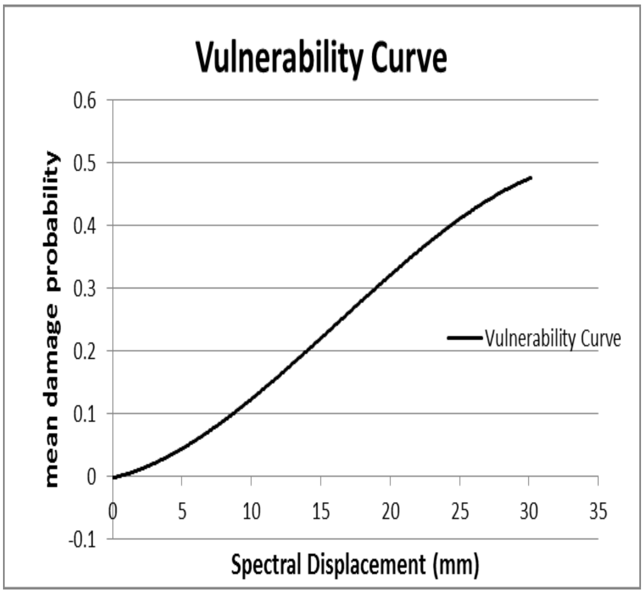

Figure 8: Vulnerability Curve for Low-Rise 2D building in terms of Sd

The results of all the probabilities associated with this two low-rise 2D and low-rise 3D building model is shown in table 4.3.1.4.1. The results are taken considering a performance point value of spectral acceleration and spectral displacement from vulnerability and fragility curve. The values of this two ground motion parameters is also shown in table 4.3.1.4.1. The value of damage probabilities are corresponding to performance point obtained from pushover analysis. The table shows that, for low rise 2D building model the spectral displacement value is less as compared to 3D building model and vice versa if the spectral acceleration is considered.

Table 3: Damage state probabilities for low-rise 2D and 3D building Model

Building Model Type		Low-Rise 2D		Low-Rise 3D	
Curve/Damage State		Sd(mm)	Prob	Sd(mm)	Prob
Fragility	Slight	19.19	0.93	72.11	0.90
Fragility	Moderate	19.19	0.80	72.11	0.80
Fragility	Extensive	19.19	0.37	72.11	0.41
Fragility	Complete	19.19	0.11	72.11	0.13
Vulnerability	Mean	19.19	0.44	72.11	0.51

IV. CONCLUSIONS

In the present study, Low-Rise framed building is considered and designed for gravity loads as per IS 456-2000. The performance of each building is studied using the fragility and vulnerability curves using HAZUS method. Nonlinear Static Analysis is carried out on 2D and 3D building models. The relative performances of each building designed as per IS 456-2000 is compared using fragility and vulnerability curves. For the development of fragility and vulnerability curves ground motion parameters considered, namely is spectral displacement. Following general conclusions are made from the present study.

HAZUS methodology is used for earthquake loss estimation in terms of probability of damage. Basically HAZUS method is derived for US building classes, therefore some approximations are used for analysis of building such as soil conditions, dynamic behavior of building, building type information etc. HAZUS method is approximate as it depends on non-linear static procedures, but it will give results in less time. The HAZUS method uses the spectral displacement and spectral acceleration of structural and non-structural elements of a building to ground motion for vulnerability assessment.

There is 2-5% of difference in damage probability when 2D model is compared with 3D building model of low-rise building. Also the values of probability of damage are greater in 3D building model. Performance Point value of spectral displacement is more for a 3D building model having same height as with 2D building model. This study will roughly estimate the damage level of the building as the method is based on a purely approximate pushover analysis.

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