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Development of Fragility Curves for RC Buildings using HAZUS method

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Abstract - Earthquakes occurring in different parts of the country cause damages to the vulnerable structures and loss of lives. Therefore evaluation of seismic vulnerability of building before occurrence of an earthquake is essential step in preventing damages to the buildings and loss of lives. The seismic vulnerability of the building can be evaluated by using fragility curve. Fragility curves are used to describe the probability of damage being exceeded a particular damage state. Fragility curves can be developed from either analytical or empirical methods based on source of the data and type of analysis. This paper focuses on the development of fragility curve using analytical method. For the development of fragility curves guidelines given by the **HAZUS** technical manual have been used and the performance of the two 10 storey Reinforced Concrete buildings have been evaluated and compared.

Key Words: fragility curve, HAZUS methodology, damage states, modelling of infill wall, nonlinear static analysis, performance point.

1. INTRODUCTION

Building fragility curves are lognormal functions that describe the probability of reaching, or exceeding, structural and non-structural damage states, given median estimates of spectral response, for example spectral displacement. Fragility curves define boundaries between damage states. For example, in figure shaded region illustrates the probability response space associated with **moderate** damage.

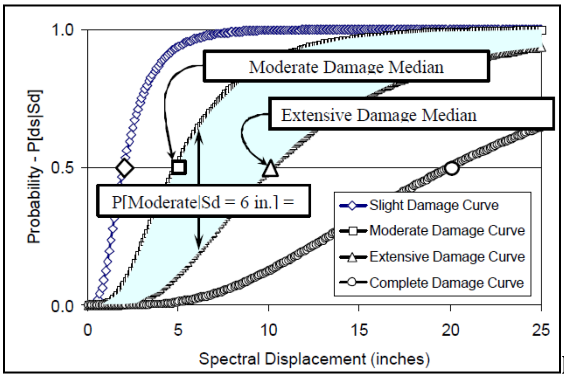

Figure-1. Example of fragility curve

The probability of moderate damage at a given level of spectral demand is calculated as a probability of moderate damage less the probability of extensive damage. The most common and accurate method for developing the fragility curve for any building is complete nonlinear time history analysis, but this method is very much complex and it requires more time for completion.

1.1 HAZUS methodology:

For the development of fragility curves, guidelines given by HAZUS technical manual have been used. HAZUS methodology was developed for FEMA by National Institute of Building Science (NIBS) to reduce seismic hazard in United States. HAZUS technical manual provides the procedure for deriving the fragility curves for different types of structures. Building fragility curves are lognormal functions that describe the probability of reaching, or exceeding, structural and non-structural 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. 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.

$$p(ds/s_d) = \emptyset\left[\frac{1}{\beta_{ds}}\ln\left(\frac{s_d}{s_{d,ds}}\right)\right] \quad (1)$$

Where;

s_d, ds = Threshold spectral displacement for a given damage state.

β_{ds} = Standard deviation of natural logarithm of the damage state.

$\emptyset$ = Standard normal cumulative distribution function.

s_d = Spectral displacement of the structure.

$p[S/S_d]$ = probability of being in or exceeding slight damage state, S.

$p[M/S_d]$ = probability of being in or exceeding moderate damage state, M.

$p[E/S_d]$ = probability of being in or exceeding extensive damage state, E.

$p[C/S_d]$ = probability of being in or exceeding collapse damage state, C.

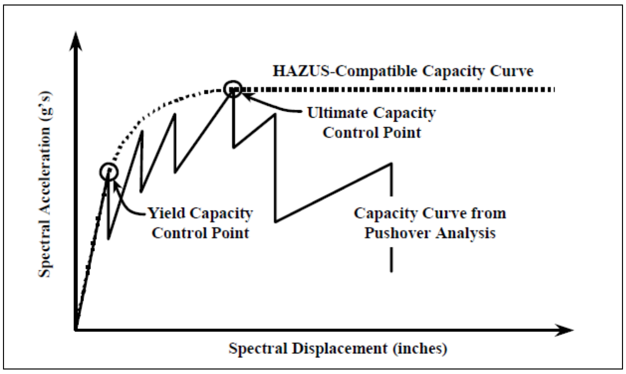

Figure 2: Example damage state medians of "saw-tooth" pushover curve

Following table shows the damage state thresholds defined with the agreement of capacity spectrum (figure-1).

Table 1. Damage state thresholds

Damage states	Spectral displacements (sd,ds)
Slight	0.7Dy
Moderate	Dy
Extensive	Dy + 0.25(Du-Dy)
Collapse	Du

Where;

Ay = Yield spectral acceleration.

Au = Ultimate spectral acceleration.

Dy = Yield spectral displacement.

Du = Ultimate spectral displacement.

1.2Development of damage state variability

The lognormal beta or standard deviation describes the total variability of the damage states. The variability associated with the capacity curve, β_C, demand spectrum, β_D, and the variability associated with the discrete threshold of each damage state, β_{Tds} are to be accounted while calculating the total variability. The demand spectrum and capacity curves are inter dependent, the variability accounted by both are combined by convolution process. The third component β_{Tds} is mutually independent from the first two variability components and its effect is considered by combining it with the results of CONV process using SRSS method.

$$\beta_{ds} = \sqrt{\left(CONV\left[\beta_C, \beta_D\right]\right)^2 + \left(\beta_{Tds}\right)^2} \quad (2)$$

$\beta_{ds}$is the lognormal standard deviation parameter that describes the total variability of damage state, ds.

$\beta_C$is the lognormal standard deviation parameter that describes the variability of the capacity curve.

$\beta_D$is the lognormal standard deviation parameter that describes the variability of the demand spectrum.

$\beta_{Tds}$is the lognormal standard deviation parameter that describes the variability of the threshold of damage state, ds.

These values can also be directly obtained from the tables (table 6.5, 6.6 and 6.7) of HAZUS manual (MH MR-1).

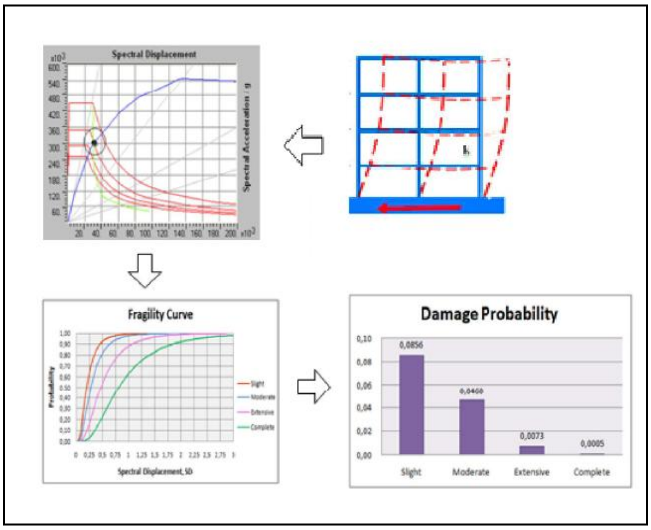

Figure -3: Procedure to be followed

2. MODELLING

A typical 10 storeyed 6 bay RC frame building is considered in this study. The building was designed in STAAD Pro. and modelled in SAP 2000 for performing non-linear static analysis. Here two building frame models were considered one without considering infill wall stiffness and another with considering stiffness of the infill wall. The performance of these two frames is compared with the help of "fragility curves" in terms of the discrete damage probabilities of each damage state.

Table 2: description of building model

Description	value
Number of stories	10
Height of storey	3.2m
Grade of steel	Fe 415
Grade of concrete	M25
Live load on floors	3 kN/m²
Live load on terrace	1.5 kN/m²
Number of bays in each direction	6
Bay width	3 m
Thickness of infill wall	230 mm
Thickness of slab	150 mm

2.1Modelling of infill wall:

Infill walls are modelled as equivalent diagonal struts having width equal to (diagonal length of wall/4). SAP 2000 does not have auto hinge tool for assigning hinges to infill wall, so manual hinges were assigned to the infill wall. The failure load for infill wall is considered to be minimum of the failure load corresponding to shear failure load (Rs) and crushing load (Rc). These loads can be found out from the following equation. (Smith and Carter, 1969)

$$Rc = \alpha_c \sec\theta \qquad (3)$$

$$\alpha_c = \text{[illegible]} \qquad (4)$$

$$\frac{R_s}{f_{bs}\,ht} = 1.65(l'/h')^{0.6}(\lambda h)^{-0.05(l'/h')} \qquad (5)$$

$$\lambda h = \sqrt[2]{\frac{E_s t \sin 2\theta}{4 E_c I_c h'}} \qquad (6)$$

Where;

E_s = elastic modulus of the equivalent strut

E_c = elastic modulus of the column in the bonding failure

I_c = moment of inertia of the column

h' = clear height of infill wall

h = height of column between centrelines of beams

t = thickness of infill wall

θ = slope of the infill wall diagonal to the horizontal

f'_{bs} = bond shear strength between masonry and mortar

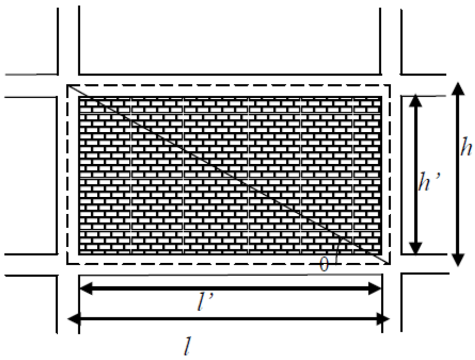

Figure-4: typical panel of infill wall

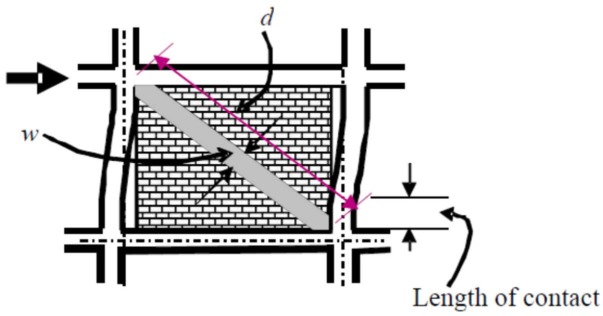

Figure-5: behavior of typical panel subjected to lateral load

3. Work done

3.1 Bare frame: Bare frame representing the 3-D symmetric building was modeled in SAP 2000 to perform the non-linear static analysis.

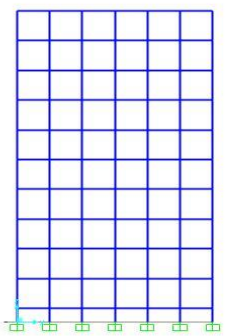

Figure -6: Model of Bare Frame

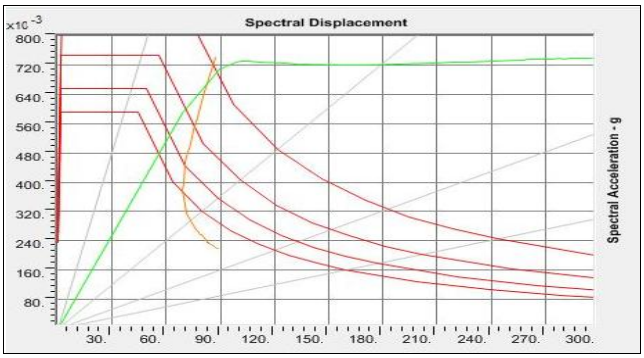

Figure -7: capacity curve for bare frame

Plot of capacity curve of the building obtained as shown in figure. This figure represents the capacity and response spectrum plots. The graph obtained from the pushover curve is converted into ADRS (Acceleration Displacement Response Specrum) format. Yield capacity control point **(D_y,A_y)** is selected as a point where significant yielding is just beginning to occur. Ultimate capacity control point displacement, **D_u,** is selected as the greater of either the spectral displacement at the point of maximum spectral acceleration or the spectral displacement corresponding to Equation;

$$D_u = 2 \cdot D_y \frac{A_u}{A_y} \tag{7}$$

Table 3: yield and ultimate capacity control points

Yield spectral displacement (D_y)	98.597 mm
Ultimate displacement (D_u)	297.746mm

Table 4: damage state threshold values ($S_{d,}$ ds) for bare frame

Damage state	**Threshold values (S_d,ds)**
Slight	69.017 mm
Moderate	98.597 mm
Extensive	148.384 mm
Collapse	297.746 mm

3.2Damage state variability:

Table 5: variability values used for ten storey building

Damage state	**Kappa factor (k)**	**Degradation values for**		
		Damage (β_{Tds})	**Capacity curve (β_c)**	**Total (β_{ds})**
Slight	Minor degradation (0.9)	Moderate (0.4)	Moderate (0.3)	**0.7**
Moderate	Major degradation (0.5)	Moderate (0.4)	Moderate (0.3)	**0.85**
Extreme	Extreme degradation (0.1)	Moderate (0.4)	Moderate (0.3)	**1.05**
Collapse	Extreme degradation (0.1)	Moderate (0.4)	Moderate (0.3)	**1.05**

3.3Generation of fragility curve:

Substituting all these values in equation (1), fragility curves are obtained for each damage states, which shows the continuous distribution of damage states at performance point.

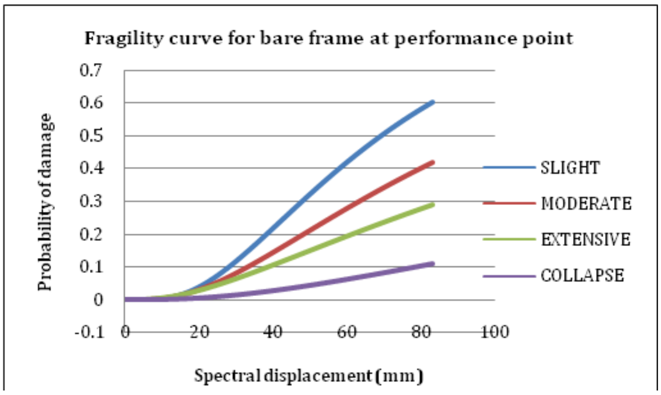

Figure 8: continuous probability of damage for bare frame at performance point

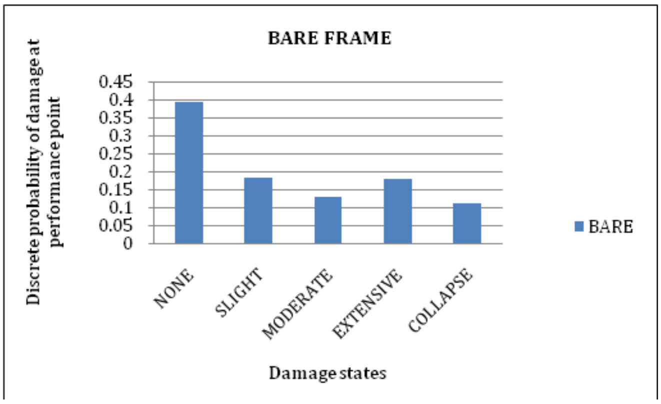

Figure 9: discrete probability of damage for bare frame at performance point

3.4 Infill frame:

Infill walls were modeled as an equivalent strut and strength of infill wall was calculated as per the equations (3),(4) and (5).

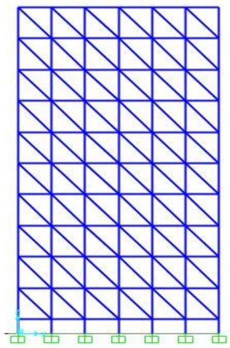

Figure 10: Model of infill frame

Axial hinges were manually assigned to the equivalent struts and nonlinear static analysis was performed to evaluate the performance of infill frame.

Figure 11: capacity curve for infill frame

Yield and ultimate capacity control points were obtained from the capacity curve and equation (7).

Table 6: yield and ultimate capacity control points

yield spectral displacement (D_y)	18.559 mm
Ultimate spectral displacement (D_u)	40.874 mm

Table 7: damage state threshold values ($S_{d,}$ ds) for infill frame

Damage state	Threshold values ($S_{d,}$ds)
Slight	13.019 mm
Moderate	18.599 mm
Extensive	24.167 mm
Collapse	40.874 mm

Damage state variability values were considered as per the table 5 and fragility curves were developed using equation (1).

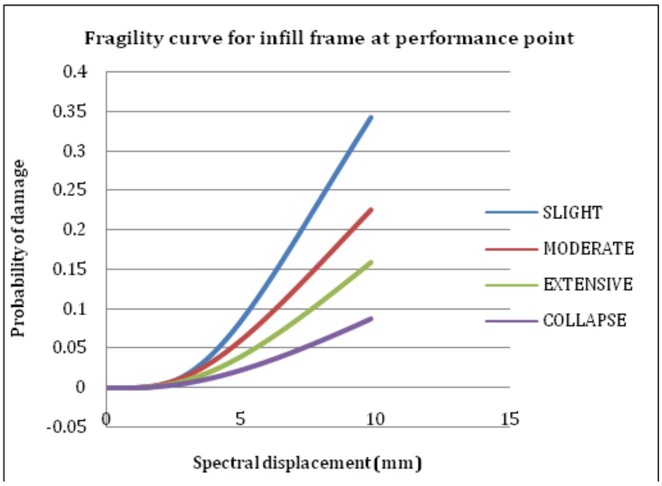

Figure 12: continuous probability of damage for infill frame at performance point

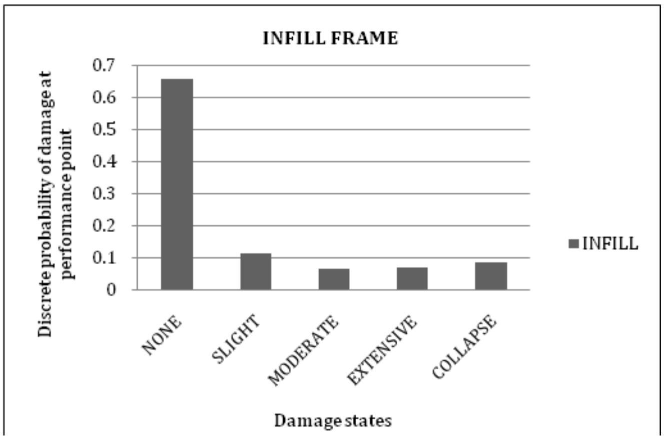

Figure 13: discrete probability of damage for infill frame at performance point

4. COMPARISON OF RESULTS:

Table 8: comparison of continuous probability of damage for with infill and infill frame

Damage states	Bare frame	Infill frame
Slight	0.605	0.343
Moderate	0.420	0.226
Extensive	0.290	0.159
Collapse	0.112	0.087

Table 9: comparison of discrete probability of damage for bare and infill frame at performance point

Damage states	Bare frame	Infill frame
None	0.395	0.657
Slight	0.185	0.117
Moderate	0.13	0.067
Extensive	0.178	0.07
Collapse	0.112	0.087

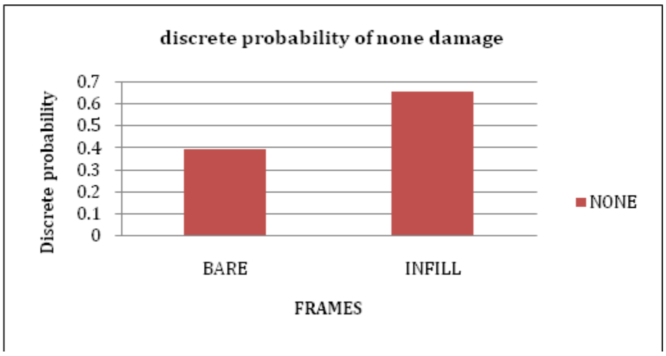

Figure 14: discrete probabilities of "none" damage for bare and infill frame at performance point

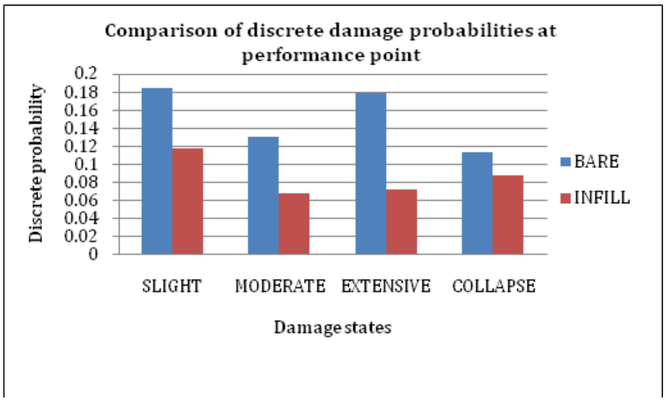

Figure 15: discrete probabilities of damage of various states for bare frame and infill frame

4.1 At 30 mm spectral displacement:

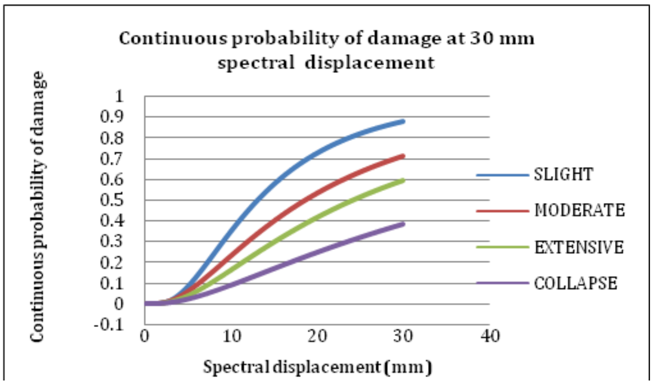

Figure 16: continuous probability of damage for infill frame at 30mm spectral displacement

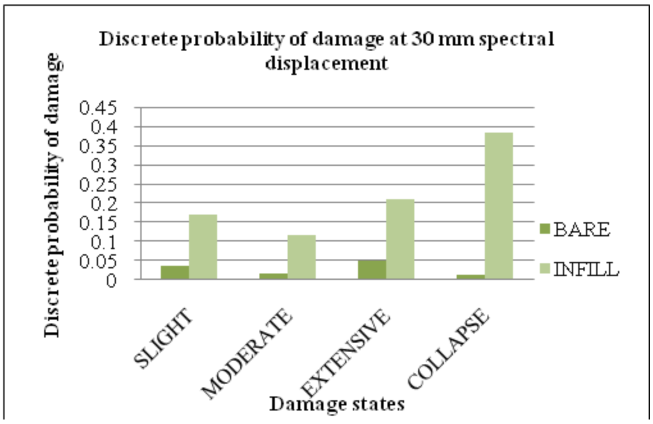

Figure 17: discrete probabilities of damage for bare and infill frame at 30 mm spectral displacement

IV SUMMARY AND CONCLUSIONS

In this study, HAZUS methodology for the generation of fragility curves is discussed and the fragility curves are generated for 10 storey RC building structure considering with infill and without infill walls. Considering the fact that the results are based on the analytical data and guidelines given in the HAZUS technical manual, the following conclusions can be stated:

1) This methodology gives an idea to predict the damage level of building corresponding to particular value of spectral displacement. The damage state of the building is also identified from the above analysis.
2) Increase in strength and stiffness of RC building is significant due to addition of the infill walls when compared with the corresponding values of the bare frame building.
3) For a specified level of spectral displacement at performance point bare frame has more probability of damage compared to the infill frame.
4) The infill frame is having higher base shear capacity of around **1600 kN** but it fails soon after reaching the value of **21mm.** in other words despite of high load withstanding value this building frame is not considered as the effective because it fails soon without warning. So this type of frame is more vulnerable than others with the fact that it reaches its maximum permissible value within shorter time period.
5) At **30 mm** of spectral displacement infill frame is having higher probability of damage compared to the bare frame.
6) As HAZUS method works on non-linear static Procedures, it is also concluded that the results from this paper need to be compared with another method, such as time history, which is expected as future scope for this paper.

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