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Fragility Analysis of Open Ground Storey Buildings Using Nonlinear Static Analysis

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ABSTRACT

The main objective of the present study is to develop the fragility curves for the open ground storey buildings designed as per the modification factors suggested by the different international codal provisions and compare the relative performance on the probabilistic basis by developing the fragility curves. For the development of the fragility curves the nonlinear static analysis method is adopted here. The building model considered is having 10 storeys and 6 bays in both the directions and it is assumed to be situated in Zone V. The building is symmetrical in plan. So, only plane frame model can be considered for the representation of the whole building. The building is first designed in the STAAD. The Ground storey columns are designed according to the modification factors suggested by the different codes such as 1 and 2.5 (Indian), 3 (Bulgarian), 2.1 (Israel), 4.68 (Euro code) and approach suggested by Kaushik et. al (2009).These building frames are modeled in SAP. The capacity curve of the building is obtained from the nonlinear static analysis and the capacity curve control points of the building (yield and ultimate capacity control points) are obtained. From this control points the damage state median values are identified and fragility curves are developed for each damage states showing the cumulative probability of reaching or exceeding each damage state at given value of spectral displacement.

Keywords: Open Ground Storey building Fragility curves, methods of development of fragility curves, nonlinear static analysis, damage state medians

I. INTRODUCTION

For the development of fragility curves from the nonlinear static analysis, 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.

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

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.

Following figure provides graphical representation of the steps to be followed for the development of fragility curve using this method.

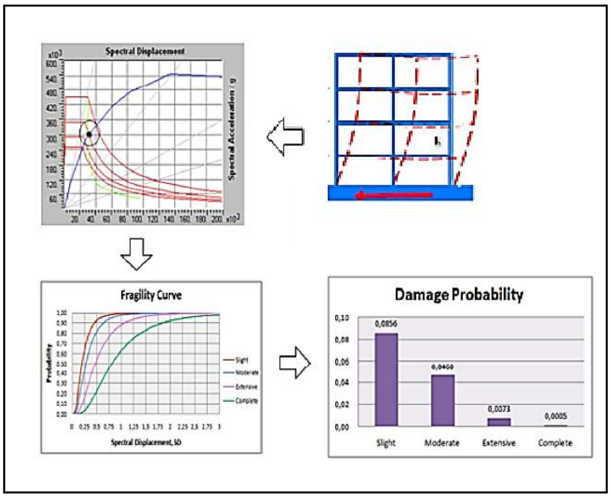

Figure 1. Graphical representation of steps to be followed for the fragility curve development of building

II. METHODS AND MATERIAL

A. Details of case study building

A typical ten-storey six-bay OGS RC frame that represents a symmetric building in plan is considered in the present study.

- **Seismic Design Data**

Seismic load is taken according to IS 1893 (2002).The building considered is located in seismic **zone V** having **Z = 0.36** and medium soil is considered and in the analysis R value considered as 3 for ordinary RC moment resisting frame (OMRF).

Table 1. Seismic Design Data

Design parameter	Value
Seismic Zone	V
Zone factor (Z)	0.36
Response Reduction Factor (R)	3
Importance factor (I)	1
Soil Type	Medium Soil
Damping ratio	5%
Frame type	Ordinary Moment Resisting Frame (OMRF)

- **Material data and section properties**

Table 2. Material Properties Considered

Material	Property
Concrete	M25
Reinforcement	Fe 415
Density of masonry	20 kN / m^3

Table 3. Section Properties

Section	Property (mm X mm)
Column	350 X 350
Beam	230 X 350

- **Geometrical properties**

Table 4. Geometrical Properties

Elements	Value
Bay width	3 m
Column height	3.2m
Slab thickness	150mm
Thickness of the wall	230mm
Number of storeys	10
Number of bays	6
Height of the parapet wall	0.6 m
Live load (terrace) (floor)	1.5 kN / m^2 3 kN / m2

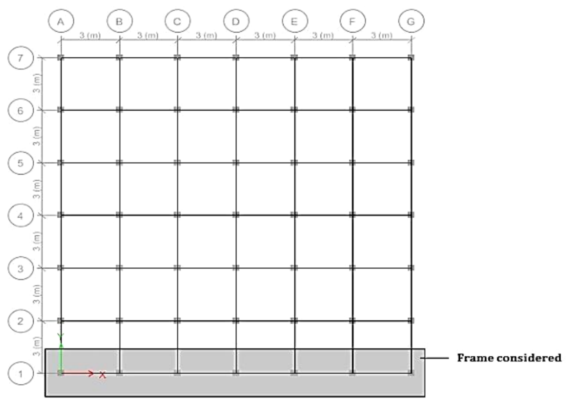

Figure 2. Plan of the building considered

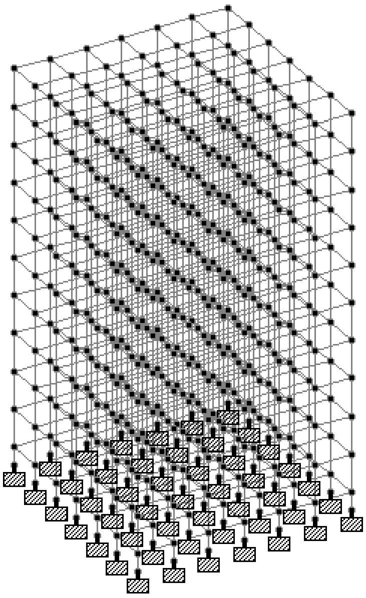

Figure 3. Modelling in STAAD Pro.

The building is modelled and designed in STAAD Pro for the following load cases and combinations.

Type	L/C	Name
Primary	1	EQX
Primary	2	EQZ
Primary	3	DL
Primary	4	LL
Combination	5	1.5(DL+LL)
Combination	6	1.2(DL+LL+EQX)
Combination	7	1.2(DL+LL-EQX)
Combination	8	1.2(DL+LL+EQZ)
Combination	9	1.2(DL+LL-EQZ)
Combination	10	1.5(DL+EQX)
Combination	11	1.5(DL-EQX)
Combination	12	1.5(DL+EQZ)
Combination	13	1.5(DL-EQZ)
Combination	14	0.9DL+1.5EQX
Combination	15	0.9DL-1.5EQX
Combination	16	0.9DL+1.5EQZ
Combination	17	0.9DL-1.5EQZ

From the STAAD output file, the design forces in the ground storey columns are found out and columns are designed considering the worst combination of the load cases.

From the output file, following values can be obtained for the ground storey columns as follows.

- Governing load combination — 1.5 (DL + EQz)
- Design force (Pu) — 1505 kN
- Design moment (M_z) — 30.10kN.m
- Design moment (M_y) — 74 kN.m
- Diameter of bar — **16mm**
- No. of bars provided — **20**
- Percentage (%) of reinforcement provided — 3.28%
- Tie reinforcement — 10 mm dia bar @ 190 mm c/c

The forces in the ground storey columns are multiplied with the modification factors suggested by different codes and they are designed accordingly.

Table 5. Details of ground storey columns

<table>
<tr><th rowspan="3">Frame</th><th rowspan="3">Designation</th><th colspan="4">Ground storey column</th></tr>
<tr><th rowspan="2">Section (mm) (width×depth)</th><th rowspan="2">% Reinforcement provided</th><th colspan="2">Details of longitudinal reinforcement</th></tr>
<tr><th>Diameter of bar(mm)</th><th>Number of bars provided</th></tr>
</table>

10 storey 6 bay,OGS (MF=1) Indian Code	Indian 1.0	350 × 350	3.28%	16	20
10 storey 6 bay,OGS (MF=2.5) Indian Code	Indian 2.5	750 × 750	3.5%	40	16
10 storey 6 bay,OGS (MF=3)	Bulgarian	800 × 800	3.75%	40	20
10 storey 6 bay,OGS (MF=3.97)	Kaushik et. al. (2009)	1100 × 1100	3.7%	40	36
10 storey 6 bay,OGS (MF=4.68)	Euro	1250 × 1250	3.5%	40	44
10 storey 6 bay,OGS (MF=2.1)	Israel	650 × 650	3.65%	32	20

B. Modelling and analysis in SAP:

Table 6. Reinforcement details of Beam sections

Beam ID	**Reinforcement details**			
	Top steel		**Bottom steel**	
	Diameter of bar	**Number of bars**	**Diameter of bar**	**Number of bars**
B1C	16	7	25	2
B1M	16	6	16	4
B2C	16	7	20	3
B2M	20	4	12	8
B3C	16	7	20	3
B3M	20	4	12	8
B4C	20	4	12	8
B4M	16	6	12	7
B5C	16	6	12	7
B5M	16	6	12	7
B6C	16	6	16	3
B6M	16	6	20	2
B7C	20	3	12	4
B7M	20	3	12	5
B8C	12	7	12	3
B8M	12	7	12	3
B9C	12	4	12	2
B9M	12	5	12	2
B10	12	2	12	2

The structural and non-structural elements are modelled in SAP.

- **Modelling of the structural elements**

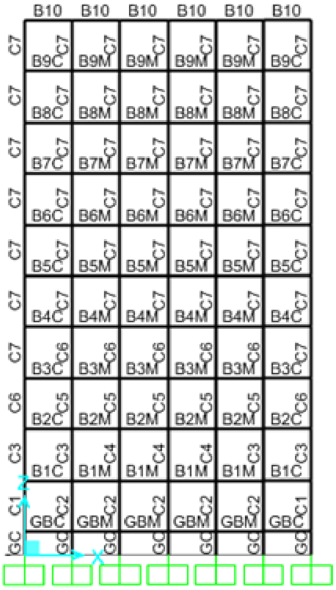

Figure 4. Model of the building frame with section labels

- **Modeling of infill wall:**

Infill walls are 2 dimensional elements that can be modelled as the 2-D orthotropic plate elements. But non linear behaviour of the plate elements could not be understood well. So, it has to be modelled as equivalent strut element for the nonlinear analysis of the building.

The modelling of infill wall as on equivalent diagonal compression member was introduced by Holmes (1961).The thickness of the equivalent diagonal strut was recommended as the thickness of the infill wall itself and width recommended as one third of the diagonal length of infill panel.

Table 7. Reinforcement details of column section

Column Id	Longitudinal reinforcement	
	Diameter of bar	**Number of bars**
C1	16	20
C2	12	24
C3	25	4
C4	12	16
C5	16	8
C6	12	12
C7	20	4

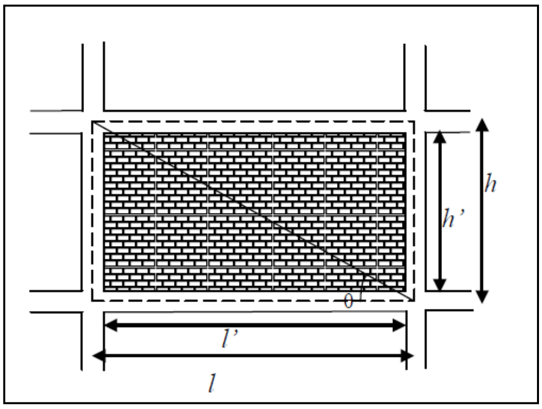

Figure 5. Typical pane of infill wall

The geometric and material properties of the infill wall are as follows.

Table 8. Details of infill wall

Property	Value
Thickness of infill wall	230 mm
Compressive strength of masonry (f_m')	6.5 MPa
Modulus of elasticity of infill material (E_m) (=750* f_m')	4875 MPa
Bond shear between masonry and mortar (f'bs)	0.24 MPa
Floor height (h)	3200 mm
Depth of beam (s)	350 mm
Clear height of infill panel (h'=h-s)	2850 mm
Bay width (l)	3000 mm
Width of column (b)	350 mm
Clear bay width (l'=l-b)	2650 mm
Diagonal length of infill wall ($d=\sqrt{l'^2 + h'^2}$)	3752 mm

- **Equivalent Strut Model**

For an infill wall located in a lateral load-resisting frame, the stiffness and strength contribution of the infill has to be considered. Non-integral infill walls subjected to lateral load behave like diagonal struts. Thus an infill wall can be modelled as an equivalent 'compression only' strut in the building model. The length of the strut is given by the diagonal distance (d) of the panel and its thickness is equal to the thickness of the infill wall. The elastic modulus of the strut is equal to the elastic modulus of masonry (E_m).

The width of the equivalent strut (w) is estimated as:

$$\mathbf{w} = \frac{\mathbf{d}}{\mathbf{4}}$$

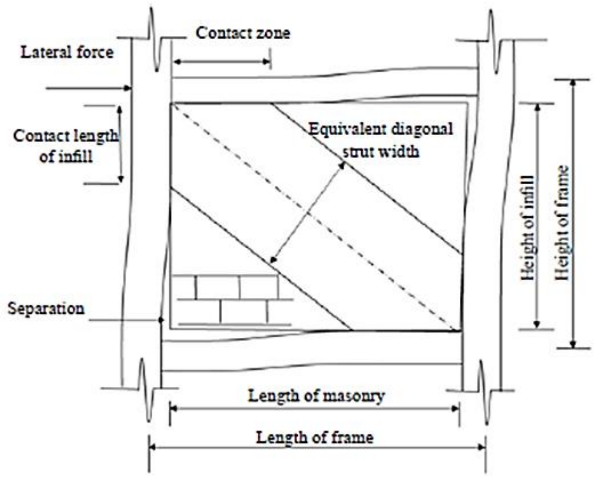

Figure 6. Deformation of in filled frame under lateral load

Here; According to this formula, width of the equivalent strut is taken as **938 mm.**

C. Nonlinear static analysis and development of capacity curves

The gravity loads are assigned to all the beams and force controlled pushover analysis is performed for the defined nonlinear static gravity load case **(DL + 0.25LL)**.After that lateral PUSH was applied to the building in form of uniform acceleration at the base. The building was pushed in the lateral direction until the development of the collapse mechanism.

Building capacity curves are constructed for each model building type and represent different levels of lateral force design and for a given loading condition, expected building performance. Each curve is defined by two control points: (1) the "yield" capacity, and (2) the "ultimate" capacity.

Here, the capacity curves are plotted for each of the building frame considered and yields as well as ultimate capacity points are found out for each capacity curve generated.

Table 8. curve control points and performance points for each frame

Frames	Performance point		Control points (mm)	
	(V,D)	(Sa,Sd)	Yield point (Dy)	Ultimate point (Du)
BARE	(565.407,105.28)	(0.673,83.154)	98.597	297.746
INFILL	(775.113,9.031)	(0.9,9.809)	18.559	30.106
OGS-1	(709.682,27.321)	(0.736,26.724)	28.826	115.309
OGS-2.5	(920.842,16.833)	(0.837,16.069)	17.567	54.775
OGS-3	(953.431,16.721)	(0.847,15.864)	16.415	54.609
OGS-3.97	(1097.818,17.232)	(0.816,15.804)	14.177	64.713
OGS-4.68	(1172.936,17.987)	(0.786,16.261)	13.311	76.053
OGS-2.1	(1012.104,16.942)	(0.845,15.353)	15.371	36.862

D. Identification of the damage state medians

After obtaining the capacity curve control points, the damage state medians for the various damage states can be obtained as shown in Tables 9 and 10.

Table 9. Damage state medians

Damage states	Threshold values
Slight	0.7Dy
Moderate	Dy
Extensive	Dy +0.25(Du-Dy)
Complete	Du

Table 10. Damage state threshold values for each frame

FRAMES	Damage state thresholds (mm)			
	SLIGHT	MODERATE	EXTENSIVE	COLLAPSE
BARE	69.0179	98.597	148.38425	297.746
INFILL	13.0193	18.599	21.47575	30.106
OGS-1	20.1782	28.826	50.44675	115.309
OGS-2.5	12.2969	17.567	26.869	54.775
OGS-3	11.4905	16.415	25.9635	54.609
OGS-3.97	9.9239	14.177	26.811	64.713
OGS-4.68	9.3177	13.311	28.9965	76.053
OGS-2.1	10.7597	15.371	20.74375	36.862

	Point corresponding to SLIGHT damage
	Point corresponding to MODERATE damage
z	Point corresponding to EXTENSIVE damage
	Point corresponding to COLLAPSE damage

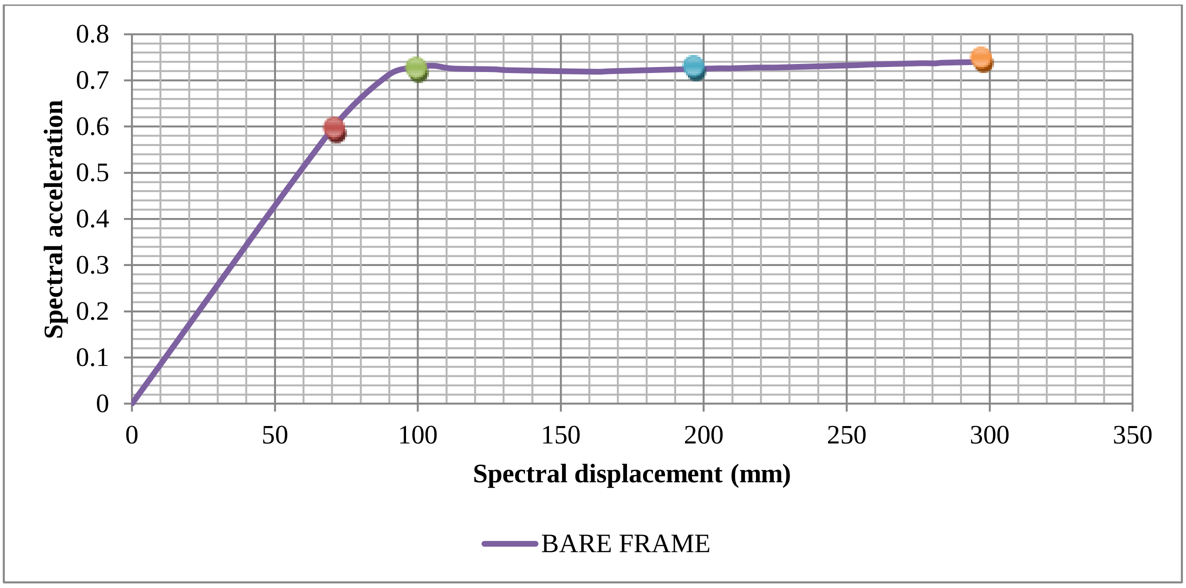

Figure 7. Example curve showing the identification of the damage state thresholds for Bare frame

E. Development of damage state variability

The damage state variability of the given building has been discussed in the chapter-4.The total variability in the damage state can be found out from the following equation.

$$\beta_{ds} = \sqrt{\left(\mathrm{CONV}[\beta_{C,}\beta_{D}]\right)^{2} + (\beta_{Tds})^{2}}$$

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

$\boldsymbol{\beta_{C}}$ is the lognormal standard deviation parameter that describes the variability of the capacity curve.

$\boldsymbol{\beta_{D}}$ is the lognormal standard deviation parameter that describes the variability of the demand spectrum.

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

HAZUS (2003) has presented variability for fragility estimation of American (Californian) buildings, where the total variability in structural damage is considered to be contributed by the three sources as described in Eq.

(8) and is obtained by combining the three variabilities using a complex convolution process. Although India has suffered several major earthquakes in the past, unfortunately, such systematic data is lacking for Indian conditions. However, the aim of the present study is not to prescribe standard fragility functions for Indian buildings, but to examine the role of URM Infills and modification factors on the fragility of RC frame building. Therefore, the HAZUS values of variability, for the corresponding cases, as reproduced in Table, have been considered.

The parameters considered here are

- Building Height Group – High-Rise Buildings (Table-6.7)
- Post yield degradation of the Structural system- Minor for slight damage, Major for moderate damage and Extreme for extensive and collapse damage.
- Damage state Threshold variability- Moderate
- Capacity curve Variability- Moderate

Table 11. 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**

F. Development of fragility curves

Fragility curves are developed for each building considered using the equation

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

Each term in this equation has been discussed in the chapter-4. All the values are substituted in the above equation.

III. RESULTS AND DISCUSSION

A. Comparison of fragility curves at performance point:

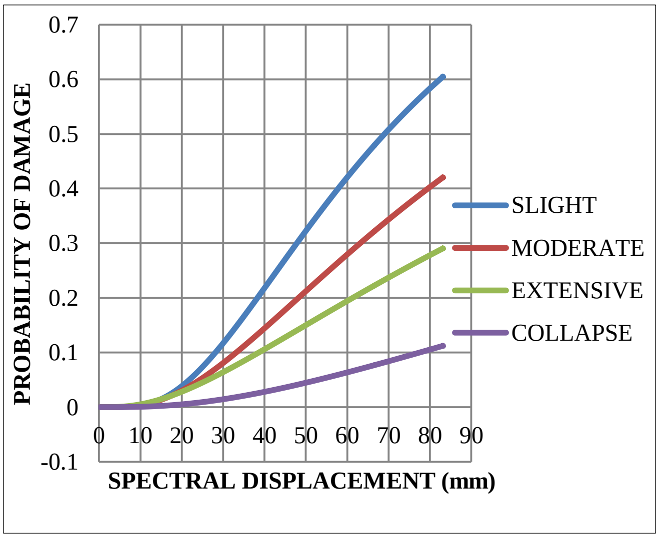

Figure 8. Probability of damage for bare frame at performance point

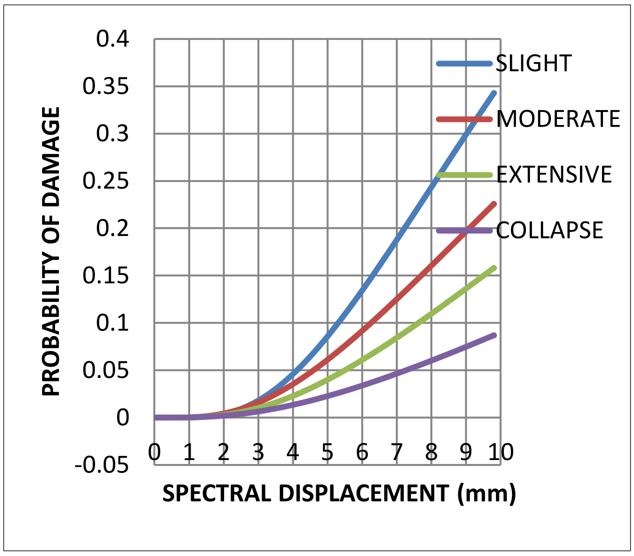

Figure 9. Probability of damage for infill frame at performance point

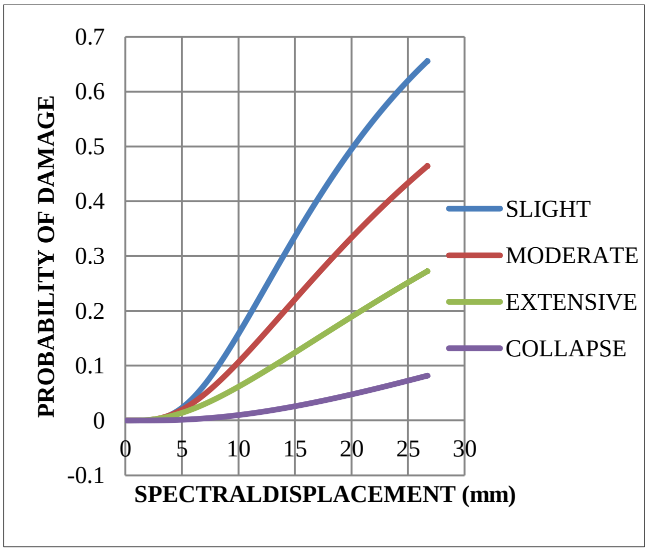

Figure 10. Probability of damage of OGS-1 at performance point

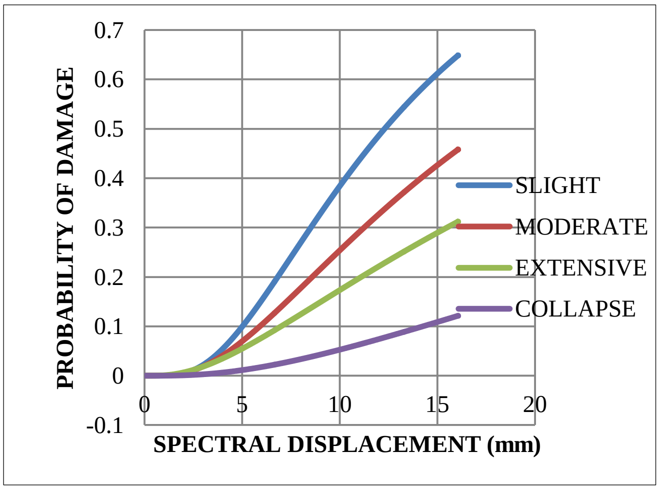

Figure 11. Probability of damage for OGS-2.5 at performance point

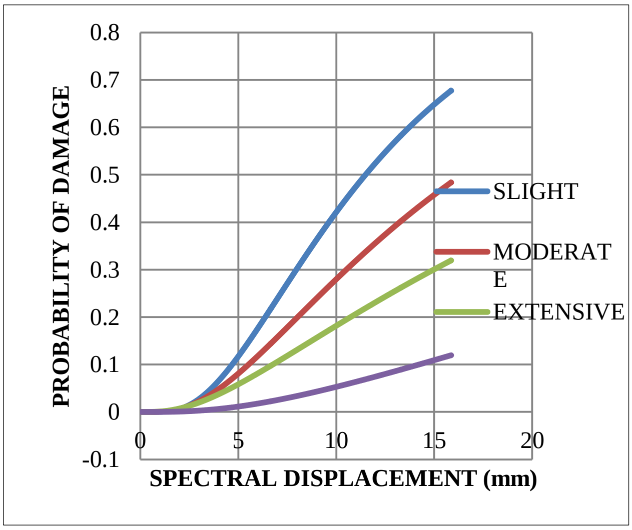

Figure 12. Probability of damage of OGS-3 at performance point

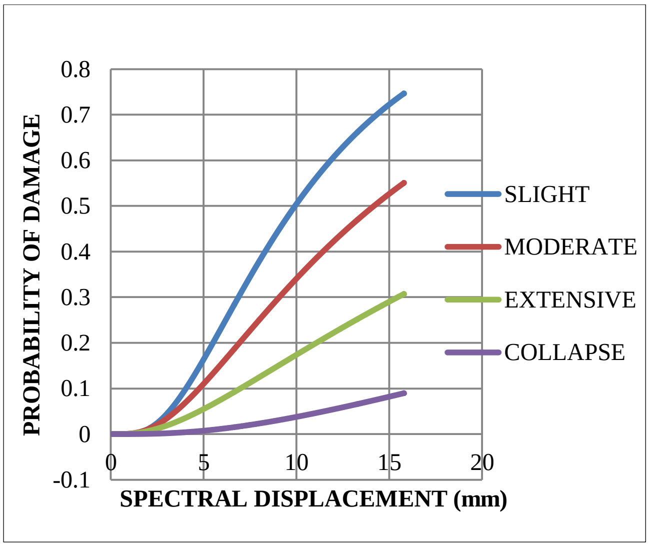

Figure 13. Probability of damage of ogs-3.97 at performance point

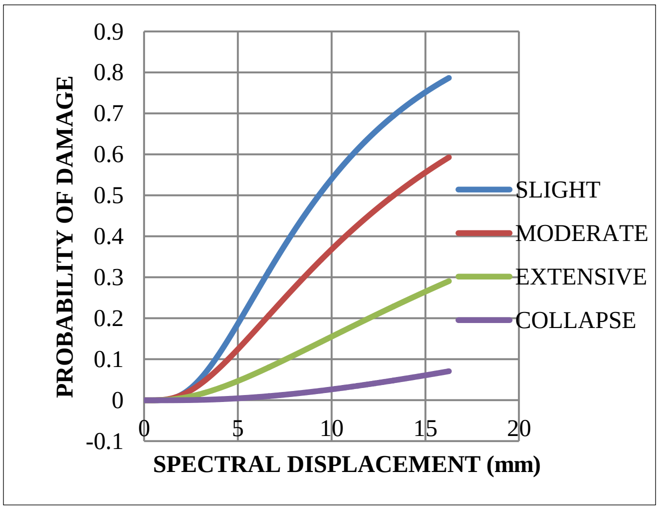

Figure 14. Probability of damage of OGS-4.68 at performance point

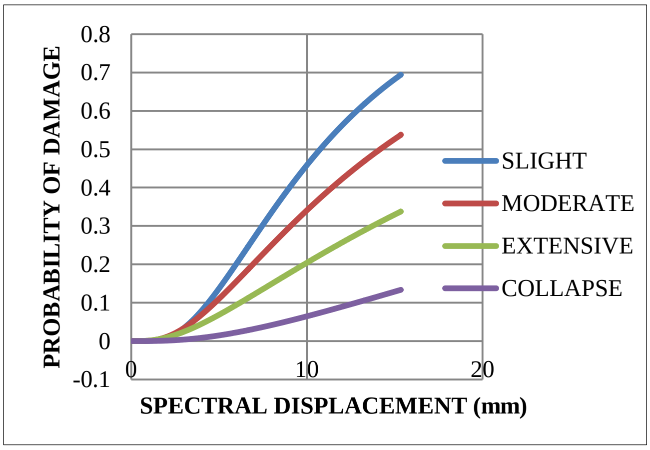

Figure 15. Probability of damage of OGS-2.1 at performance point

B. Comparison of building frame for each damage state

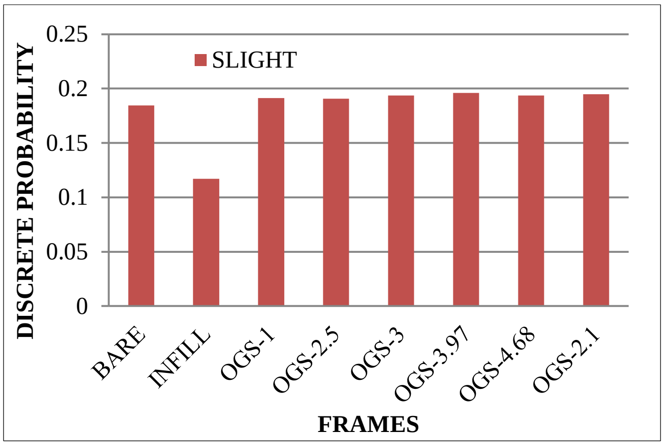

Figure 16. Discrete probabilities of SLIGHT damage at performance point for each building frame

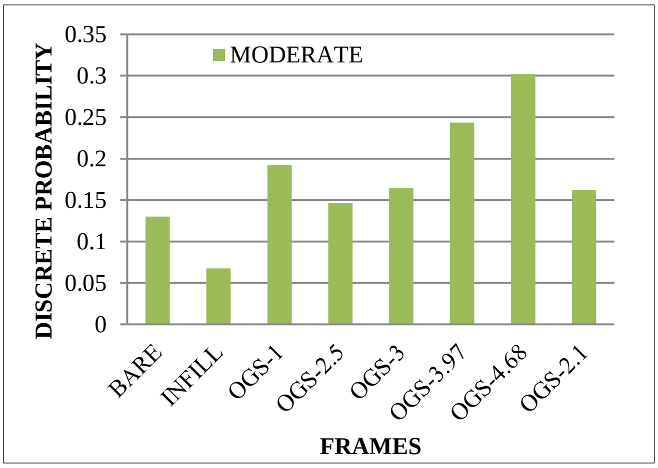

Figure 17. Discrete probabilities of MODERATE damage at performance point for each building frame

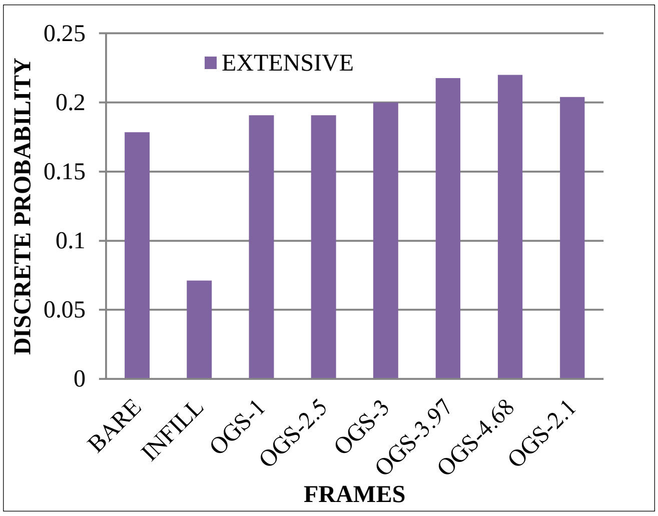

Figure 18. Discrete probabilities of EXTENSIVE damage at performance point for each building frame

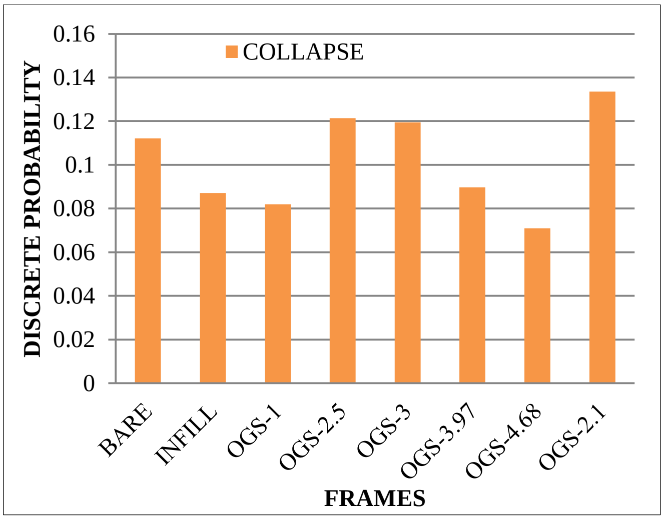

Figure 19. Discrete probabilities of COLLAPSE damage at performance point for each building frame

C. Discussion:

At the performance point,

- Probabilities that the frame will be subjected to **SLIGHT, MODERATE, EXTENSIVE and COLLAPSE** damage are least for **INFILL** frame. Thus infill frame will be subjected to less amount of SLIGHT damage compared to other frames.
- Among the **OGS** frames, all the frames are having the same probability of reaching the SLIGHT damage state.
- Among the OGS frames, the frame designed with **MF=4.68** is having the highest probability of **MODERATE** damage.
- Among the OGS frames, the frame designed with **MF=4.68** is having the highest probability of **EXTENSIVE** damage.

- Among the OGS frames, the frame designed with **MF=2.1** is having the highest probability of **COLLAPSE** damage.

IV. CONCLUSION

The following points can be derived from the present study;

- The performance of the INFILL wall is superior compared to the any other frames.
- The performance of the different OGS frames can be compared with the help of fragility curves developed using non-linear static analysis buildings.
- The non-linear static analysis procedure is relatively easy to apply and gives quick results, but at the same time it is less accurate.
- The complete nonlinear behavior of any structure can be assessed only with the help of nonlinear dynamic analysis.
- This can be the future scope of this paper.

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