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SEISMIC FRAGILITY ANALYSIS OF REGULAR AND SETBACK RCC FRAMES – A FEW HYPOTHETICAL CASE STUDIES

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ABSTRACT

The damage of structures due to earthquake is the cause of loss of life and property and hence it is necessary to study the vulnerability characteristics of structures subjected to such seismic excitations. In this paper a brief review of seismic performance evaluation of a G+10 Reinforced Cement Concrete (RCC) frame by Capacity Spectrum Method (CSM) is presented as per IS: 1893 (Part 1):2002.Further the vulnerability assessment of different RCC frames and the applicability of HAZUS drift ratio based damage state thresholds for building designed as per IS 456: 2000 code are also studied. Fragility curves were developed for frames with setbacks on different storeys indifferent bays for frames with and without infill walls. Infill is provided by “Diagonal Strut Method” and their damage probabilities are compared. Study of performance of shear wall placed in least stiffness direction as a remedial measure for setback frames was also carried out. It was concluded from this study that setback frames are more vulnerable compared to regular frames, however setback frames with provision of infill are found to perform as regular RC frames.

Keywords: Fragility curves; R.C building; probability of damage state; setback frame.

1. INTRODUCTION

Losses inflicted on modern buildings from recent earthquakes have reiterated the need for investigation on the seismic safety of code-compliant buildings at various performance limit states. This need has stimulated significant research to develop methodologies for deriving fragility relationships, which are key components in seismic loss assessment. The seismic vulnerability of a structure can be described as its susceptibility to damage by ground

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shaking of a given intensity. [1] The aim of a vulnerability assessment is to obtain the probability of a given level of damage to a given building type due to earthquake. Damage functions are to be developed to assess the damage level for a given level of earthquake. The outcome of vulnerability assessment is useful for loss estimation which is essential parameter in disaster mitigation and emergency preparedness. The present study is aimed at seismic performance evaluation of various regular and setback RC frames located on hard soil and in Zone II using Response spectrum Method.

2. LITERATURE REVIEW

Basically two methods of analysis are available to predict the seismic performance of structures [2]. They are

1. Elastic Method of Analysis
a) Seismic Coefficient Method
b) Linear Elastic Dynamic Analysis.
2. Inelastic Method of Analysis
a) Inelastic Time History/Nonlinear Response History Analysis (NRH)
b) Nonlinear Static Analysis or Pushover Analysis.
3. ATC 40 (1996) has developed a simple iterative procedure (Fig. 1) to estimate seismic inelastic displacement for given level of earthquake, i.e., Capacity Spectrum Method (CSM). By using capacity spectrum method performance point (i.e. inelastic displacement of the structure for the given level of earthquake) can be obtained.

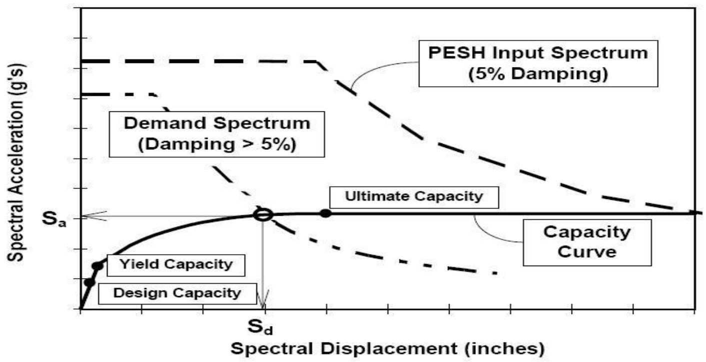

Figure 1. Capacity Spectrum method

Different researchers adopted different methods for seismic frugality assessment of RCC frames with mass irregularities, [4] and [5]. Valmundson and Nau [6] concluded that ELF procedure prescribed by UBC 97 code predicts seismic response accurately up to mass ratio of five. Al-Ali and Krawinkler [7] studied the seismic response of 10 storey building frames with different types of vertical irregularities and Presence of mass irregularity at top had maximum impact on drift as compared to the case when mass irregularity was present at bottom and at mid-height. Goel and Chopra [8] developed period formula for moment resisting frames. The mass irregularity had negligible impact on seismic response [9]. Das and Nau [10] determined the seismic response of 5, 10 and 20 storey buildings with mass, stiffness and strength irregularities by equivalent lateral force procedure as prescribed by UBC 97 code and found that seismic response showed variation in vicinity of irregularities. Choi [11] concluded that the frames with mass irregularity especially at lower or upper floors had severe impact on seismic response which was evaluated in terms of plastic hinge distributions and rotations. Ayidin [12] conducted analytical studies on a 5, 10 and 20 storey frames with mass irregularities using ELF procedure as prescribed by UBC 97 code, from analytical studies and found that mass irregularity affects shear in storey below and ELF procedure overestimates the seismic response. Athanassiadou [13] found that the setback frames designed as per [14] EC8 provisions showed better seismic performance. Karavasiliset al. [15] determined seismic response parameters of multi-storey steel frames, the expressions for parameters were developed on basis of regression analysis. Sehgal et al. [16] based on their analytical studies observed combination of stiffness and setback irregularities to generate the maximum seismic response as compared to the case when they are singly present. Michael et al. ([17] conducted studies on Seismic fragility of RC framed and wall-frame buildings designed to the EN-Eurocodes. Varadharajan et al. [18] conducted a detailed review of effect of different structural irregularities in the building on the seismic response of the building and concluded that the performance varies drastically near the vicinity of irregularity. He also observed that short period irregular structures exhibit a strong response compared to long period structures and determined the inelastic seismic response of setback frames designed as per [14] EC8:2004 and IS 456 [19] provisions. The results of analytical study as per EC 8 provisions were found to be over conservative in estimation of seismic demands. He also concluded that the presence of irregularity results in variation of fundamental time period.

3. OBJECTIVE AND SCOPE OF THE STUDY

The objective of this study is to assess the

1. Damage states in buildings with setbacks at different storeys and bays
2. Seismic fragility analysis for vertical setback buildings
3. Seismic fragility of regular bare building Frame and Building frame provided with vertical Setback at 4^{th} storey in various bays
4. Influence of infill wall (diagonal struts) on buildings
5. Influence of shear wall on bear frame building

An RCC frame‘S+10’ (Stilt + 10 Storyes) with a regular plan and elevation shown in Figs. 2(a) and 2(b) is considered assuming it to be located in seismic Zone II and Soil Zone III (hard strata) for this study.

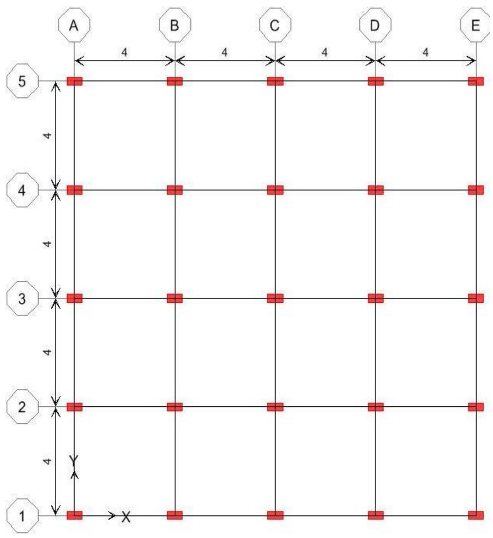

Figure 2 (a). Plan area of the building

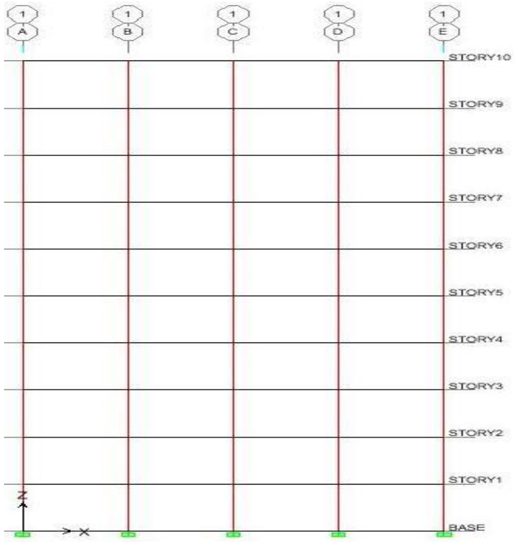

Figure 2 (b). Elevation of the building

Other details of this frame are as follows.

Analysis and Design parameters

Type of Structure	= Residential Building
Materials	= M20 grade concrete and Fe 415 grade steel
Seismic analysis method	= Equivalent Static method ([20] IS 1893 (Part 1): 2002)
Design Philosophy	= Limit State Method ([19] IS 456: 2000)

Geometric parameters

Foundation level to Ground level	= 1.8 m
Number of bays in X- direction	= 4
Number of bays in Y- direction	= 4
Spacing of bays in X-direction	= 4m
Spacing of bays in Y-direction	= 4m
Height of each story	= 3m

Dimensions of structural members

Plinth beam (PB)	= 0.23m x 0.3 m
Floor beam (FB)	= 0.3m x 0.45 m
Roof beam (RB)	= 0.23m x 0.45 m
Column	= 0.45m x 0.6 m
Thickness of the slab	= 0.185 m
Thickness of external wall	= 0.23 m
Thickness of internal wall	= 0.115 m
Thickness of parapet wall	= 0.15 m
Height of parapet wall	= 1.2 m

Loads considered

Live load on slab ($L.L_s$)	= 3 kN/m	
Vehicle parking Live load ($L.L_V$)	= 4 kN/m	
Unit weight of brick masonry	= 20 kN/m^3	
Unit weight of R.C.C	= 25 kN/m^3	
Self-Weight of external wall (W_E)	= 0.23 x 20 x (3-0.3)	= 12.42 kN/m^2
Self-Weight of internal wall (W_I)	= 0.115 x 20 x (3-0.3)	= 6.20 kN/m
Self-Weight of parapet wall (W_p)	= 0.15 x 20 x (1.2)	= 3.60 kN/m
Self-Weight of slab (W_s)	= 25 x 0.185	= 4.63 kN/m
Self-Weight of floor finish (W_{FF})	= 0.75 kN/m	
Unexpected dead load (W_U)	= 0.75 kN/m	

4. METHODOLOGY

Fragility curves describe the probability of damage to building [21]. 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. The fragility curves distribute damage among slight, moderate, extensive and complete damage states. For any given value of spectral response, discrete damage-state probabilities are calculated as the difference of the cumulative probabilities of reaching, or exceeding, successive damage states. Each fragility curve is defined by a median value of the demand parameter (e.g., spectral displacement) that corresponds to the threshold of that damage state and by the variability associated with that damage state. The typical fragility curve is shown in Fig. 3. The steps involved in development of fragility curves as per [21] HAZUS-MH MR1 are explained in Fig. 4.

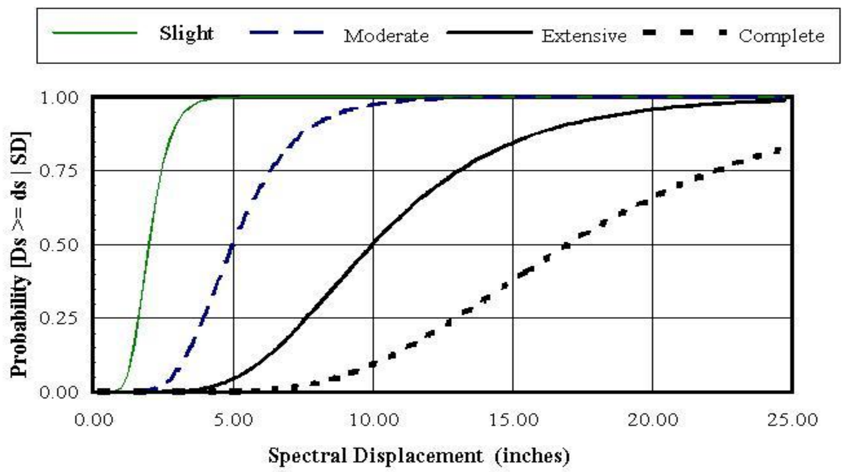

Figure 3. Log-normally distributed seismic fragility curves of a building [21]

A flowchart describing procedure to develop damage probability matrix is presented in Fig. 4.

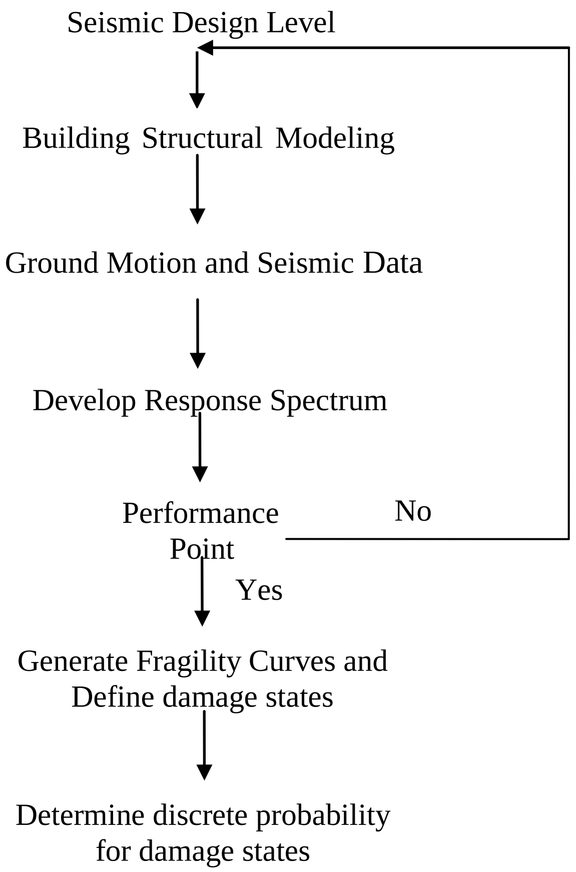

Figure 4. Flowchart to develop damage probability matrix

The detailed step by step procedure for developed based on theoretical background on fragility curves is described as follows ([22] and [23]):

1. Building Type and Classification

Buildings are classified both in terms of their use, or occupancy class, and in terms of their structural system, or model building type. Buildings are classified based on structural characteristics like number of storeys as Low-rise (1-3 storeys), Mid-rise (4-7 storeys), High-rise (8+ storeys).

2. Seismic Design Levels and Quality of Construction

Different buildings are expected to perform differently during an earthquake. These differences in expected building performance are determined primarily on the basis of seismic zone location, design vintage and use. Damage functions are provided for three "code" seismic design levels, labeled as High-code, Moderate-code and Low-code, and an additional design level for Pre-code buildings.

3. Damage States

Damage states are defined separately for structural and nonstructural systems of a building. Damage is described as four discrete damage states: slight, moderate, extensive, and complete. Loss functions relate the physical condition of the building to various loss parameters (i.e., direct economic and functional loss, casualties).

4. Calculation of Cumulative Damage Probabilities of Particular Damage State [24]

The damage function is assumed to be lognormal function. To define a probability distribution median and standard deviation values are required. For a given median spectral displacement Sdds, standard deviation 'β' for a particular damage state 'ds' and design level the conditional probability of being in or exceeding is defined by

$$P\left[\frac{ds}{S_d}\right] = \varphi[\left(\frac{1}{\beta ds}\right)\ln(\frac{S_d}{S_{d,ds}})]$$

where,

$S_{d,ds}$ =Median value of spectral displacement at which the building reaches the threshold of damage state, ds

β_{ds} =Standard deviation of natural logarithm of spectral displacement for damage state, ds

φ= Standard normal cumulative distribution function.

S_d= Given peak spectral displacement.

P[S/S_d]=Probability of being in or exceeding slight damage state.

P[M/S_d]=Probability of being in or exceeding moderate state.

P[E/S_d]=Probability of being in or exceeding extensive state.

P[C/S_d]=Probability of being in or exceeding collapse state.

5. Calculation of Discrete Damage Probabilities of Damage States

The probability of discrete damage state ds is given below

Probability of Complete damage state P[C] =P[C/S_d]

Probability of Extensive damage state P [E] =P[C/S_d]-P[E/S_d]

Probability of Moderate damage state P [M] =P[E/S_d]-P[M/S_d]

Probability of Slight damage state P[S] =P[M/S_d]-P[S/S_d]

Probability of No damage state P [N] =1-P[S/S_d]

There are certain key aspects to the damage functions of which the designers must be aware when developing fragility parameters. [25], [26] Firstly, the damage functions should predict damage without bias such as that inherent to the conservatism of seismic design codes and guidelines. In general, limit states of the NEHRP guidelines (or [3] ATC 40, 1996) will under-predict the capability of the structure, particularly for the more critical performance objectives, such as collapse prevention (CP).The median spectral displacement for each damage state is given in Table 1.

Table 1: Damage state thresholds (Barbat [26])

Median Spectral Displacement	**Damage State**
$\overline{S}_{d,S} = 0.7\ S_{d,y}$	Slight
$\overline{S}_{d,M} = S_{d,y}$	Moderate
$\overline{S}_{d,E} = S_{d,y} + 0.25\ (S_{d,u} - S_{d,y})$	Extensive
$\overline{S}_{d,C} = S_{d,u}$	Complete

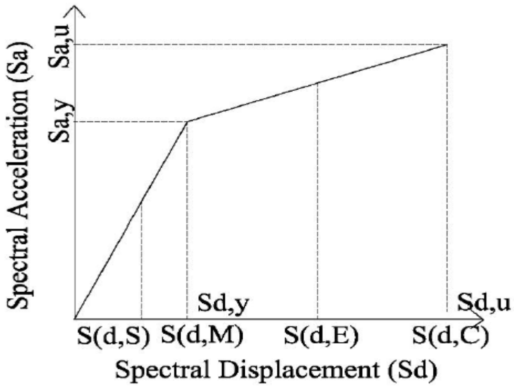

Figure 5. Damage state thresholds on bilinear capacity spectrum (Barbat et al. [26])

The median roof displacement for each damage state is given by equation

$$S_{d,ds} = \Delta ds * HR * \alpha 1$$

Δds= Average inter-storey drift ratio at the threshold of damage state, ds
HR= Height of building at the roof level.
α1= Modal mass participation factor for the first natural mode.

Average inter-storey drift ratios at threshold of damage state for Concrete moment frame (C1) type building are given as follows.

Table 2: Average inter-storey drift ratio for structural damage states ([21] HAZUS-MHMR1)

Structural Damage States			
Slight	**Moderate**	**Extensive**	**Collapse**
Low rise building –High- code design level			
0.005	0.010	0.030	0.080
Low rise building –Moderate- code design level			
0.005	0.009	0.023	0.060
Low rise building –Low- code design level			
0.005	0.008	0.020	0.050
Low rise building –Pre- code design level			
0.004	0.006	0.016	0.040
Mid-rise buildings			
2/3*LR	2/3*LR	2/3*LR	2/3*LR
High rise buildings			
1/2*LR	1/2*LR	1/2*LR	1/2*LR

Masonary infilled RC Frame with soft storey was analysed by using “Equivalent Diagonal Strut Method”. In the present study each infill panel was replaced by two diagonal struts and analyzed for its strength, fragility curves were plotted and then compared with that of the building frames without infill walls. Following gives the calculation of strut width and length.

From Table 1 of IS 1905: 1987, [28]
Compressive strength of brick (Class'A') = 5 to 12.5 N/mm^2
Compressive strength of mortar of 1:6 = 3N/mm^2 (M_2 Type)
Compressive strength of brick = 10 N/mm^2
Grade of mortar (1:6) = M_2 grade
From Table 8 of IS 1905: 1987, [28]
Compressive strength of infill wall
$(f_{ck})_{infill}$ = 0.44 + (0.94 - 0.44) x 5/7.5 = 0.77 N/mm^2
Possions ratio of brick masonary(μ) = 0.17
Modulus of elasticity of brick (E_i) = 550 x $(f_{ck})_{infill}$ = 425.31N/mm^2

Calculation of strut width for masonry infill panels was proposed by [29] Mainstone in 1971 where the cross sectional area of strut was calculated by considering the sectional properties of the adjoining columns. The details of model with strut width and strut position are shown in Figure

6. Width of diagonal strut is given by,

$$W = 0.175 * D * (\lambda H)^{-0.4}$$

where,

$$\lambda = \frac{(E_i * t * \sin 2\theta)}{(4 * E_f * I_c * h)^{1/4}}$$

H = Height of the floor (m)
E_i = Modulus of elasticity of infill material
E_f = Modulus of elasticity of frame material
T = Thickness of wall (m)
H = Height of the infill (m)
I_c = Moment of inertia of column (m^4)
θ = Slope of infill diagonal to the horizontal.
D = Diagonal length of infill panel

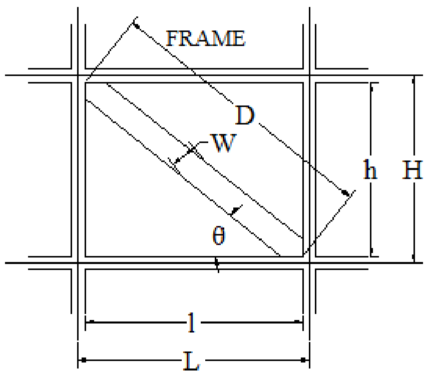

Figure 6. Strut replacing infill

Then by using above given formula width of struts are calculated and obtained as follows.

Struts in external infills parallel to y-direction $(W_1)_{ext}$ = 0.638 m
Struts in internal infills parallel to y-direction $(W_1)_{int}$ = 0.683 m
Struts in external infills parallel to x-direction $(W_2)_{ext}$ = 0.590 m
Struts in internal infills parallel to x-direction $(W_2)_{int}$ = 0.635 m

In the study on analysis of masonary infilled RC Frame with soft storey by considering shear wall, the building frames with setbacks provided at 4th floor in 1st, 2nd, 3rd bays (for which probability exceedence of failure damage state was high in their respective bays) were considered with a shear wall placed in least lateral siffiness direction.A shear wall of M20 grade concrete and Fe 415 grade HYSD steel rebar with a thickness of 230 mm was adopted.

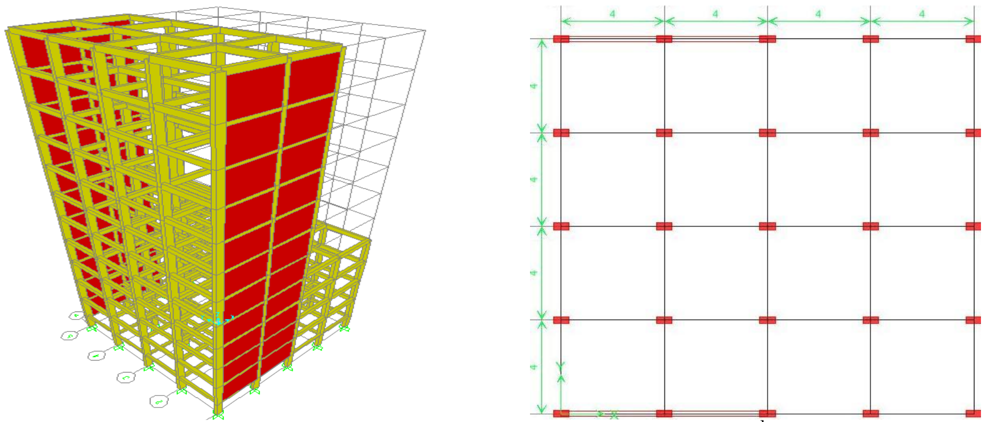

Figure 7. Elevation and Plan of building frame with setback in 2nd bay and shear wall

5. RESULTS AND DISCUSSION

5.1 Damage states in buildings with setbacks at different story's and bays

For rendering the variation in slight, moderate, extensive, collapse damage states median of roof displacement, a ten storey bare frames (with setbacks at different stories in different bays) are considered. Graphs showing the variation in collapse damage state median with setbacks (Figs. 8, 9, 10 and 11).

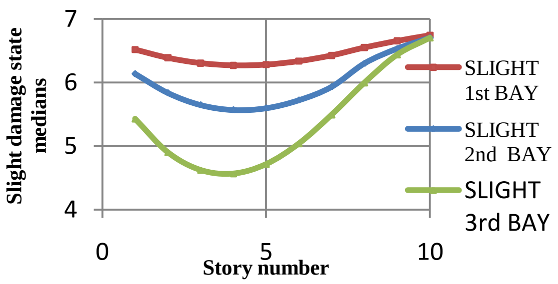

Figure 8. Slight damage state medians

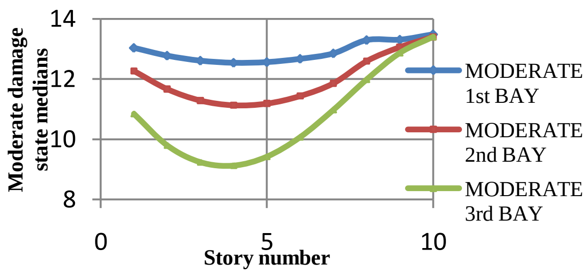

Figure 9. Moderate damage state medians

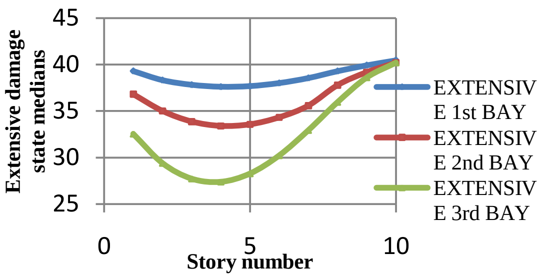

Figure 10. Extensive damage state medians

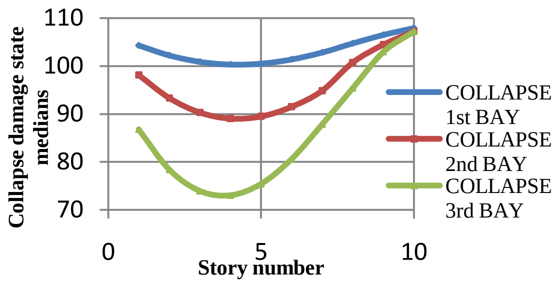

Figure 11. Collapse damage state medians

It can be observed that damage state median is least for 4th storey setback which causes more seismic damage to the frame compared to the setbacks at remaining storeys for earthquake of same intensity.

5.2 Seismic fragility analysis for vertical setback buildings

The three 10- storey bare frames with vertical setbacks are provided at different storeys in different bays. These frames are analyzed by push over and modal analysis [7], [30] and their probabilities of exceeding for different damage states are calculated. Subsequently fragility curves were plotted. Figs. 12, 13 and 14 show the variation of probabilities (Fragility curves) of 10 SBF with setbacks at 4th, 1st, 10th storeys in 1st, 2nd and 3rd bays respectively.

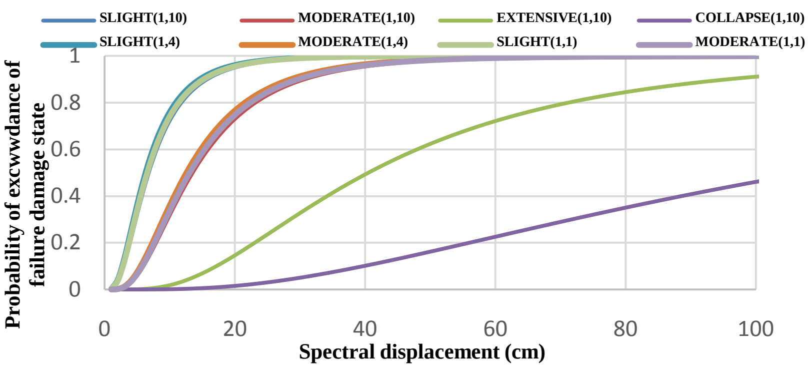

Figure 12. Fragility curves for setbacks in 1st bay

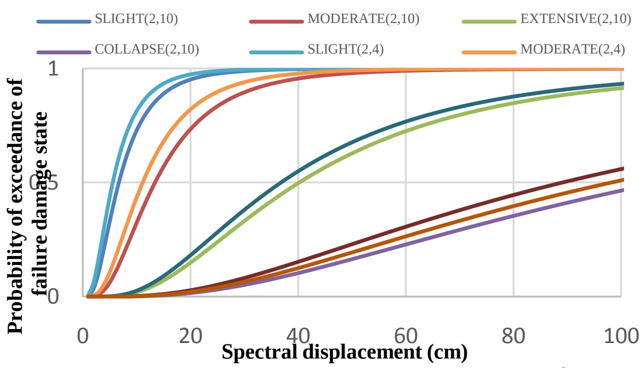

Figure 13. Fragility curves for setbacks in 2nd bay

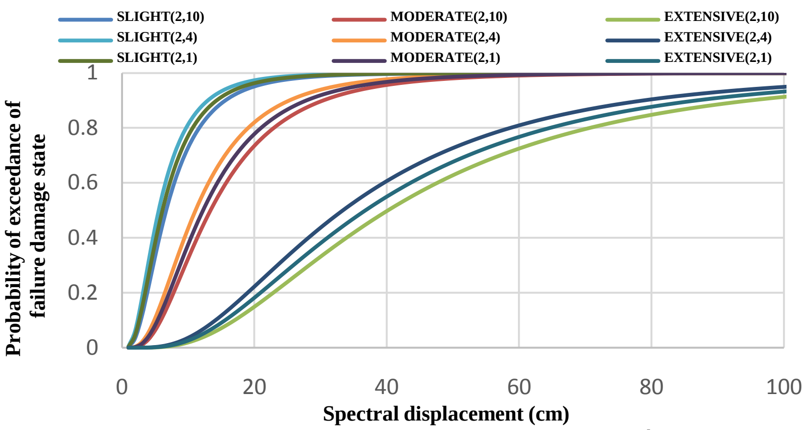

Figure 14. Fragility curves for setbacks in3rd bay.

From Fig. 14, it can be observed that the probability of failure in different damage states is more when setback is provided at 4th floor than that of the 1st and 10th floors irrespective of bays. From these curves damage states (i.e.., collapse, extensive, moderate and slight damages) for 4th storey are more and are identified earlier compared to 1st and 10th storeys at which setbacks are provided. Therefore care should be taken while providing setbacks to RC buildings and it is recommended to avoid provision of setbacks at center storeys.

5.3 Seismic fragility of 10 storey regular bare building Frame and Building frame provided with vertical Setback at 4th storey in various bays

The seismic fragility analysis of 10 Storey Regular Bare Frame and building frame provided vertical Setback at 4th storey is performed and seismic fragility curves were developed and compared. Seismic fragility curves for 10 SBF regular building and 10 SBF building provided with setback at 4th floor in 1st, 2nd and 3rd bays are presented in Figs. 15, 16 and 17.

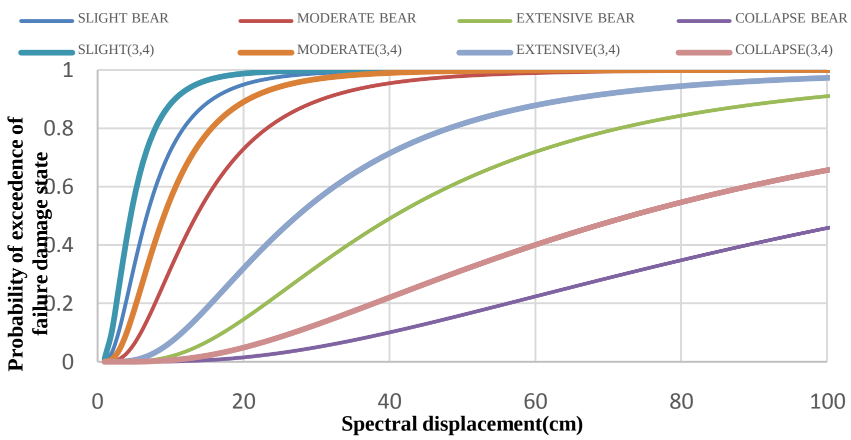

Figure 15. Seismic fragility curves for 10 SBF regular building and 10 SBF building provided with setback at 4th floor of 1st bay

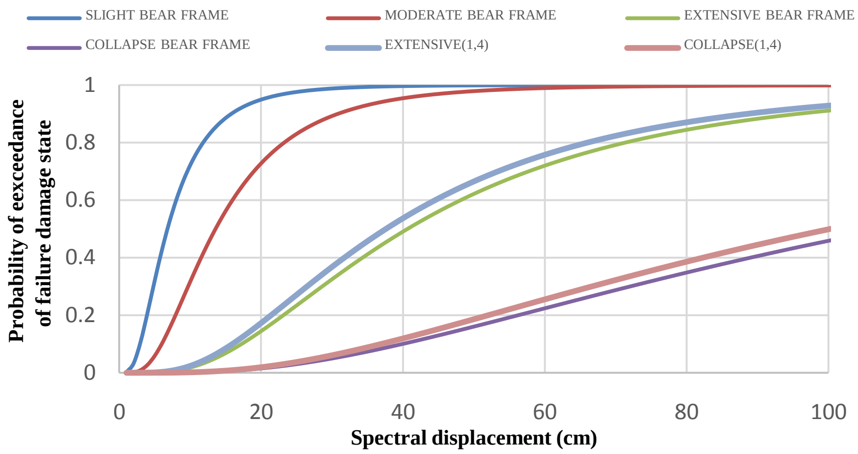

Figure 16. Seismic fragility curves for 10 SBF regular building and 10 SBF building provided with setback at 4th floor of 2nd bay

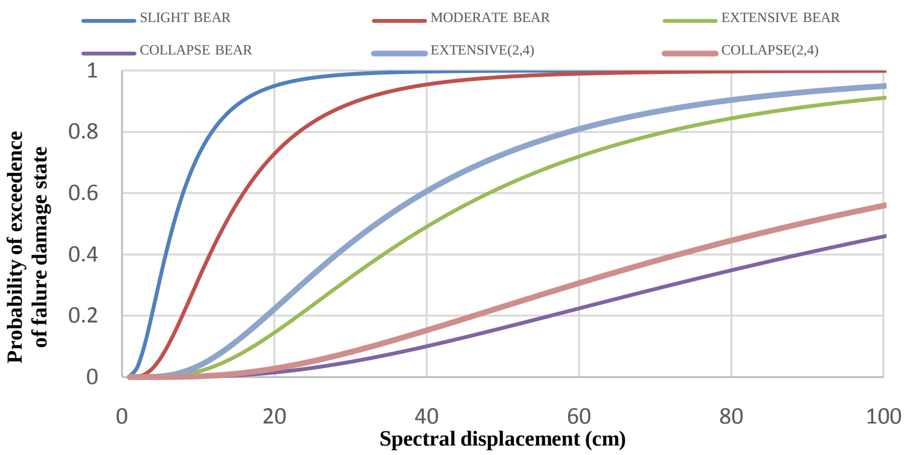

Figure 17. Seismic fragility curves for 10 SBF regular building and 10 SBF building provided with setback at 4th floor of 3rd bay

From the fragility curves shown in Figs. 15, 16 and 17, for all damage states, the damage is more for the vertical setback building frames as compared to regular building frame and the damage is identified earlier also.

5.4 Influence of considering infill wall (diagonal struts) building without infill walls

Seismic fragility analysis is carried out for 10 storey building without infill walls provided setback at 4th floor in 1st, 2nd and 3rd bays without infill walls and with infill walls replaced by diagonal struts. Figs. 18, 19 and 20show the variation of probabilities of exceeding the failure damage states for building without infill walls with and without struts.

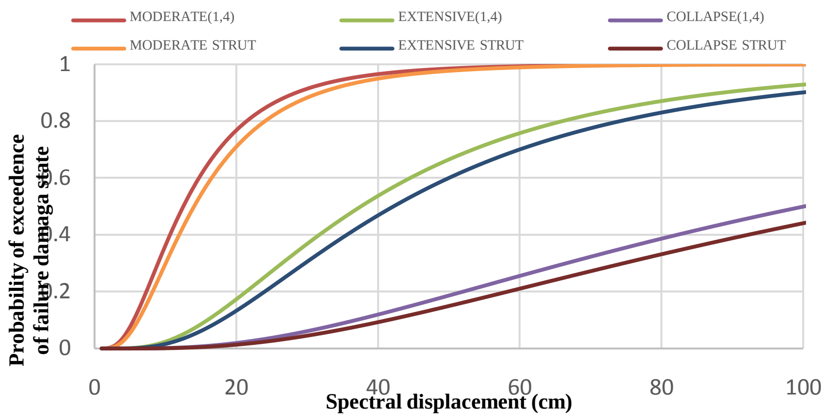

Figure 18. Seismic fragility curves for different damage states of 10 SBF building provided vertical setback at 4th floor of 1st bay with and without diagonal struts

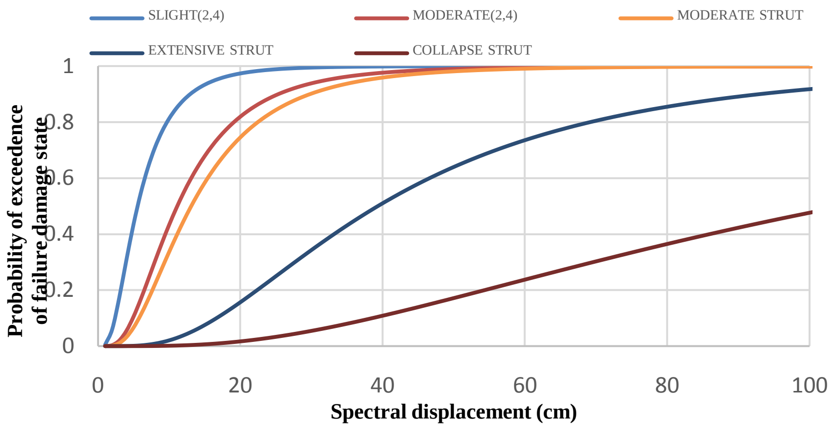

Figure 19. Seismic fragility curves for different damage states of 10 SBF building provided vertical setback at 4th floor of 2nd bay with and without diagonal struts

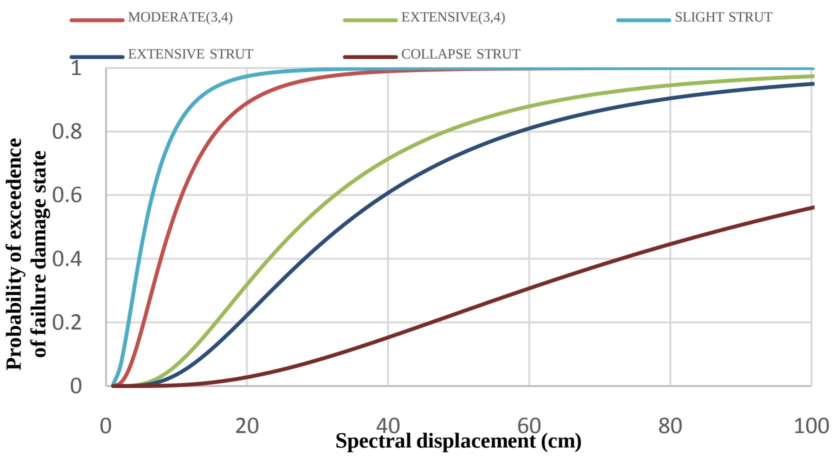

Figure 20. Seismic fragility curves for different damage states of 10 SBF building provided vertical setback at 4th floor of 3rd bay with and without struts

From Figs. 18, 19 and 20, it can be inferred that the performance of the building will be enhanced by considering infill walls (i.e. diagonal struts). In the building provided vertical setback at 4th floor of 1st bay, collapse damage state probability of failure is decreased by nearly 8%, For the building provided vertical setback at 4th floor of 2nd bay collapse damage state probability of failure is decreased by nearly 10% and the building provided vertical setback at 4th floor of 3rd bay for collapse damage state probability of failure is decreased by nearly 15% for building with struts.

5.5 Influence of shear wall and Comparison the shear wall effect with bear frame building

In the present study shear wall was considered with the shear wall placed in least lateral siffiness direction. The shear wall enhances the stiffness of the building and subsequently resistance of the builiding for seismic forces were increased. Figs. 21, 22 and 23show the comparison of fragility curves of building frames (setback at 4th floor in 1st bay) with and without shear wall.

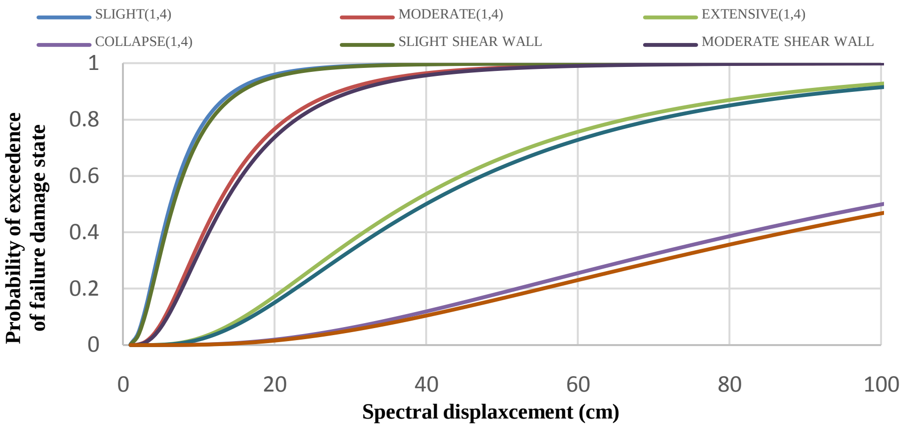

Figure 21. Seismic fragility curves for different damage states of 10 SBF building provided vertical setback at 4th floor of 1st bay with and without shear wall

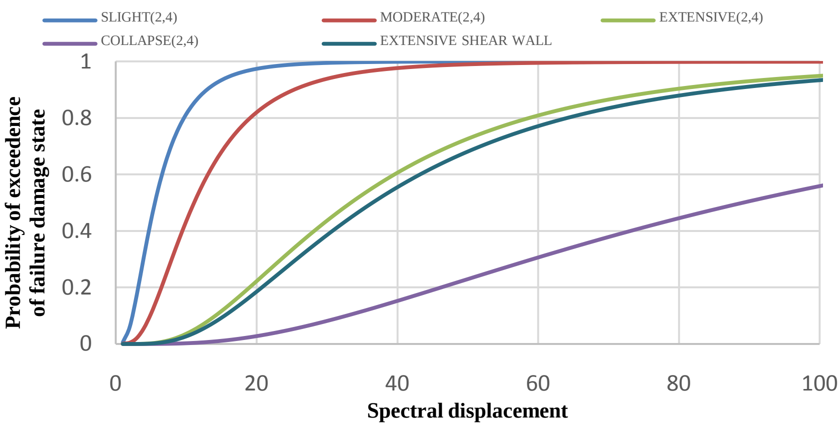

Figure 22. Seismic fragility curves for different damage states of 10 SBF building provided vertical setback at 4th floor of 2nd bay with and without shear wall

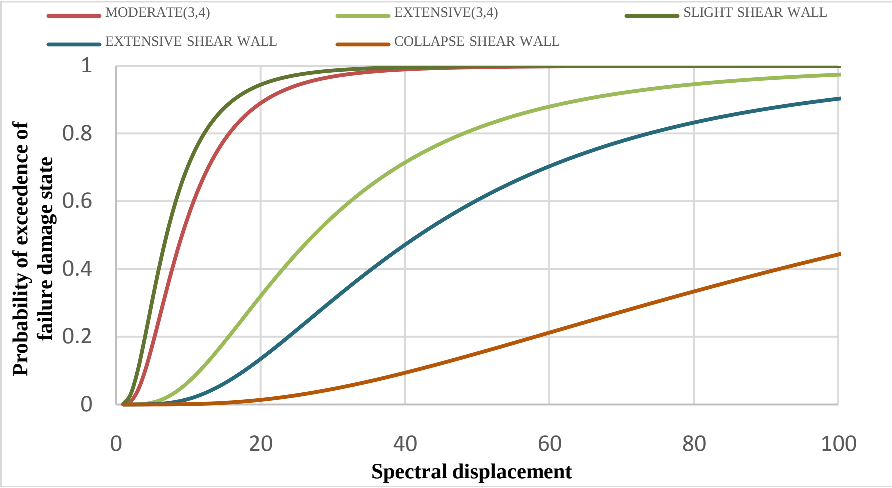

Figure 23. Seismic fragility curves for different damage states of 10 SBF building provided vertical setback at 4th floor of 3rd bay with and without shear wall

From Figs. 21, 22 and 23, it can be observed that the performance of the building will be enhanced by considering shear walls. In this case the probability of failure for all damage states was more for building frame without considering shear walls. For the building provided vertical setback at 4th floor of 1st, 2nd, 3rd bays for collapse damage state, probability of failure is decreased by 5%, 6% and nearly 20% respectively for building with shear wall. So the shear wall is effective in the 10 storey building frame with setback at 4th floor in 3rd bay rather than the building frames with setback at 4th floor in 1st bay and 2nd bay.

6. CONCLUSIONS

Seismic vulnerability assessment for regular RC frames and vertically geometric irregular frames with and without in fills has been studied for various seismic intensity areas and soil conditions. The fragility curves for the above mentioned buildings have been developed for the various performance levels defined by HAZUS manual [21]. Demand spectra have been obtained based on the inputs from IS 1893 (Part 1): 2002 [21] code for corresponding soil conditions in high seismic intensity area. Capacity spectrum has been developed for the corresponding buildings using pushover analysis and performance points are obtained from the intersection of demand spectrum and capacity spectrum using capacity spectrum method. From analysis carried out the following conclusions can be drawn.

1. The probability of damage in RC frames is found to be high when setbacks were introduced at middle storey when compared with RC frames with setbacks at other storeys.
2. Setbacks introduced at middle storey in 1st, 2nd, 3rd bays RC frames without infill walls the probability of damage is 5%, 10%, 20% more as compared with the RC frames with infill walls.

3. RC frames with infill walls are seismically more resistant than RC frames without infill walls for all damage states.
4. The effect of consideration of infill wall (diagonal strut) stiffness is more significant in the building with setback provided at middle storey in 3rd bay as compared with the frames with setbacks in other storeys.
5. The seismic resistance of the setback frames having setback at middle storey can be improved similar to that of regular R.C. building by considering infill walls stiffness of the building.
6. Setbacks introduced at middle storey in 1st, 2nd, 3rd bays RC frames with shear wall, the probability of collapse damage is decreased by 2.5%, 5%, 20% as compared with the RC frames without a shear wall.
7. The influence of provision of shear wall in least lateral stiffness direction has shown more significant effect in reducing the collapse damage state probability. Further, Provision of shear wall in least lateral stiffness direction has enhanced the seismic resistance of the building.
8. This fragility analysis is useful in assessment of state (damage state) of the structure if seismic zones are revised.

Shear wall is effective for the building with setback provided at middle storey in 3rd bay as compared with the frames with setbacks in other storey.

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