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Estimating Limit State Capacities for OGS Building having different Multiplication Factor

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Abstract – Seismic fragility curves are one of the famous methods to address the problem of performance of building in probabilistic approaches. It considers the uncertainties in load and demand; it gives reliable results to take decisions. In seismic fragility analysis, curves for different structural performance levels are plotted against the structural demand. The structural capacities or structural limit state (LS) capacities is of crucial importance. LS capacities are elaborated in design codes and several research has done to estimate the LS capacities using Push over analysis. However, there is an uncertainty in the building due to the presence of infill walls as well; infill walls add additional stiffness against lateral loads. And in the case of Open Ground Storey (OGS), the complexity is added to one more level due to the absence of infill walls in ground storey. International codebooks suggest to use magnification factor (MF) in ground storey to have good performance under lateral loads for OGS building. The present study focuses on evaluating the LS capacities for buildings of two storey and four storey buildings with different scheme of MF. The results shows that there is a wide disparity in storey wise LS capacities.

***Keywords*: F**ragility curves, infill walls, Open Ground Storey (OGS), Limit State Capacities.

1. Introduction

In seismic risk assessment, development of fragility curve is one of the key components. The seismic fragility curves represent a comparison between structural demand (*SD*) with different Limit State (*LS*) capacities. Several literatures/codes, defines a capacity for RC moment resisting frames with and without infill walls such as ASCE/SEI 41-06 [1], Ghobarah [2], etc. However, these recommendations cannot be adopted for all the cases, especially for the OGS buildings. In general, failure of building under seismic loading is initiated by failure of particular storey depend upon many factors, and further whole building is collapsed. In case of OGS building, the failure is initiated by ground storey due to the absence of infill walls in that storey. International codes suggest to use MF for Ground storey, that will increase the storey stiffness. There is different disparity of MF suggested among international codes. Haran *et. al* (2016), [3] has worked on two to six storey OGS building designed with different MFs and studied its performances using fragility curves. They considered LS capacities as 1% and 4% for light repairable damage (*IO*) and near collapse (*CP*) performance level respectively. But, FEMA HAZUS – MH [4] suggests to perform a pushover analysis according to the first mode shape lateral loads. And from resulting pushover curves limit states capacities can be identified. Similarly, N2 method Fajfar [5], combines pushover analysis of a multi-degree-of-freedom (MDOF) model with the response spectrum analysis of an equivalent single-degree-of-freedom (SDOF) and from resultant push over curves limit states capacities can be identified. Rajeev and Tesfamariam [6] reported that, HAZUS does not consider the presence of different irregularities (soft storey) in the assessment, as a result, can underestimate level of expected losses. These methods are defining the limit states capacities globally and failed to consider the presence of irregularities in different storeys. To overcome this problem, pushover curves analyses are carried out in each storey level to define the capacities at each storey level in terms of inter storey drifts.

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2. Building performance levels

In terms of qualitative building performance, one can articulate the safety provided to building occupants both during and after an earthquake, along with assessing the feasibility and cost associated with restoring the building to its pre-earthquake state. Additionally, the conditions of building services and the time-dependent aspects of repair, as well as the broader impacts such as economic, architectural, or historical implications on the community, contribute to the overall performance evaluation.

These performance attributes are directly linked to the level of damage experienced by the building in the event of an earthquake. The evaluation encompasses three distinct performance levels, namely Damage Limitation (*DL*), where overall damage is minimal; Significant Damage (*SD*), characterized by notable structural and non-structural damage; and Collapse Prevention (*CP*), where the structure withstands severe damage.

Fig. 1 graphically represents the performance levels for both bare frame and infilled frame structures. The study incorporates three distinct limit states: Damage Limitation (*DL*), Significant Damage (*SD*), and Collapse Prevention (CP), as shown in Fig. 1 for both bare frame storeys and fully infilled frame storeys. In the context of the bare frame, the assumption is made that the *DL* limit state is reached at the yield displacement of the idealized pushover curve. Conversely, for infilled frames, the *DL* limit state is achieved when the deformation reaches the point at which the last infill in a storey begins to degrade, as suggested by Dolsek and Fajfar [8]. It is noteworthy that the *SD* and *CP* levels for both bare and infilled frames remain consistent, as illustrated in Fig. 1.

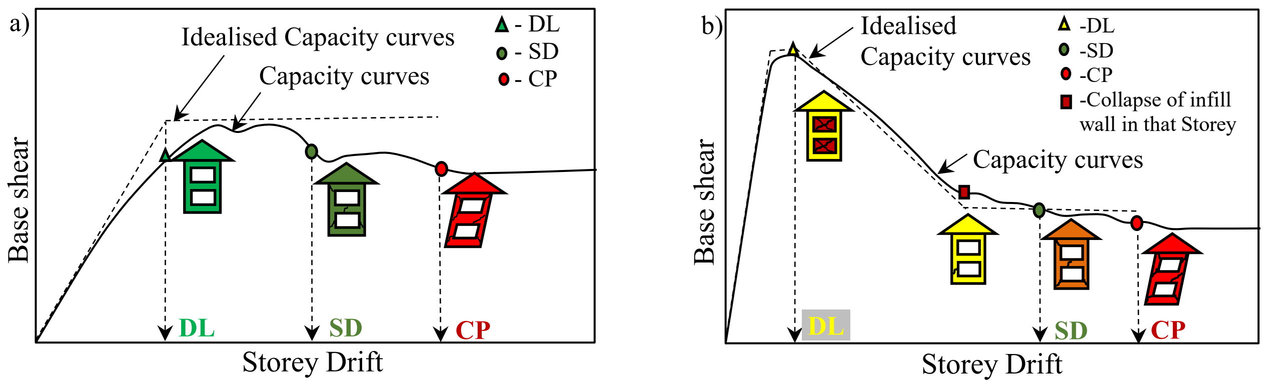

Fig. 1. Typical Performance levels for bare frames and infilled frames a) Bare frame. b) Infilled frame

International design codes identify OGS buildings as structures with soft or weak storeys, necessitating special consideration. The design codes examined exhibit remarkable similarity in defining soft storeys and weak storeys. Table 1 provides a concise summary outlining the characterization of soft storeys according to these design codes. It is noted that OGS buildings, in the majority of instances, are categorized as either extreme soft storeys, extreme weak storeys, or both. Design codes mostly do not recommend the construction of buildings with such extreme soft or weak storeys.

The Indian Standard IS 1893, revised in 2002 for Open Ground Storey (OGS) buildings, lacks specific design guidelines for extreme soft storeys despite defining the category. In Clause 7.10.3(a), it recommends using the equivalent static method with a multiplication factor (MF) of 2.5 for both columns and beams in soft storey design. However, research by Fardis and Panagiotakos [16] indicates potential seismic demand increases on columns with strengthened beams. The 2016 version of IS 1893 removes the above clause, advising the addition of RC shear walls or braced frames, preferably connected to the moment-resisting frame. In this study, various frames with different MF schemes are considered. The bare storey capacity curve is idealized as a bilinear curve, and the infilled storey capacity curve is idealized as a quadric-linear curve. Limit state capacities (DL, SD, CP) are determined for the 4O1 frame as well as 2 and 4 storey frames, are calculated in Table 2 & 3.

3. Frames Considered

The numerical analysis in this study focuses on a building frame designed for the highest seismic zone (Zone V with a PGA of 0.36g), adhering to the Indian standard IS 1893 (2016) and considering medium soil conditions (N-value 10 to 30). Concrete and steel possess characteristic strengths of 25MPa and 415MPa, respectively. The buildings are presumed to exhibit plan symmetry, leading to the selection of a single-plane frame representing the structure along one direction. Typical dimensions, with a bay width of 5m and column height of 3.2m, are chosen based on observations from existing residential buildings. The study incorporates building configurations with storey heights with 2 and 4 storeys, featuring two bays for the two-storey frame and four bays for the four-storey frame.

Table 1 Characterization of soft-storey building as per international design codes

Design Codes	Soft Storey Building	Extreme Soft Storey Building
IS 1893:2002 [8]	$K_i < 0.7K_{i+1}$ or $K_i < 0.8\left(\frac{K_{i+1}+K_{i+2}+K_{i+3}}{3}\right)$	$K_i < 0.6K_{i+1}$ or $K_i < 0.7\left(\frac{K_{i+1}+K_{i+2}+K_{i+3}}{3}\right)$
ASCE/SEI 7-10 [9]	Same as IS 1893:2002	Same as IS 1893:2002
ICC IBC-2012 [10]	Same as IS 1893:2002	Same as IS 1893:2002
EC 8 (2003) [11]	×	×
NZS 1170.5:2004 [12]	Same as IS 1893:2002	×
SI 413:1995 [13]	Same as IS 1893:2002	×
NBC 201:1995 [14]	Qualitative	×
FCEACR 1986 [15]	×	$K_i < 0.5K_{i+1}$
K_i= The lateral stiffness of i'th storey of the building '×' represents that the code does not explicitly define		

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The slab's dead load (5m×5m panel), inclusive of floor finishes, is set at 3.75 kN/m^2, with a live load of 3 kN/m^2. The design base shear (V_B) is determined using the equivalent static method in accordance with IS 1893 (2002). Structural analysis for both vertical and lateral loads is conducted, following a conventional approach that neglects the strength and stiffness of infill walls. The design of RC elements adheres to IS 456 [17] and is detailed as per IS 13920 [18].

To investigate the impact of Multiplication Factor (*MF*) values on OGS building performance, various MF values, including 1.5, 2.0, 2.5, and 3.0, are considered for the design of ground storey columns and/or upper storey columns.

The study also includes Fully Infilled Frames (*FF*) and Bare Frames (*BF*) for comparative analysis, both designed without applying any Multiplication Factor (MF = 1.0). The frames in this study are introduced based on the MF value at the design stage and the modelling approach for infill walls during nonlinear analysis. Frames designated as 'OGS' (Open Ground Storey) and 'FF' (Fully Infilled Frames) incorporate the stiffness and strength of infill walls in the nonlinear analysis. To distinguish between frames with different MF values in various stories, subscripts are used to represent the MF values in the corresponding stories. For instance, $O_{x,y}$ indicates an Open Ground Storey with an MF used in the ground storey denoted as 'x' and that in the first storey as 'y'. Fig. 2 provides examples of frames with various MF values and infill wall configurations, accompanied by their respective designations.

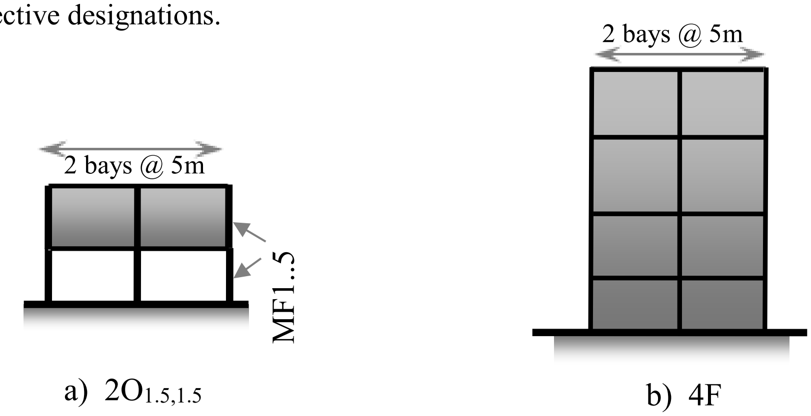
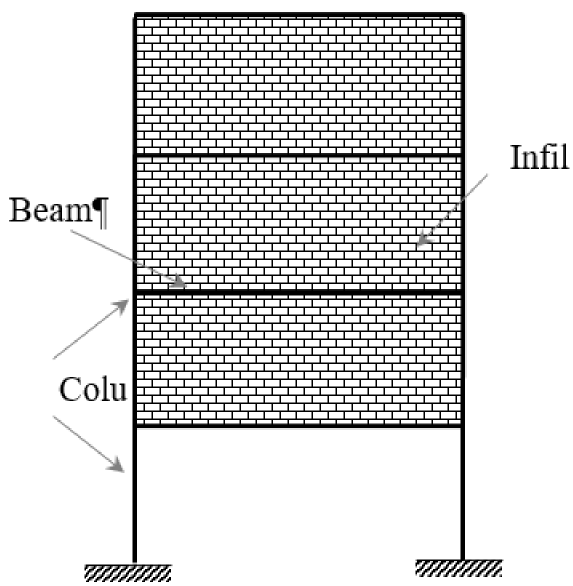


Fig. 2. Typical examples of chosen building frames

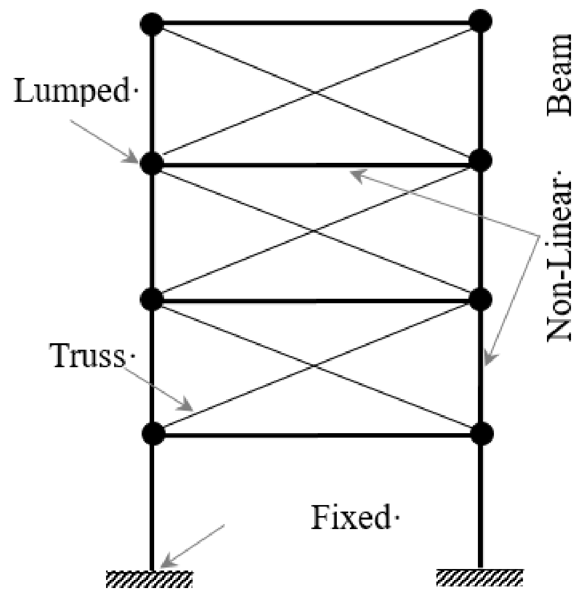
4. Material models and Element model

The concrete materials, covering both the cover and core concrete, are defined separately, and their parameters are determined using Mander et al.'s [19] methodology. Steel reinforcing bars are modelled using the Menegotto and Pinto [20] model with Isotropic Strain Hardening (Steel02 in the OpenSEES [21] material library). This model presents a stress-strain relationship for finite terms between two subsequent reversal points, using an explicit algebraic stress-strain relationship. Infill Walls are modelled as a diagonal strut used by Celarec et. al. [22]

OpenSEES, an open-source C++ software, is used for the present study for non-linear time history analysis for building models using the Non-linear beam-column element. It supports various stress-strain models for materials and incorporates both Point and Spread Plasticity models. The masonry equivalent strut is modelled with a truss element, following the approach by Ravichandran and Klinger [23]. Similar model can be seen [24][25][26]. Fig. 3 shows the building model and computational model.

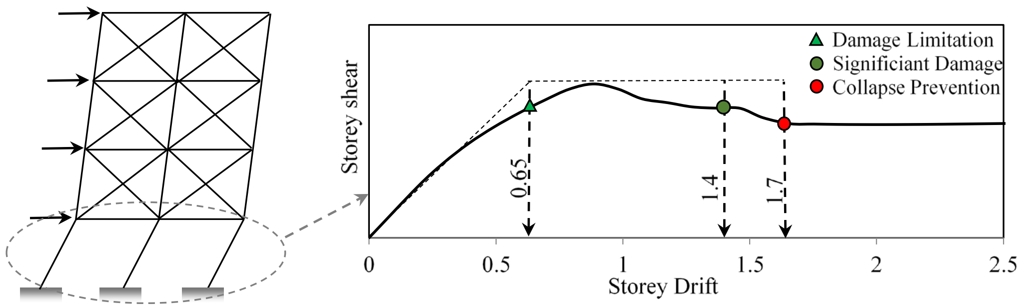


a) Building Model

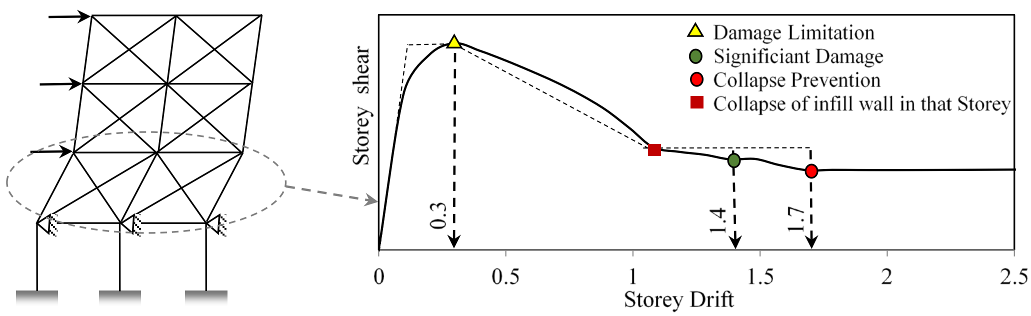


b) Computation Model

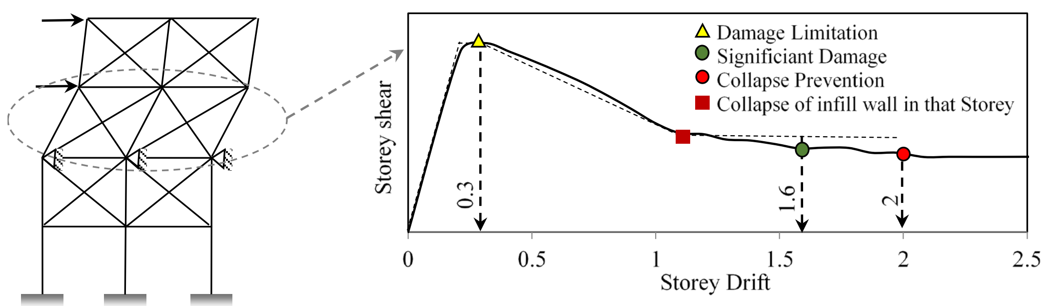
Fig. 3. Building model and computational model.



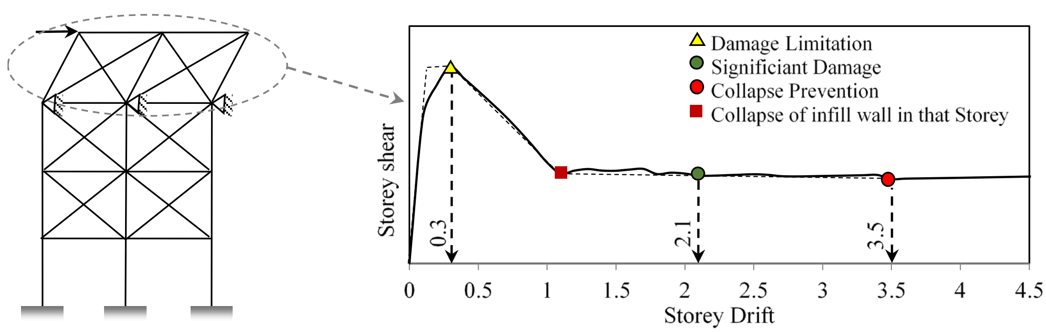
a) Ground Storey-Typical behaviour and capacity curve



b) First Storey-Typical behaviour and capacity curve



c) Second Storey-Typical behaviour and capacity curve



d) Third Storey-Typical behaviour and capacity curve

The tables present limit state capacities for 2-storey and 4-storey frames under different scenarios, indicating performance levels (*DL, SD, CP*) for each frame identity and storey level. For 2-storey frames, variations in Multiplication Factor (*MF*) values influence the capacity values. In the case of 4-storey frames, different configurations and MF values impact the frame capacities across storey levels. The results provide insights into the structural performance under various conditions, guiding the assessment and design considerations for buildings.

Table 2 Limit State Capacities for 2-storey frames

Frame Identity	Storey level	DL	SD	CP
2B	G	1.3	2.7	3.4
	I^st	0.9	2.3	2.9
2F	G	0.3	1.7	2.4
	I^st	0.3	1.9	2.9
2O	G	0.8	1.8	2.3
	I^st	0.3	1.9	2.9
$2O_{1.5}$	G	0.65	1.9	2.2
	I^st	0.3	1.9	2.9
$2O_{2}$	G	0.7	1.7	2.4
	I^st	0.3	1.9	2.9
$2O_{2.5}$	G	0.65	1.5	2.4
	I^st	0.3	1.9	2.9
$2O_{1.5,1.5}$	G	0.65	1.9	2.2
	I^st	0.3	2	3.3
$2O_{2,2}$	G	0.7	1.7	2.4
	I^st	0.3	1.9	2.4
$2O_{2.5,2.5}$	G	0.65	1.5	2.4
	I^st	0.3	1.9	2.3
$2O_{2,1.5}$	G	0.7	1.7	2.4
	I^st	0.3	2	3.3
$2O_{2.5,2}$	G	0.65	1.5	2.4
	I^st	0.3	1.9	2.9

Table 3 Limit State Capacities for 4-storey frames

Frame Identity	Storey level	DL	SD	CP
4B	G	0.65	1.3	1.9
	I^st	0.65	1.3	1.9
	II^nd	0.65	1.8	2.4
	III^rd	0.8	2.1	3.5
4F	G	0.3	1.4	1.7
	I^st	0.3	1.4	1.7
	II^nd	0.3	1.6	2
	III^rd	0.3	2.1	3.5
$4O_{1}$	G	0.65	1.4	1.7
	I^st	0.3	1.4	1.7
	II^nd	0.3	1.6	2
	III^rd	0.3	2.1	3.5
$4O_{1.5}$	G	0.65	1.3	1.9
	I^st	0.3	1.4	1.7
	II^nd	0.3	1.6	2
	III^rd	0.3	2.1	3.5

$4O_2$	G	0.7	1.7	2.3
	I^{st}	0.3	1.4	1.7
	II^{nd}	0.3	1.6	2
	III^{rd}	0.3	2.1	3.5
$4O_{2.5}$	G	0.7	1.7	2.3
	I^{st}	0.3	1.4	1.7
	II^{nd}	0.3	1.6	2
	III^{rd}	0.3	2.1	3.5
$4O_3$	G	0.65	1.7	2.3
	I^{st}	0.3	1.4	1.7
	II^{nd}	0.3	1.6	2
	III^{rd}	0.3	2.1	3.5
$4O_{1.5,1.5}$	G	0.65	1.3	1.9
	I^{st}	0.3	1.4	2
	II^{nd}	0.3	1.6	2
	III^{rd}	0.3	2.1	3.5
$4O_{2,2}$	G	0.7	1.7	2.3
	I^{st}	0.3	1.4	2.4
	II^{nd}	0.3	1.6	2
	III^{rd}	0.3	2.1	3.5
$4O_{2.5,2.5}$	G	0.7	1.7	2.3
	I^{st}	0.3	1.4	2.4
	II^{nd}	0.3	1.6	2
	III^{rd}	0.3	2.1	3.5

In the 2-storey frames, the analysis of bare frame 2B, which doesn't include infilled walls, reveals a Damage Limitation (*DL*) capacity of 1.3 for the ground storey, while the 1st storey, shows a DL of 0.9. Fully framed 2F and 2O share similar DL values of 0.3 for 1st storeys, as both configurations include infill walls. However, in 2O, where the ground storey doesn't include infill walls, the DL capacity is slightly higher at 0.8. This variation underscores the impact of infilled walls on the DL capacity. In the 4-storey frame building the trends and considerations in seismic performance align with those observed in the 2-storey frames. The presence or absence of infill walls, coupled with the storey level, continues to play a critical role in determining (*DL, SD, CP*) capacities.

4. Conclusion

In summary, this study has effectively explored the estimation of Limit State (LS) capacities for Open Ground Storey (OGS) buildings through seismic fragility curves. Pushover analysis was performed after the non-linear analysis to derive LS capacities, aligning with established frameworks in design codes. The absence of infill walls in the ground storey of OGS buildings introduced an additional layer of complexity, addressed through the recommended use of magnification factors (MF) from international codebooks to optimize performance under lateral loads. The outcomes revealed a major disparity in storey-wise LS capacities, emphasizing the design considerations required for OGS structures should state concisely the most important propositions of the paper as well as the author's views of the practical implications of the results.

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