Estimating Limit State Capacities for OGS Building having different MF using Push over Analysis

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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 from two storey to eight storey buildings with different scheme of MF. The results shows that there is a wide disparity in storey wise LS capacities.

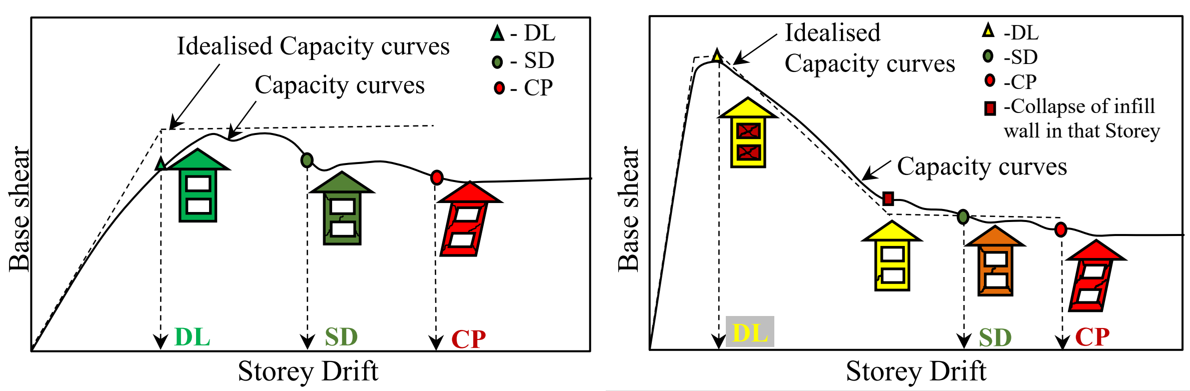
1. INTRODUCTION

In seismic risk assessment, development of fragility curve is one of the key component. The seismic fragility curves represent a comparison between structural demand (SD) with different LS capacities. Several literatures/codes, defines a capacities for RC moment resisting frames with and without infill walls such as ASCE/SEI 41-06 (2007), Ghobarah (2000), 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 suggests to use MF for Ground storey, that will increase the storey stiffness. There are different disparity of MF suggested among international codes. Haran *et. al* (2016) 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 (2003) suggests to perform a pushover analyses according to the first mode shape lateral loads. And from resulting pushover curves limit states capacities can be identified. Similarly, N2 method (Fajfar, 2000) 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 (2012) 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.

2. BUILDING PERFORMANCE LEVELS

Qualitatively building performance can be described in terms of, safety to the building occupants during and after an earthquake, possibility and cost of repairing the building to pre-earthquake conditions, building services and repairing conditions with respect to time, economic, architectural, or historic impacts on the community at large.
These performance characteristics will be directly related to the extent of damage sustained by the building during a damaging earthquake. Based on the different levels of building damage three performance levels are considered namely Damage Limitation (DL) - Overall damage to the building is light, Significant Damage (SD) - Structural and non-structural damage is significant and Collapse Prevention (CP) - The structure sustains severe damage.

The performance levels are illustrated graphically in Fig. 1 for bare frame and infilled frame. The three different limit states are used in this study namely Damage Limitation (*DL*), Significant Damage (*SD*) and collapse prevention (*CP*) as shown in Fig. 1 for bare frame storey and fully infilled frame storeys. For the bare frame it was assumed that the DL limit state is attained at the yield displacement of the idealized pushover curve. In the case of infilled frames, the *DL* limit state is attained at the deformation when the last infill in a storey starts to degrade (Dolsek & Fajfar, 2008). Whereas for *SD* and *CP* level for bare and infilled frames are same as shown in Fig. 1. Monalisa *et.al* (2013), Haran *et.al* (2014), have used pushover analysis for calculating limit states.



a) Bare frame b) Infilled frame

Fig. 1: Typical Performance levels for bare frames and infilled frames

3. OGS buildings:

International design codes recognise OGS buildings as soft or weak storey buildings that require special attention. The design codes reviewed here are almost identical to define the soft storey and weak storey buildings. Table 1 summarise the characterization of soft storey, as per the design codes. Similar work can be seen in Haran (2015). It is to be noted that OGS buildings, in most of the cases, fall either in the extreme soft storey or extreme weak storey category or both. Majority of the design codes do not recommend the construction of such extreme soft/weak storey buildings.

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

Design Codes	Soft Storey Building	Extreme Soft Storey Building
IS 1893:2002	$K_i < 0.7K_{i+1}$ 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	Same as IS 1893:2002	Same as IS 1893:2002
ICC IBC-2012	Same as IS 1893:2002	Same as IS 1893:2002
EC 8 (2004)	×	×
NZS 1170.5:2004	Same as IS 1893:2002	×
SI 413:1995	Same as IS 1893:2002	×
NBC 201:1994	Qualitative	×
FCEACR 1986	×	$K_i < 0.5K_{i+1}$
K_i = The lateral stiffness of i'th storey of the building '×' represents that the code does not explicitly define		

Indian Standard IS 1893 has been revised in 2002 to include new recommendations for the design of OGS buildings. Although IS 1893:2002 defines extreme soft storey category of building irregularity it is silent about any design guideline for this building type. However, in the Clause 7.10.3(a), the code recommends the use of equivalent static method for analysis and design of soft storey type buildings with certain modifications as follows: "The columns and beams of the soft storey are to be designed for 2.5 times the storey shears and moments calculated under seismic loads of bare frame". This is to be noted that the code recommends the multiplication factor (MF) factor of 2.5 even for the beams whereas the research (Fardis and Panagiotakos, 1997) has shown that increasing the beam strength would further increase the seismic demands on the columns. Indian Standard IS 1893 (2016), has removed the above clause and suggested to add RC shear walls or braced frames and preferably connected to the moment resisting frame of the building. How ever in this study, different frames are considered having various MF schemes. Push over analyses is carried out for each storey to find out the story capacities for all the frames. Fig 7 shows the $4O_1$ frame with boundary conditions along with pushover loading profile and the corresponding storey capacities in terms of storey shear vs. storey drift. For bare storey capacity curve is idealised to bilinear curve and for infilled storey capacity curve is idealised to quadric-linear curve. According to limit state definition, the three different limit state capacities *DL*, *SD* & *CP* are found out and shown in the Fig.7 for the frame $4O_1$. Similarly, for 2 storey frames to 8 storey frames limit state capacities are calculated and shown in the Table.3 -6.

4. Frames Considered

The building frame considered for numerical analysis in the present study is designed for the highest seismic zone (zone V with PGA of 0.36g) as per Indian standard IS 1893 (2016) considering medium soil conditions (N-value 10 to 30). The characteristic strength of concrete and steel are taken as 25MPa and 415MPa respectively. The buildings are assumed to be symmetric in plan, and hence a single plane frame is considered to be representative of the building along one direction. Typical bay width and column height in this study are selected as 5m and 3.2m respectively, as observed from the study of typical existing residential buildings. A configuration of building storey height ranging from 2 storeys to 8 storeys are considered in the present study with a bay of two bays for two, four and six storey frames and four bays for eight storey frame.

The dead load of the slab (5 m × 5 m panel) including floor finishes is taken as 3.75 kN/m^2 and live load as 3 kN/m^2. The design base shear (V_B) is calculated as per equivalent static method (IS 1893, 2002). The structural analysis for all the vertical and lateral loads is carried out by ignoring the infill wall strength and stiffness (conventional). The design of the RC elements are carried out as per IS 456 (2000) and detailed as per IS 13920 (1993).

In order to study the effect of MF values on the OGS building performance, different MF values such as 1.5, 2.0, 2.5 and 3.0 are considered to design the ground storey columns and/or upper storey columns.

Fully infilled frame (FF) and bare frame (BF) are also considered in the study for comparison which are designed without applying any MF (MF = 1.0). Depending on the value of MF at the design stage and the modelling of infill walls during nonlinear analysis, various naming schemes are introduced to represent all the frames considering in the present study. For the frames designated as 'OGS' (Open Ground Storey) and 'FF' (Fully Infilled Frames), the stiffness and strength of the infill walls are modelled in the nonlinear analysis. As different MF values are used in the different stories, subscripts are used to represent the MF values in the corresponding stories differentiate between each OGS frame. For example, $O_{x,y}$ indicates, an Open Ground Storey with MF used in the ground storey as '*x*' and that used in the first storey as '*y*'. Fig. 2 shows typical example frames with various MF values and infill wall configurations along with their designations. Tables 2 summarize the details of columns and beam sections of each frame.

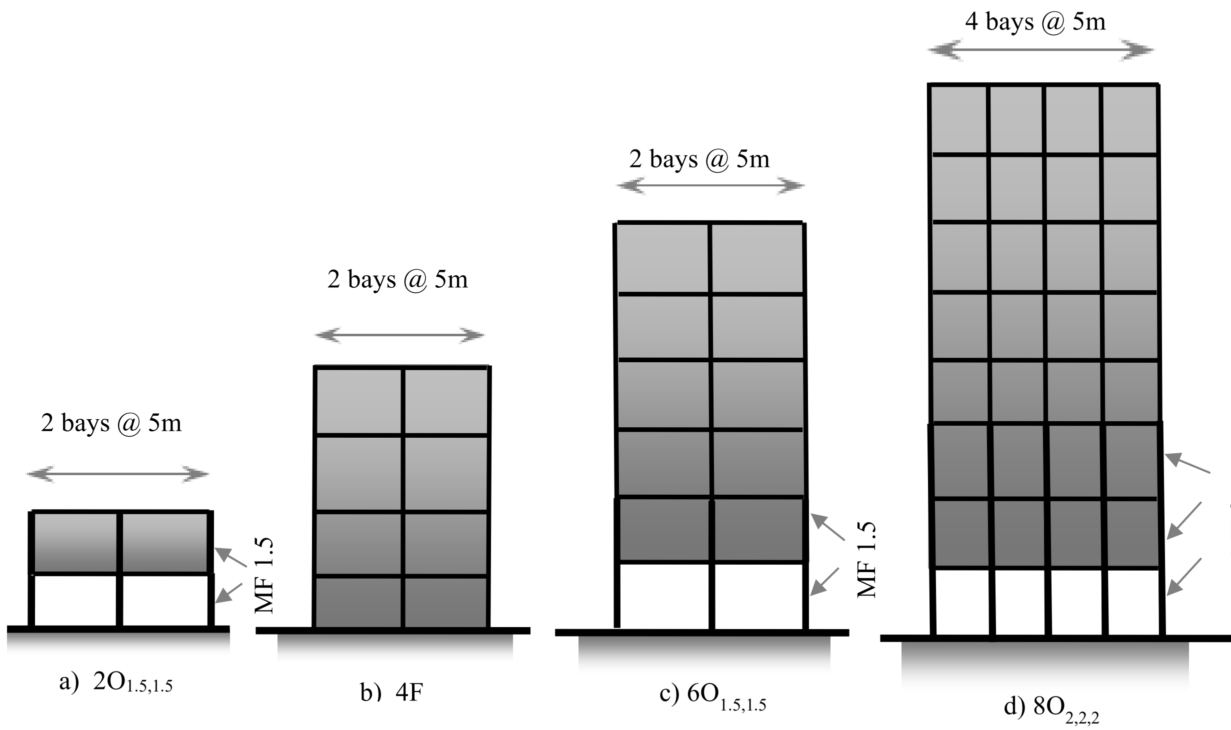


Fig. 2: Typical examples of chosen building frames

5.MATERIAL MODELS

An elemental cross-section in an RC member is composed of three types of materials: unconfined concrete, confined concrete and reinforcing steel. All reinforced concrete components are detailed with transverse steel which provide both shear resistance and confining action. The confining effects of transverse steel are considered implicitly by modifying the stress-strain response of the core concrete. Numerous researchers have developed stress-strain models of confined concrete based on observed experimental behaviour. The concrete cover will typically spall at relatively small strain levels therefore the modelling of unconfined concrete is generally not critical for damage limit states in the inelastic range. The response of RC components and consequently the system is a function of the behaviour of the confined core and the longitudinal steel.

5.1 Concrete Modelling

Cover concrete and core concrete materials are considered and defined separately and the corresponding parameters are calculated based on the Mander et.al. (1988), and modelled using Concrete02 material model in Open System for Earthquake Engineering Simulation (OpenSEES, 2013). The Concrete02 model is a uniaxial material model that includes tensile strength and linear tension softening.

Table 2: Design data for the selected frames

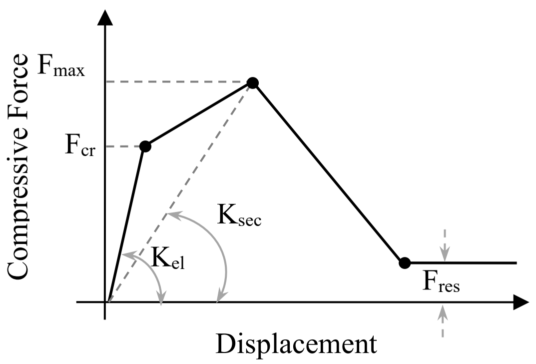
Frame	Storey	Width (mm)	Depth (mm)	Reinforcement Details (uniformly distributed)	Lateral ties
8B	G	450	450	8 - 32ϕ	
	Ist - IInd	450	450	8 - 25ϕ	
	IIIrd - VIIth	450	450	4 - 25ϕ	
8F	G	450	450	8 - 32ϕ	
	Ist - IInd	450	450	8 - 25ϕ	
	IIIrd - VIIth	450	450	4 - 25ϕ	
8O1.0	G	450	450	8 - 32ϕ	
	Ist - IInd	450	450	8 - 25ϕ	
	IIIrd - VIIth	450	450	4 - 25ϕ	
8O1.5	G	550	550	12 - 32ϕ	
	Ist - IInd	450	450	8 - 25ϕ	8mm ϕ rectangular ties, @ 175mm c/c throughout
	IIIrd - VIIth	450	450	4 - 25ϕ	
8O2.0	G	600	600	12 - 25ϕ	
	Ist - IInd	450	450	8 - 25ϕ	
	IIIrd - VIIth	450	450	4 - 25ϕ	
8O2.5	G	700	700	16 - 25ϕ	
	Ist - IInd	450	450	8 - 25ϕ	
	IIIrd - VIIth	450	450	4 - 25ϕ	
8O1.5,1.5	G- Ist	550	550	12 - 32ϕ	16mm ϕ rectangular ties, @ 85mm c/c for a distance of 535mmfrom supports,
	IInd	450	450	8 - 25ϕ	
	IIIrd - VIIth	450	450	4 - 25ϕ	
8O2.0,2.0	G- Ist	600	600	12 - 25ϕ	
	IInd	450	450	8 - 25ϕ	
	IIIrd - VIIth	450	450	4 - 25ϕ	
8O2.5,2.5	G- Ist	700	700	16 - 25ϕ	
	IInd	450	450	8 - 25ϕ	
	IIIrd - VIIth	450	450	4 - 25ϕ	
8O2.0,2.0,2.0	G- IInd	600	600	12 - 25ϕ	
	IIIrd - VIIth	450	450	4 - 25ϕ	
8O2.5,2.5,2.5	G- IInd	700	700	16 - 25ϕ	
	IIIrd - VIIth	450	450	4 - 25ϕ	
8O2.5,2.5,2.5,2.5	G- IIIrd	700	700	16 - 25ϕ	
	IVth - VIIth	450	450	4 - 25ϕ	

5.2 Reinforcement Modelling

Steel reinforcing bars are modelled using a Menegotto and Pinto, (1973) model with Isotropic Strain Hardening (referred to as Steel02 in the Opensees material library) as shown in Fig. 4.2 with a schematic cyclic behaviour. This model consists of a stress-strain relationship, in finite terms, for branches between two subsequent reversal points (loading branches), this model used an explicit algebraic stress-strain relationship.

5.3 Infill wall Modelling

Infill walls are modelled as equivalent diagonal single strut in both diagonals of each bay used by several authors (Dolsek and Fajfar 2008, Ravichandran and Klinger, 2012). This approach requires much less computational effort than micro-modelling approaches such as the finite element method, yet still provides reasonable accuracy, thereby allowing easy analytical representation of multi-story, multi-bay frames. In the equivalent-strut approach, the infill is represented as a combination of two compression-only truss elements, each acting independently. Each equivalent strut element is assigned an appropriate hysteretic force-deformation relationship, generally including a descending post-peak strength, in-cycle degradation, and pinching. Fig. 3 shows the typical quadrilinear force-displacement relationship of the diagonal struts (in compression), measured in the axial direction used in this study.



F_{max} – Maximum strength

F_{cr} – Shear cracking strength

F_{res} – Residual strength

K_{sec} – Secant stiffness

K_{el} – Elastic stiffness

Fig. 3: Force-displacement relationship of the diagonal struts used by Celarec *et. al*. (2012)

In order to model the strength and stiffness degradation of the infill walls in the time history analysis, pinching material model is used, which is implemented in Opensees by Ibarra *et. al.* (2005). Pinching material model is used for hysteretic modelling of infill walls under cyclic loading by many studies (Landi *et.al*, 2012; Ravichandran and Klinger, E. R., 2012, Durai *et.al*, 2016; Pragalath et. al, 2015 etc).

6 ELEMENT MODEL

Open System for Earthquake Engineering Simulation (OpenSEES, 2013) is used for running non-linear time history analysis for buildings models. OpenSees is open source software written on C++ platform can be editable from Tool command language (TCL) programming language. It uses both Point plasticity and Spread plasticity models. OpenSees has various in-build uniaxial stress-strain models for different models, such as modelling concrete, steel and masonry struts. In this study, Non-linear beam column element (present in Opensees Library) is used for buildings models (beams & columns), which is based on the non-iterative/iterative force formulation, and considers the spread of plasticity along the element. Masonry equivalent strut is modelled using truss element as used by researchers. (Ravichandran and Klinger, 2012, Yousif MS and Haran Pragalath 2024). OpenSEES uses the Gauss-Lobatto quadrature rule to evaluate the integrations. The Typical building model and corresponding computational model are shown in Fig. 4.

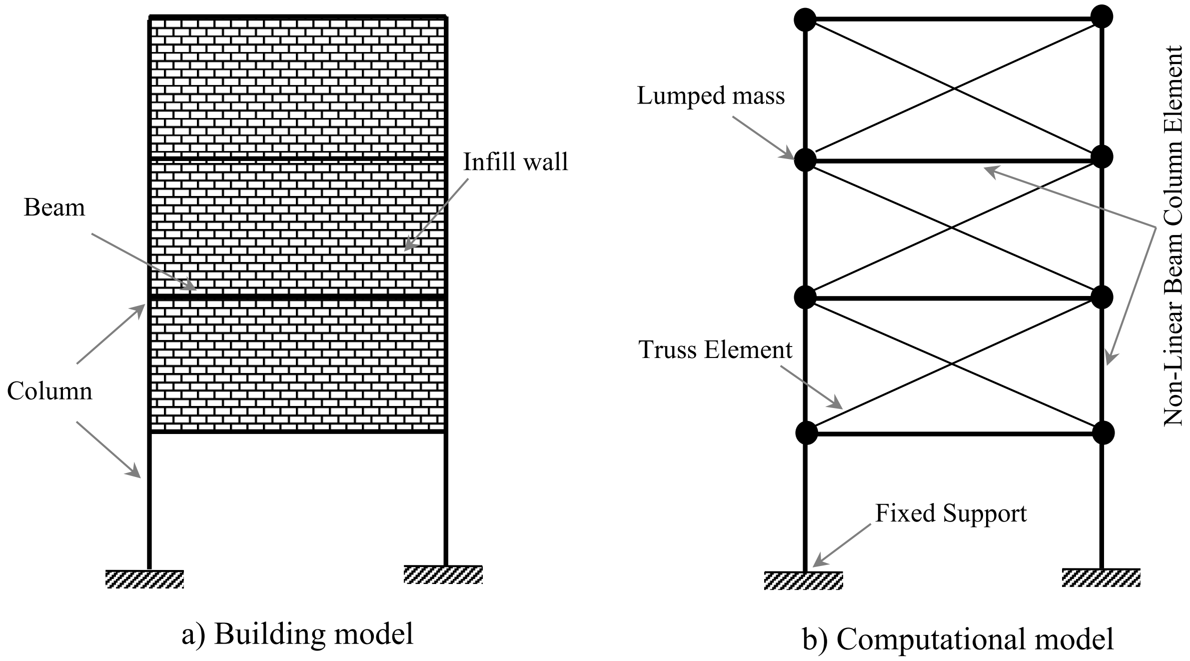


Fig. 4: Typical building model and corresponding computational model

7 Validation Study: One storey one bay RC infilled frame (Colangelo, 1999)

The pseudo-dynamic experimental test carried out by Colangelo (1999) on single storey infilled plane frame as shown in Fig. 5 is chosen for validating the computational model. The frame was tested with a pseudo-dynamic load using the E-W component of the 1976 Friulli earthquake. Detailed description of the test-rig, the material properties, as well as the loading regime, can be found in Biondi *et al.* (2000) and Seismosoft (2013). The nonlinear pseudo-dynamic time history analysis is conducted and the base shear time histories are recorded. Fig. 6 shows the comparison between the base shear time history obtained from the experimental study and the present computational study, it can be seen that the two results match closely.

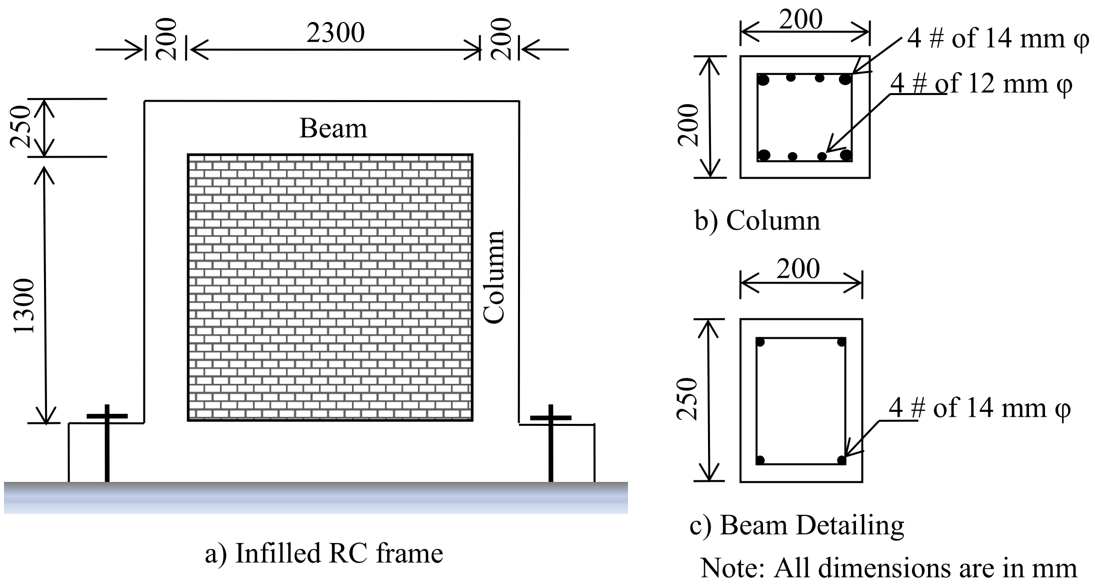


Fig. 5: Infilled frame tested by Colangelo (1999)

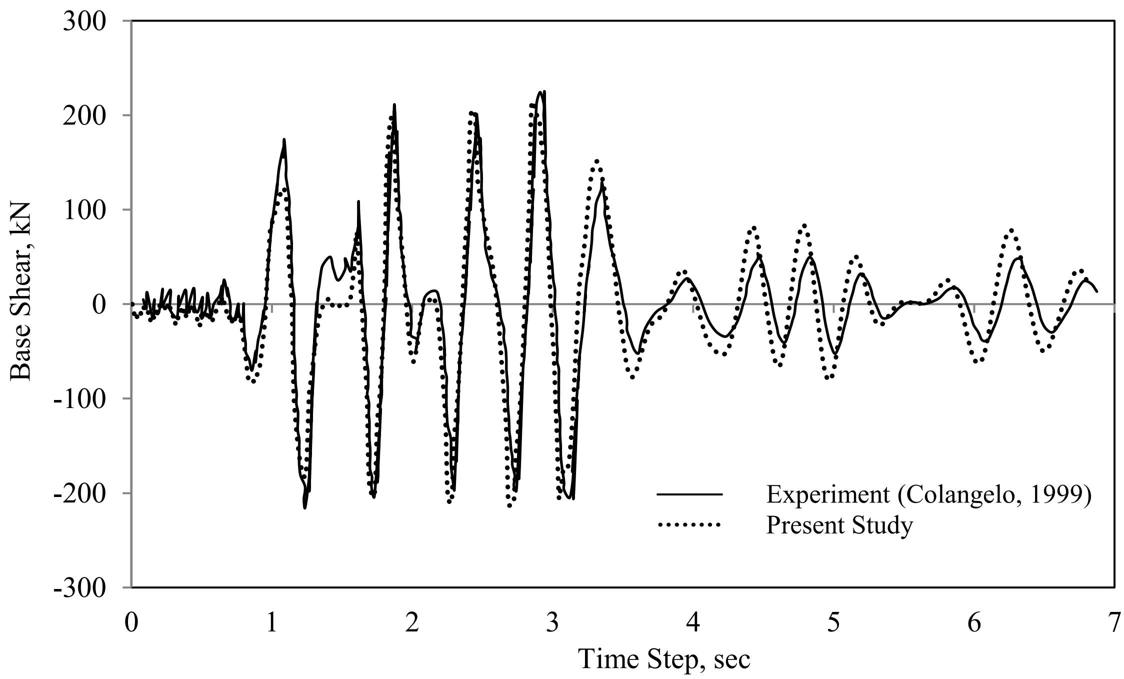
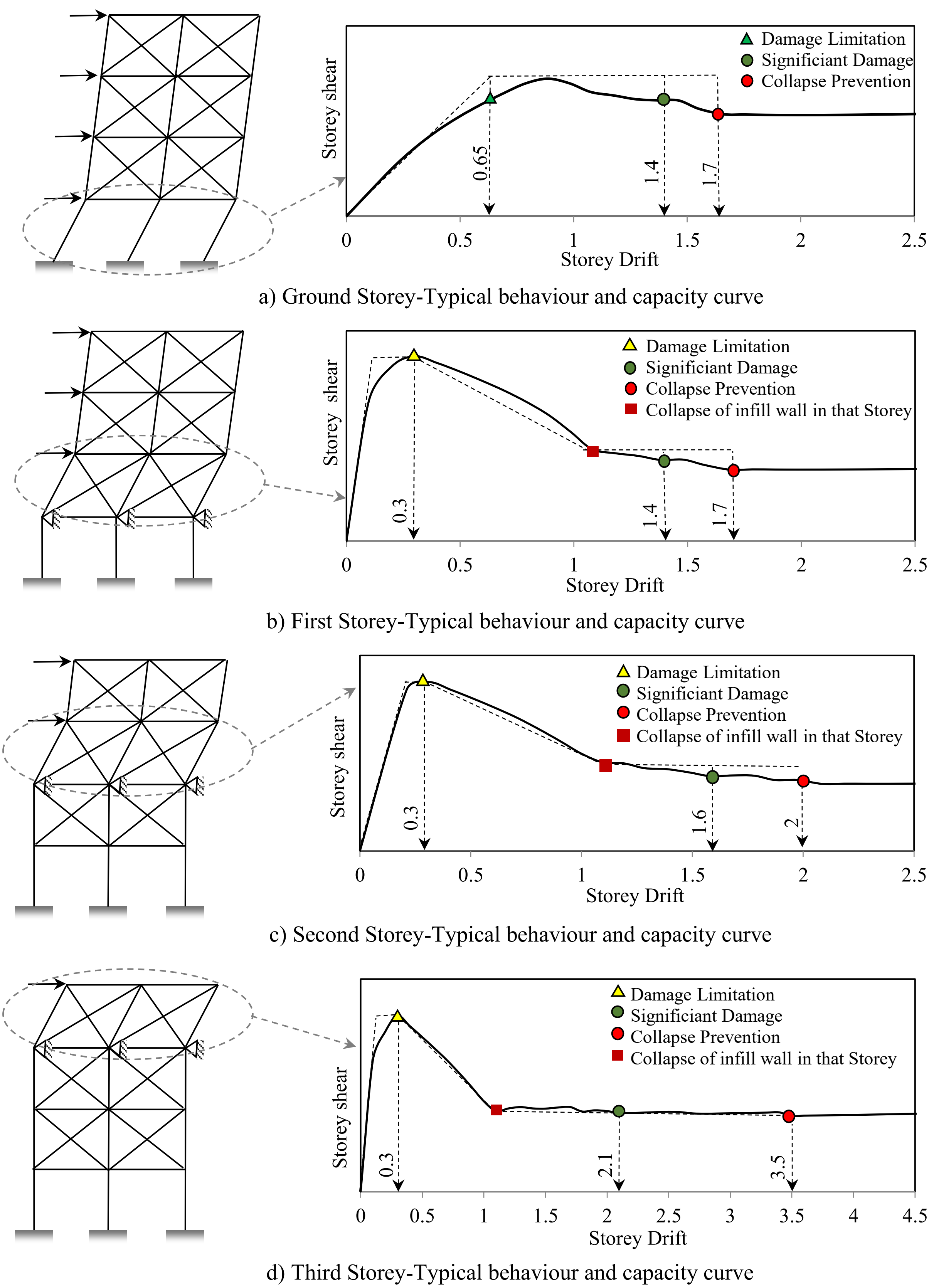


Fig. 6: Comparison of base shear histories obtained from experimental and computational study.

From these three studies it is clear that the computational model and the analysis procedure adopted in the present study yields the reasonably accurate behaviour of structures when subjected to dynamic and pseudo-dynamic loading.



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

Fig. 7: Pushover loading profile and Storey capacity curve for frame $4O_1$

Table 3: 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

*G-Ground

Table 4: 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
	G	0.65	1.3	1.9

$4O_{1.5}$	I^{st}	0.3	1.4	1.7
	II^{nd}	0.3	1.6	2
	III^{rd}	0.3	2.1	3.5
Frame Identity	Storey level	DL	SD	CP
$4O_{2}$	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
$4O_{3,3}$	G	0.65	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
$4O_{2.5,2,1.5}$	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
$4O_{3,2.5,2}$	G	0.65	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

Table 5: Limit State Capacities for 6-storey frames

Frame Identity	Storey level	DL	SD	CP
6B	G	0.5	1.25	1.7
	Ist	0.5	1.25	1.7
	IInd	0.5	1.25	1.7
	IIIrd	0.6	1.9	2.4
	IVth	0.65	2	2.8
	Vth	0.65	2.3	2.8
6F	G	0.6	1.2	1.5
	Ist	0.6	1.2	1.5
	IInd	0.6	1.2	1.5
	IIIrd	0.3	1.3	1.7
	IVth	0.3	1.7	2.3
	Vth	0.3	2	2.8
$6O_1$	G	0.5	1	1.5
	Ist	0.6	1.2	1.5
	IInd	0.6	1.2	1.5
	IIIrd	0.3	1.3	1.7
	IVth	0.3	1.7	2.3
	Vth	0.3	2	2.8
$6O_{1.5}$	G	0.75	1.5	2
	Ist	0.6	1.2	1.5
	IInd	0.6	1.2	1.5
	IIIrd	0.3	1.3	1.7
	IVth	0.3	1.7	2.3
	Vth	0.3	2	2.8
$6O_2$	G	0.6	1.3	1.5
	Ist	0.6	1.2	1.5
	IInd	0.6	1.2	1.5
	IIIrd	0.3	1.3	1.7
	IVth	0.3	1.7	2.3
	Vth	0.3	2	2.8
$6O_{2.5}$	G	0.6	1.2	1.5
	Ist	0.6	1.2	1.5
	IInd	0.6	1.2	1.5
	IIIrd	0.3	1.3	1.7
	IVth	0.3	1.7	2.3
	Vth	0.3	2	2.8
$6O_{1.5,1.5}$	G	0.75	1.5	2
	Ist	0.6	1.4	1.9
	IInd	0.6	1.2	1.5
	IIIrd	0.3	1.3	1.7
	IVth	0.3	1.7	2.3
	Vth	0.3	2	2.8

$6O_{2,2}$	G	0.6	1.3	1.5
	I^{st}	0.6	1.3	1.6
Frame Identity	Storey level	DL	SD	CP
$6O_{2,2}$	II^{nd}	0.6	1.2	1.5
	III^{rd}	0.3	1.3	1.7
	IV^{th}	0.3	1.7	2.3
	V^{th}	0.3	2	2.8
$6O_{2.5,2.5}$	G	0.6	1.2	1.5
	I^{st}	0.6	1.2	1.5
	II^{nd}	0.6	1.2	1.5
	III^{rd}	0.3	1.3	1.7
	IV^{th}	0.3	1.7	2.3
	V^{th}	0.3	2	2.8
$6O_{2,2,2}$	G	0.6	1.3	1.5
	I^{st}	0.6	1.3	1.6
	II^{nd}	0.6	1.3	1.8
	III^{rd}	0.3	1.3	1.7
	IV^{th}	0.3	1.7	2.3
	V^{th}	0.3	2	2.8
$6O_{2.5,2.5,2.5}$	G	0.6	1.2	1.5
	I^{st}	0.6	1.2	1.5
	II^{nd}	0.6	1.2	1.7
	III^{rd}	0.3	1.3	1.7
	IV^{th}	0.3	1.7	2.3
	V^{th}	0.3	2	2.8
$6O_{2.5,2,1.5}$	G	0.6	1.2	1.5
	I^{st}	0.6	1.3	1.6
	II^{nd}	0.6	1.6	2
	III^{rd}	0.3	1.3	1.7
	IV^{th}	0.3	1.7	2.3
	V^{th}	0.3	2	2.8

Table 6: Limit State Capacities for 8-storey frames

Frame Identity	Storey level	DL	SD	CP
8B	G	0.9	2	3.2
	I^{st}	0.9	1.9	2.4
	II^{nd}	0.9	2	3.2
	III^{rd}	0.9	1.7	3.2
	IV^{th}	0.9	2.1	3.2
	V^{th}	0.9	1.9	2.8
	VI^{th}	0.9	1.9	2.8
	VII^{th}	0.9	1.9	2.8
8F	G	0.6	2	3.2
	I^{st}	0.6	1.9	2.4
	II^{nd}	0.6	2	3.2
	III^{rd}	0.6	1.7	3.2
	IV^{th}	0.6	2.1	3.2
Frame Identity	Storey level	DL	SD	CP

	V^{th}	0.6	1.9	2.8
	VI^{th}	0.6	1.9	2.8
	VII^{th}	0.6	1.9	2.8
$8O_{1}$	G	0.9	2	3.2
	I^{st}	0.6	1.9	2.4
	II^{nd}	0.6	2	3.2
	III^{rd}	0.6	1.7	3.2
	IV^{th}	0.6	2.1	3.2
	V^{th}	0.6	1.9	2.8
	VI^{th}	0.6	1.9	2.8
	VII^{th}	0.6	1.9	2.8
$8O_{1.5}$	G	0.9	2	3.2
	I^{st}	0.6	1.9	2.4
	II^{nd}	0.6	2	3.2
	III^{rd}	0.6	1.7	3.2
	IV^{th}	0.6	2.1	3.2
	V^{th}	0.6	1.9	2.8
	VI^{th}	0.6	1.9	2.8
	VII^{th}	0.6	1.9	2.8
$8O_{2}$	G	0.9	1.9	3.2
	I^{st}	0.6	1.9	2.4
	II^{nd}	0.6	2	3.2
	III^{rd}	0.6	1.7	3.2
	IV^{th}	0.6	2.1	3.2
	V^{th}	0.6	1.9	2.8
	VI^{th}	0.6	1.9	2.8
	VII^{th}	0.6	1.9	2.8
$8O_{2.5}$	G	0.9	1.9	3.2
	I^{st}	0.6	1.9	2.4
	II^{nd}	0.6	2	3.2
	III^{rd}	0.6	1.7	3.2
	IV^{th}	0.6	2.1	3.2
	V^{th}	0.6	1.9	2.8
	VI^{th}	0.6	1.9	2.8
	VII^{th}	0.6	1.9	2.8
$8O_{1.5,1.5}$	G	0.9	1.9	3.2
	I^{st}	0.6	1.9	2.4
	II^{nd}	0.6	2	3.2
	III^{rd}	0.6	1.7	3.2
	IV^{th}	0.6	2.1	3.2
	V^{th}	0.6	1.9	2.8
	VI^{th}	0.6	1.9	2.8
	VII^{th}	0.6	1.9	2.8
$8O_{2,2}$	G	0.9	1.9	3.2
	I^{st}	0.6	1.9	2.4
	II^{nd}	0.6	2	3.2
	III^{rd}	0.6	1.7	3.2
Frame Identity	Storey level	DL	SD	CP
$8O_{2,2}$	IV^{th}	0.6	2.1	3.2
	V^{th}	0.6	1.9	2.8
	VI^{th}	0.6	1.9	2.8
	VII^{th}	0.6	1.9	2.8
$8O_{2.5,2.5}$	G	0.9	1.9	3.2
	I^{st}	0.6	1.9	2.4
	II^{nd}	0.6	2	3.2
	III^{rd}	0.6	1.7	3.2
	IV^{th}	0.6	2.1	3.2
	V^{th}	0.6	1.9	2.8
	VI^{th}	0.6	1.9	2.8

	VIIth	0.6	1.9	2.8
$8O_{2,2,2}$	G	0.9	1.9	3.2
	Ist	0.6	1.9	2.4
	IInd	0.6	2	3.2
	IIIrd	0.6	1.7	3.2
	IVth	0.6	2.1	3.2
	Vth	0.6	1.9	2.8
	VIth	0.6	1.9	2.8
	VIIth	0.6	1.9	2.8
$8O_{2.5,2.5,2.5}$	G	0.9	1.9	3.2
	Ist	0.6	1.9	2.4
	IInd	0.6	2	3.2
	IIIrd	0.6	1.7	3.2
	IVth	0.6	2.1	3.2
	Vth	0.6	1.9	2.8
	VIth	0.6	1.9	2.8
	VIIth	0.6	1.9	2.8
$8O_{2.5,2.5,2.5,2.5}$	G	0.9	1.9	3.2
	Ist	0.6	1.9	2.4
	IInd	0.6	2	3.2
	IIIrd	0.6	1.7	3.2
	IVth	0.6	2.1	3.2
	Vth	0.6	1.9	2.8
	VIth	0.6	1.9	2.8
	VIIth	0.6	1.9	2.8

Conclusion

This study estimated storey-wise limit state (LS) capacities of Open Ground Storey (OGS) reinforced concrete buildings with heights ranging from two to eight storeys. Along with the different magnification factor (MF) schemes, using nonlinear pushover analysis. Unlike conventional approaches that define global LS capacities, the adopted storey-level assessment explicitly captured the effects of vertical irregularity arising from infill wall discontinuity and MF distribution.

The results clearly demonstrate that LS capacities are highly non-uniform along the building height, with the ground storey consistently emerging as the most vulnerable level in OGS configurations. Bare and fully infilled frames exhibit comparatively uniform capacity distributions, whereas OGS frames show pronounced reductions in Damage Limitation (DL), Significant Damage (SD), and Collapse Prevention (CP) capacities at the ground storey when MF is insufficient or applied only locally. Increasing MF at the ground storey improves its capacity, but the improvement is neither linear nor sufficient in all cases, especially for mid- and high-rise buildings.

Frames designed with uniform or staged MF distribution over multiple lower storeys perform better than those with MF applied only at the ground storey, indicating that concentrating strength and stiffness at a single level can merely shift, rather than eliminate, the weak-storey mechanism. The study also confirms that commonly assumed drift limits (e.g., fixed global IO and CP values) can significantly misrepresent actual performance when storey-wise behavior and infill effects are ignored.

Overall, the findings highlight that:

1. Storey-specific LS capacities are essential for realistic seismic fragility assessment of OGS buildings.
2. Code-prescribed single MF values are inadequate to address the complexity of OGS behaviour across different building heights.
3. Performance-based design of OGS buildings should rely on nonlinear analysis with explicit modelling of infill walls and distributed strength enhancement, rather than simplified global assumptions.

The proposed storey-wise LS capacity estimation framework provides a more rational basis for developing fragility curves, assessing seismic risk, and formulating improved design and retrofit strategies for OGS buildings in high seismic regions.

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