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DESIGN AMPLIFICATION FACTOR FOR OPEN GROUND STOREY RC STRUCTURE WITH INFILL OPENINGS IN UPPER STOREYS

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Abstract

Reinforced concrete structures with open ground storey have shown very poor earthquake performance during past events. Despite of considering the design recommendations provided in the various international codes of practices for structural elements of open ground storey, the damage in the building has not reduced significantly. Literature shows damage to structural members in the soft storey depends on their relative stiffness with respect to adjacent storeys and eventually affects the deformation characteristics. Hence the problem of soft storey cannot be addressed independently without considering the relative effects of adjacent storeys.

In this paper, the seismic response of open ground storey structure with openings in the upper storeys is studied and amplification factor for designing and strengthening of open ground storey members is determined. Static Nonlinear pushover analysis is used to carry out the study. The main parameters investigated are stiffness, strength, inter-storey drift and fundamental period. It is found that the presence of wall opening in upper storey will decrease its stiffness and strength significantly compared to full infill, which directly leads to reduction in the deformation and decrease in amplification factors for design and strengthening of ground storey members.

Keywords: Open ground storey; infill opening; design provision; pushover analysis;

1. Introduction

Earthquake reconnaissance reports of past earthquakes show that, presence of soft storey or open ground storey in multistorey building will lead to total collapse of a multistorey building. Presence of wall infill in the upper floors only, except ground floor for parking or social gatherings, is termed as open ground storey structure (OGSS). Such structures will have severe damage in the ground storey structural members, resulting in total collapse of the building. Distribution of strength, stiffness and mass should be cinsistent throughout the building horizontally and vertically, as per seismic design philosophy. Improper orientation of wall infill, vertically and horizontally, in the structure will result in soft storey, weak storey, torsion, and short column effect. Presence of irregularity in structure will alter the load path that lead to severe damage during seismic events.

Due to the real estate boom in metros, availability of space is difficult for parking and other facilities, and that leaves the choice of OGSS. Thus, open ground storey as construction practice is difficult to eliminate from the architect's design criteria and hence it is preferable to provide special design criteria for such structural configuration. Absence of wall infill in ground storey will change the force transfer mechanism in the structure and open ground storey columns will accumulate higher stresses that lead to higher damage [1]. More amount of energy will be absorbed by soft storey members, causing larger interstorey drift leading to higher deformation in ground storey columns. Design criteria of OGSS depend on relative stiffness and strength of ground floor with respect to the adjacent upper floor. International seismic codes suggest that columns and beams of the floor having soft storey are to be designed for higher moments to reduce the soft storey effect. Indian seismic code IS 1893-2002 recommends, beam and columns having soft storey effect require to be designed for 2.5 times higher design forces, to reduce soft storey effect [2]. Seismic response of OGSS with full infill in the upper storey cannot be improved significantly even after using an amplification factor of 5 for ground storey columns [3]. Presence of openings in infill panel decreases the stiffness and strength, thus recommended amplification factor for design of soft storey in upper floors should depend on the opening area in the upper storey.

In the present paper, a study is done to compute the amplification factor for design forces of ground storey members of a building having open ground storey effect with respect to different openings in infill in the adjacent upper storey. Provided amplification factor is based on the interstorey drift and shift of damage from ground to upper storey. Limiting values of stiffness and strength ratios of upper storey with respect to ground storey are also proposed. The computed amplification factor can be used for design of new buildings or for retrofitting of members of existing buildings having a capacity equivalent to amplified design force. Ratios of lateral stiffness and strength of the upper storey with respect to ground storey to overcome soft storey effect are also computed.

2. Methodology

Ideally to have continuity of stiffness and strength in the structure vertically the member dimensions and infill should not be altered significantly in adjacent floors, but because of space limitation and to avail parking facility results in open ground storey structures. Stiffness and strength of ground storey are substantially less than the upper storey, which leads to failure of ground storey columns without any amount of damage to the upper storey. In OGSS mostly capacity of only ground storey is used to resist lateral forces in place of the whole structure, the ideal condition will exist when most of the members of structure participate to resist lateral force. Thus, the objective is to increase the capacity of the ground storey columns to the extent that damage shifts from ground storey to the upper storey and capacity of the whole structure can be utilized. Shift in damage can be identified by: failure of structural members or wall infill in the upper storey and inelastic interstorey drift profile obtained from non linear static pushover analysis. It is difficult and tedious process to check the safety of OGSS for different increased capacities, thus to simplify the process capacity of the ground storey column at which soft storey effect nullified is correlated with the design forces.

3. Structural Details

For the current study a G+3 storey reinforced concrete building is considered. The building is assumed to be located in the seismic zone IV as per IS 1893-2002. External, internal wall thickness and slab thickness are considered as 230 mm, 100 mm and 120 mm, respectively. Floor finish of 1 kN/m^2 is considered. Design live loads are assumed as 2.5 kN/m^2, 1.25 kN/m^2 and 5 kN/m^2 on floors, roof and staircase, respectively. M25 and Fe415 grade of concrete and steel (HYSD) are considered, respectively. Depth of foundation is considered as 2 m from ground level. For design, dead load, imposed load and seismic loads were considered as per IS 875-1987 [4] and IS 1893-2002, respectively. Design of building is done as per IS as per IS 456-2000 [5] and IS 13920-1993 [6]. Previous study [3] shown that beam column joints attract high stresses because of infill panel, which leads to shear failure in normal detailed structure, to overcome above problem ductile detailing as per IS 13920-1993 is considered. Fig.1 shows the considered RC frame.

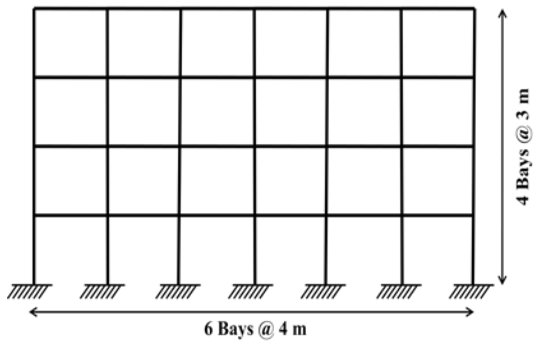


Fig. 1- Building Frame

4. Infill Modeling

In structural analysis brick infill is considered as non structural element and only its mass is considered to compute design forces. Lateral strength and stiffness of the infills are neglected because of variation in masonry construction practices. Brick infill can be assumed as non structural element, only if it is not in contact with the structural elements (beams and columns): Thus unknowingly brick infill which is in contact with the structural elements contribute in resisting loads. Owing to above mentioned reasons brick infill need to be considered in numerical modeling especially when performance of the structure need to be evaluated.

Effect of infill on the frame can be considered by micro (using area element) or macro level modeling (using strut models). Micro modeling takes huge computation time compared to macro modeling, thus in the current study macro modeling was considered. Numerous strut models single, two and three are available in literature among them three strut model give the response of the structure closer to the actual behavior of frame with infill in continuum modeling and better than single strut model [7]. Material properties of masonry were taken as reference [7].

Width of the struts has been proposed by many researchers 0.33 d, 0.25d and 0.20d (where d is the diagonal length of the panel) Holmes, Paulay and Priestley, and Smith , respectively. In the present study three strut model [8-10] with width (W_d) of the diagonal strut as one-fourth of the diagonal length of the infill was taken. The width of central diagonal strut and off-diagonal strut was taken as one-eithth and one sixteenth, respectively of the diagonal length of wall. The central strut was connected diagonally to beam column joint and the off-diagonal struts were connected at a distance half of α_m Fig.2, α_m is the contact length between infill and structural members.

$$\alpha_m = \frac{\pi}{2} \sqrt[4]{\frac{4E_c I_c h_m}{E_m t \sin(2\theta)}} \, (mm) \tag{1}$$

Where E_c and E_m are modulus of elasticity of column and masonry (MPa), respectively, I_c is moment of inertia of column section (mm^4), h_m and t are height and thickness of masonry infill wall (mm), respectively, and θ is angle of inclination of the equivalent diagonal strut with the horizontal in degrees.

Presence of opening in infill panel will affect the stiffness and strength of frame, the effect can be incorporated by reducing the width of the diagonal strut. The stiffness reduction factor to consider opening effect in infill in numerical modeling [11] is given by:

$$W_{do} = (1 - 2.5A_r)W_d \tag{2}$$

Where A_r is the opening area ratio, which is the ratio of face area of opening to the face area of infill.

The above relation is valid for opening in wall greater than 5% and lesser than 40%.

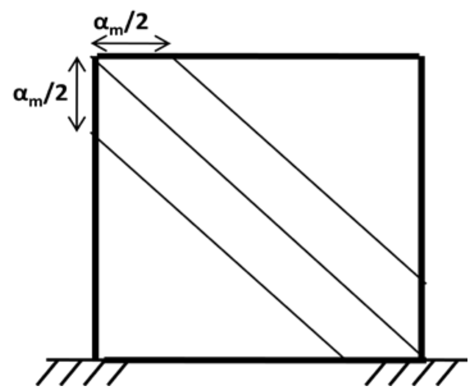


Fig. 2- 3 Strut Model

Table 1- Strut dimensions for different openings

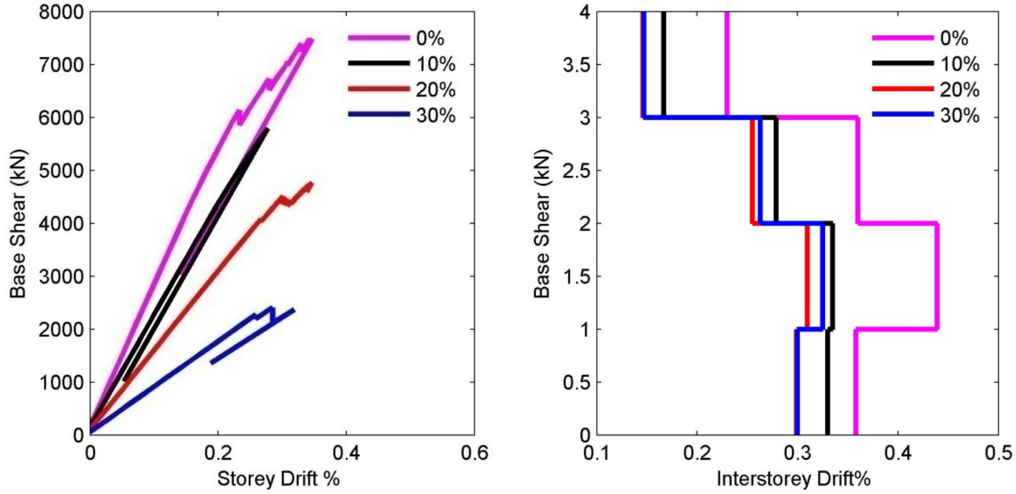
Opening %	Width (m)	Height (m)	Width (mm)		Axial Capacity (kN)	
			Central Strut	Off-Diagonal Strut	Central Strut	Off-Diagonal Strut
0	-	-	625	313	949	474
10	1	1	466	233	708	354
20	2	1	308	154	467	234
30	2	2	229	114	347	174

5. Pushover Analysis

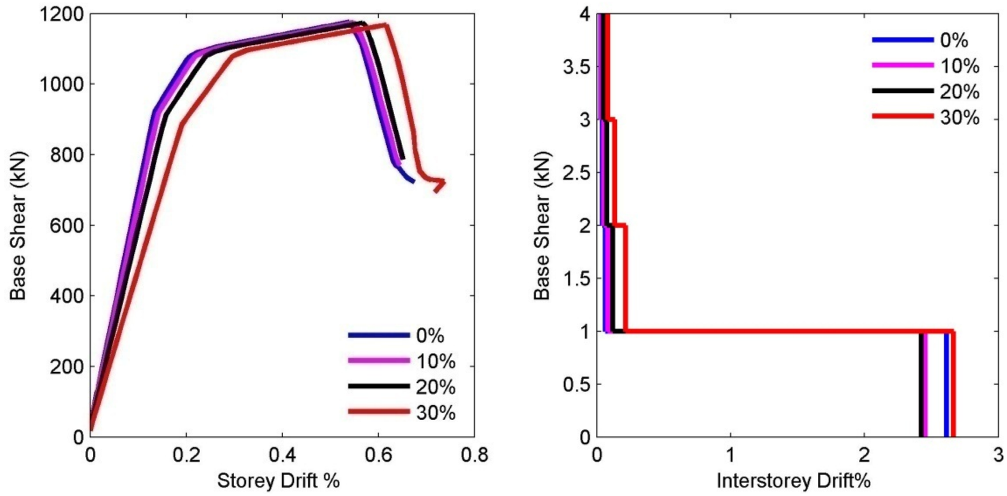
Pushover analyses were done for all the models considering the flexural and shear hinge in beams and columns, and axial hinge in struts. Shear capactiy of members were calculated as per IS:456 removing the partial safety factors and increased value of compressive strength of concrete (f_{ck}) due to confinement was considered. Axial capacity of struts were computed by multiplying crossection area with compressive strength of masonry (Table 1). The failure in shear and axial hinges were defined as brittle type. In pushover analysis displacement control method and load pattern as per seismic demand was considered and performed using SAP2000 Version 16 [12].

6. Bare Frame, Brick Infill And Open Ground Storey

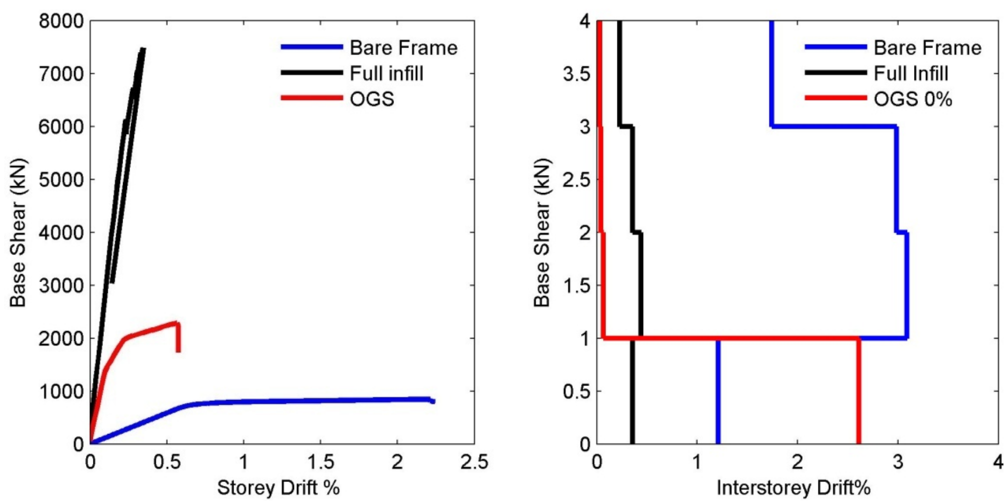
Pushover analysis was done on the bare frame, infill frame with different openings and OGSS with different openings. Fig.3 shows the capacity curve and interstorey drift profile of structures. Interstorey drift calculated was maximum drift between two storeys, obtained during the pushover analysis. Table 2 shows the change



(a) Full infill with different openings



(b) OGSS with different openings



(a) Effect of infill with O% opening

Figure 3: Pushover and max. interstorey drift profile

in elastic stiffness, strength, drift at maximum strength and first mode time period of the structure because of full infill, openings in infill and openings in OGSS.

Infill frame with 0% opening had damage in Ist and IInd storey wall with some amount of damage in beams and columns. Shear failure was observed in beams of ground Storey and in some columns of IInd storey. The extent of damage in beams and columns reduced as openings in the infill increased. Brick infill has effect on initial capacity of the structure, once the failure in infill occurred the entire load will be taken by frame only, care should be taken to make sure that structural members are not failing because of strut action in infill and same can be reduced by increasing the shear capacity of members near the joints.
OGSS with full infill columns of ground storey failed in flexure. OGSS with 30% opening had failure in columns of ground storey and damage in upper storey struts. Thus with normal design provisions even with opening in upper storey upto 30%, the failure had occurred in ground storey columns only. Table 2 shows the comparison of initial stiffness ($K_{elastic}$), maximum base shear (V_{max}), storey drift at V_{max} and first mode time period. Table clearly shows significant increase in elastic stiffness and strength, and decrease in time period, in full infill frame compared to bare frame and OGS structure.

Table 2 - Comparison of parameters for Full brick infill and open ground storey structure

Structure	Full Brick Infill				Open Ground Storey			
	$K_{elastic}$ (kN/m)	V_{max} (kN)	Drift at V_{max} (%)	T (sec.)	$K_{elastic}$ (kN/m)	V_{max} (kN)	Drift at V_{max} (%)	T (sec.)
Bare Frame	9760	846	2.21	1.03	-	-	-	-
0% Opening	223908	7483	0.35	0.07	54601	1176	0.54	0.17
10% Opening	176621	5790	0.28	0.08	52244	1174	0.55	0.17
20% Opening	124862	4766	0.35	0.09	46837	1174	0.62	0.18
30% Opening	71396	2410	0.28	0.12	37950	1168	0.62	0.19

7. Column Strengthening

Shear force and bending moments in the ground storey members increases significantly because of soft storey effect leading to shear and flexural failure in columns. Forces in columns increased more significantly than beams, thus in the present study strengthening of only columns in ground storey is done. It has been observed that shear failure in columns can be reduced to some extent by providing ductile detailing.

The OGSS was strengthened by increasing the load carrying capacity of columns at ground storey. As per IS code (IS 1893-2002), amplification factor of 2.5 is used for structure having soft storey. The design amplification factor will be different for different opening percentages, as it depends on the relative stiffness and strength of the upper storey with respect to ground storey. Amplification factor used to eliminate OGS effect for different openings was computed by increasing the design forcé in columns to the extent till damage in the ground storey members shifts to the upper storey. For the amplified design forces the columns are designed by increasing the columns geometry and keeping the reinforcement nearly same, but for higher amplification factors both geometry and reinforcement were increased. Details of column geometry and reinforcement for amplified design forces are shown in Table 3.

Table 3: Geometry and reinforcement details of ground storey columns

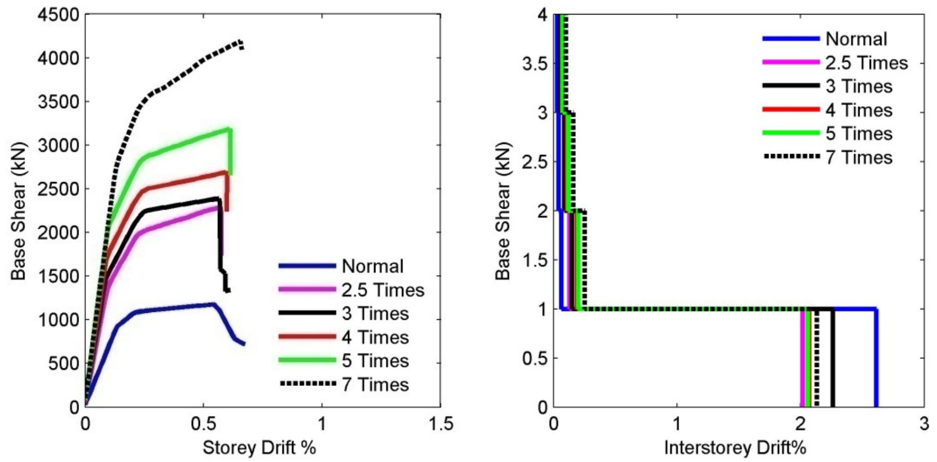
Depth	Width	AF	M_{Design} (kN/m)	V_{Design} (kN)	Long. Rein.	Shear Rein. in Confinement Zone
350	350	1	129	76	16Y16	3 Leg Y8 @75 mm c/c
500	500	2.5	292	190	16Y16	3 Leg Y8@75 mm c/c
550	550	3	351	228	16Y16	3 Leg Y8 @75 mm c/c
600	600	4	468	304	4Y20 & 12Y16	3 Leg Y8 @75 mm c/c
650	650	5	702	380	12Y20 & 4Y16	3 Leg Y8 @75 mm c/c
650	650	7	819	532	12Y25 & 4Y20	3 Leg Y8 @75 mm c/c

Table 4: Damage status in OGS structures with aplified design forces from pushover analysis

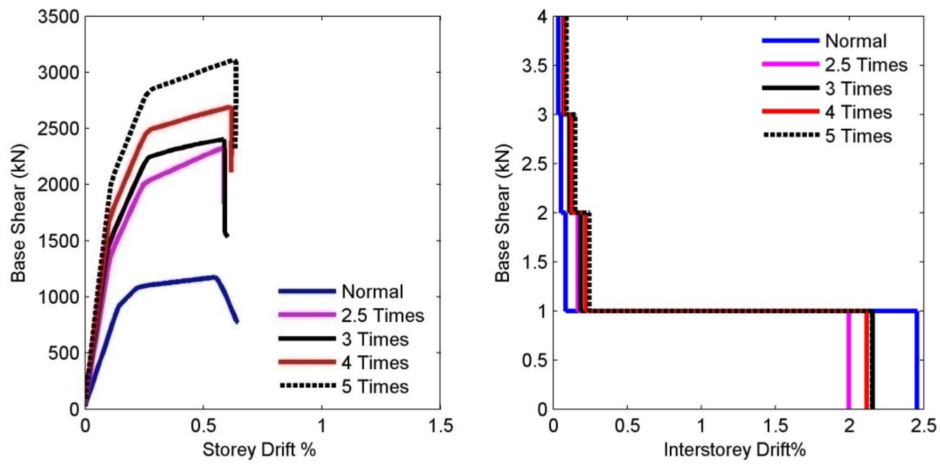
AF	% Opening	Damage/ Failure State
2.5	0	Damage in beams and columns of ground storey
	10	Damage in beams and columns of ground storey
	20	Damage in IInd storey struts and failure of ground storey columns
	30	Failure in IInd storey struts and damage in ground storey columns
3	0	Damage in beams and columns of ground storey
	10	Damage in beams and columns of ground storey
	20	Failure in IInd storey struts and damage in ground storey columns
	30	Failure in IInd storey struts and damage in ground and IInd storey members
4	0	Damage in beams and columns of ground storey
	10	Damage in IInd storey struts and failure of ground storey columns
	20	Failure in IInd storey struts and damage in ground and IInd storey members
	30	Failure in IInd and IIIrd storey struts and damage in ground storey columns
5	0	Slight damage in IInd storey struts and failure in ground and IInd storey members
	10	Failure in IInd storey struts and damage in ground and IInd storey columns
	20	Failure in IInd and IIIrd storey struts and damage in ground and IInd storey members
	30	Failure in all storey struts and damage in ground storey columns
7	0	Failure in IInd storey struts and damage in ground and IInd storey members

Pushover curves and Interstorey drift of building with increased column dimensions are shown in Fig.4. It was observed that by strengthening columns of ground storey done as per code (2.5 amplification factor), non linear response of structure does not improved significantly for openings less than 30%, whereas for 30% opening the damage was shifted from ground storey to IInd storey. Damage state for different amplification factors with different openings are shown in Table 4.

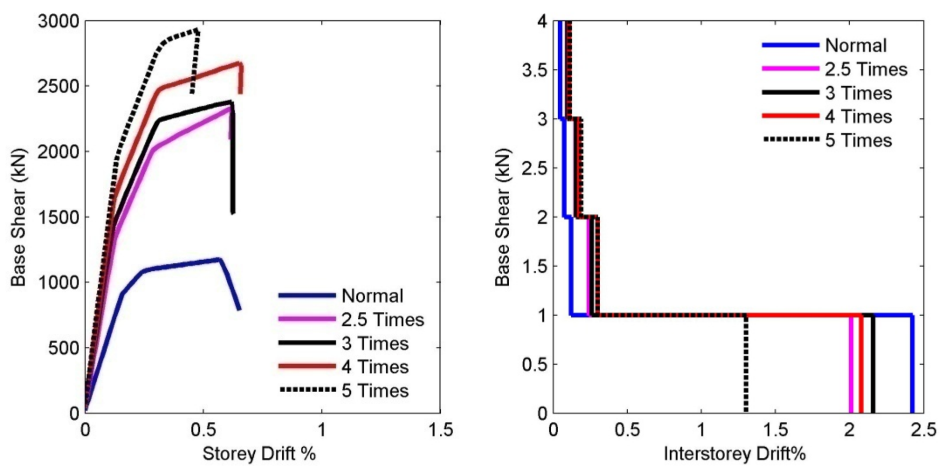
Damage states shown in table 4 clearly shows that for 0%, 10%, 20% and 30% openings the amplification factors need to be considered in design of ground storey columns are 7, 5, 3 and 2.5, respectively.



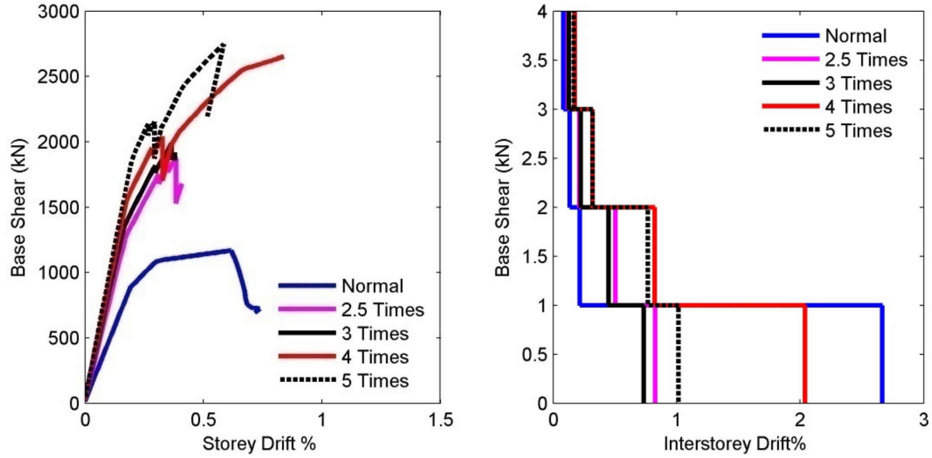
(a) 0% opening



(b) 10% opening



(c) 20% Opening



(d) 30% Opening

Figure 4: Pushover curves and max. interstorey drift for different openings in OGSS

Table 5 Parameters for open ground storey structure with different openings

Opening (%)	**Amplification Factor**	**$K_{elastic}$ (kN/m)**	**V_{max} (kN)**	**Drift at V_{max} (%)**	**T (sec.)**
0	2.5	113875	2284	0.57	0.11
	3	133646	2389	0.56	0.10
	4	152558	2688	0.59	0.09
	5	171228	3185	0.61	0.09
	7	**171228**	**4188**	**0.65**	**0.09**
10	2.5	102708	2330	0.59	0.12
	3	118237	2403	0.59	0.11
	4	133359	2692	0.61	0.10
	5	**149239**	**3111**	**0.63**	**0.09**
20	2.5	86022	2332	0.62	0.12
	3	**97613**	**2379**	**0.62**	**0.11**
	4	108369	2674	0.65	0.11
	5	118522	2931	0.48	0.10
30	**2.5**	**60936**	**1871**	**0.38**	**0.14**
	3	67038	1986	0.36	0.13
	4	72644	2651	0.84	0.12
	5	77758	2749	0.59	0.12

Table 5 clearly shows the elastic stiffness and time period values corresponding to suggested amplification factors are close to full brick infill structures Table 2, whereas the strength need not to be close to full brick infill.

8. Stiffness and Strength

Amplification factors obtained from performing pushover analysis were based on the number of attempts; it will be difficult to perform analysis for so many times to remove OGS effect. More generalized way will be to check the ratio of stiffness and strength of Ist storey wrt strengthened ground storey. To compute the stiffness of storey floor level of particular storey was restrained in the numerical model and displacement at slab level of the same storey was observed corresponding to the seismic force. The shear force at storey divided by obtained displacement will give stiffness of particular storey. To compute the strength, max base shear obtained from pushover analysis of particular storey with all the vertical loads applied at the top was considered.

Table 6 shows the stiffness and strength ratios, respectively of Ist storey wrt to ground storey for OGS structures.

Table 6: Stiffness ratio of Ist storey wrt to ground storey

Parameter	**Stiffness Ratio (K_I/K_G)**					
Opening/AF	**1**	**2.5**	**3**	**4**	**5**	**8**
0	11.1	4.1	3.2	2.6	2.0	**2.0**
10	8.8	3.3	2.6	2.1	**1.6**	**-**
20	6.3	2.4	**1.9**	1.5	1.2	**-**
30	3.8	**1.5**	1.2	0.9	0.7	**-**

Table 7: Strength ratio of Ist storey wrt to ground storey

Parameter	**Strength Ratio(V_I/V_G)**					
Opening/AF	**1**	**2.5**	**3**	**4**	**5**	**8**
0	7.3	4.1	4.1	3.6	3.1	**2.4**
10	5.7	3.2	3.2	2.8	**2.4**	1.9
20	5.0	2.9	**2.9**	2.5	2.1	1.7
30	4.4	**2.5**	2.5	2.1	1.8	1.4

Table 6 shows stiffness ratios for 0%, 10%, 20% and 30% openings to remove the OGS effect are 2.0, 1.6, 1.9 and 1.5, respectively. Table 7 shows stiffness ratios for 0%, 10%, 20% and 30% openings to remove the OGS effect are 2.4, 2.4, 2.9 and 2.5, respectively. The average of the obtained values can be considered as upper limit. From the obtained results to remove OGS effect the stiffness and strength ratios of Ist storey wrt to ground storey should not be greater than 1.8 and 2.5 respectively, which can be considered in design approach.

9. RESULTS

Amplification factor for OGSS of 2.5 suggested for ground storey members by IS code will be suitable for openings greater than or equal to 30% in upper storey.

Amplification factors for OGSS with 0%, 10%, 20% and 30% openings in upper storey can be considered as 7, 5, 3 and 2.5, respectively.

Lateral stiffness and strength ratio of Ist storey wrt to ground storey should not be greater than 1.8 and 2.5 respectively to avoid OGS effect.

10. Conclusions

Study done shows that, presence of openings in the upper storey will reduce damage in structure having OGS. Open ground storey should be avoided as far as possible, under unavoidable circumstances the ground storey members need to be designed for proposed amplification factors with respect to openings in upper storey. Stifness and strength both parameters need to be considered to eliminate open ground storey effect. For full infill in the upper storey the proposed amplification factor may not be feasible in that case shear wall having equivalent design capacity can be constructed. The proposed design amplification factor, stiffness and strength ratios will vary based on the aspect ratio of building and is limited to ductile detailed reinforced concrete frame only.

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