EFFECT OF ASPECT RATIO ON RESPONSE REDUCTION FACTOR OF RC FRAMED STRUCTURES WITH SEMI-INTERLOCKED MASONRY AND UNREINFORCED MASONRY INFILL

by

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EFFECT OF ASPECT RATIO ON RESPONSE REDUCTION FACTOR OF RC FRAMED STRUCTURES WITH SEMI-INTERLOCKED MASONRY AND UNREINFORCED MASONRY INFILL

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Abstract

In building construction, reinforced concrete (RC) Frame structures are frequently used due to ease of construction and rapid progress of work. In this study, two types of infill's are used i.e., unreinforced masonry infill and semi-interlocked masonry infill. For the analysis purpose of infill, a double strut nonlinear cyclic model is used. The main objective of the study is to investigate the importance of interlocked brick infill in the RC frame structure. For understanding the same, nonlinear static pushover analysis is carried out on analytical models using finite element based software, SeismoStruct. The response reduction factor components such as ductility reduction factor and overstrength factors were computed from nonlinear static pushover analysis and finally, the response reduction factor is calculated for all models. The primary focus is given to numerical modeling, nonlinear behavior of brick masonry RC buildings subjected to lateral loads and calculation of the response reduction factor of 'RC' infilled frames with different aspect ratios.

Keywords: Nonlinear static pushover analysis, Response reduction factor, Semi-interlocked masonry, Un-reinforced masonry.

1. INTRODUCTION

Masonry is one of the most popular and economical building materials in the construction system. The most common structural system for both residential and office buildings consist of multi-level framed structures which are masonry infilled RC frames so, it is important to determine the earthquake behavior of RC structures with infill walls under seismic load. The masonry panels are generally not considered in the analysis and design process and it is treated as an architectural component. Nevertheless, the presence of masonry infill walls has a significant impact on the seismic response of a reinforced concrete frame building as it increases structural strength and stiffness. The design of masonry with improved earthquake resistance presents a challenge for structural engineers. Semi-interlocked masonry is a new type of framed masonry built of dry stack semi-interlocking brick units as shown in Figure 1 (Totoev 2015). These semi-interlocked masonry (SIM) units are capable of relative sliding in a plane and locked relative movement out of plane. Most of the countries have started the utilization of interlocked brick infills, especially in seismically active regions. The interlocking brick system is a fast and cost-effective construction system which offers a good solution in construction. Hence, there is a need to determine the effectiveness of interlocking brick in the construction system.

The author and his colleagues at the University of Newcastle in Australia and Harbin Institute of Technology (Shenzhen Graduate School) conducted all previous research on framed SIM infills. Wang Z. *et al.* [1] in present work developed a new masonry system at the University of Newcastle. It uses masonry panels made of dry stack semi-interlocking masonry (SIM) units capable of relative sliding in-plane and interlocked to prevent sliding out-of-plane. The major objective of the system was to improve the earthquake performance of framed structures with masonry panels acting as energy dissipation devices (EDD). This paper presents the results of a numerical simulation of earthquake vibrations on a multi-story steel frame with three-dimensional finite elements. Wang Z. *et al.* [2] showed to study the effect of SIM infill panels on the yield displacement, the displacement ductility, and damage mechanisms of a multi-story steel frame structure through finite element numerical simulation of non-linear static response. Panels were designed in such a way that it dissipates earthquake energy through sliding friction between bricks during seismic vibration. The authors concluded that SIM infill may have the potential to reduce damage in buildings during the earthquake. Ibrahim Serkan

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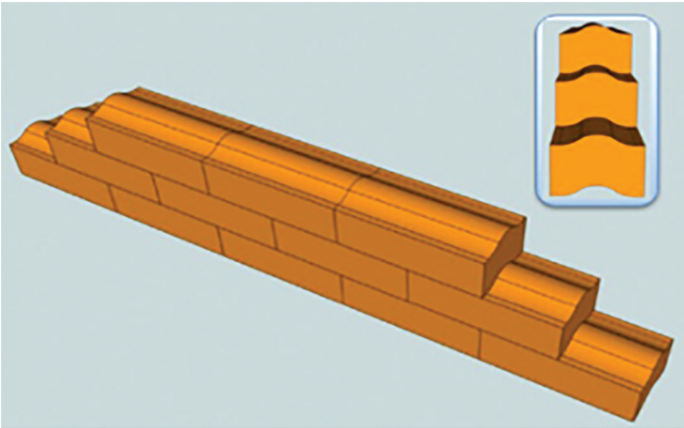


(a) Semi-interlocked masonry

(b) Unreinforced masonry

Figure 1: Types of masonry infill: a) semi-interlocked masonry, b) Unreinforced masonry

Misir *et al.* [3] studied the effects of a new type of infill called locked brick infill adopting horizontal sliding joints in reducing the soft-story formation in RC frames The parameters of frame and infill elements that were used in numerical simulations were obtained from half-scale RC infilled frame tests that had been performed by the author covering single-story single-bay frames infilled with standard and locked bricks. Alguhane T.M. *et al.* [4] presented the study that an existing RC building in Madinah is seismically evaluated with and without an infill wall. Four model systems have been considered i.e. model I (no infill), model IIA (strut infill-update from field test), model IIB (strut infill- ASCE/SEI 41), and model IIC (strut infill-Soft story- ASCE/SEI 41). The response modification factor (R) for the 5 storys RC building was evaluated from capacity and demand spectra (ATC-40) for the studied models. Smyrou *et al.* [5] presented the implementation; within a fiber based finite element program of an advanced double strut nonlinear cyclic model for masonry panel is described. The accuracy of the model is first assessed through comparison with experimental results obtained from the pseudo-dynamic test of large or full-scale frame models. This is followed by a sensitivity study whereby the relative importance of each parameter necessary to calibrate the model is evaluated. Furthermore, a representative range of values for geometrical and material properties of infill panels has been also defined.

The response reduction factor is one of the design tools to show the level of inelasticity present in the structures which is of great importance in the earthquake engineering field. Many researchers did work on this important response reduction factor of the different RC frames. From the analytical study, the value of R is more when the infill is considered in the frame so the R-value is sensitive to the material & geometrical configuration of the structure. Also, the evaluated values of R for the bare frames are lesser than the recommended value by BIS code. The R-factor significantly decreases by considering the opening in masonry infills, as the height of the structure increases, and the seismic zone increases [6-14].

This paper explored analytically the response reduction factor (R factor) of RC infilled frames and how it varies from the R factor values recommended by the Indian code for earthquake resistant design of structures [15]. In this study, the following attempts have been made:

I. To calculate the actual value of Response reduction factor "R" for RC infilled frame by using two different infills namely SIM and Unreinforced Masonry (URM) infill.
II. To compare the values of R obtained from the interpretation of analytical results.
III. To obtain a pattern in the variation of R values with changing the aspect ratio of frames.

2. DESCRIPTION OF DIFFERENT PARAMETERS

2.1 Response reduction factor (R)

The response reduction factor is a force reduction factor used to reduce linear elastic response spectra to inelastic response spectra. In other words, the response reduction factor is the ratio of elastic to inelastic design strength. The response reduction factor is also named as the response modification factor and behavior factor. The value of the R factor varies from 3 to 5 in IS-1893 depends on the type of resisting frame [ordinary moment resisting frame (OMRF) and special moment resisting frame (SMRF)]. From the review of existing literature, it can be seen that the response reduction factor depends upon three parameters; ductility, overstrength, and redundancy.

$$\mathrm{R} = R_{\mu}\,\Omega \quad (1)$$

where, R is the response reduction factor, R_{μ} is the ductility reduction factor and Ω is an overstrength factor.

The philosophy of earthquake-resistant design is that a structure should resist earthquake ground motion without collapse, but with some allowable damage. Consistent with this philosophy, the structure is designed for much less base shear forces than

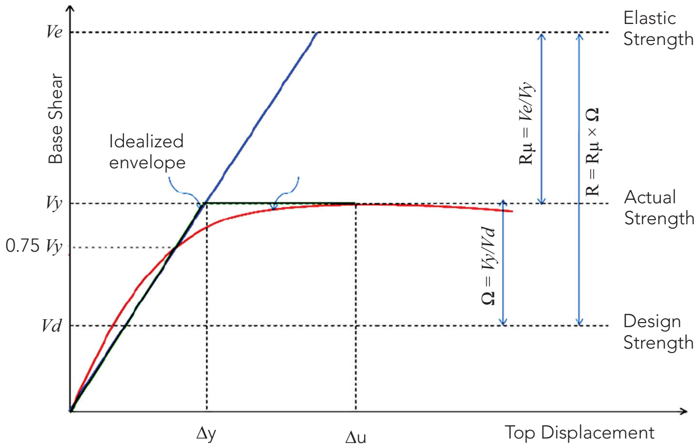


Figure 2: Relationship between response reduction factor, structural over-strength (Ω) and ductility reduction factor (R_μ) [4]

would be required if the building is to remain elastic during severe shaking at a site. Such large reductions are mainly due to two factors: a) the ductility reduction factor (Rμ) which reduces the elastic strength to the level of the actual strength of the structure and b) the over-strength factor (Ω) which accounts for the over-strength introduced in code-designed structures, ATC-19 [16]. Thus, the response reduction factor (R) is simply evaluated by the product of over-strength factor and ductility reduction factor as shown in Figure 2.

2.2 Ductility reduction factor (Rμ)

In the event of an earthquake, ductile structures have been found to perform better than brittle structures. The ductility reduction factor is a measure of the global nonlinear response of a structure. It is a function of both, ductility and fundamental time period of the structure. The global ductility or displacement ductility μ is represented as

$$\mu = \frac{\Delta_{max}}{\Delta_y} \quad (2)$$

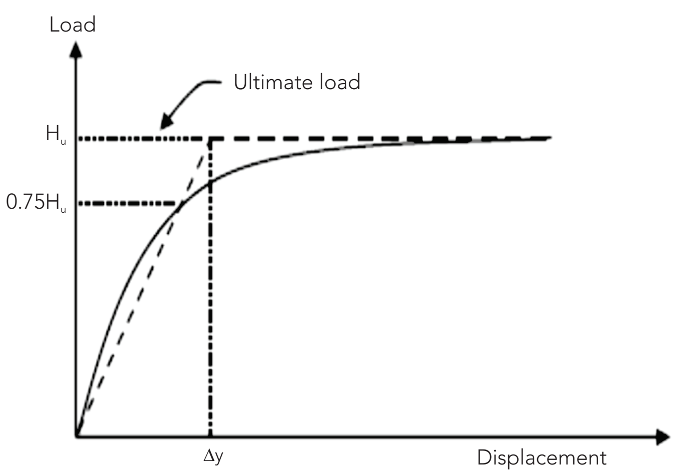


Figure 3: Reduced stiffness method

where, Δ_{max} = maximum displacement and Δ_y = yield displacement.

Yield displacement is calculated by the reduced stiffness method [17] as shown in Figure 3.

Different formulations have been proposed by researchers for the determination of the ductility factor. The R-μ-T relationships developed by Newmark and Hall [18] have been used in this study to calculate Rμ as follows;

Short period	T < 0.2 Seconds	$R_\mu = 1$	
Intermediate period	0.2 < T < 0.5 Seconds	$R_\mu = \sqrt{2_\mu - 1}$	(3)
Long period	T > 0.5 Seconds	$R_\mu = \mu$	

2.3 Overstrength Factor

The overstrength factor is a measure of additional strength a structure has beyond its design strength. It may be expressed as

$$\Omega = \frac{V_y}{V_d} \quad (4)$$

where, V_y is the ideal yield base shear and V_d is the design base shear

The main sources of the overstrength factor are:

a. The difference between actual and design material strength
b. Load factors and multiple load cases
c. Participation of nonstructural element
d. Redundancy

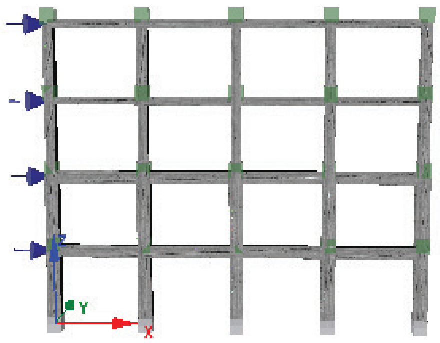
2.4 Redundancy factor

Redundancy is usually defined as exceeding what is necessary or naturally excessive i.e., the gap between the local yield point to global yield point of the structure. The building should have a high degree of redundancy for lateral resistance. In this study, redundancy factor is incorporated into the overstrength factor.

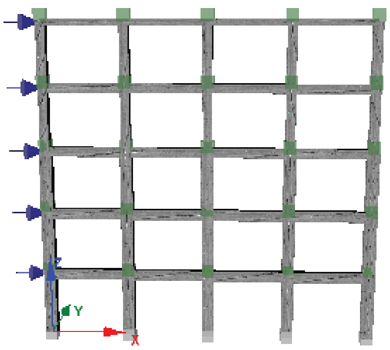
3. MODEL DESCRIPTION

For this study, 4 story - 4 bay, 5 story - 4 bay and 6 story - 4 bay two-dimensional frames with each bay span is 4m and floor height is 3m as shown in figure 4. This building is considered to be situated in seismic zone v and designed in compliance with the Indian code of practice for earthquake resistant design of structures. The building is modeled using SeismoStruct software. Models are studied for comparing the response reduction factor of RC frame structure with SIM and URM infill as follows:

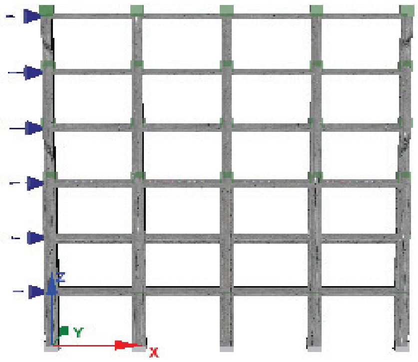
1) Bare frame
2) URM (open ground RC frame)
3) URM (only side bay infilled at ground of RC frame)



(a) Four story - four bay frame



(b) Five story - four bay frame



(c) Six story - four bay frame

Figure 4: Different two dimensional frames

4) URM (Full infilled RC frame)
5) SIM (Full infilled RC frame)
6) SIM (open ground RC frame)
7) SIM (only side bay infilled at ground of RC frame)

3.1 Inelastic infill panel element

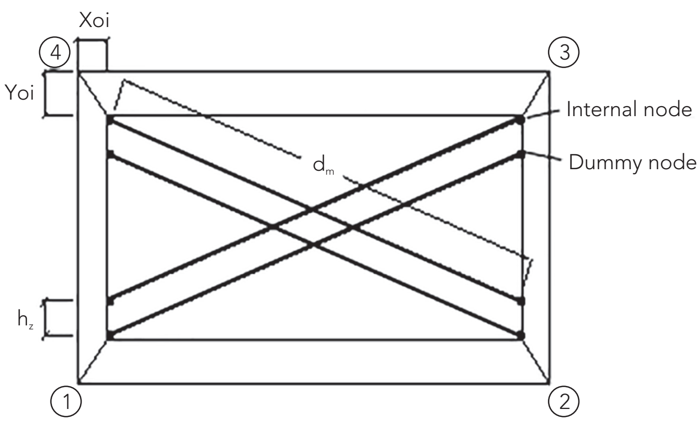
Each infill panel element is represented by four axial struts and two shear springs, as shown in Figure 5.This element is able to define with three groups of parameters. The first group is about physical characteristics of the infill panel, the second group is about compression/tension struts defined by strut curve parameters, and the third group is about shear spring that defined by shear curve parameters. Four node panel masonry element developed by the researcher Crisafulli [19,20]. It accounts separately compressive and shear behavior of masonry. It shows the adequate representation of the hysteretic response. It shows the accuracy of the model to evaluate the nonlinear response of the structure. Another name of this model is the "Double strut nonlinear cyclic model".

3.2 Data compilation and calculation

Lumped mass is calculated and applied for each node which is due to the dead weight of the floor slab and the infill walls. Reinforcements in beam and column sections for the structures are calculated according to analytical results of a frame from SAP-2000 using gravity load and seismic load condition with M30 concrete and Fe-500 steel reinforcement. These sections are assigned to the simulation of the structure made in SeismoStruct and lumped masses are also assigned to each node. Thus the frames are simulated in SeismoStruct with different infill conditions. This structure is loaded from x-axis to get the performance curves in the respective axis.

4. PUSHOVER ANALYSIS

The pushover analysis is a static non-linear analysis under permanent vertical loads and gradually increasing lateral loads. The equivalent static lateral loads approximately represent earthquake-induced forces. Pushover analysis is a static, nonlinear procedure in which the magnitude of the structural loading is incrementally increased in accordance with a certain predefined pattern. With the increase in the magnitude of the loading, weak links, and failure modes of the structure are found. The loading is monotonic with the effects of the cyclic behavior and load reversals being estimated by using modified monotonic force-deformation criteria and with damping approximations. The capacity curve is shown in Figure 6.



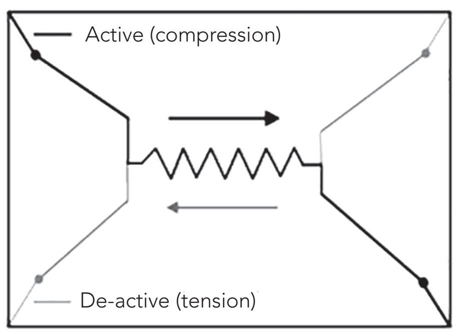


Figure 5: Inelastic infill panel element

Table 1: Structural details of RC frame structure

TYPE OF STRUCTURE	SPECIAL MOMENT RESISTING FRAMES
Seismic zone	V
Number of stories	G+3 , G+4, G+5
Floor Height	3m
Bay length	4m
Infill wall	URM wall -113 mm SIM wall - 110 mm
Type of soil	Soft soil
Size of column	450 × 600, 450 × 450
Size of beam	300 × 300 , 300 × 450, 300 × 500
Depth of slab	150 mm
Live load	2.5 kN/m^2
Material	M 30 grade and Fe 500 reinforcement
Damping in structure	5%
Importance factor	1.5

The nonlinear static procedures help to determine the parameters such as initial stiffness, yield load, yield displacement, maximum base shear, possible location of the failure, modified stiffness, and maximum displacement. The performance of a building is measured by the state of damage under a certain level of earthquake. The state of damage is expressed as the "building performance levels". Building performance levels are by the state of damage to structural and non-structural components under inelastic drift given at a controlled node of the roof. Pushover analysis is an approximate analysis method in which the structure is subjected to monotonically increasing lateral earthquake forces with an invariant height-wise distribution until a target displacement is reached.

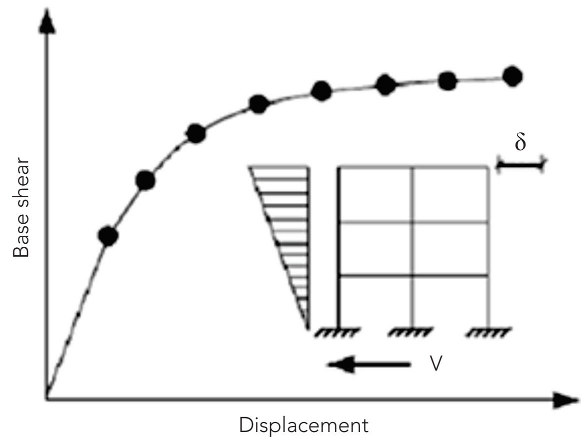


Figure 6: Capacity curve

5. RESULTS AND DISCUSSION

5.1 Pushover curves

The use of nonlinear static analysis came into practice in 1970's but the potential of pushover analysis has been recognized from the last two decades. In this study, a four-node panel element infill model is used for numerical simulation of frames. The several parameters like strength, ductility, R factor, etc. we can find out from pushover curves and another important thing is that significance of infill plays important role in the RC frame. Ultimately from pushover curves, we can get the capacity of the whole structures.

As per the Figure 7, the base shear is lowest in a bare frame as compared to all other frames. Nearly 16.70% increases for SIM full infilled frame as compared to the URM full infilled frame. In the case of open ground story frames, there is a variation of 1.15%. And for SIM side bay infilled frame has maximum base shear by 12.35% as compared to URM side bay infilled frame.

Table 2: Beam dimensions and detailing

BEAM	LENGTH	WIDTH	HEIGHT	LONGITUDINAL REINFORCEMENT		SHEAR REINFORCEMENT
				TOP	BOTTOM	
B1 (At Ground and 1st floor)	4000	300	500	3 bars @ 20 mm dia.	3 bars @ 20 mm dia.	8 mm @ 300 mm c/c
B3 (At 2nd and 3rd floor)	4000	300	450	3 bars @ 20 mm dia.	3 bars @ 20 mm dia.	8 mm @ 300 mm c/c
B5 (At 4th floor and 5th floor)	4000	300	300	2 bars @ 20 mm dia.	2 bars @ 20 mm dia.	8 mm @ 300 mm c/c

Table 3: Column dimensions and detailing

COLUMN	HEIGHT (mm)	SIZE (mm)	MAIN REINFORCEMENT	SHEAR REINFORCEMENT
C1 (From ground to 2nd floor)	3000	450 × 600	8 nos. of 20 mm diameter	8 mm @ 250 mm c/c
C2 (For 3rd, 4th and 5th floor)	3000	450 × 450	6 nos. of 20 mm diameter	8 mm @ 250 mm c/c

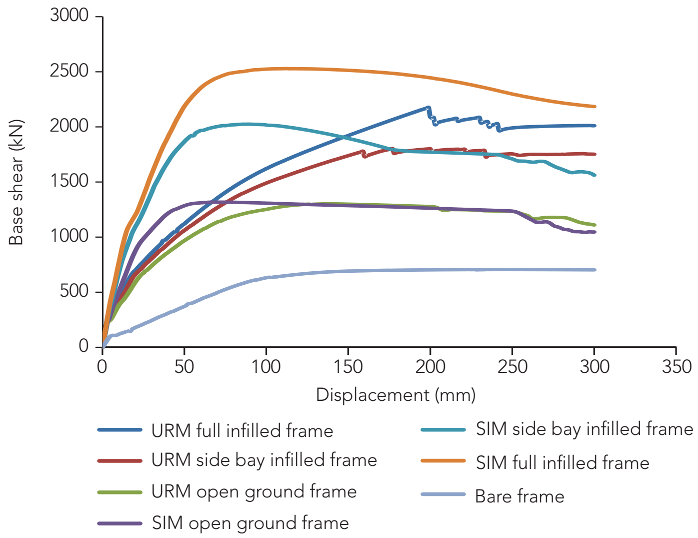


Figure 7: Comparison of pushover curves of 4 story - 4 bay frame

As per the Figure 8, the base shear is lowest in a bare frame as compared to all other frames. Nearly 19.52% increases for SIM full infilled frame as compared to URM full infilled frame. In the case of open ground story frames, there is a variation of 2.12%. And for SIM side bay infilled frame has maximum base shear by 12.43% as compared to URM side bay infilled frame.

As per the Figure 9, the base shear is lowest in a bare frame as compared to all other frames. Nearly 21.53% increases for SIM full infilled frame as compared to URM full infilled frame. In the case of open ground story frames, there is a variation of 3.82%. And for SIM side bay infilled frame has maximum base shear by 15.28% as compared to URM side bay infilled frame.

In general, we know that pushover curves show the capacity of structures so here there are different RC infilled frames in which SIM full infilled frames give maximum capacity as compared to all other frames. In the case of open ground frames, there is a small variation in the maximum capacity of SIM and URM infilled frames. And capacities of all infilled frames have a maximum capacity as compared to the bare frame because infill plays important role in the seismically active zone.

As per the Table 4, the ductility is higher in the bare frame as compared to all other frames. Nearly 44.89% increases for SIM full infilled frame as compared to URM full infilled frame. In the case of open ground story frames, there is a variation of 4.5%. And for SIM side bay infilled frame has maximum ductility by 19.76% as compared to URM side bay infilled frame. The ductility reduction factor is higher in the bare frame as compared to all other frames. Nearly 29.49% increases for SIM full infilled frame as compared to URM full infilled frame. In the case of open ground story frames, there is a variation of 2.89%. And for SIM side bay infilled frame has a maximum ductility reduction factor by 13.07% as compared to the URM side bay infilled frame.

As per the Table 5, the ductility is higher in the bare frame as compared to all other frames. Nearly 36.60% increases for SIM full infilled frame as compared to the URM full infilled frame. In the case of open ground story frames, there is a variation of 12.23%. And for SIM side bay infilled frame has maximum ductility by 33.76% as compared to the URM side bay infilled frame. The ductility reduction factor is higher in the bare frame as compared to all other frames. Nearly 24.47% increases for SIM full infilled frame as compared to URM full infilled frame. In the case of open ground story frames, there is a variation of 7.83%. And for SIM side bay infilled frame has a maximum ductility reduction factor by 22.22% as compared to the URM side bay infilled frame.

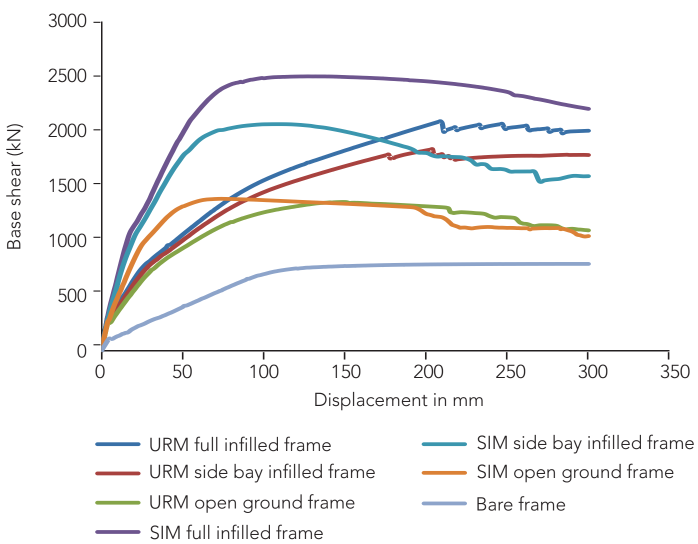


Figure 8: Comparison of pushover curves of 5 story-4 bay frame

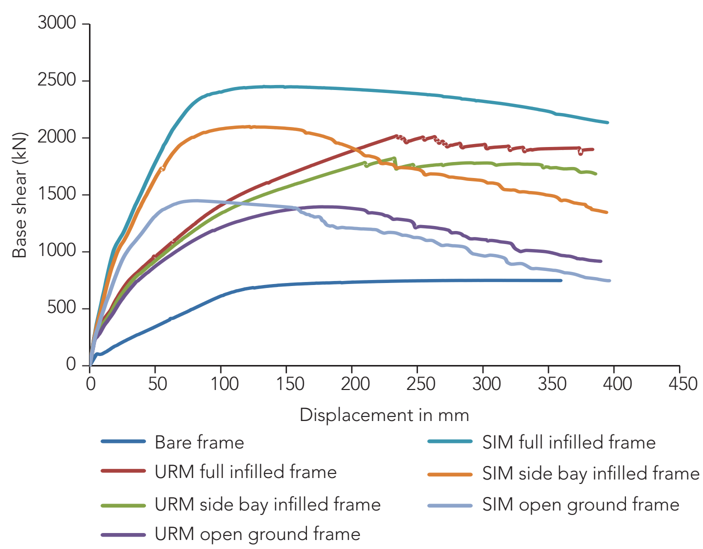


Figure 9: Comparison of pushover curves of 6 story-4 bay frame

Table 4: Various parameters from pushover curves of 4 story - 4 bay frame

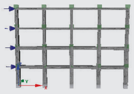
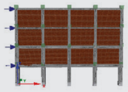
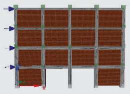
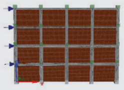
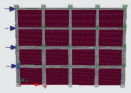
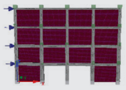
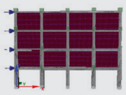
NAME	DIAGRAM	STRENGTH (kN)	YIELD DISPLACEMENT Δy (mm)	ULTIMATE DISPLACEMENT Δmax (mm)	DUCTILITY (Δmax/Δy)	R FACTOR Rμ × Ω = R
Bare frame		705.73	101.06	246	2.43	2.43 × 1.68 = 4.08
URM open ground RC frame		1302	67.73	136	2	1.73 × 3.10 = 5.36
URM (only side bay infilled at ground of RC frame)		1801.9	106.21	177	1.67	1.53 × 4.29 = 6.56
URM (Full infilled RC frame)		2176	135.36	199	1.47	1.39 × 5.18 = 7.20
SIM (Full infilled RC frame)		2528.70	52.69	112.5	2.13	1.80 × 6.02 = 10.84
SIM (only side bay infilled at ground of RC frame)		2024.50	44.8	90	2	1.73 × 4.82 = 8.34
SIM open ground RC frame		1317	33.46	70	2.09	1.78 × 3.14 = 5.59

Table 5: Various parameters from pushover curves of 5 story - 4 bay frame

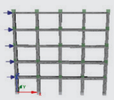
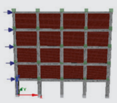
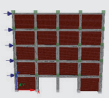
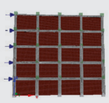
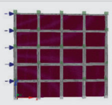
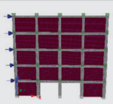
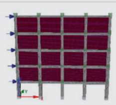
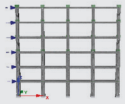
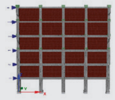
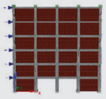
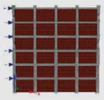
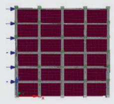
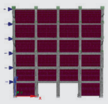
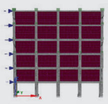
NAME	DIAGRAM	STRENGTH (kN)	YIELD DISPLACEMENT Δy (mm)	ULTIMATE DISPLACEMENT Δmax (mm)	DUCTILITY (Δmax/Δy)	R FACTOR Rμ × Ω = R
Bare frame		793.00	107.21	300	2.79	2.79 × 1.44 = 4.01
URM open ground RC frame		1357.5	79.06	149	1.88	1.66 × 2.47 = 4.10
URM (only side bay infilled at ground of RC frame)		1838.10	131.97	204	1.54	1.44 × 3.34 = 4.80
URM (Full infilled RC frame)		2093.30	136.46	209	1.53	1.43 × 3.80 = 5.43
SIM (Full infilled RC frame)		2502.00	61.13	128	2.09	1.78 × 4.55 = 8.10
SIM (only side bay infilled at ground of RC frame)		2066.70	52.49	108	2.06	1.76 × 3.76 = 6.62
SIM open ground RC frame		1386.30	35.01	74	2.11	1.79 × 2.52 = 4.51

Table 6: Various parameters from pushover curves of 6 story - 4bay frame

NAME	DIAGRAM	STRENGTH (kN)	YIELD DISPLACEMENT Δy (mm)	ULTIMATE DISPLACEMENT Δmax (mm)	DUCTILITY (Δmax/Δy)	R FACTOR Rμ × Ω = R
Bare frame		749.01	120.55	313.68	2.60	2.60 × 1.14 = 2.96
URM open ground RC frame		1395.30	95.57	177.71	1.86	1.65 × 2.13 = 3.51
URM (only side bay infilled at ground of RC frame)		1821.16	140.19	232.42	1.66	1.52 × 2.78 = 4.22
URM (Full infilled RC frame)		2017.39	155.86	234.31	1.50	1.41 × 3.08 = 4.34
SIM (Full infilled RC frame)		2451.93	69.97	132.92	1.90	1.67 × 3.74 = 6.24
SIM (only side bay infilled at ground of RC frame)		2099.55	62.38	122.05	1.96	1.71 × 3.20 = 5.48
SIM open ground RC frame		1448.70	45.69	81.58	1.79	1.60 × 2.21 = 3.54

As per the Table 6, the ductility is higher in the bare frame as compared to all other frames. Nearly 26.66% increases for SIM full infilled frame as compared to URM full infilled frame. In the case of open ground story frames, there is a variation of 3.9%. And for SIM side bay infilled frame has maximum ductility by 18.07% as compared to the URM side bay infilled frame. The ductility reduction factor is higher in the bare frame as compared to all other frames. Nearly 18.43% increases for SIM full infilled frame as compared to URM full infilled frame. In the case of open ground story frames, there is a variation of 3.12%. And for SIM side bay infilled frame has a maximum ductility reduction factor by 12.5% as compared to the URM side bay infilled frame.

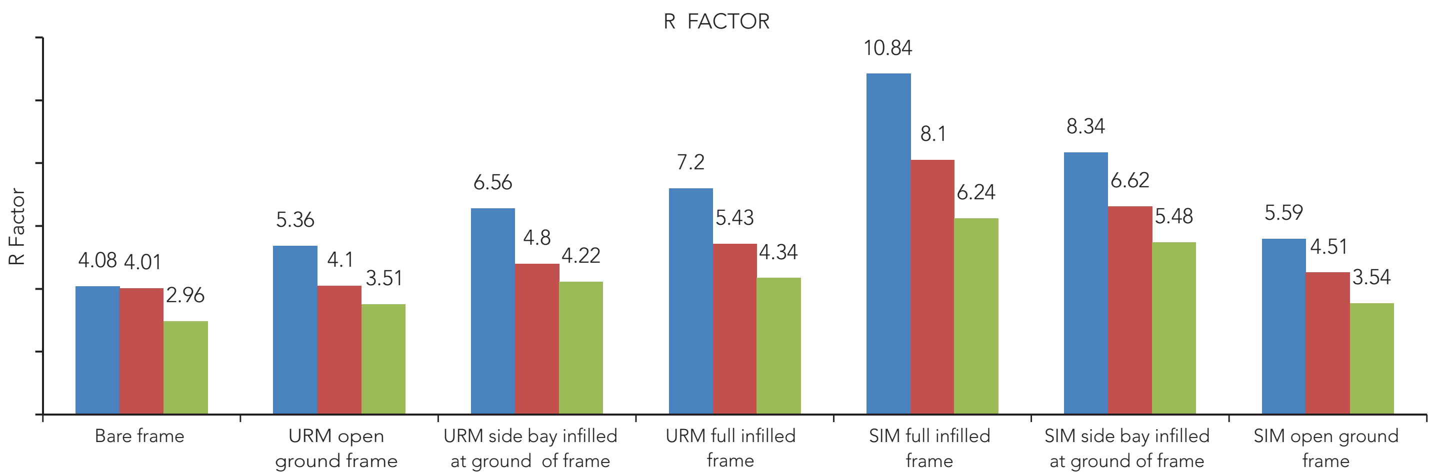


Figure 10: R-factor of different frames for different aspect ratio

As per the Figure 10, the response reduction factor is minimum for the bare frame as compared to all other frames. R factor is nearly 25.27% decreases when 4 story - 4 bay frame converted to 5 story - 4 bay frame for SIM full infilled frame and 22.96% decreases when 5 story-4 bay frame converted to 6 story -4 bay frame. In the case of open ground story frames, there is a small variation when the aspect ratio changes. And the R-factor changes averagely by 18.92% for SIM side bay infilled frame when the aspect ratio of the frame changes.

6. CONCLUSIONS

After the interpretation of analytical results and comparison of values, the conclusions drawn from this study are as summarized below:

1. The base shear value is largest in the SIM infilled frame as compared to the URM infilled frame.
2. Ductility is higher in the bare frame compared to all infilled frames because there is no infill in the frame so it allows for maximum drift.
3. The over-strength factor depends on infill in the frame so over-strength factor increase as the frame is infilled with SIM and URM.
4. The response reduction factor of SIM infilled frame is higher than URM infilled frame because SIM panels have significant energy dissipation capacity due to friction between the masonry units.
5. As per the study, R factor is sensitive to both material and geometric configuration.
6. The values of Response reduction factor decreases with the increase in the number of storys, because of the increase in flexibility of structures.
7. In different aspect ratio of frames on an averagely, the R factor increases by 47.83% for SIM full infilled frames as compared to URM full infilled frames. In the case of open ground story frames, there is an average variation of 5.04% in the R factor. And for SIM side bay infilled frames have R factor which increases averagely by 31.63% as compared to URM side bay infilled frames.

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