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SEISMIC RESPONSE ASSESSMENT OF RC FRAME-SHEAR WALL BUILDINGS WITH VERTICAL SETBACK IRREGULARITIES

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ABSTRACT

Shear walls integrated with conventional moment-resisting frames are used as an effective means of enhancing lateral resistance against wind or earthquake actions. While the strategic placement of these shear walls is one of the major issues concerning their effectiveness, vertical discontinuities are often overlooked due to functional, aesthetic, or economic reasons. The structural efficiency of a framing system is also intrinsically governed by geometric regularity, as discontinuities along the vertical profile may disrupt the distribution of seismic forces and magnify overall structural responses. In this regard, the current study conducts an analysis to assess the seismic responses of medium-rise, RC dual-frame buildings with vertical setback irregularities. Nonlinear response history analyses were performed using eleven ground motion records compatible with the design spectrum. Nonlinear static analyses were also performed to develop the force-displacement capacity curve of the frames. Finally, structural responses were assessed and compared for the roof displacement, story drift ratio (SDR), peak floor acceleration (PFA), etc. The result reveals that vertical setback significantly increases the influence of higher modes in RC dual-frame buildings. Setback configurations caused reduced drift ratio at mid-height and localized drift amplification at upper stories where geometric irregularities are introduced. In addition, inclusion of setback irregularity substantially amplified the PFA from 34% to 42%. A pushover capacity comparison indicates a 5% to 10% reduction in frame capacity with multiple setbacks. These findings underscore the influence of vertical setback on a better understanding of the seismic behaviour of vertically irregular RC frame-shear wall buildings.

Keywords: *RC dual-frame, vertical irregularity, nonlinear time history analysis, seismic performance*

1. INTRODUCTION

Reinforced concrete (RC) frame shear walls are the most commonly used lateral load-resisting system for mid to high-rise buildings. An RC frame shear wall building (dual-frame system) is in the structural system, where the frame resists at least 25% of the lateral load (HBRI, 2020). The capability of this system to resist lateral loads like earthquakes is widely explored in the scientific community. Due to aesthetic reasons, for use purposes, or other functional requirements, irregularities are introduced in buildings, including RC frame shear wall buildings, which may result in higher responses leading to increased vulnerability. These effects can be observed in the floor response, floor acceleration, inter-story drift as well as in the spectral acceleration (Blasi et al., 2024) and other responses of the building.

Vertical setback is a very common geometric irregularity nowadays in buildings. Various building codes define different threshold values for vertical setback as a ratio of the horizontal dimension of the lateral load-resisting system on any floor to the dimensions of the adjacent floor. This value is 0.23, 0.25 and 0.20 in the US, Chinese and Euro codes, respectively. Figure 1 shows the setback dimensions that result in vertical geometric irregularity, as mentioned in the Bangladesh National Building Code, BNBC 2020 (HBRI, 2020).

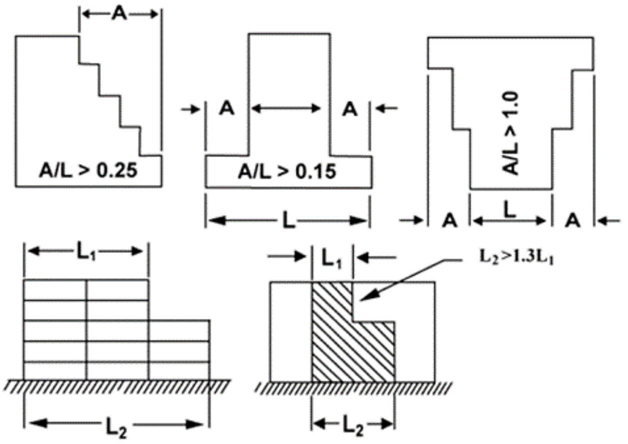


Figure 1: Vertical geometric irregularity (HBRI, 2020)

Irregularities used in buildings for architectural aesthetic or purposes are of great concern due to their effects, especially their dynamic characteristics. The existence of a vertical setback leads to increased inter-story drift at the location of the setback in a building, resulting from the reduced lateral stiffness at that position (Jiang et al., 2021). RC Frames with setbacks experience greater acceleration amplification under ground excitation compared to uniform frames (Wood, 1992). The presence of irregularity can also exceed the design limit state assumption for the plastic rotation demand, which may lead to earlier collapse of the code-based designed structure (Giannakouras & Zeris, 2019). A comparative study (Benaied et al., 2023) showed a higher seismic response for the buildings with stiffness irregularity. A study of 2D steel moment frames with setback showed that the location and degree of setback play a crucial role in the dynamic characteristics. The natural period of buildings decreases with increasing degree of setbacks. The combination of different vertical irregularities leads to less seismic capacity and higher seismic demand, which affects their performance. This signifies the necessity of extra care during the design of buildings with such irregularities (Ahmed et al., 2021).

Given the significance of the effects of vertical setback on the seismic response of buildings, this study aims to evaluate the seismic performance of 2D mid-rise RC frame-shear wall structures using non-linear time history analysis (NTHA) and also nonlinear static pushover analysis. Five 8-storied frames with 5 spans and different setback configuration were considered in this study. The seismic responses, including interstorey drift ratio, floor acceleration, base shear, as well as the capacity curves of the irregular frames, were compared with the regular frames for the comparative performance assessment.

2. METHODOLOGY

2.1 Building Information and Modelling Approach

Five 8-story (structural height H = 25.6 m) RC dual-frame buildings, consisting of a concrete moment-resisting frame and peripheral shear walls, were selected to compare the seismic responses of the typical mid-rise residential buildings due to vertical setback irregularities. Among the five, there were four models (A2, A3, A4, A5), except one (A1), that were buildings having different configurations of setback irregularities with setback ratios of 0.2, 0.4, 0.2 and 0.4, respectively. Figure 2 illustrates the elevation and aerial views of these buildings. Figure 3 shows the geometrical dimensions and longitudinal reinforcement ratios of the members. A numerical 3D model for each of these buildings was developed and equivalent static analysis (ESA) was performed following BNBC 2020 to finalize the design sections of the structural system, as well as to ensure the dual system criterion.

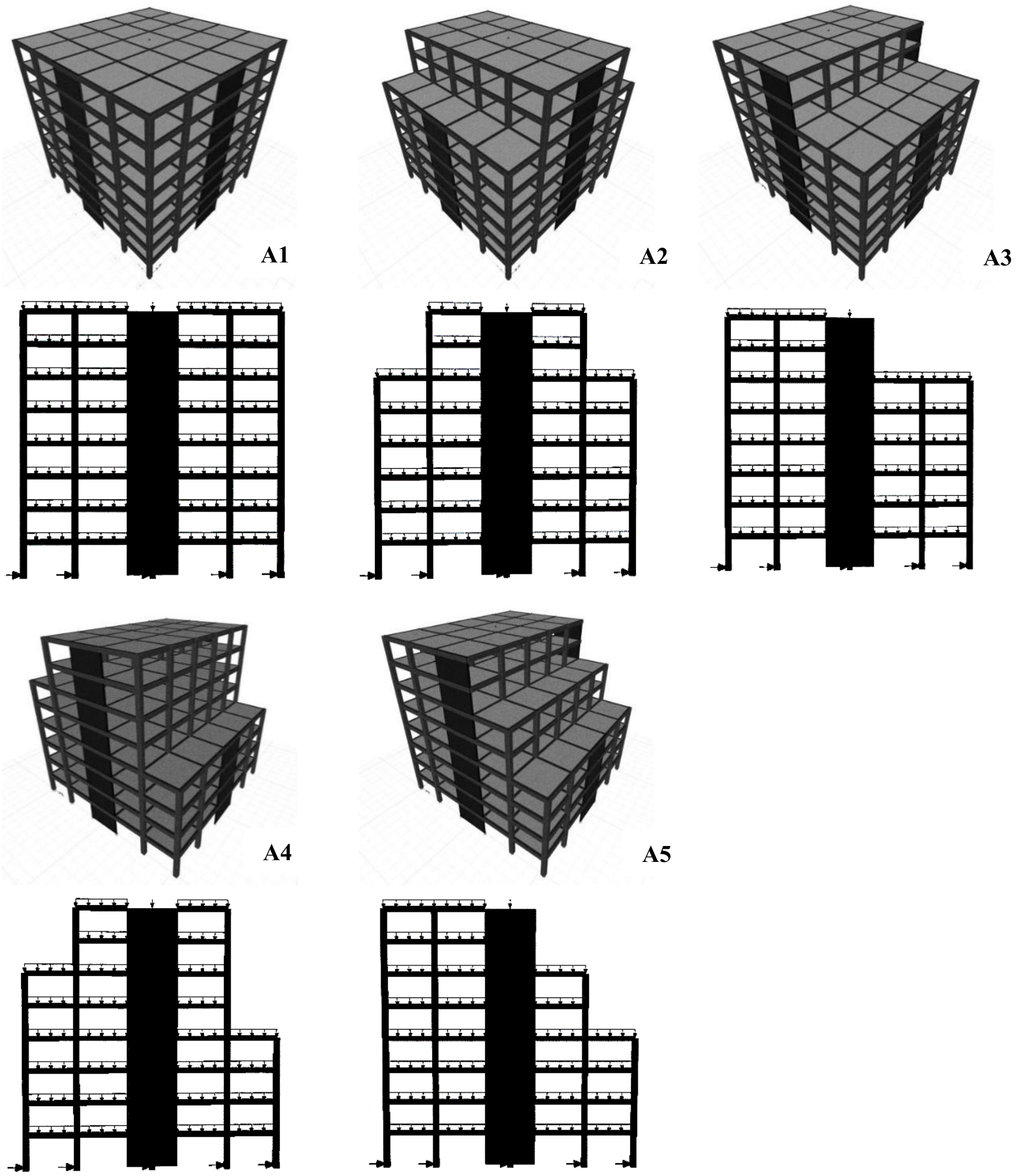


Figure 2: 3D view and elevation of RC dual-frame buildings with and without setbacks

The 2D models of the outer frame-shear wall of the buildings were developed in SeismoStruct for the purpose of nonlinear time history analysis (NTHA). Mander's model and Menegotto-Pinto models were used to simulate the nonlinear material behaviors of 28 MPa concrete and 420 MPa rebar, respectively. The seismic weight was determined considering a concrete density equal to 24 KN/m^3. Superimposed dead loads and live loads were applied based on the BNBC 2020 design code, as tabulated in Table 1. It is noteworthy that, in the 3D models, all the superimposed loads were either distributed area loads on slabs and distributed line loads on beams. At the same time, the 2D models employed a load combination of 1.0D + 0.25L as per ASCE 7-10 (ASCE, 2010)for axial loads on columns and shear walls and distributed loads on beams estimated by means of tributary area considerations.

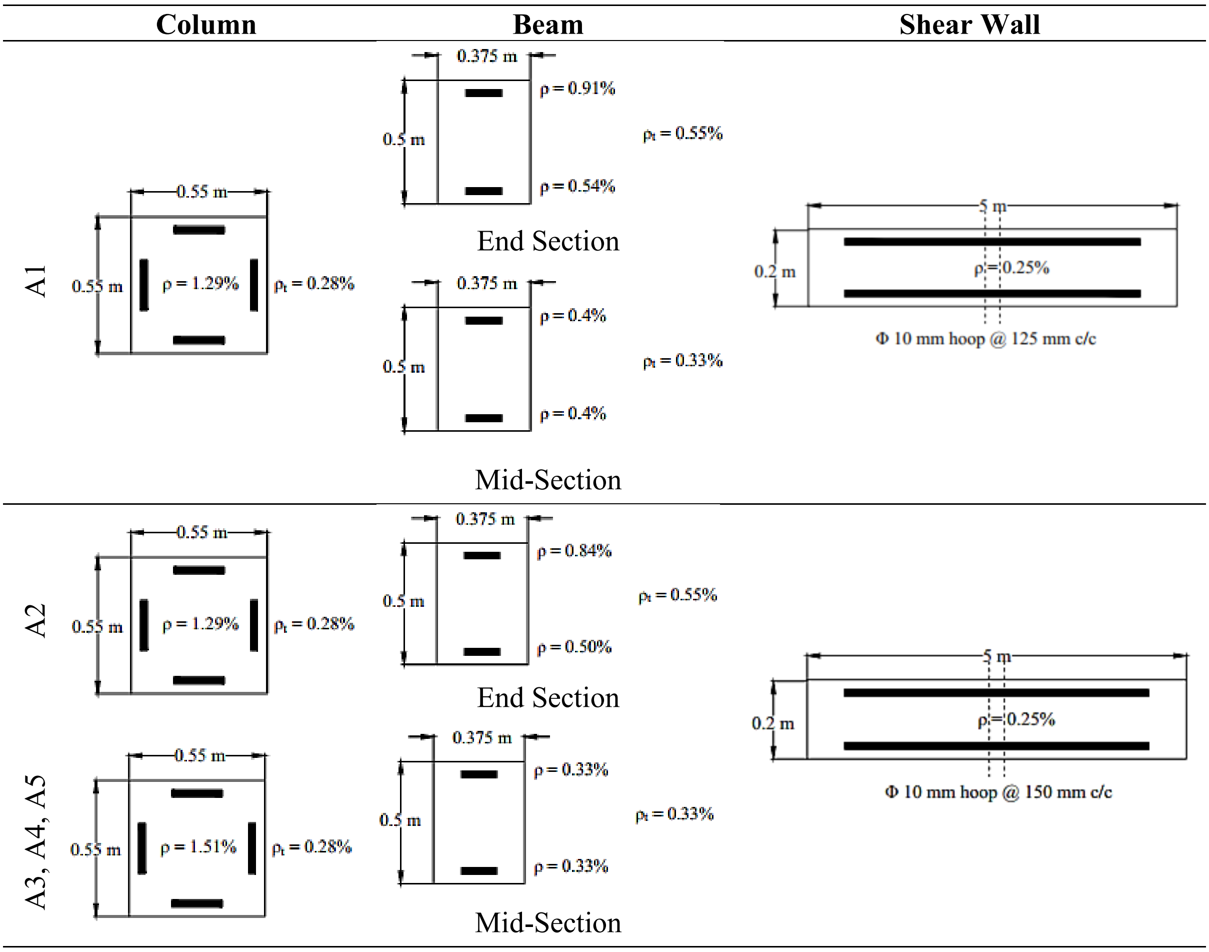


Figure 3: Element section and reinforcement details

Table 1: Applied loads as per BNBC 2020

Description	Unit	Roof [setback]	Residential Floor
Live Load	KN/m^2	1 [4.8]	2
Roof / Floor Finish	KN/m^2	1.13	0.5
Partition Wall	KN/m	-	4.8

2.2 Ground Motion Selection

Due to the significant randomness involved in the ground motion (GM) records, structural responses may vary significantly from the results of the time history analyses. To achieve acceptable responses with reliable confidence while maintaining the inherent randomness, a minimum of 11 acceleration time history records is suggested for nonlinear time history analysis according to ASCE 7-16 (ASCE, 2016). Thus, a suite of eleven ground motion records was selected from the Pacific Earthquake Engineering Research (PEER) NGA-West2 ground motion database (Ancheta et al., 2013). Ground motions were selected in such a way that the mean spectra represent the design target spectra for earthquakes with a 475-year return period for SC soil with seismic zone coefficient Z = 0.28 (MCE level) in Chattogram, Bangladesh. It is to be noted that only one horizontal direction was considered for GM data selection. For seismic response history procedures, earthquake data were scaled to the spectral level within the period range of 0.2T and 1.5T, where T is the fundamental period of the building as per various guidelines. The detailed information about the ground motion records is described in Table 2 and the corresponding acceleration spectrums, with a 5% damping ratio, are shown in Figure 4.

Table 2: Information of Ground Motion Records

ID	RSN	Event	Year	M_w	Fault	Scale Factor	Unscaled PGA (g)	Scaled PGA (g)
1	578	Taiwan SMART1(45)	1986	7.3	Reverse	0.98	0.160	0.157
2	580	Taiwan SMART1(45)	1986	7.3	Reverse	1.18	0.171	0.202
3	988	Northridge-01	1994	6.69	Reverse	1.11	0.256	0.284
4	1003	Northridge-01	1994	6.69	Reverse	0.84	0.468	0.393
5	1048	Northridge-01	1994	6.69	Reverse	0.78	0.341	0.266
6	1082	Northridge-01	1994	6.69	Reverse	0.96	0.277	0.266
7	3680	Taiwan SMART1(45)	1986	7.3	Reverse	1.28	0.117	0.150
8	4849	Chuetsu-oki_Japan	2007	6.8	Reverse	0.9	0.253	0.228
9	4860	Chuetsu-oki_Japan	2007	6.8	Reverse	0.88	0.323	0.284
10	4866	Chuetsu-oki_Japan	2007	6.8	Reverse	0.92	0.357	0.328
11	5814	Iwate_Japan	2008	6.9	Reverse	0.84	0.236	0.199

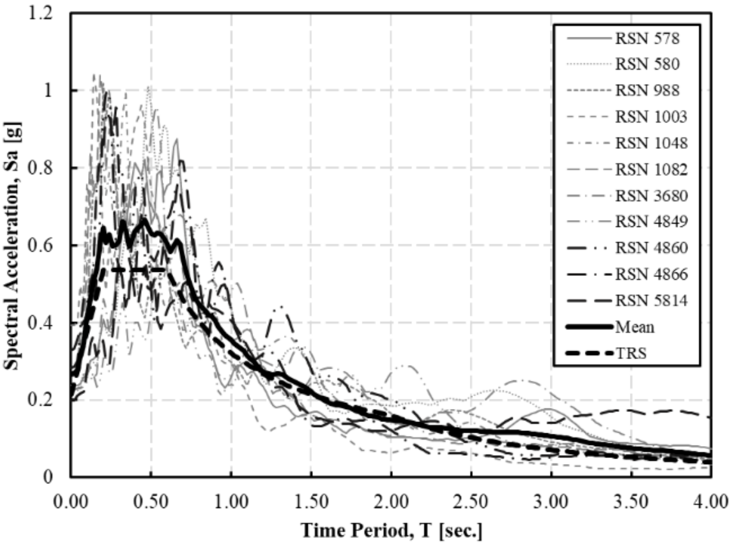


Figure 4: Acceleration Spectrum of the Selected Ground Motions

3. RESULTS

3.1 Frame and Wall Contribution in Lateral Load Resistance

In RC dual-frame systems, shear walls are typically stiffer and stronger than the frame counterpart, and they resist a significant portion of the total base shear. For frames to be considered dual frames, the moment resisting frames must resist at least 25% of the total lateral loads or base shear. This criterion was ensured during the equivalent static analysis of the 3D model in ETABS. Table 3 shows the summarized data of the base shear carried by frames and walls.

Table 3: Contribution to resisting base shear in dual frame

ID	Total Base Shear (KN)	Wall Contribution (KN) [%]	Frame Contribution (KN) [%]
A1	4093.38	2984.10 [72.90]	1109.29 [27.10]
A2	3940.73	2874.75 [72.95]	1065.98 [27.05]
A3	3734.85	2727.22 [73.02]	1007.63 [26.98]
A4	3940.73	2877.00 [73.01]	1063.73 [26.99]
A5	3734.85	2726.69 [73.01]	1008.16 [26.99]

3.2 Dynamic Characteristics of Dual-frame

The dynamic characteristics of both 3D and 2D model of 8-story regular RC dual frames and dual frames with vertical setback irregularity, with their corresponding modal time period (T_n) and modal mass participation ratio (α_n) for the first three fundamental periods, are presented in Table 4. It can be observed that the fundamental time period decreased for the buildings with setbacks compared to buildings without setbacks. This trend was slightly higher for buildings with setbacks on both sides (A2 and A4) compared to the buildings with setbacks on one side of the building (A3 and A5). Besides this, an additional setback in the building (A4, A5) further reduced the modal time period due to the reduction of mass content as well as a decrease in relative stiffness at the top levels compared to the lower levels. A similar trend was also visible for the effective mass participation ratio. One notable thing is that in the 3D model of the RC dual frame buildings, the effective modal mass participation ratio of the first mode governs in the case of the regular building, while the effective modal mass participation ratio of the second mode governs for the buildings with vertical setback irregularity.

Table 4: Modal time period and effective mass participation ratios for RC dual buildings [frames]

ID	T_1(s)	T_2(s)	T_3(s)	α_1	α_2	α_3
A1	1.334 [0.446]	1.334 [0.109]	1.000 [0.074]	0.731 [0.706]	0.001 [0.155]	0.0 [0.0]
A2	1.233 [0.394]	1.209 [0.103]	0.856 [0.069]	0.000 [0.691]	0.717 [0.159]	0.0 [0.0]
A3	1.232 [0.405]	1.217 [0.105]	0.865 [0.073]	0.000 [0.683]	0.714 [0.166]	0.0 [0.0]
A4	1.222 [0.384]	1.180 [0.102]	0.826 [0.068]	0.000 [0.668]	0.698 [0.177]	0.0 [0.0]
A5	1.223 [0.394]	1.192 [0.104]	0.821 [0.073]	0.000 [0.660]	0.694 [0.184]	0.0 [0.0]

N.B. The time period and the effective mass participation ratio of the 2D frames are shown in brackets

3.3 Story Drift Ratio

Inter-story drift ratio (IDR) is an accepted demand parameter related to seismic damage. Figure 5 illustrates the IDR for the frames for all records, as well as the mean IDR. Apparently, the regular frame model A1 had shown comparatively higher IDR than the models with setback irregularities, primarily due to larger effective seismic mass. However, localized amplification of IDR was observed at the top stories due to the setbacks at the top two floors for cases A2 and A3, compared to the building frame without setback irregularity. Similar phenomena at setback locations have been consistently reported in earlier studies on a 20-story 3D RC frame shear wall building, where the demand is more pronounced due to building height. Furthermore, introducing two additional setback floors for cases A4 and A5 escalated the IDR demand at the top floors. This also aligns with the findings of (Jiang et al., 2021) with a different setback configuration.

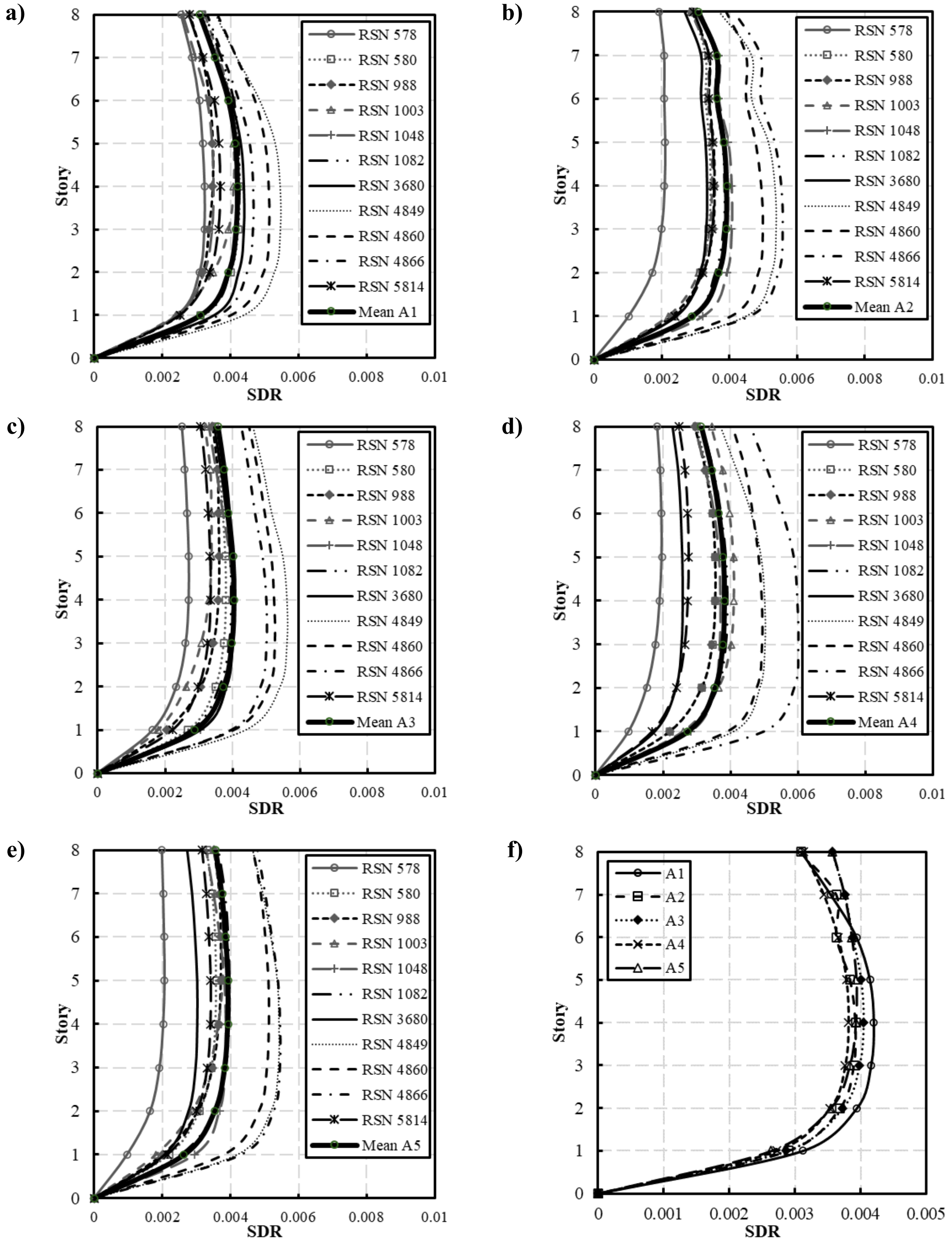


Figure 5: Inter-story drift ratio for the buildings- a) A1, b) A2, c) A3, d) A4, e) A5, f) Mean

3.4Floor Acceleration

Floor acceleration is an important demand parameter for non-structural components. Figure 6 shows the floor acceleration of the RC dual frames. The presence of the setback led to floor acceleration increased by 37.84%, 36.42%, 34.15% and 42.12% respectively, for A2, A3, A4 and A5, due to the higher flexibility of upper floors compared to frames without setback (A1). Furthermore, when the number of setback stories was increased, the floor acceleration value for A4 decreased compared to A2, while it showed the opposite trend for A5 with respect to A3. Though there is no related study associated with the peak floor acceleration response (PFA) for the frame shear wall structure. Although this trend aligns with findings reported by (Blasi et al., 2024) who demonstrated the influence of vertical setback in RC moment-resisting frames, intensifying floor acceleration demand in the stories above the setback due to stiffness and mass discontinuities.

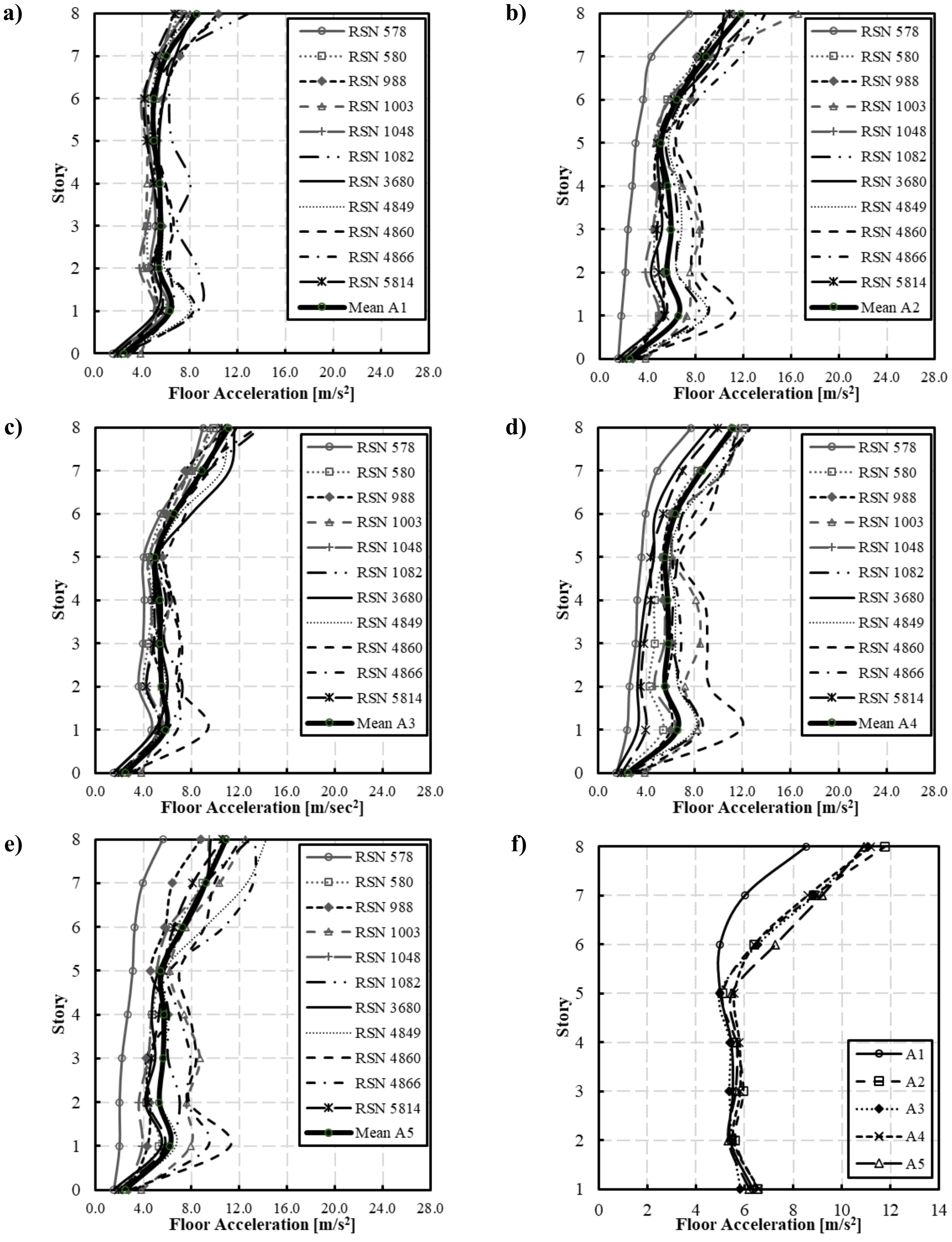
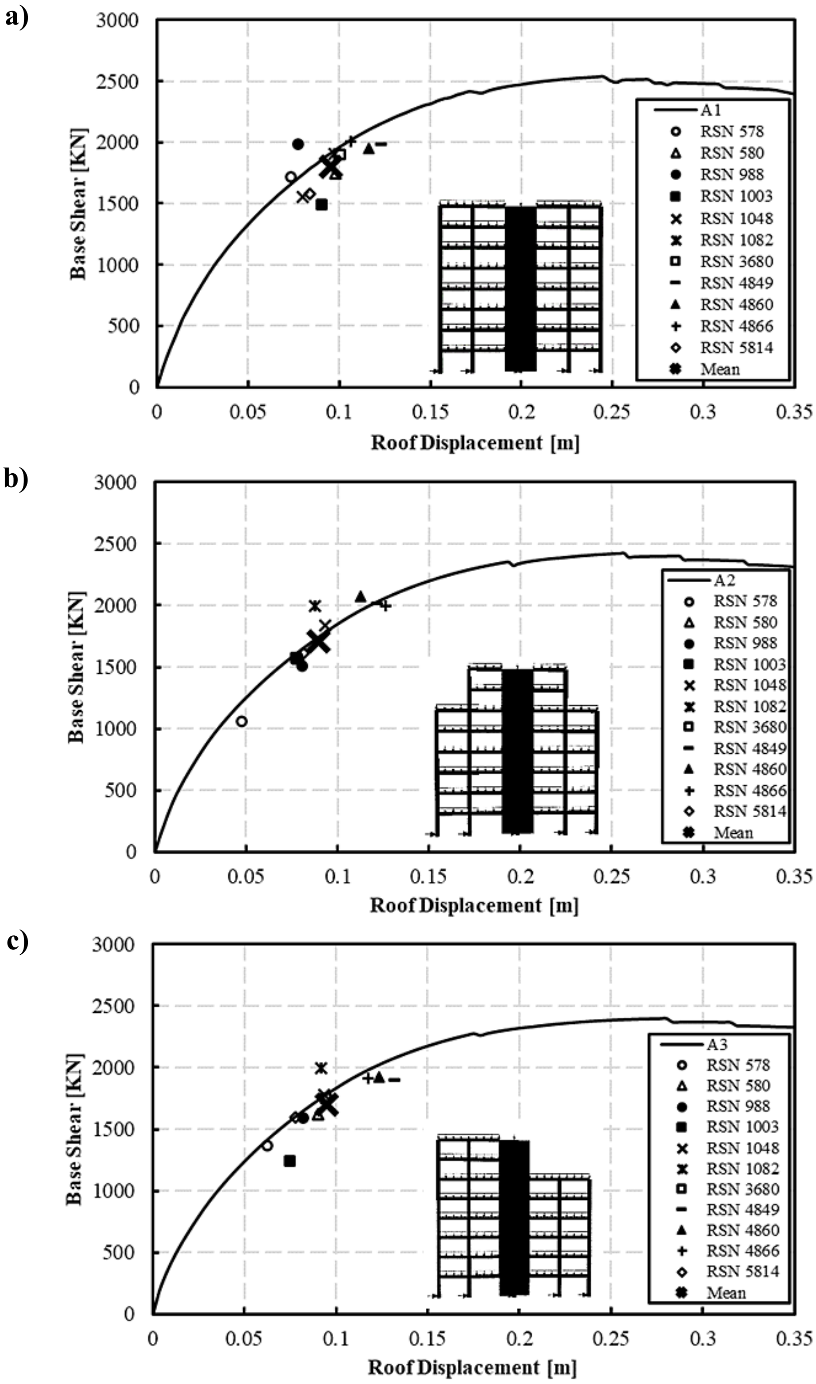


Figure 6: Floor acceleration for the RC dual frames- a) A1, b) A2, c) A3, d) A4, e) A5, f) Mean

3.5 Lateral Load Resisting Capacity

Capacity curves (base shear vs roof displacement) were developed for all the models through nonlinear static (pushover) analysis. Figure 7 illustrates the capacity curve along with the responses for the same (base shear and roof displacement) from the NTHA. From Figure 7, it can be observed that the capacity roof displacement was rarely attained during NTHA, while higher base shears were seen to develop within the frames as the setback irregularity was introduced. This was more pronounced for dual frames with setbacks on both sides (A2, A4). It was also noticeable that, with the increase of setback stories, though the base shear decreases due to reduced loading, the probability of NTHA base shear exceeding the designed capacity was higher. Moreover, the pushover capacity for setback irregular RC frame wall building shows a progressive reduction of 5.1%, 5.8%, 5.7%, and 10.7%, for the cases A2, A3, A4 and A5 respectively, due to reduced lateral stiffness at the setback floors.



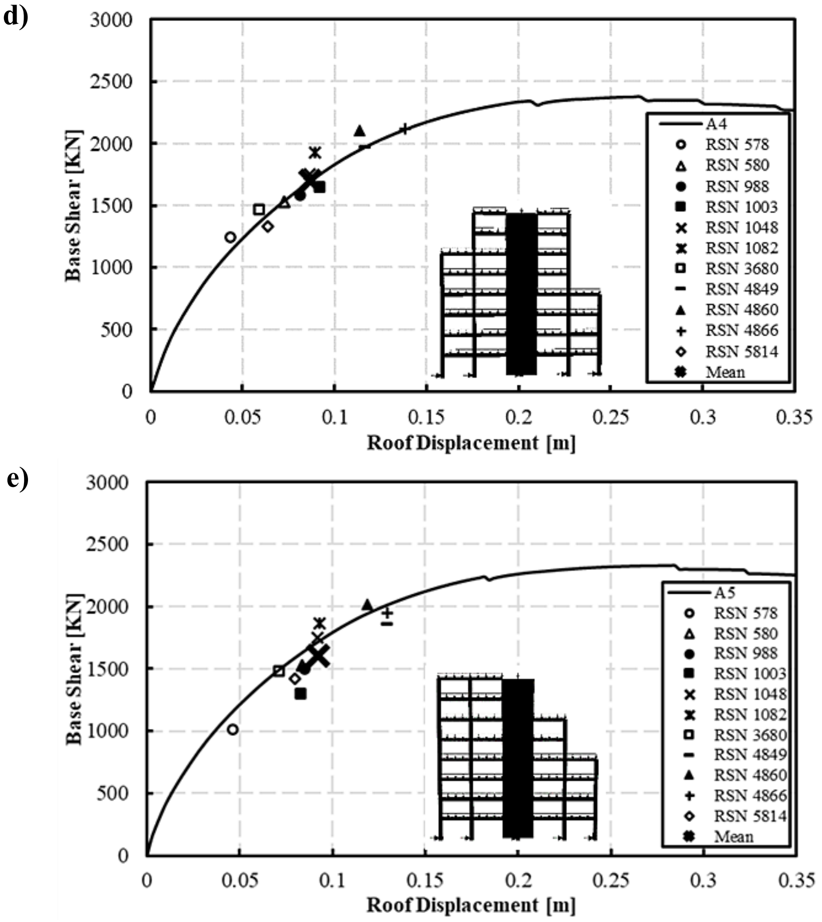


Figure 7: Capacity curves and the NTHA peak base shear and roof displacement

4. CONCLUSIONS

The objective of this study is to evaluate the seismic performance of the typical mid-rise RC dual-frame residential building due to the presence of vertical geometric/setback irregularity. Four-archetype irregular RC dual frame buildings, along with one regular building, are considered. In this regard, pushover analyses were performed to develop the capacity curve of the considered models. Nonlinear time history analyses were also performed using eleven (11) earthquake ground motion records compatible with the design acceleration spectra and also the seismic fault scenario of the location. For the studied cases, the following points can be concluded as follows:

- The fundamental time period, as well as the effective modal mass participation for the RC dual-frame building, shows a declining trend with the increase of vertical geometric irregularity/setback compared to the regular RC dual frame.
- Despite the inter-story drift ratio (IDR) seeming to decrease at the mid-height of the irregular frames, a slight increase in demand is observed at the top floors compared to the regular frame. The reduction in floor mass at the setbacks produces lower displacement, leading to lower drift. However, the similarity in floors above setbacks again introduces a comparable mass of adjacent floors, which leads to a slight increase in IDR at the top floors.
- For the structural models A2, A3, A4 and A5, the effect caused by the vertical setback irregularity is more significant for floor acceleration demand. Its presence leads to an increase of 37.84%, 36.24%, 34.15% and 42.12% in the floor acceleration, respectively for the four models, due to the higher flexibility of upper floors. This further strengthens the necessity to

check the floor acceleration for irregular buildings to ensure better safety, especially for non-structural components.

- The influence of setback on the overall lateral capacity of the structure is not significant, specifically 5-10% less compared to the regular frame wall building. However, with the vertical setbacks, the RC-wall frames tend to exceed their capacity, as evident from the comparison of the pushover curve and responses obtained from NTHA. The location of setbacks and the height of setbacks influence this phenomenon.

It has been observed that the increase in the number of locations of setback is found to increase the structural response and demand of the structure. Also, the greater the height of the setback from the ground level, the more profound this phenomenon. The findings highlight the importance of special design consideration for RC dual frame buildings with setback irregularities, with special attention to the proper location selection for the introduction of the setback in buildings.

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