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Impact of irregular masonry infill walls on the seismic response of reinforced concrete frame buildings using linear dynamic analysis

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ABSTRACT

This paper aimed to investigate the seismic response of reinforced concrete (RC) frame buildings using linear dynamic analysis. The study focused on the effects of irregular distributions of masonry infill walls both in elevation (soft story at different levels) and in horizontal (plan) distribution on seismic behavior. Seventeen models were analyzed, including infill frame models with soft stories, models with infill panels only in certain bays, and bare frame models. All models were analyzed using the linear response spectrum (RS) dynamic analysis method. Structural design typically focuses on peak response values, and response spectrum analysis examines the structure's behavior and performance through these peak values. The analysis results indicate that masonry infill walls significantly affect the building's fundamental time period, base shear, story shear, and inter-story drift.

1. Introduction

The recent 6.4 magnitude earthquake in Jajarkot, Nepal, caused 153 deaths and 364 injuries in Jajarkot and Rukum West districts. Nepal's seismic history, dating back to 1255 AD, underscores the region's vulnerability to earthquakes, and the region's seismic record illustrates its frequent and severe earthquake activity. The 1934 Nepal-Bihar Earthquake, measuring 8.3, caused extensive damage and around 8,500 fatalities. Similarly, the 2015 Gorkha earthquake, magnitude 7.8, triggered numerous aftershocks until 2018, emphasizing Nepal's seismic vulnerability. Three aftershocks surpassed magnitude 6.0, with one reaching 7.3 on the Moment Magnitude Scale(Mw), according to USGS (Martin et al., 2015)

Nepal lies within the Himalayan range, formed by the ongoing collision of the Indian and Eurasian tectonic plates, advancing at a rate of 40-50 mm/year, as per the US Geological Survey (USGS) (Martin et al., 2015). The continuous collision between the Indian and Eurasian tectonic plates generates significant stress along plate boundaries. Eventually, this stress exceeds plate strength, leading to the release of seismic waves. Nepal, situated in this tectonically active region, faces frequent earthquakes, rendering it one of the most seismically hazardous areas worldwide. Due to ongoing tectonic plate movement, Nepal is poised to encounter significant earthquakes, potentially surpassing previous magnitudes. While total elimination of the earthquake hazard may be unattainable, enhancing structural safety and reducing vulnerability are paramount. This entails enforcing earthquake-resistant building codes, fostering earthquake preparedness awareness, and investing in resilient infrastructure. Such measures are essential for mitigating the impact of seismic events on communities and infrastructure in Nepal, ensuring greater resilience and safeguarding lives and property against future earthquakes.

Pradhan et al. (2017) studied how partial infill walls affect reinforced concrete (RC) frames when subjected to lateral forces. They used scaled-down models of single-story, single-bay RC frames, reduced to one-third of the original size, to observe the differences between frames with and without infill walls. While both types of frames primarily failed at the joints, the frames with partial infill walls also showed column failure at the points where the infill walls ended, similar to cantilever walls due to the short column effect. The study highlights the significant role that infill walls play in the structural

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behavior of RC frames, stressing the need to account for these effects in design and analysis to improve safety and performance during earthquakes.

Zovkic et al. (2013) conducted cyclic loading tests on ten masonry-infilled RC frames, each representing a one-bay one-story configuration and scaled at 1/2.5 following EC-8 standards. Various types of masonry infills were considered. Results indicated that the structure exhibited monolithic behavior up to a drift of 0.1%, reaching maximum capacity at 0.3% drift and sustaining it until approximately 0.75% drift. Beyond this, the structural behavior became primarily influenced by the frame alone. Minor damage was observed in the frame at a 1% drift, but it endured up to around 2% drift without any loss of capacity. These findings underscore the effectiveness of masonry infills in enhancing the structural performance of RC frames under cyclic loading conditions, with the frame demonstrating resilience and capacity to withstand significant drifts without catastrophic failure.

Kaushik et al. (2006) undertook a thorough review of seismic design codes regarding infilled RC frames, comparing seventeen national codes. They identified critical issues like natural period, irregularities, response reduction factors, and infill strength. The study highlighted shortcomings in these codes and suggested areas for future research on Masonry Infill RC frames. This comprehensive analysis emphasized the necessity for a unified model code that integrates these factors to enhance seismic performance and ensure structural safety in seismic zones. By addressing these deficiencies, the construction industry can advance towards more resilient and earthquake-resistant structures, reducing the risk of damage and loss during seismic events.

Studies by Chaulagain et al. (2013), Dilmac et al. (2018), Mouzzoun and Cherrabi (2019), and Patankar and Joshi (2021) show positive effects of infill on RCC structures Studies by Chandel and Yamini Sreevalli (2019), Di Trapani et al. (2018), Jalaeefar and Zargar (2020), Mulgund and Kulkarni (2011), and Shah et al. (2021) emphasized the importance of considering masonry infill in RC frame analysis and design. Recent research by Abdelaziz et al. (2019), Elmalyh et al. (2018), Ko et al. (2014), and Misir et al. (2012) confirmed the significant impact of infills on structural behavior, whether positive or negative. These findings highlight the necessity of incorporating infill effects into structural assessments to ensure accurate and reliable analysis and design of RC frame buildings.

Masonry infills are often treated as nonstructural elements during structural analysis, with only their dead load considered. However, they significantly influence a structure's behavior and response, whether full, partial, or open. Hence, it's crucial to incorporate infill action in assessing RC frame structures' seismic behavior. Numerous studies have explored infill wall behavior, yet no definitive solution has emerged. Therefore, it's imperative to comprehensively study infill action on structures and compare responses with and without masonry infill. Such investigations can provide valuable insights for developing more accurate and effective seismic design methodologies, ensuring structures are adequately resilient against seismic forces while optimizing construction costs and efficiency.

The significance of this research lies in its investigation of the seismic behavior of infilled frames, particularly in terms of quantifying the influence of various masonry types and openings. While prior studies have extensively investigated the cyclic loading of infilled frames, there has been a notable lack of research focusing on the specific effects of different masonry compositions and types of openings.

To address this gap, this study conducted tests on 17 infilled frames featuring two distinct masonry types and a range of different openings. By doing so, it aimed to provide empirical data that could clarify how these factors impact the seismic performance of infilled frames.

Overall, this research contributes to the field of earthquake engineering by offering valuable insights into the behavior of infilled frames, which can eventually inform the design and construction of more resilient structures in regions prone to seismic activity.

2. Analytical modeling

2.1. General

A parametric study was conducted to analyze the seismic response of a four-story reinforced concrete moment-resisting frame building, typical of structures in Nepal. The building, comprising three bays, each 4 meters wide, spans a total width of 12 meters with a consistent floor height of 3 meters across all levels. The study evaluates the impact of infill walls and their irregular distribution on the building's seismic behavior. Through two-dimensional modeling, various scenarios are explored to understand how factors such as wall presence and placement affect structural response to seismic forces. This investigation aids in enhancing understanding of seismic vulnerability and informs strategies for improving the seismic resilience of multi-story reinforced concrete frame buildings in seismic-prone regions like Nepal. Seventeen building models were meticulously developed to scrutinize the effect of infill distribution on structural behavior. These models encompass diverse infill placements, spanning combinations of distributions to gauge their impact. The models are classified into bare frame, fully infilled, partially infilled with vertical continuity, and partially infilled with horizontal continuity. Analysis was conducted using SAP 2000, chosen for its adeptness in macro-modeling and parametric studies. Key modeling parameters, integral to the investigation, are detailed in subsequent sections, ensuring a comprehensive exploration of seismic response in multi-story reinforced concrete frame buildings.

2.2. Material modeling

2.2.1. Concrete

Table 1 shows the properties of concrete used for research. Table 1 outlines material properties for Grade M20 concrete (Indian Standard IS:456 for plain and reinforced concrete code of practice) used in structural modeling. It includes a density of 25 kN/m^3, modulus of elasticity (E) at 22360 N/mm^2, Poisson's ratio (ν) of 0.15, and characteristic strength (fck) of 20 N/mm^2. These parameters are crucial for accurately simulating behavior in finite element analysis software like SAP 2000.

Table 1: Concrete elastic material properties

Parameter	Value
Grade	M20
Density	25 KN/m^3
Modulus of elasticity (E)	22360 N/mm^2
Poisson's ratio (ν)	0.15
Characteristic strength (fck)	20 N/mm^2

The concrete properties post-yielding is characterized by the plasticity of nonlinear hinges. Columns are assigned interacting P-M2-M3 hinges, while beam sections are designated M3 hinges. Default hinge properties from FEMA 356 are employed in SAP 2000 to define the moment-curvature curve at the concentrated hinge. (FEMA, 2000)

2.2.2. Steel rebar

Properties of rebar used for modeling have been shown in Table 2. Table 2 presents the material properties of Grade Fe 415 steel, which is essential for structural analysis. It includes a density of 76.98 kN/m^3, modulus of elasticity (E) at 200,000 N/mm^2, Poisson's ratio (ν) of 0.3, and yield stress (fy) of 415 N/mm^2. These parameters are crucial for accurately simulating the behavior of steel elements in structural modeling and analysis, aiding in the assessment of the building's response to various loads and conditions.

Table 2: Properties of rebar

Parameter	Value
Grade	Fe 415
Density	76.98 KN/m^3
Modulus of elasticity (E)	200000 N/mm^2
Poisson's ratio (ν)	0.3
Yield stress (fy)	415 N/mm^2

2.2.3. Masonry infill

Masonry infills are modeled as compression-only single equivalent struts with pins joined to frame structures. The strut width is computed as given by Paulay and Priestley (1992) as it is the simplest and gives the average value of strut width considered by the different researchers. The size of the Equivalent infill strut is

$$w = 0.25 \times d_{inf}$$

where, d_{inf} is the diagonal length of the infill.

2.3. Section properties

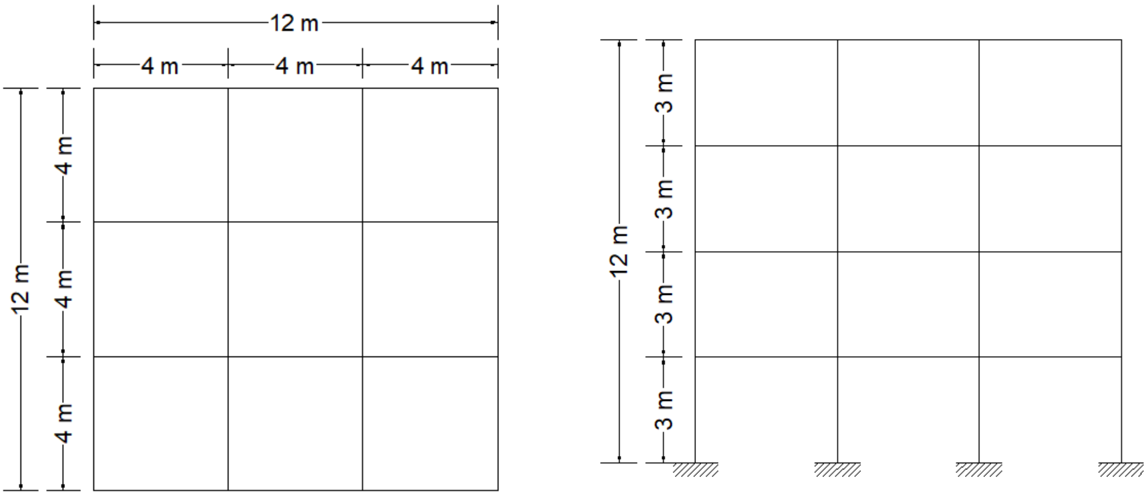
Section properties of the frame elements used are the common sections used in residential buildings of Nepal. Section properties are shown in Table 3. Table 3 outlines the dimensions of key structural elements in the model. Beams measure 250 mm in width and 400 mm in depth. Columns have dimensions of 350 mm by 350 mm. Equivalent infill struts, representing masonry infills, are 230 mm wide and 1250 mm tall. These dimensions are essential for accurately simulating the behavior of each element within the structural framework, aiding in the precise analysis of load distribution and structural response during seismic events or other loading conditions.

Table 3: Section properties

Structural element	Dimensions (mm)
Beams	250 x 400
Columns	350 x 350
Equivalent infill struts	230 x 1250

2.4. Models considered for the study

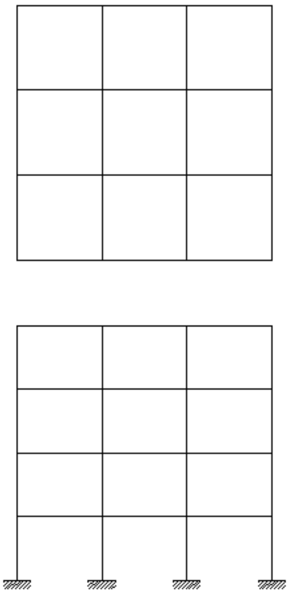
A total of 17 models were developed in SAP 2000, encompassing bare frame configurations as well as infilled frames with various distributions of infills. In these models, infills were represented as cross-diagonal struts under general loading conditions. In the bare frame models, infills' contribution to the structure's strength and deformation capability was disregarded, considering them solely as dead loads. Consequently, dynamic load resistance relied solely on frame action, inducing bending moments and shear forces in beams and columns through rigid joints. Conversely, in fully infilled buildings, infill walls were modeled as cross-diagonal struts distributed throughout the panels across all stories. Truss action occurred in each framed panel with masonry infill, leading to a reduction in induced bending moments in beams and columns but an increase in axial forces. To parameterize the study, the distribution of struts was altered across various models. This variation in distribution induced different mechanisms, leading to significant variations in response within the same model. The plan and elevation of the building sample are depicted in Fig. 1, providing a visual representation of the structure's layout. Fig. 2 illustrates the 17 different models, each representing a unique combination of infill distribution, enabling a comprehensive exploration of the structural behavior under varying loading conditions. Through this parametric study, a deeper understanding of the impact of infill distribution on seismic response in multi-story reinforced concrete frame buildings, common in regions like Nepal, was achieved.



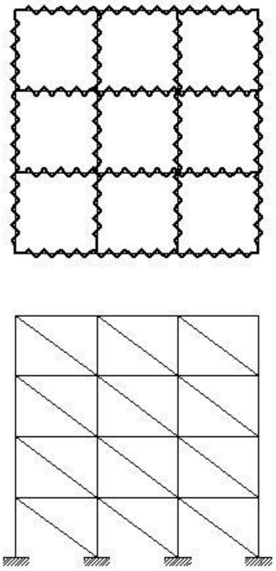
Plan of building

Elevation of building

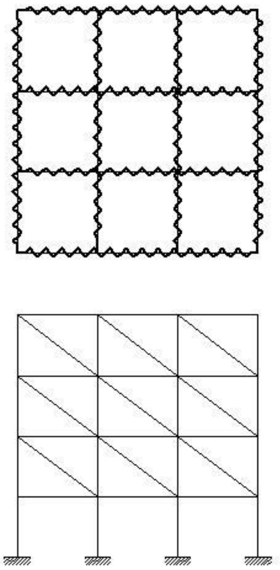
Fig. 1: Plan and elevation of building



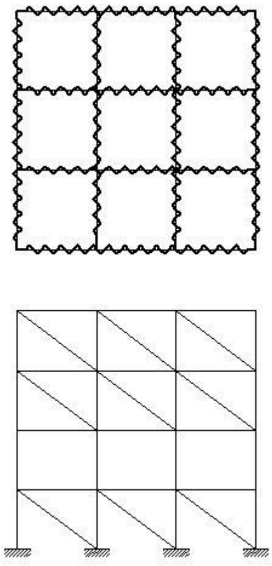
Model- 1 (BF)



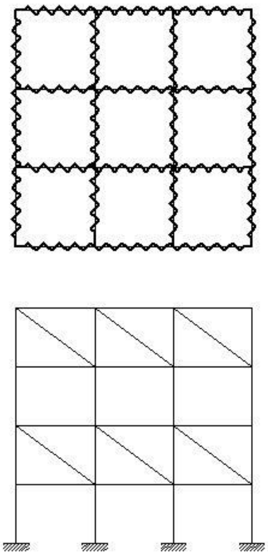
Model- 2 (AI_NS)



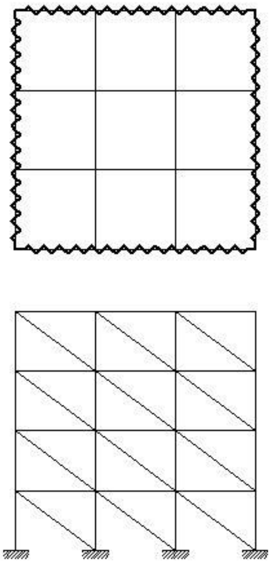
Model- 3 (AI_0S)



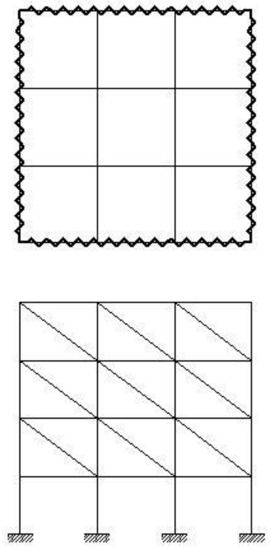
Model-4 (AI_1S)



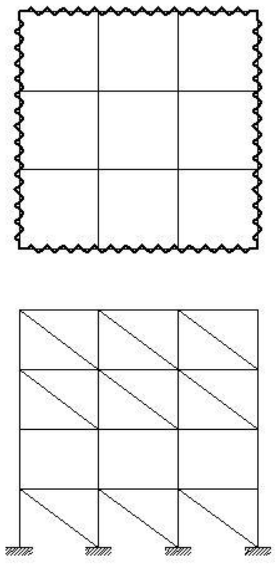
Model- 5 (AI_02S)



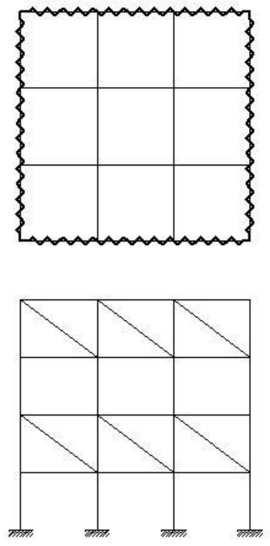
Model- 6 (OI_NS)



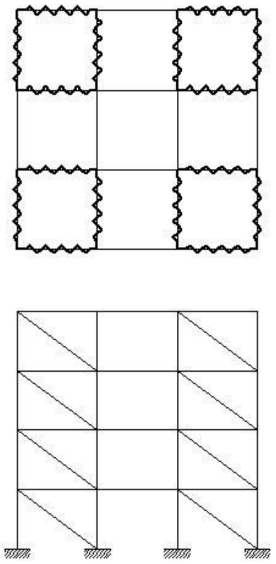
Model- 7 (OI_0S)



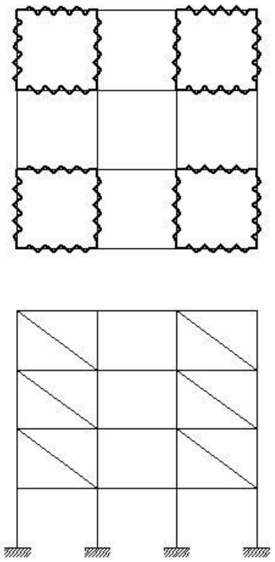
Model-8 (OI_1S)



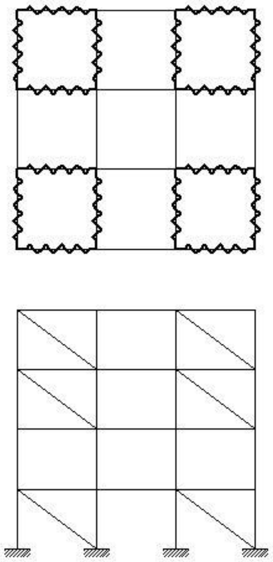
Model-9 (OI_ 02S)



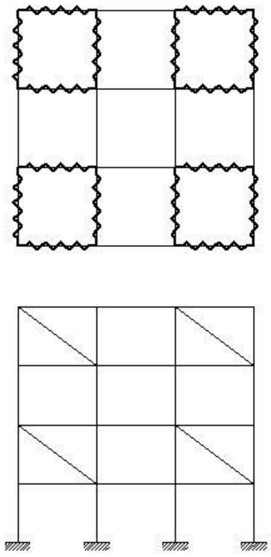
Model-10 (CI_NS)



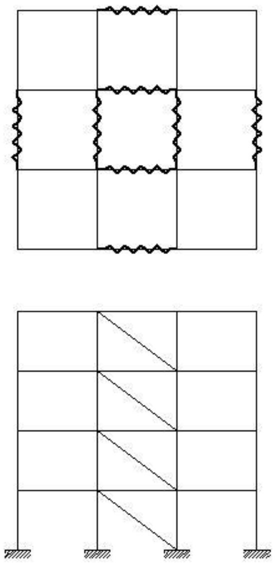
Model-11 (CI_ 0S)



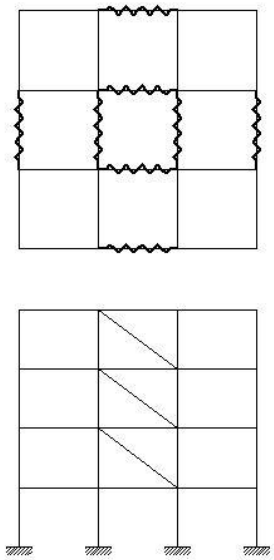
Model-12 (CI_1S)



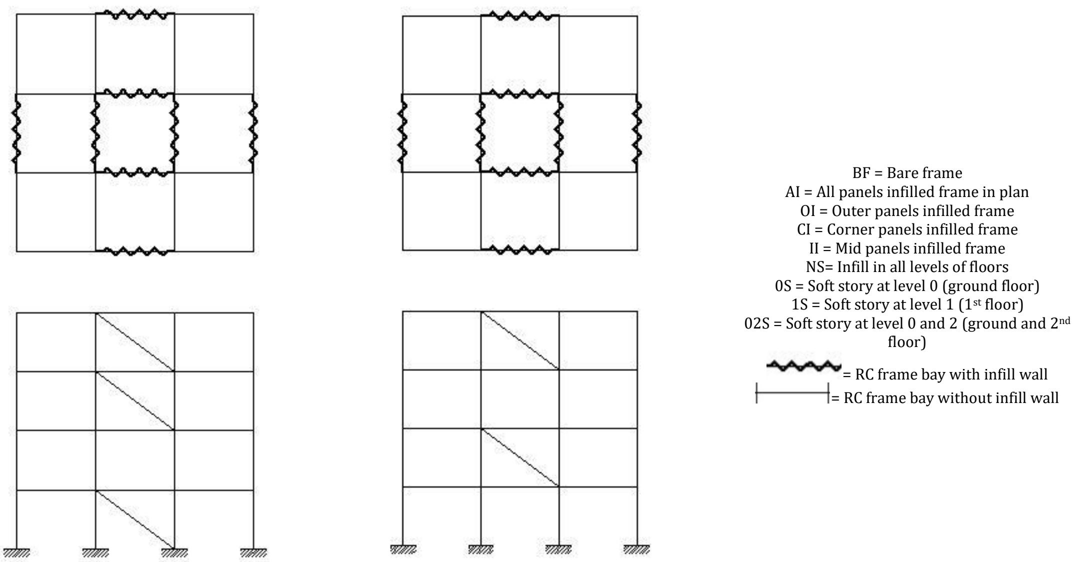
Model-13 (CI_ 02S)



Model-14 (II_NS)



Model-15 (II_0S)



Model-16 (II_1S)   Model-17 (II_ 02S)

Fig. 2: Different models developed with varying distribution of infills

Dynamic loading from earthquakes induces time-varying forces on structures, influencing their response. Peak response values are critical for structural design. Response spectrum analysis, as per Indian seismic code IS 1893 (part 1), focuses on these peak responses. It simulates structural behavior under seismic conditions, considering constituent properties. This analysis aids in designing structures resilient to earthquake-induced forces.

3. Result and discussion

This chapter compares results from analyzing models 1 to 17, focusing on infill wall panel distributions. Parameters studied include natural period, displacement, drift, shear force, and base shear, highlighting their variations and impact on structural behavior under seismic loading.

3.1. Fundamental time period

The fundamental time period, a crucial dynamic parameter, represents the time taken by a structure to complete one full oscillation cycle, determined by its mass and stiffness. In structural design, this period is integral for calculating acceleration spectra, which is essential for determining base shear. Fig. 3 demonstrates the considerable influence of modeling infill with equivalent diagonal struts on the building's fundamental natural period. Such insights are vital for optimizing structural designs to enhance seismic resilience and mitigate potential risks effectively.

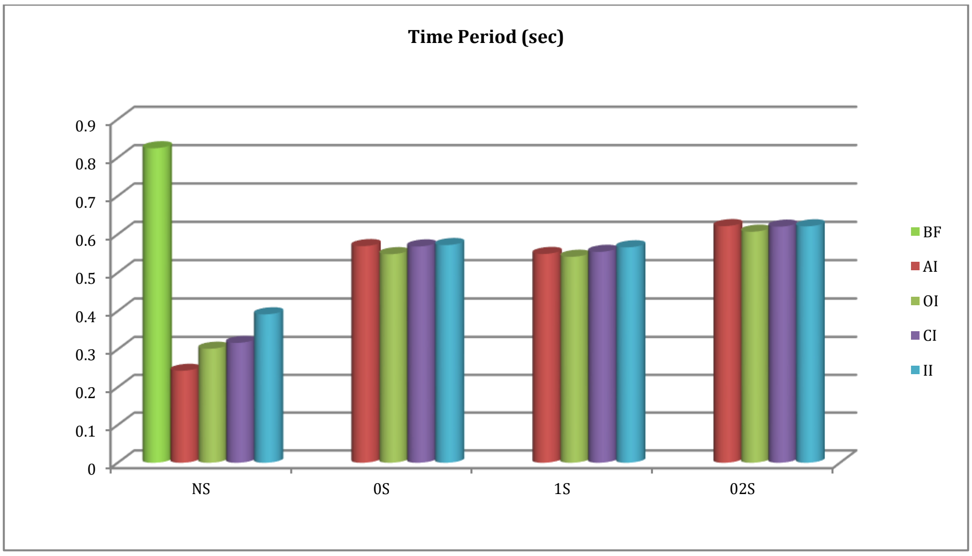


Fig. 3: Fundamental time period of considered different types of models under RS

3.2. Base shear

Seismic shear forces, crucial in seismic design, encompass base shear and shear at each story level. Fig. 4 compares the base shear values across the 17 models. Notably, the bare frame exhibits the lowest base shear compared to infilled models, regardless of horizontal or vertical irregularity. Additionally, an increase in infill panels leads to a slight rise in base shear, underlining the importance of infill walls in structural design. This emphasizes the significance of accounting for infill walls to ensure appropriate member cross-sections, enhancing structural resilience against seismic forces.

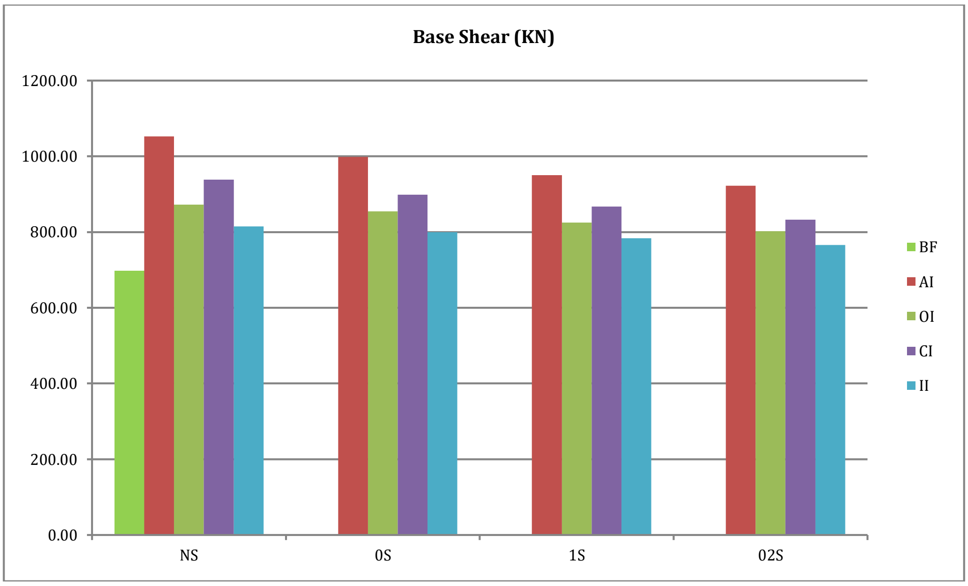


Fig. 4: Base shear different types of models

3.3. Story shear

Observations reveal higher story shear force when all bays or floors include infill walls. Models with soft stories at ground level exhibit higher story shear compared to those on the first floor, with a corresponding decrease in base shear as soft stories increase. Notably, the irregular distribution of infill walls in horizontal configuration (Fig. 6) induces more significant changes in base and story shear compared to vertical irregularities (Fig. 5). Horizontal irregularities alter the structural system's ability to resist lateral forces, leading to pronounced changes in shear forces. While vertical irregularities also impact shear forces, the effect is comparatively less pronounced, possibly due to less disruption to the overall structural system. Understanding these variations is crucial for designing structures resilient to seismic forces, emphasizing the importance of accounting for irregularities in infill wall distributions during structural analysis and design.

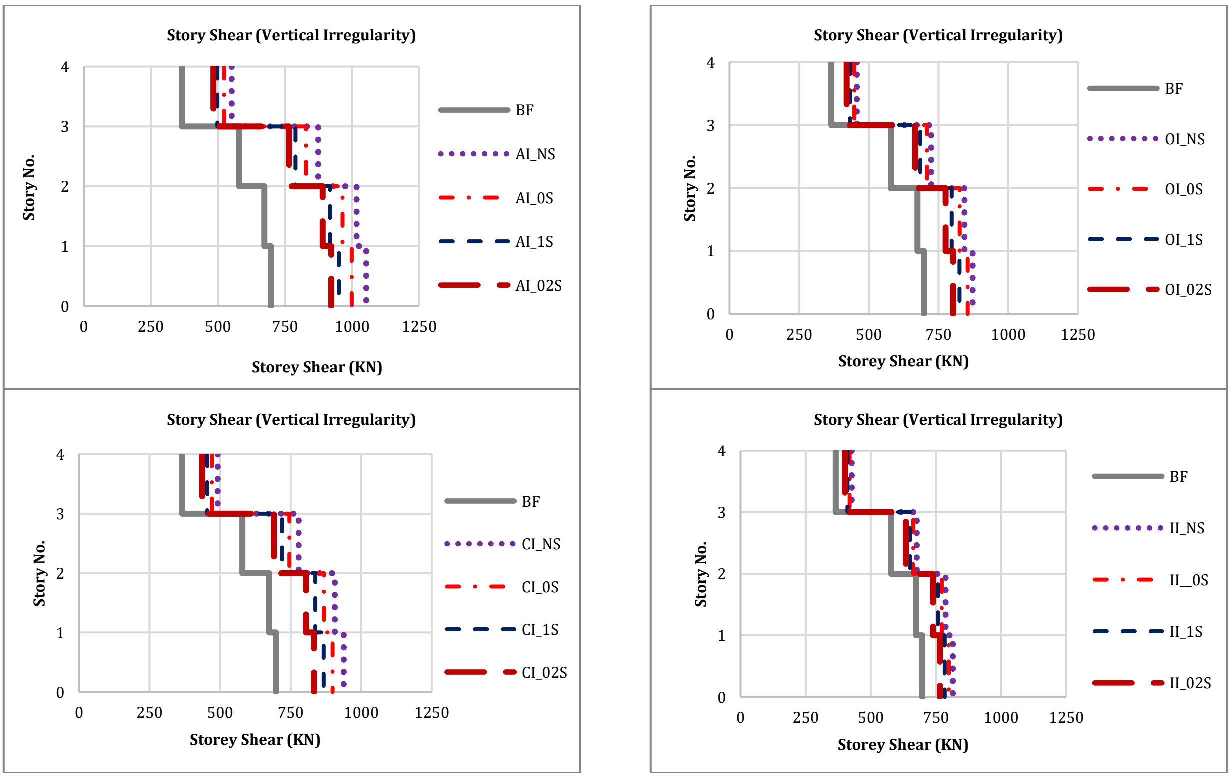


Fig. 5: Story shear forces for considered different types of models with vertical irregular distribution of infill wall

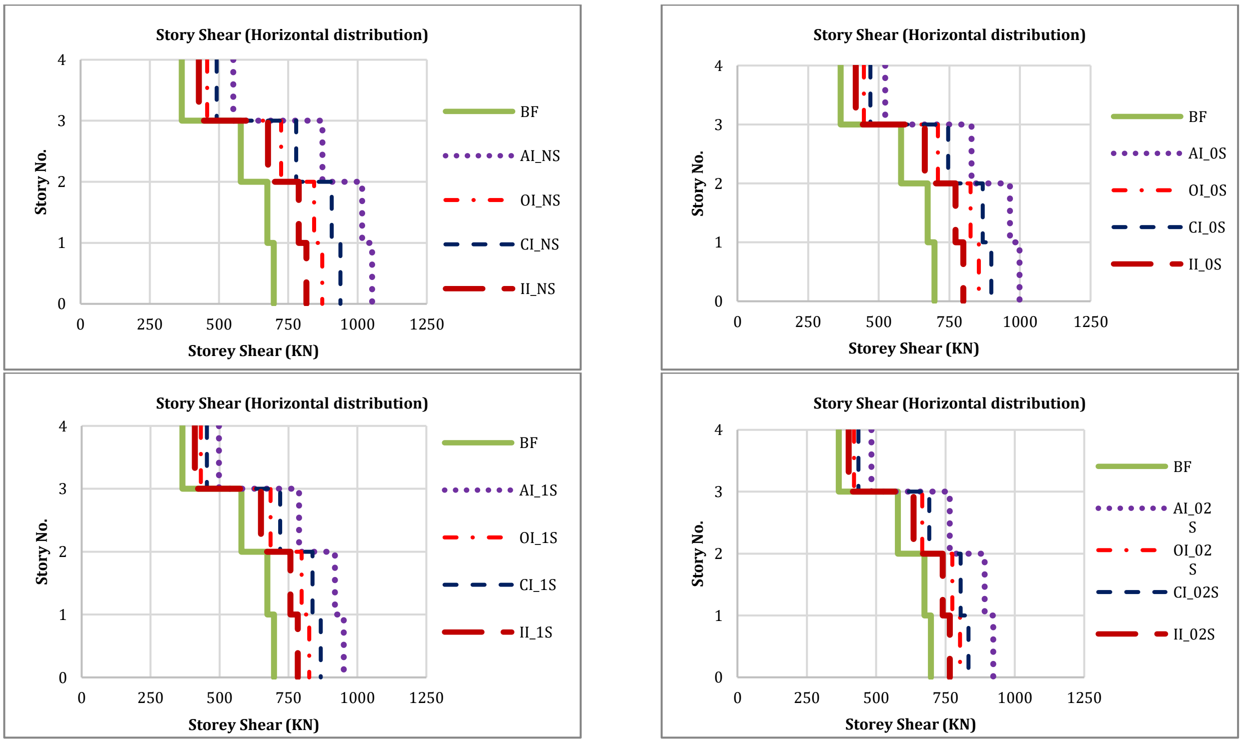


Fig. 6: Story Shear forces for considered different types of models with horizontal irregular distribution of infill wall

3.4. Story displacement

The study includes analyzing story displacements to understand building behavior under loads. Plots of peak displacement responses versus story heights (Figs. 7 to 10) illustrate the effects of masonry infill and soft story presence at various levels. Incorporating masonry infill notably reduces peak displacements compared to bare frame models, due to increased lateral stiffness. Additionally, open floors at different levels exhibit a similar trend in reducing peak displacements, akin to infilled models. This suggests that the presence of open floors can also mitigate displacements, albeit to a lesser extent than masonry infills. Understanding these effects aids in designing structures resilient to seismic loads, emphasizing the importance of considering infill walls and soft story configurations in structural design to minimize displacement and enhance overall performance.

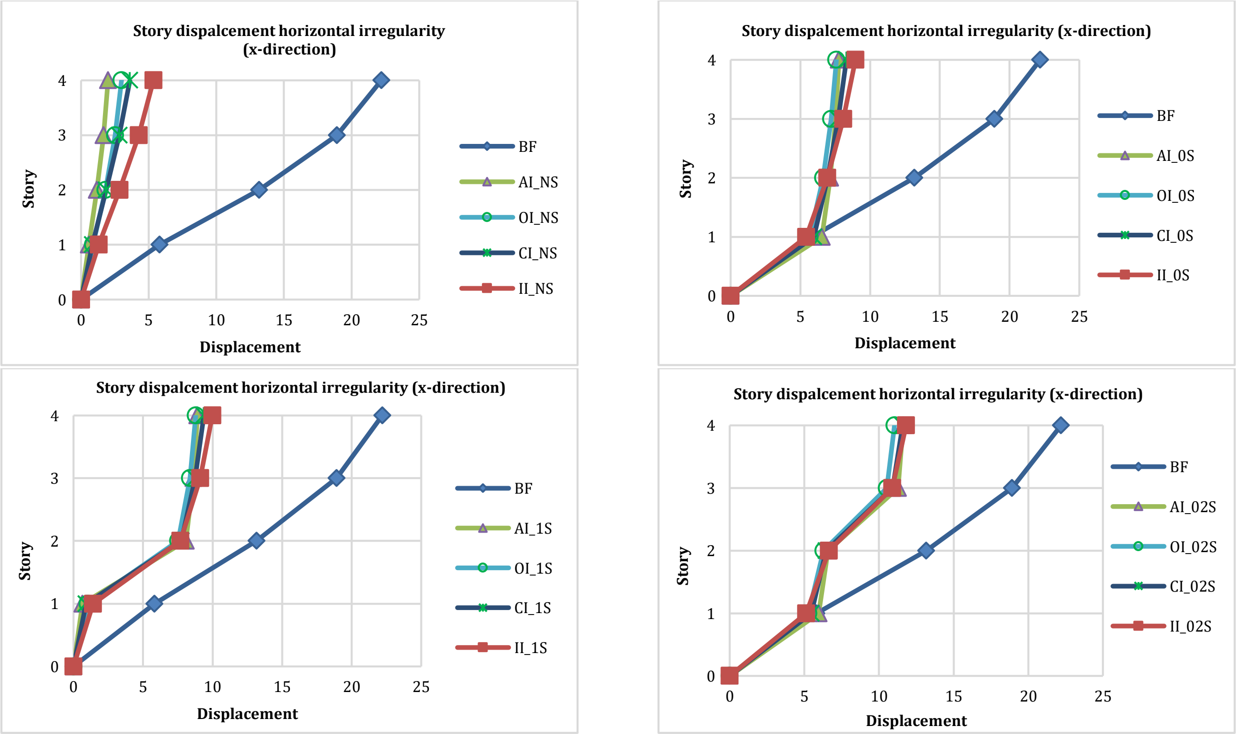


Fig. 7: Story displacement with horizontal irregular distribution of infill wall at X-direction

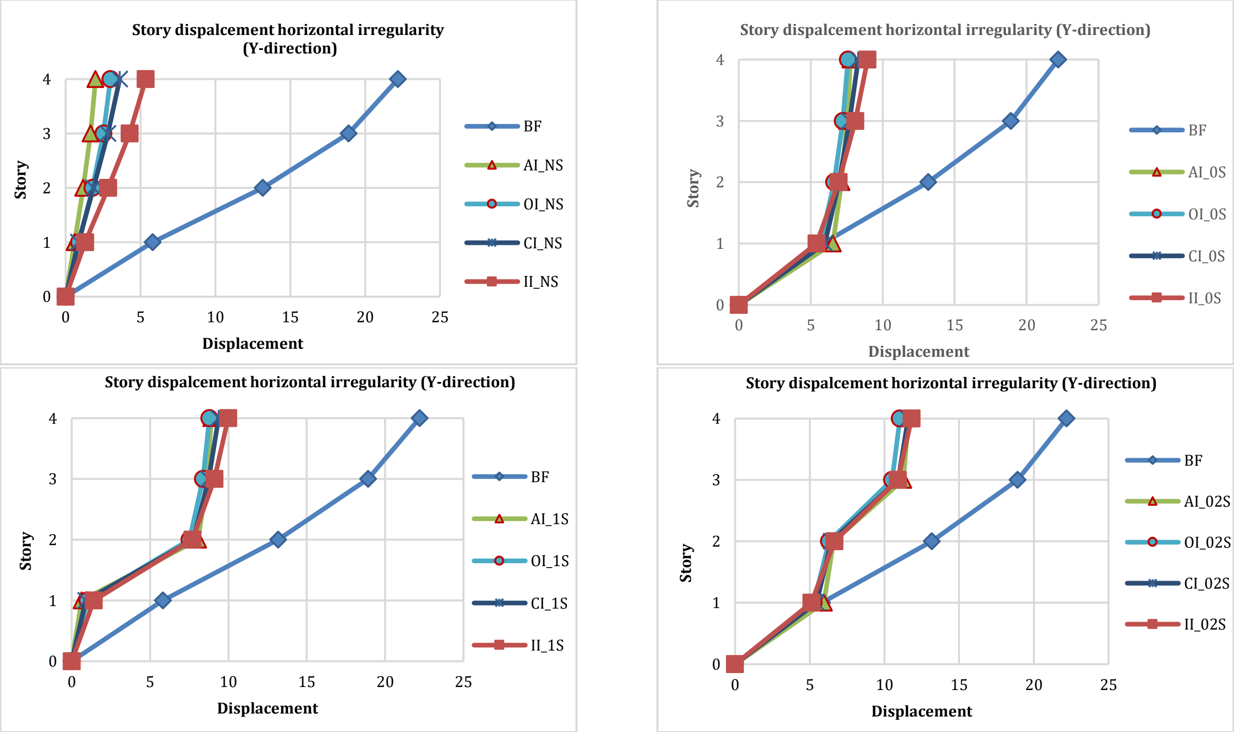


Fig. 8: Story displacement with horizontal irregular distribution of infill wall at Y-direction

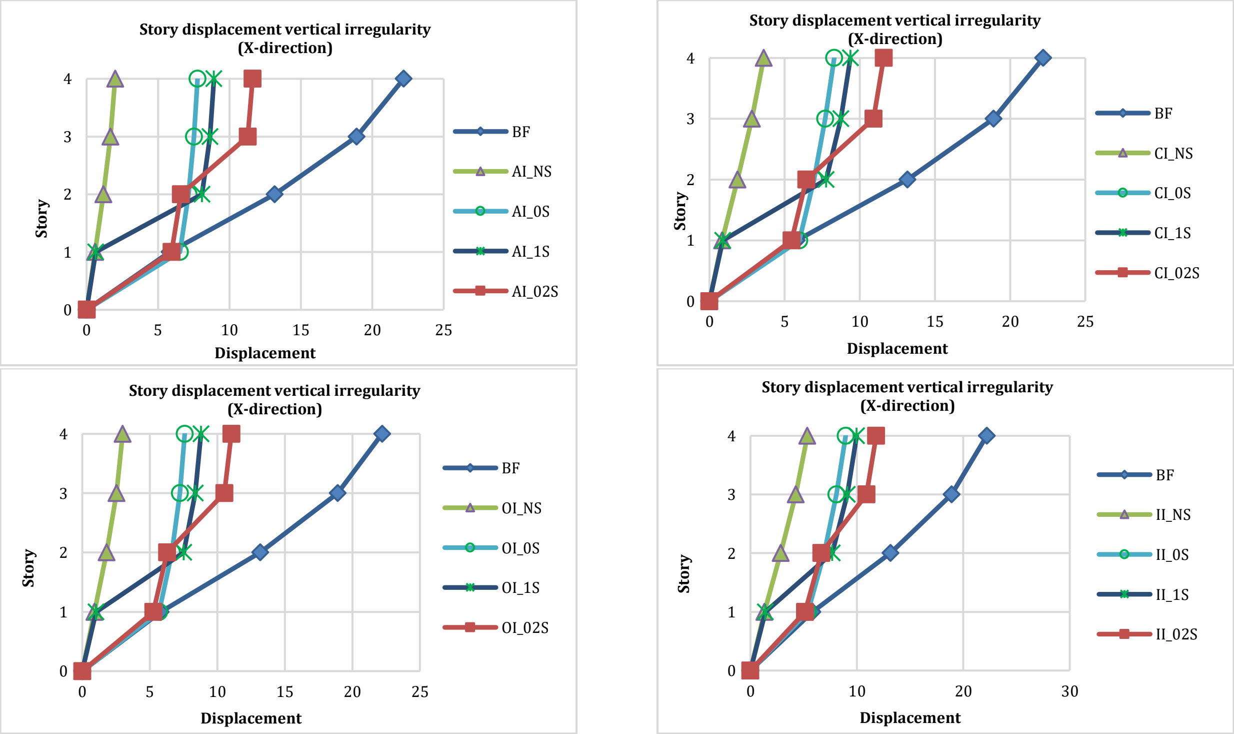


Fig. 9: Story displacement with vertical irregular distribution of infill wall at X-direction

3.5. Inter story drift

The comparison of story drift ratios across different models is crucial for assessing structural damage during seismic events. Defined as lateral displacement normalized by floor height, it is a key parameter in performance-based seismic analyses. IS 1893 (2002-Part I) stipulates that story drift should not exceed 0.004 times the height of a particular story to prevent structural damage. Figs. 11 and 12 depict inter-story drift for horizontal irregularities, while Fig. 13 illustrates drift for vertical irregularities. Incorporating masonry action consistently reduces peak story drift, highlighting its effectiveness in minimizing structural damage. Understanding these drift patterns aids in designing structures that meet safety standards and withstand seismic forces, ensuring structural integrity and occupant safety during earthquakes.

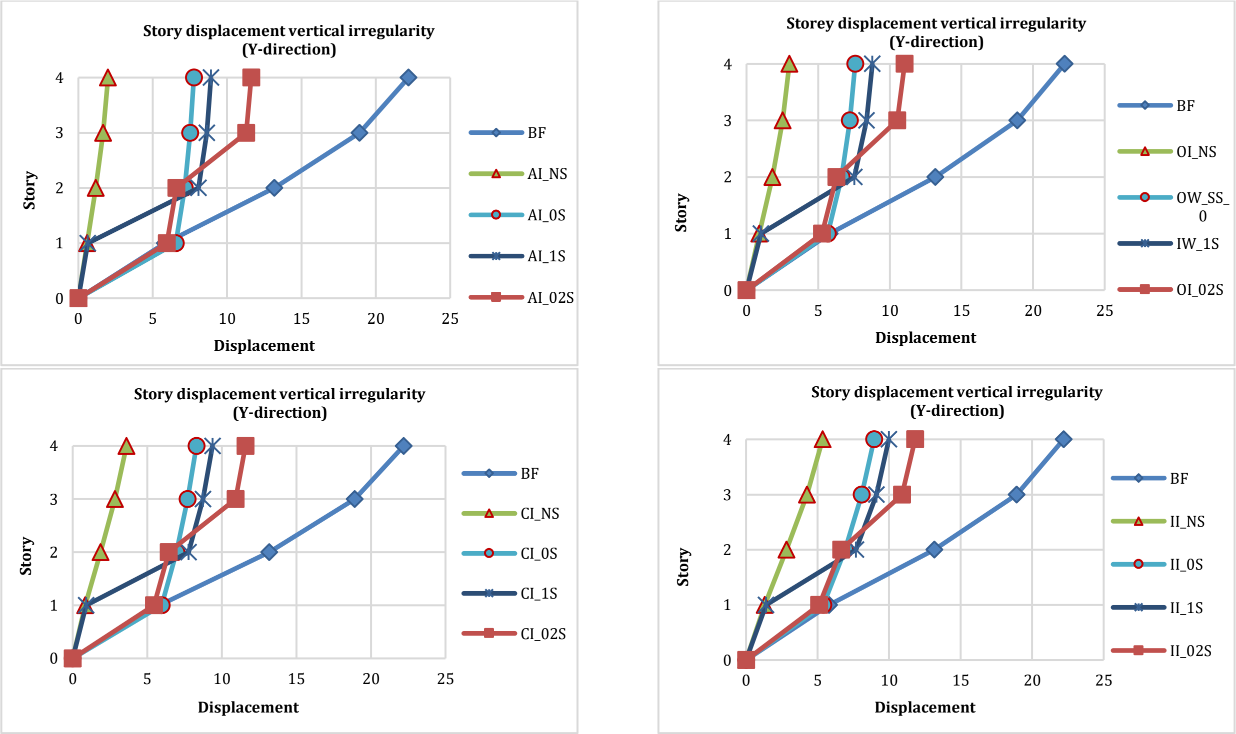


Fig. 10: Story displacement vertical irregular distribution of infill wall at Y-direction

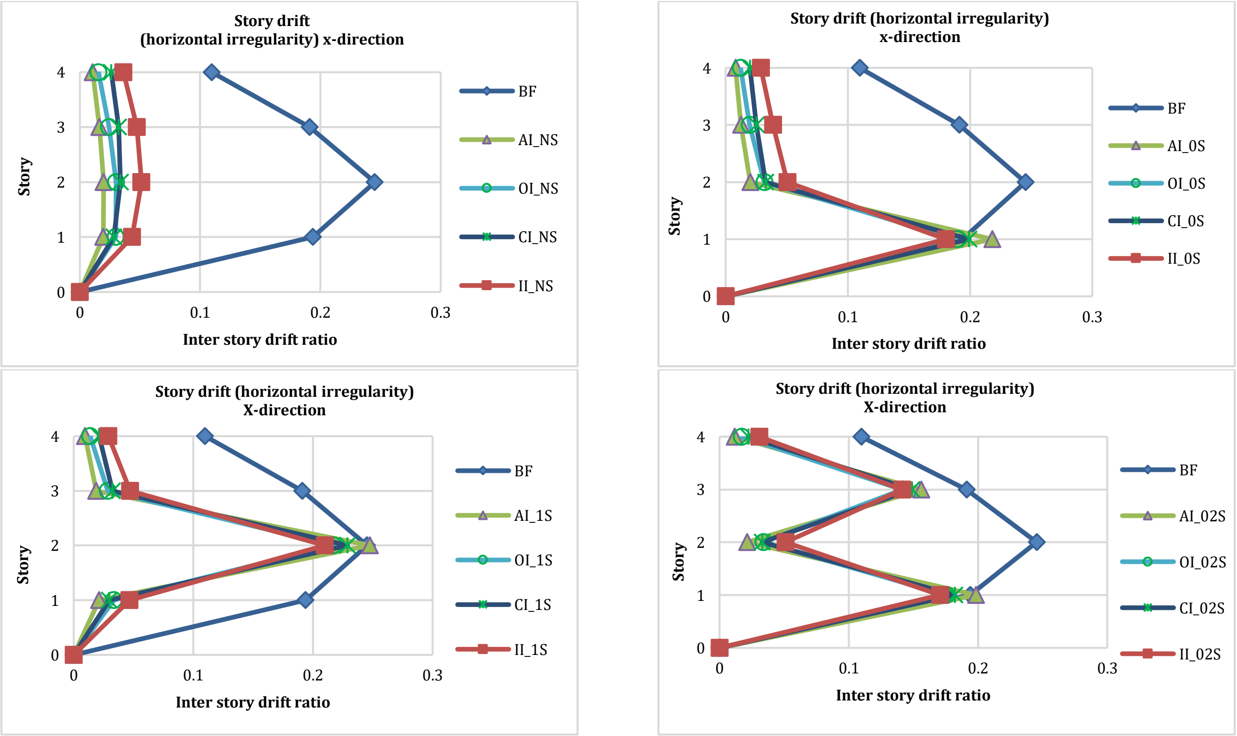
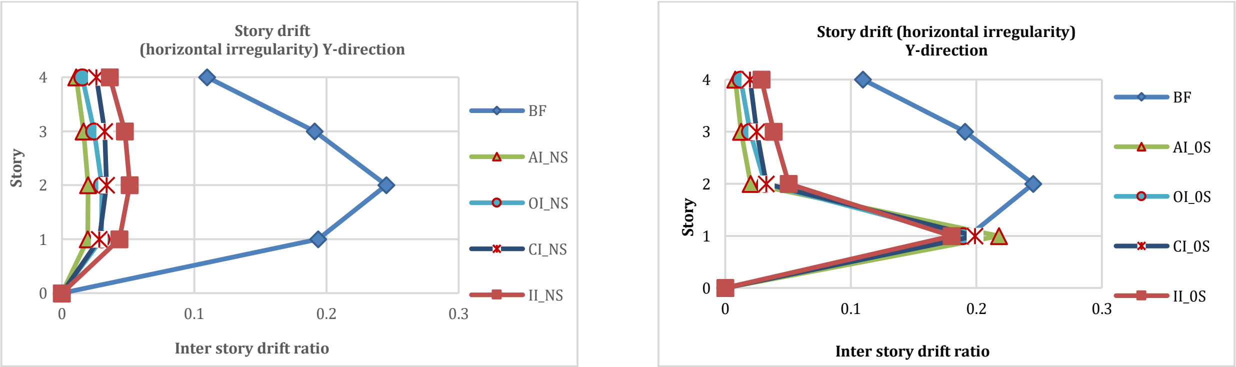


Fig. 11: Inter-story drift with horizontal irregular distribution of infill wall at X-direction



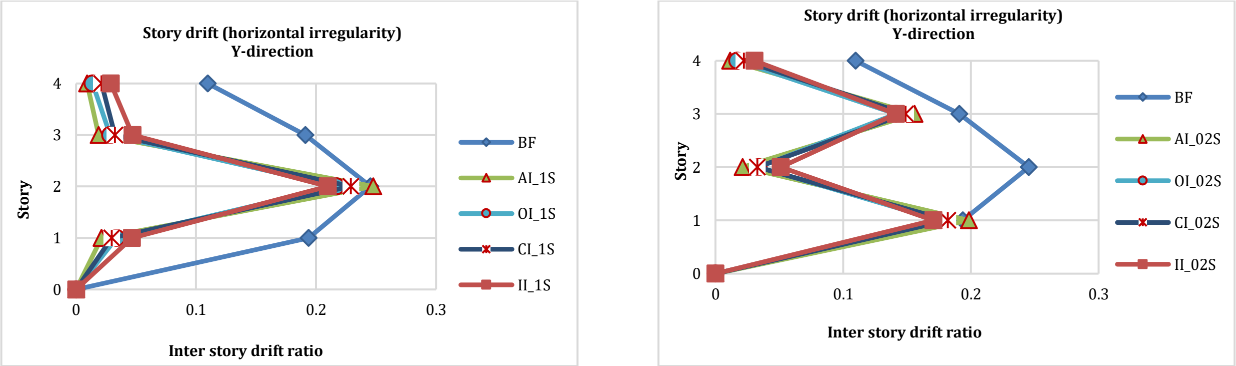


Fig. 12: Inter-story drift with horizontal irregular distribution of infill wall at Y-direction

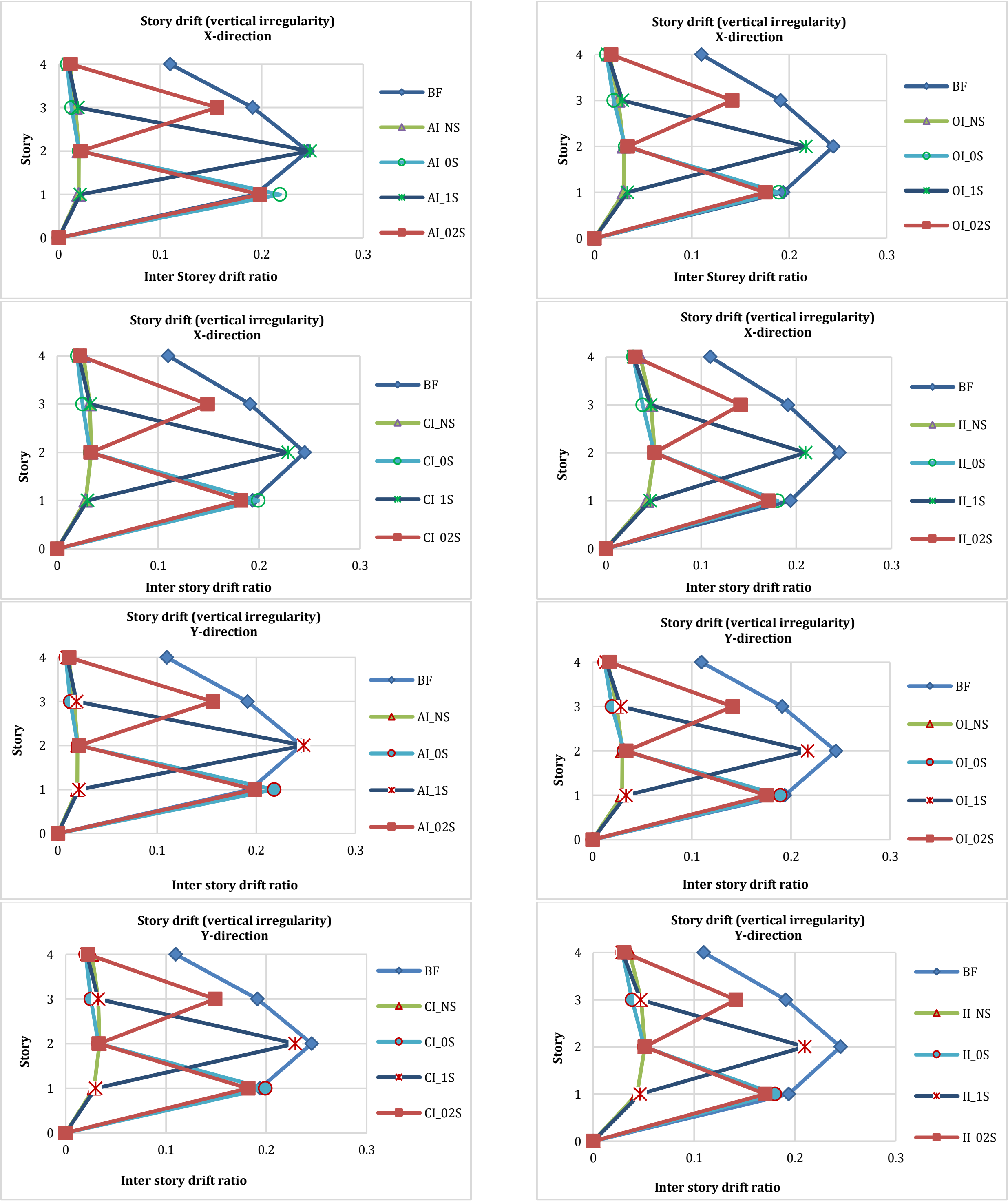


Fig. 13: Inter-story drift with vertical irregular distribution of infill wall

4. Conclusion

This study investigates the performance of RC frame building models with infill walls under earthquake load. The influence of factors related to building models such as masonry infill action and the existence of a soft story are analyzed. It is concluded that the inclusion of masonry infill action significantly changes the dynamic response behavior of the building model as compared to the bare frame model. Experimental investigations on the role of infill in structural integrity were conducted by Cai and Su (2019), Jalaeefar and Zargar (2020), and Lourenço (2012). The findings of these studies align closely with the current research. Additionally, the results of this research bear similarity to those of (Khan et al., 2019). The following main conclusions were drawn from the analysis and results of the studied different models:

1. The masonry infill action has a significant influence on the global performance of the building structure
2. Moreover, the existence of a soft story shows dramatic variation in the dynamic behavior of the infilled frame model as compared to the corresponding one without such a soft story
3. The fundamental period of the fully infilled model shows a significant decreasing trend in the obtained natural period as compared to the bare frame model.
4. However, the natural period of the infilled models with a soft story increased as compared to the model with an infill wall on all levels.

4.1. Limitation of study

1. Only analytical study carried out.
2. Properties of all material were taken from IS code not determined experimentally.
3. Nonlinear properties of mateials was not taken into consideration.
4. Performance based analysis was not taken into account

4.2. Recommendations for the further study

1. As the present study had been conducted analytical study on effect of infill wall; study can be further extended to experimental study.
2. The study can be enhanced by adding increasing different types of strut model.
3. This study could be extended to other types of building.
4. Nonlinear analysis can be added to this study.

4.3. Practical implication

1. Improve construction practices for seismic resilience.
2. Enhance structural design guidelines and building codes.
3. Instruct engineers on seismic-resistant design principles.
4. Provide guideline retrofitting strategies for existing structures.
5. Inform risk assessment and mitigation efforts.
6. Improve public safety and community resilience in earthquake-prone areas.

Compliance with ethical standards

Conflict of interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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