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Combined Effect of Unplanned Storey Addition and Building Orientation on the Seismic Response of Plan-Irregular RC Buildings

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Abstract

Rapid urbanization, population growth, rising land values, and limited availability of developable land have encouraged the vertical expansion of existing reinforced concrete (RC) buildings in many developing countries, including Nepal. In seismically active regions, additional storey is often added without detailed structural evaluation, altering the original mass and stiffness distribution of the building and potentially increasing its vulnerability during earthquakes. This concern is particularly significant for plan-irregular structures, where geometric irregularities can lead to torsional effects and uneven seismic force distribution. While previous studies have examined building orientation, structural irregularity, and vertical expansion separately, their combined influence on seismic performance remains insufficiently explored.

This study investigates the effect of unplanned storey addition and seismic excitation orientation on the response of a plan-irregular RC building. A five-storey L-shaped three-dimensional finite element model was developed in ETABS and analyzed using the Equivalent Static Method, Response Spectrum Method, and Linear Time History Analysis following the provisions of IS 1893:2016 and IS 13920:2016. Earthquake motions were applied at orientations of 0°, 30°, 45°, 60°, and 90° to evaluate directional sensitivity. Structural performance was assessed using base shear, natural time period, storey displacement, and inter-storey drift.

The results indicate that the addition of extra storey gradually increased seismic demand on the structure, leading to greater displacement and drift compared to the original building configuration by increasing structural mass and flexibility. The response also varied considerably with excitation orientation producing more critical behavior than others with certain orientations. These findings emphasize the importance of orientation-sensitive seismic assessment before vertical expansion and provide useful guidance for improving the safety and resilience of existing buildings in earthquake-prone regions.

Keywords: *Vertical expansion, Plan-irregular building, Building orientation, Storey displacement, Inter-storey drift, Time history analysis*

1. Introduction

Earthquakes remain one of the most serious natural hazards affecting the safety of buildings and infrastructure. Nepal lies in a highly earthquake-prone region and even small mistakes in building design can lead to severe damage. In many buildings, vertical and horizontal extensions are added without proper structural analysis. These unplanned loads change the mass and stiffness of the building, which directly affect its seismic response. In a seismically active country like Nepal, the need for proper structural design and careful planning is particularly important. Buildings must be designed not only to support gravity loads but also to safely resist lateral forces generated during earthquakes. The seismic behavior of a building is influenced by several structural factors such as its seismic weight, stiffness, height, mass distribution, and orientation with respect to the direction of ground motion.

1.1 Review of Earlier Studies

The seismic performance of reinforced concrete (RC) buildings is influenced by several factors, including structural configuration, building orientation, mass distribution, and modifications made during their service life. Understanding the influence of these factors is important for improving the safety and resilience of buildings in earthquake-prone regions.

Several researchers have highlighted the effect of earthquake excitation direction on structural response. Panta and Motra (2019) reported that plan-irregular RC buildings are highly sensitive to the direction of ground motion, with significant variations observed in displacement, storey drift, and torsional response. Similarly, Shahi et al. (2019) found that changes in building orientation can considerably affect seismic demand and should therefore be considered during structural evaluation and design.

The influence of vertical expansion on existing buildings has also been widely studied. Gunes et al. (2019) investigated RC buildings subjected to additional storeys and reported that vertical expansion increases both gravity and seismic demands on structural members. Their study emphasized that the safety of storey addition depends on the capacity of the original structure to resist the increased loading. In many developing countries, however, additional storey is often constructed without detailed structural assessment, increasing the potential risk during earthquakes.

Researchers have also examined the impact of plan irregularity on seismic behavior. Pandian et al. (2024) observed that irregular buildings generally experience higher displacement and torsional effects than regular structures due to uneven stiffness and mass distribution. Likewise, Zaker (2022) reported that structural irregularities significantly influence lateral displacement, storey drift, and force distribution under seismic loading.

Although previous studies have improved the understanding of building orientation, vertical expansion, and plan irregularity, these factors have largely been investigated independently. Limited research has explored their combined influence on the seismic response of plan-irregular RC buildings. Therefore, the present study examines the interaction between unplanned storey addition and earthquake excitation orientation to provide a more realistic assessment of seismic performance.

1.2 Need of the study

Unplanned vertical expansion has become increasingly common in urban areas of Nepal due to rapid urbanization, limited land availability, and the growing demand for additional floor space. In many cases, extra storeys are added to existing reinforced concrete buildings without detailed structural assessment, which may increase their vulnerability during earthquakes. The risk becomes even greater in plan-irregular buildings, where uneven mass and stiffness distribution can lead to significant torsional effects and higher seismic demand.

Figure 1: Buildings in kathmandu valley, unplanned urbanization [1]

Previous studies have shown that both building orientation and vertical expansion can significantly influence the seismic behavior of reinforced concrete buildings. However, these factors have mostly been examined separately. In practice, many buildings in Nepal undergo vertical expansion through the addition of extra storeys, often without detailed structural assessment. At the same time, the direction of earthquake ground motion can greatly affect the response of plan-irregular structures. Despite their practical importance, limited research has investigated the combined effect of these two factors. Therefore, this study examines how unplanned storey addition and earthquake excitation orientation together influence the seismic performance of plan-irregular RC buildings.

1.3 Objectives and Scope of the study

The primary objective of this study is to investigate the combined effect of unplanned storey addition and building orientation on the seismic response of a plan-irregular reinforced concrete (RC) building. The study aims to evaluate how vertical expansion influences the structural behavior of an existing building and how different earthquake excitation orientations affect its seismic performance.

A three-dimensional model of a plan-irregular RC Special Moment Resisting Frame (SMRF) building was developed in ETABS and analyzed in accordance with the provisions of IS 1893:2016 and IS13920:2016. The seismic response of the building was assessed using the Equivalent Static Method, Response Spectrum Method, and Linear Time History Analysis. To investigate the effect of earthquake direction, ground motions were applied at orientations of 0°, 30°, 45°, 60°, and 90°. The study focuses on comparing the seismic behavior of the original building and the vertically expanded building in terms of base shear, fundamental time period, storey displacement, and inter-storey drift.

2. Materials and Methods

The present study adopted a systematic analytical approach to evaluate the seismic performance of a plan-irregular reinforced concrete building under different orientation angles and storey addition conditions.

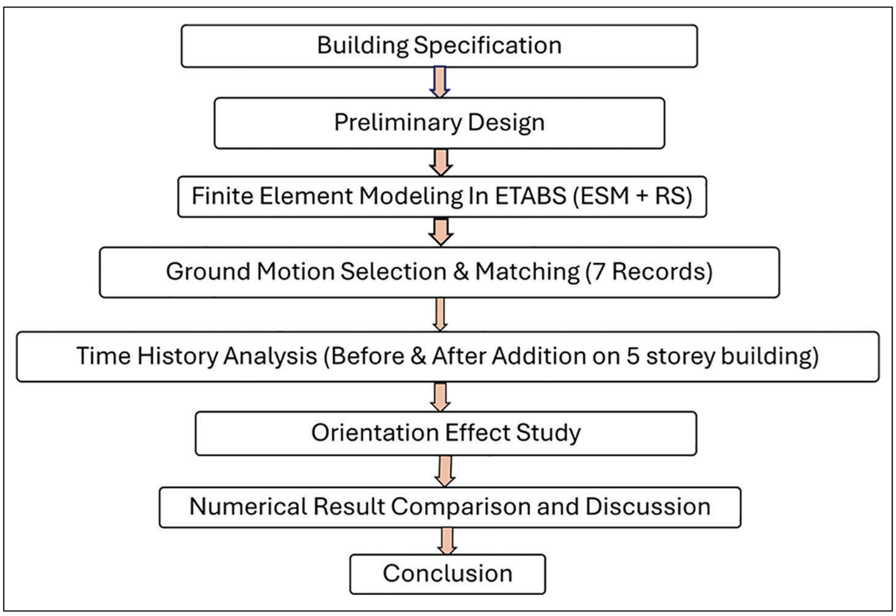


Figure 2: Research methodology workflow

The research methodology adopted in this study is illustrated in Figure 2. The study began with the selection of building specifications and preliminary structural design, followed by finite element modelling in ETABS. Seismic performance was initially evaluated using the Equivalent Static Method and Response Spectrum Method. Subsequently, seven spectrum-matched ground motion records were used for Linear Time History Analysis to assess the effects of storey addition and ground motion orientation. The results obtained from different analyses were then compared and discussed to evaluate the seismic response of the building. The methodology was developed to investigate the influence of unplanned vertical expansion and directional seismic excitation on structural behavior. Key response parameters such as base shear, displacement, storey drift, and torsional response were evaluated. The findings from the analyses were used to draw conclusions regarding the seismic safety and performance of the building under different conditions.

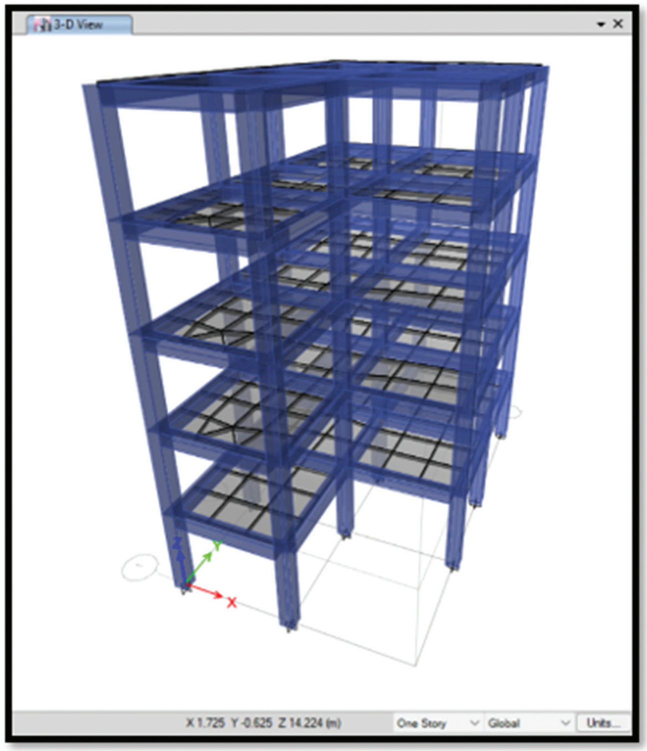


Figure 3: 5 storey Building model in ETABS

2.1 Building Description and Modeling

A five-storey plan-irregular reinforced concrete (RC) Special Moment Resisting Frame (SMRF) building representative of residential buildings commonly found in Nepal was selected for this study. The building was modelled and analyzed using ETABS software. The structural system consisted of reinforced concrete beams, columns, and slabs designed in accordance with the provisions of IS 456:2000, IS 1893:2016 and IS 13920:2016.

Table 1: Building and Structural configuration

Parameter	Value
Building Shape	L-Shaped RC SMRF
Number of Storey	G+4 (original)
Storey Height	2.84 m
No of Bay (X)	2
No of Bay (Y)	3
Beam Size	(350*400) mm
Column Size	(400*400) mm
Slab Thickness	125 mm
Concrete Grade	M20, M30
Reinforcement Grade	HYSD 500

To evaluate the effect of vertical expansion, an additional storey was introduced without modifying the existing structural members, representing an unplanned storey addition scenario. The seismic performance of the building was assessed under different earthquake excitation orientations of 0°, 30°, 45°, 60°, and 90°. Response of both the original and vertically expanded building models was compared in terms of base shear, fundamental time period, storey displacement and inter-storey drift.

2.2 Seismic Analysis Procedure

The seismic performance of the building was assessed using the Equivalent Static Method (ESM), Response Spectrum Analysis (RSA), and Linear Time History Analysis (LTHA). ESM was used to estimate design base shear, while RSA captured the dynamic response by considering multiple vibration modes. LTHA was performed using spectrum-compatible earthquake records to simulate structural behavior under realistic ground motions. The results were then compared to evaluate the effects of storey addition and excitation orientation on the building's seismic response.

The analyses were carried out in accordance with the provisions of IS 1893:2016 and IS 13920:2016. A total of seven spectrum-matched ground motion records were used in the time history analysis to ensure realistic representation of seismic loading. The building was analyzed before and after storey addition under different excitation orientations to investigate the influence of vertical expansion and earthquake direction. Key response parameters such as fundamental time period, base shear, storey displacement, inter-storey drift, and torsional response were evaluated and compared. This approach provided a basis for evaluating the safety and behavior of the building under realistic earthquake loading conditions.

2.3 Ground Motion Selection and Spectrum Matching

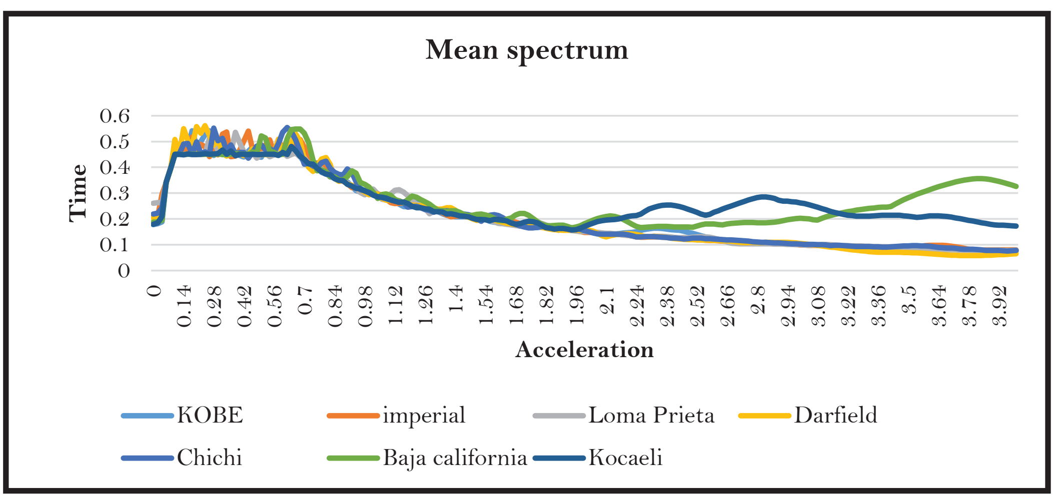


Figure 4: Mean response spectrum obtained by matching seven records

Table 2: Ground motion data

No.	Earthquake Event	Moment Magnitude (Mw)	Recording Station
1	Imperial Valley	6.95	El Centro Array
2	Kobe, Japan	6.90	Kobe University
3	Loma Prieta	6.93	APEEL10–Skyline
4	Baja California	5.50	Cerro Prieta
5	Kocaeli, Türkiye	7.51	Ambarli
6	Chi-Chi, Taiwan	5.90	CHY017
7	Darfield, New Zealand	7.00	ADCS

Linear Time History Analysis was performed using seven earthquake ground motion records selected from the PEER Ground Motion Database. The records were chosen considering their compatibility with the seismic characteristics of the study area and were scaled through spectrum matching to confirm to the target response spectrum specified by IS 1893:2016 for the selected site conditions. Spectrum matching was carried out to ensure that the selected records adequately represented the expected seismic demand over the range of structural periods considered in this study. The spectrum-matched records were then applied to the building model at orientation angles of 0°, 30°, 45°, 60°, and 90° to evaluate the influence of earthquake excitation direction and unplanned storey addition on the seismic response of the structure.

The figure 4 represents the mean response spectrum obtained from the selected and spectrum matched ground motion records. The spectral responses of the seven earthquakes show a similar trend over the considered period rang, indicating satisfactory compatibility with the target spectrum. Minor variations are observed at higher periods due to inherent characteristics of individual ground motions. Overall, the matched records provide a reliable representation of the seismic demand and are considered appropriate for evaluating structural response under earthquake loading.

3. Results And Discussion

3.1 Effect of storey Addition

To evaluate the influence of unplanned vertical expansion, additional storeys were introduced to the original five-storey building without strengthening the existing structural members. A one-storey addition resulted in a six-storey building, while a two-storey addition produced a seven-storey configuration. The objective was to examine how increased height and seismic mass affect the structural performance of the building. Design checks indicated that the six-storey model remained within acceptable design limits, although seismic response parameters increased compared to the original structure. However, the seven-storey model exhibited 4 Beam member failures due to the increased gravity and seismic demands imposed on structural elements that were originally designed for a five-storey configuration.

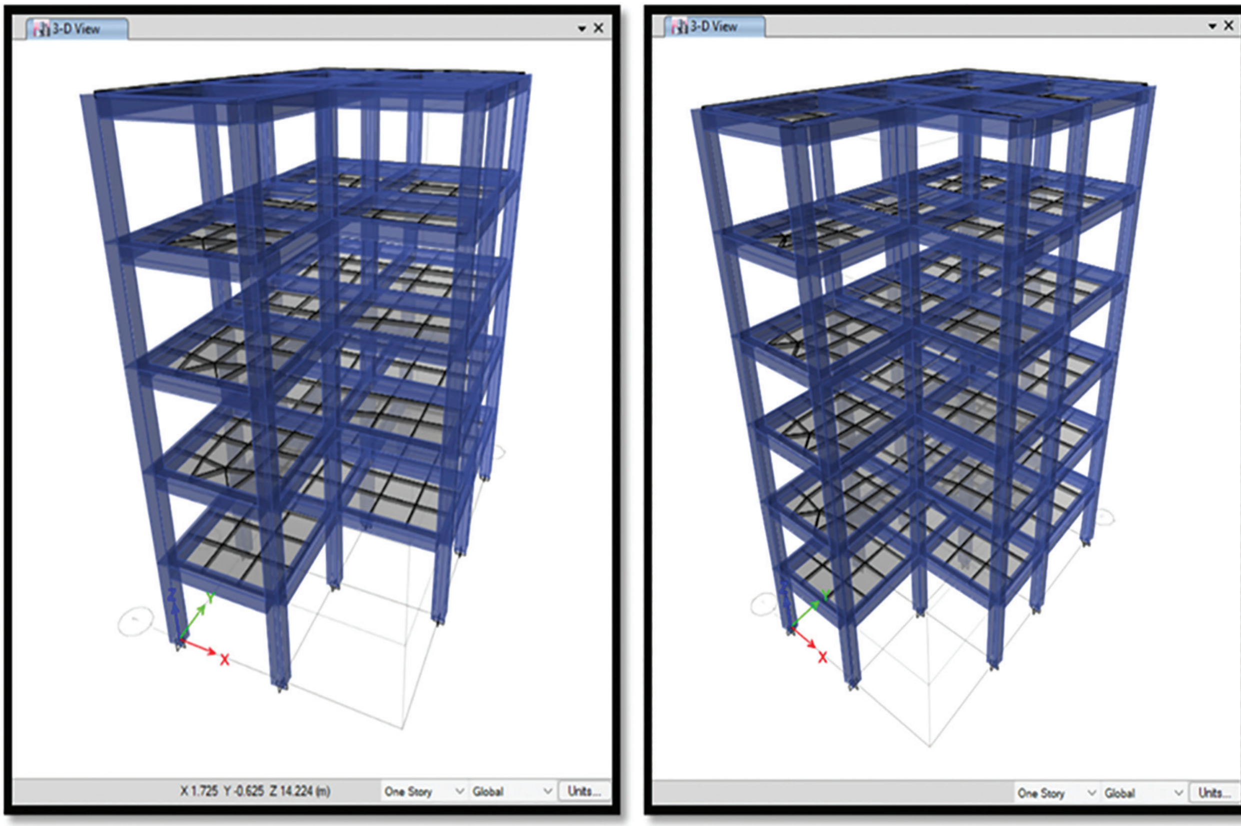


Figure 5: Planned five storey vs One unplanned addition storey building

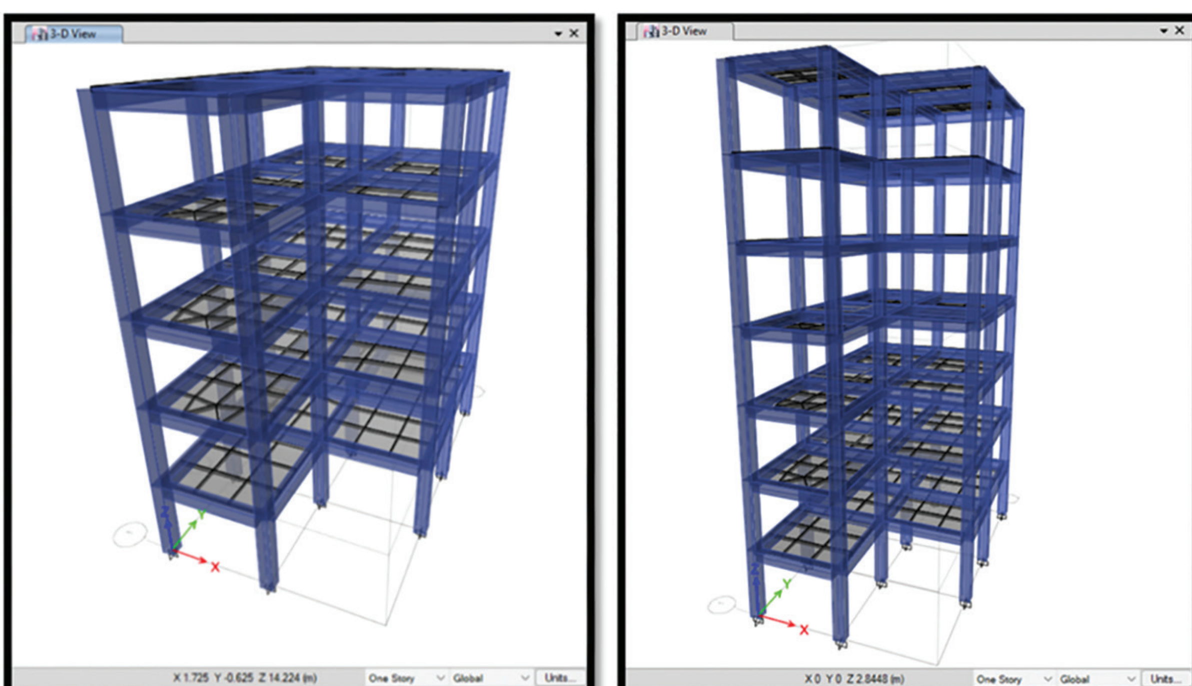


Figure 6: Planned five storey vs Two unplanned addition storey building

The analysis revealed that the first storey addition mainly influenced the serviceability performance of the building, resulting in increased displacement and drift while maintaining adequate strength capacity. In contrast, the addition of a second storey led to member failures, indicating that the imposed seismic and gravity loads exceeded the structural strength capacity. These findings demonstrate that vertical expansion can initially affect serviceability requirements and, with further addition of storeys, may compromise the strength and safety of the structure.

Table 3: Comparison of Seismic parameters after addition of one storey and two storeys in a 5 storey Building Model

After addition of one storey	After addition of two storey
All Concrete Frame passed the design check	Four concrete frames failed the design check (i.e. beam B4, B3, B9 of story 2 and beam B3 of story 4 of G+6 storey)
Base shear = 540.51 KN.	Base shear = 639.57 KN.
Storey Drift = 1.09% > 0.4% (not within Permissible Limit)	Storey drift = 1.45%> 0.4% (not within permissible limit)
Max displacement = 116.86 mm (not within permissible limit i.e. 68.28 mm)	Max displacement = 150.803 mm (not within permissible limit i.e. 79.65mm)

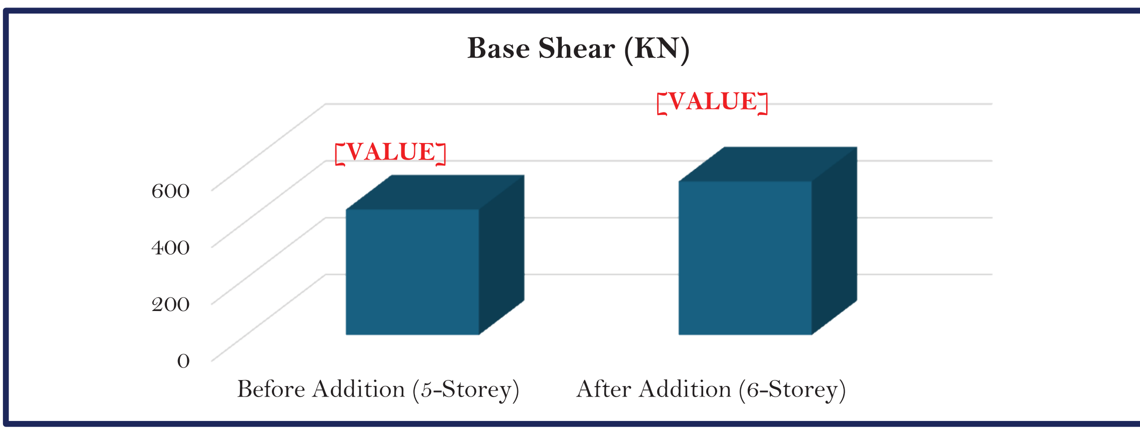


Figure 7: Comparison of base shear before and after addition of storey

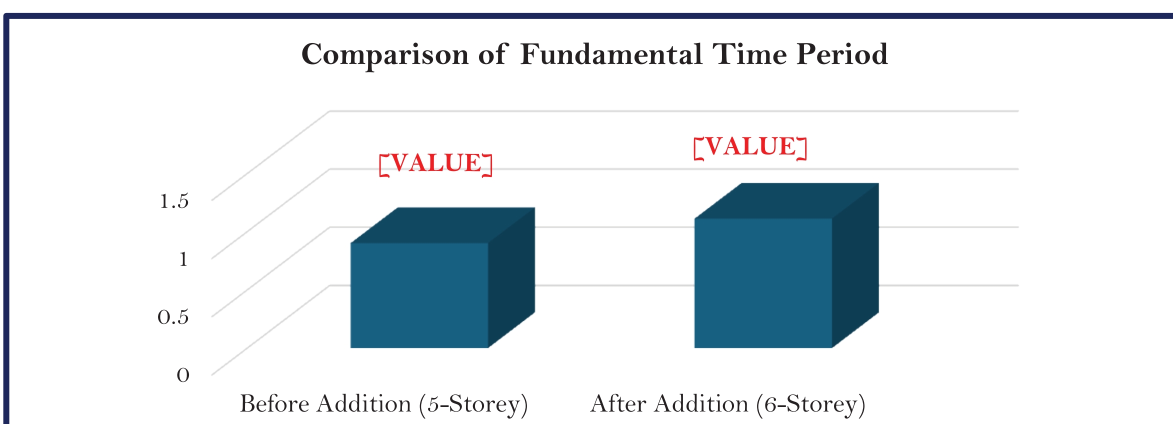


Figure 8: comparison of time period before and after addition of storey

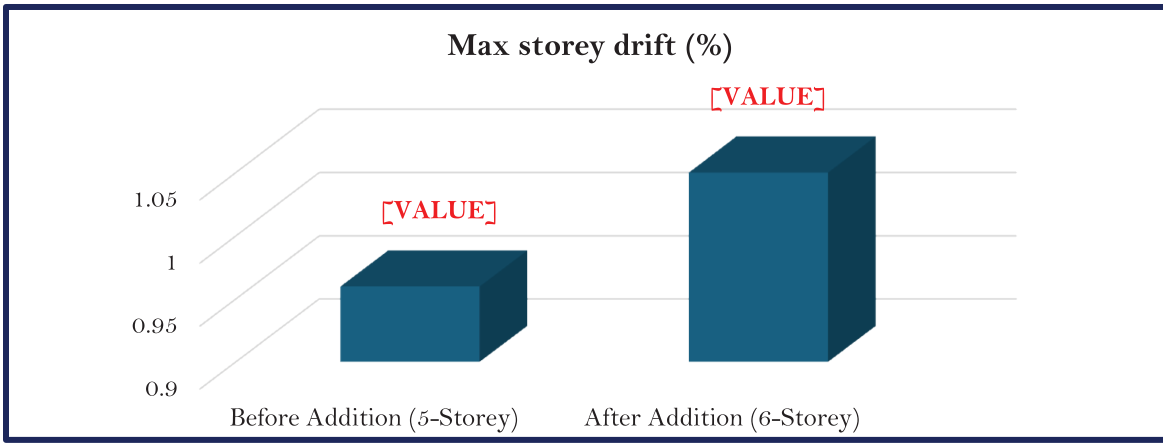


Figure 9: Comparison of maximum drift before and after addition of storey

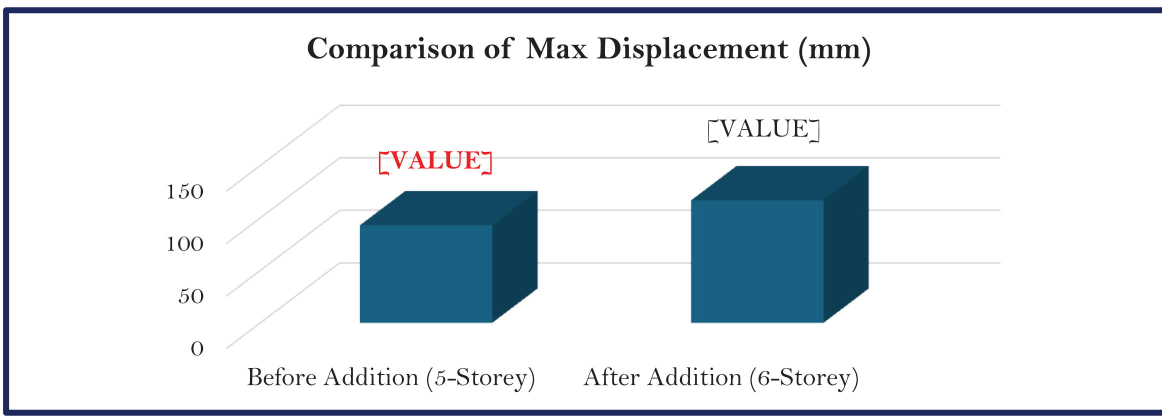


Figure 10: Comparison of maximum displacement before and after addition of storey

The results of the time history analysis indicate that unplanned storey addition significantly affects the seismic performance of the building. Comparison between the original five-storey model and the six-storey expanded model showed increases in displacement, storey drift, base shear, and member force demand. The maximum displacement increased 25.68%, while the base shear increased by 22.4% due to the additional seismic mass. Similarly, the fundamental time period increased 23.41%, indicating greater structural flexibility after vertical expansion. The maximum storey drift also increased 9.38%, reflecting higher deformation demand under seismic loading. These findings suggest that the addition of one storey primarily affects the serviceability performance of the building by increasing displacement and drift, whereas further vertical expansion may compromise the structural strength and overall seismic safety. Therefore, detailed seismic assessment is essential before undertaking vertical expansion of existing buildings in earthquake-prone regions.

3.2 Effect of orientation on L-shaped Building

To examine the influence of earthquake direction, ground motions were applied at different orientations: 0°, 30°, 45°, and 60°, 90° with respect to the global X-axis and Y-axis of the building. Time history analysis was performed for each orientation case. Comparative assessment was carried out to determine the variation in displacement, drift, and torsional effects due to change in ground motion direction.

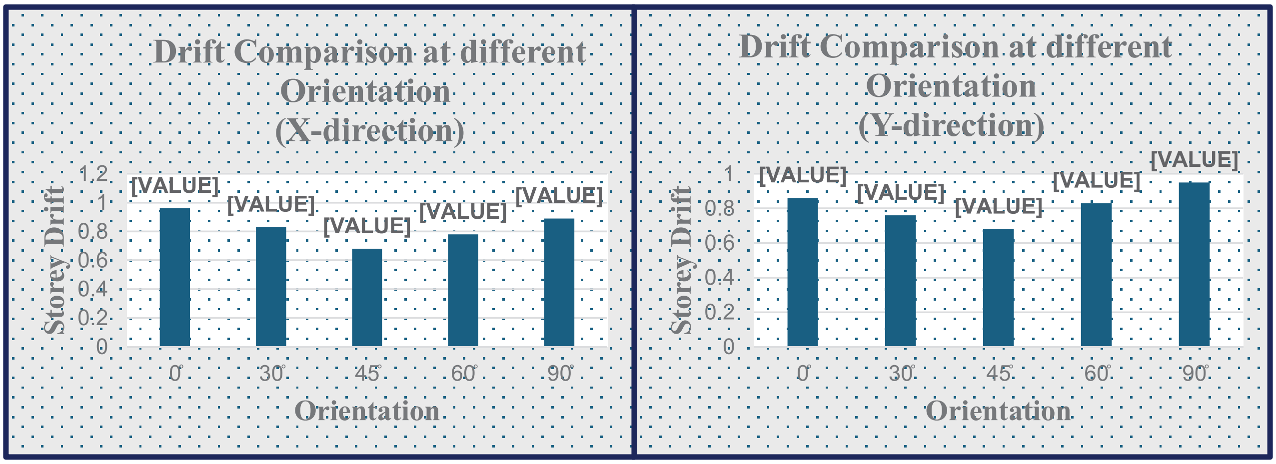


Figure 11: Inter Storey Drift comparison of L-shaped Building model at different orientation in X-direction and Y-direction

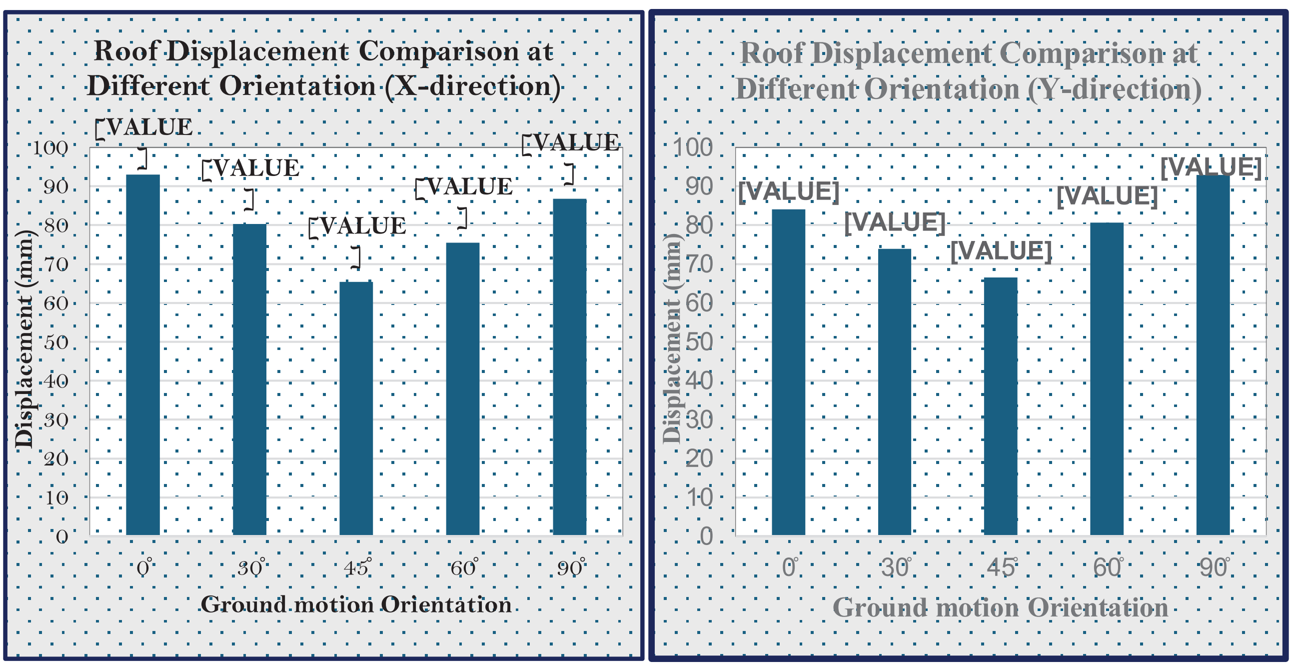


Figure 12: Roof Displacement comparison of L-shaped building model at different orientations in X-direction and Y-direction

The results of the time history analysis show that ground motion orientation significantly influences the seismic response of the L-shaped building. Variations in earthquake excitation direction produced noticeable changes in storey displacement and inter-storey drift, highlighting the directional sensitivity of plan-irregular structures. The maximum displacement and drift were observed at 0° orientation, indicating the most critical structural response along this direction. As the excitation angle increased, both parameters gradually decreased and reached their minimum values around 45°, before increasing again towards 90°. This trend suggests that the stiffness and mass distribution of the building are not uniform in all directions, resulting in different levels of seismic demand under different excitation angles. The observed variation in response across the building height further indicates that certain storeys are more sensitive to orientation changes than others. Overall, the results demonstrate that earthquake excitation direction plays a crucial role in the seismic performance of plan-irregular buildings and should be considered during structural assessment and design to ensure a realistic evaluation of seismic behavior.

3.3 Combined effect of storey addition and orientation

The combined effect of storey addition and ground motion orientation provides a clearer understanding of the seismic behavior of the building. When both factors are considered together, the structural response becomes more critical compared to the effect of each factor individually. The addition of an extra storey increases the seismic mass and reduces the overall stiffness of the structure, resulting in higher displacement at all considered orientations.

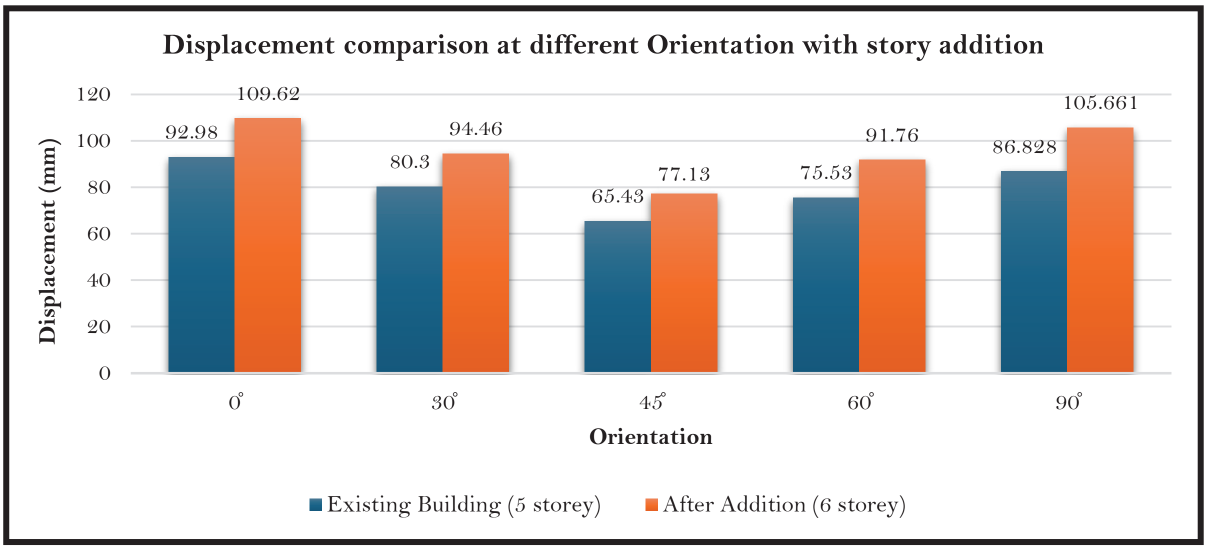


Figure 13: Displacement comparison of L-shaped building at different orientation before and after story addition

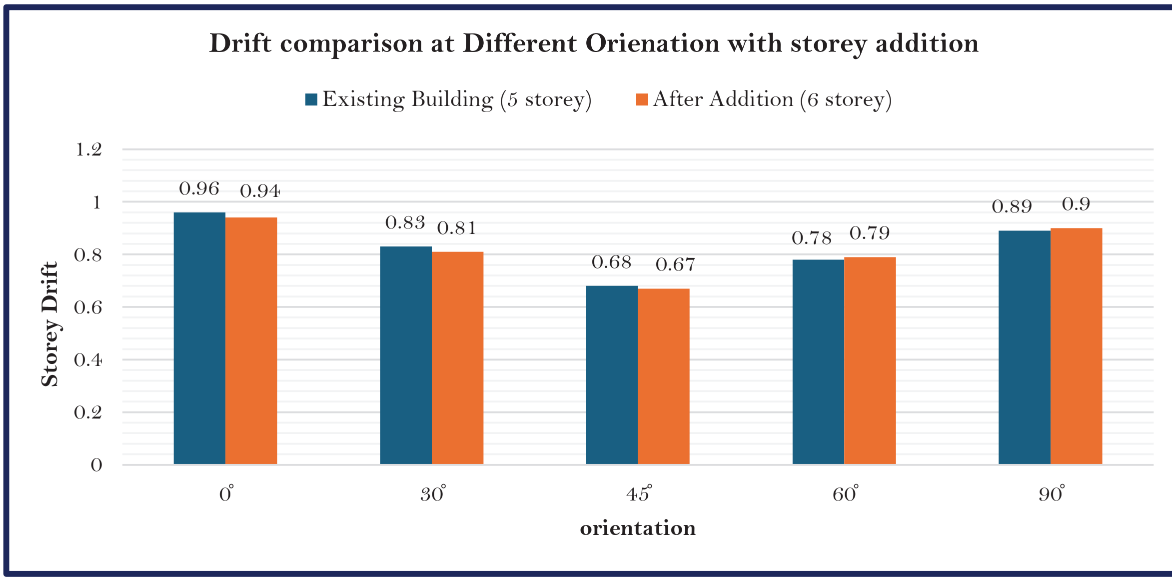


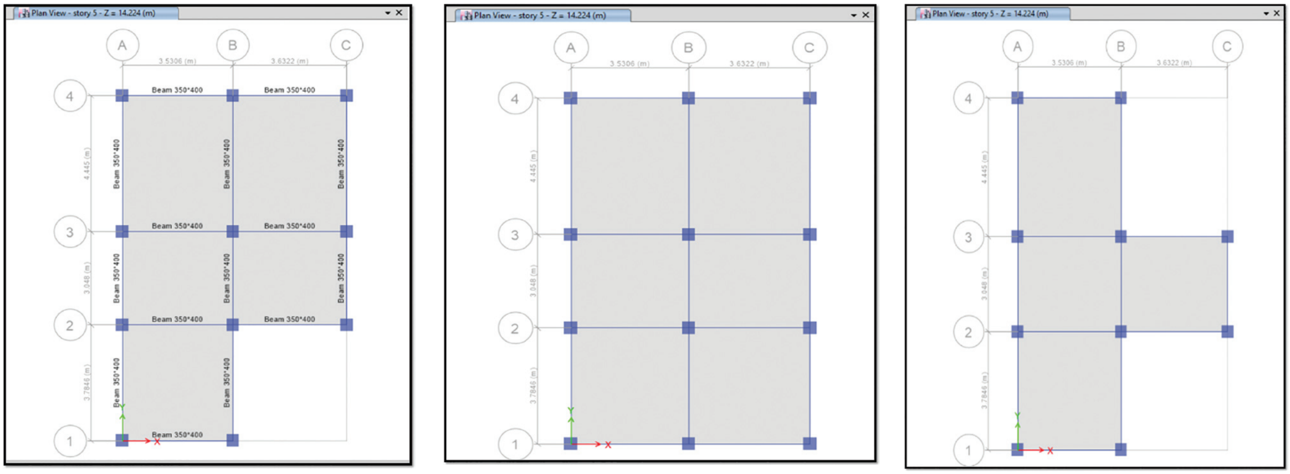
Figure 14: Inter storey drift comparison of L-shaped building at different orientation before and after story addition

The results show that the maximum displacement occurs at 0° orientation, while comparatively lower values are observed around 45°. This indicates that the response of the building is highly dependent on the direction of earthquake excitation. Even after storey addition, the same trend is observed, suggesting that building orientation continues to play an important role in governing seismic performance. A similar pattern is observed for inter-storey drift, although the variation is less significant than that of displacement and due to the structural stiffness. The increase in drift after storey addition indicates greater deformation demand on the structure, while the relatively small variation with orientation suggests that the overall drift response is influenced more by the increase in height and mass than by the change in excitation direction.

Overall, the results demonstrate that unplanned vertical expansion and earthquake excitation direction should not be evaluated separately. Their combined influence can significantly alter the seismic response of plan-irregular buildings and may lead to an underestimation of structural demand if not properly considered during seismic assessment and design.

3.4 Comparison of L-shape, rectangular and T-shaped Building

To investigate the influence of building configuration on seismic behavior, rectangular, L-shaped, and T-shaped building models were analyzed under the same loading and seismic conditions. The comparison was carried out using key response parameters such as storey displacement and inter-storey drift. Since the geometric configuration of a building directly affects its stiffness distribution and seismic behavior, the comparison helps to identify the relative performance of regular and plan-irregular structures under earthquake loading.



(a) (b) (c)

Figure 15: Plan Configurations of (a) L-shaped (b) Rectangular Shaped (c) T-shaped Building models

3.4.1 Inter-Storey Drift Response under X and Y Direction Ground Motion.

The inter-storey drift values obtained under X-direction ground motion indicate that the response of all building models changes with orientation. At 0° orientation, the rectangular building showed the highest drift value of 1%, whereas both the L-shape and T-shape buildings showed slightly lower drift values of 0.96%.

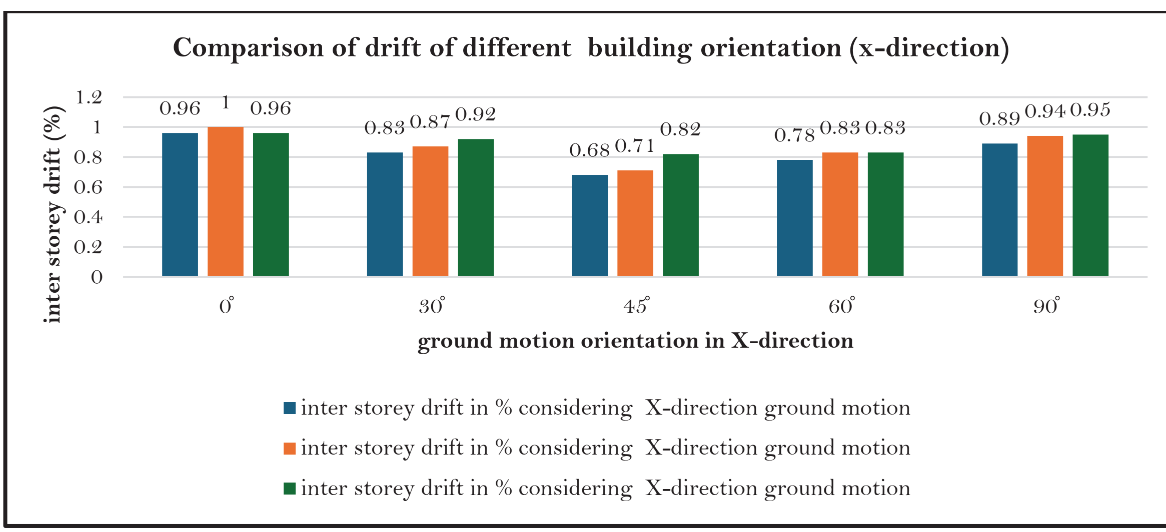


Figure 16: Comparison of drift of different building orientation (X-direction)

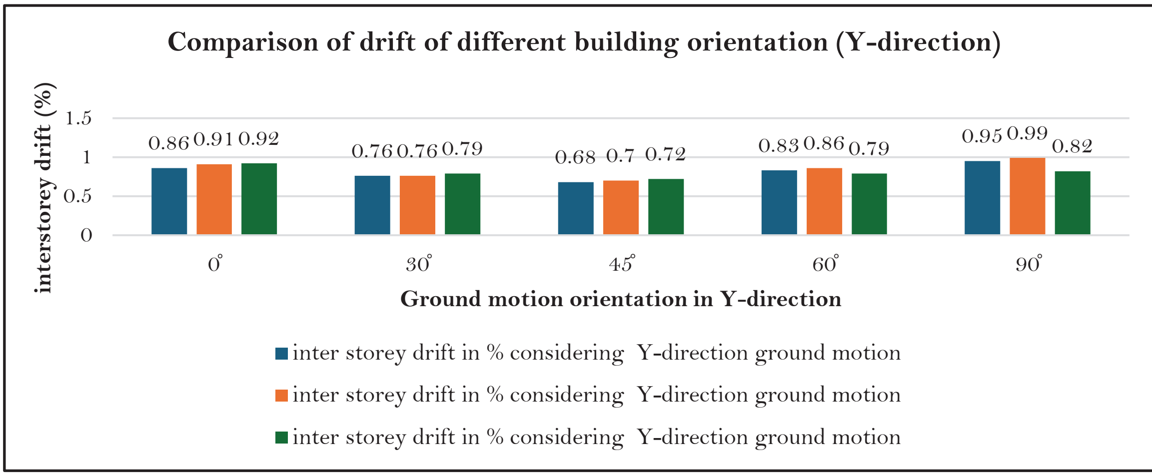


Figure 17: Comparison of drift of different building orientation (Y-direction)

The inter-storey drift response of the L-shaped, rectangular, and T-shaped buildings exhibited a similar trend under both X- and Y-direction ground motions. For all building configurations, the drift values gradually decreased from 0° to 45° orientation and increased again towards 90°, indicating that building orientation significantly influences seismic response. The minimum drift was consistently observed near 45° orientation, while comparatively higher drift values occurred at 0° and 90°. Among the three building configurations, the L-shaped building generally exhibited the lowest drift values in both loading directions, indicating comparatively better lateral performance. In contrast, the T-shaped building showed relatively higher drift values due to torsional effects associated with its plan irregularity. Although the rectangular building demonstrated stable behavior, it did not consistently produce the lowest drift response. Overall, the results indicates that seismic performance is governed not only by plan geometry but also by stiffness distribution, structural configuration, and earthquake excitation direction.

3.4.2 Displacement Response under X and Y-Direction Ground Motion

The displacement response of the L-shaped, rectangular, and T-shaped buildings exhibited a similar trend under both X- and Y-direction ground motions. For all building configurations, the displacement gradually decreased from 0° to 45° orientation and increased again towards 90°, indicating that earthquake excitation direction significantly influences structural response. The minimum displacement was consistently observed at 45° orientation.

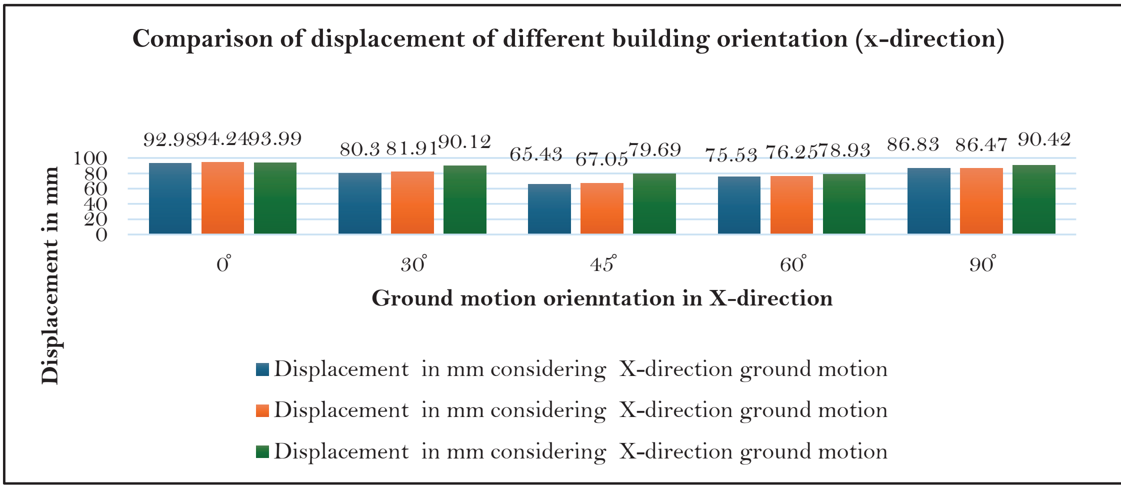


Figure 18: Comparison of Displacement of different building orientation (X-direction)

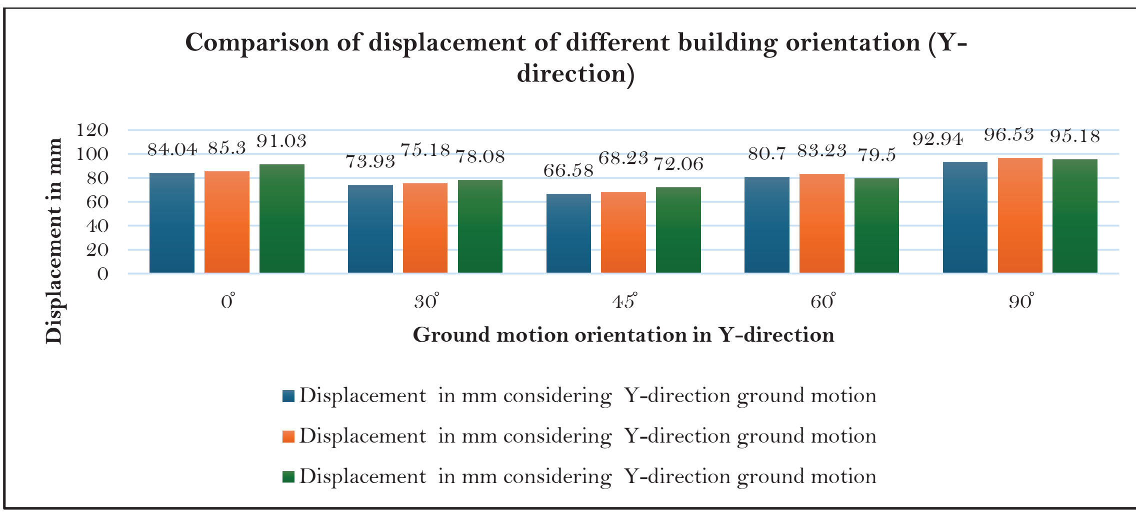


Figure 19: Comparison of Displacement of different building orientation (Y-direction)

Among the three building configurations, the L-shaped building generally exhibited the lowest displacement response, indicating comparatively better seismic performance. In contrast, the T-shaped building showed higher displacement values at most orientations due to increased torsional effects and structural flexibility associated with its plan irregularity. Overall, the results indicate that seismic displacement is influenced not only by building geometry but also by stiffness distribution and earthquake excitation direction, with the 45° orientation providing the most favorable structural response.

4. Conclusion

This study investigated the combined effect of unplanned storey addition and ground motion orientation on the seismic response of a plan-irregular reinforced concrete building. The results showed that unplanned vertical expansion significantly increased the seismic demand of the structure, while additional storey adversely affected its serviceability and, with further expansion, compromised structural safety. Ground motion orientation also had a considerable influence on seismic response, with the most critical behavior generally observed at 0° orientation and the least critical response near 45°. Comparison of different building configurations further highlighted the influence of plan irregularity on seismic performance. Overall, the findings demonstrate that unplanned vertical expansion and earthquake excitation direction should be considered simultaneously during seismic assessment to obtain a realistic evaluation of structural behavior. Therefore, detailed dynamic analysis is recommended before undertaking vertical expansion of existing buildings in seismic regions such as Nepal.

The present study was limited to linear dynamic analysis and future studies should investigate nonlinear time history analysis, soil–structure interaction, material deterioration, and retrofitting techniques to better evaluate the seismic performance of vertically expanded buildings.

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References:

https://www.dreamstime.com/buildings-kathmandu-city-unplanned-urbanization-nepal-view -random-image209027075

Panta, D., Motra, G. B., & Department of Civil Engineering, Pulchowk Campus, IOE, Tribhuvan University, Nepal. (2019). A case study for the influence of earthquake directions on the seismic behaviour of plan irregular RC infilled school buildings of Kathmandu Valley. In *Proceedings of IOE Graduate Conference* (Vol. 6, pp. 445–454).

Sahi, B., Rimal, A., Bhattrai, D., Rajkarnikar, P., Deuja, R., & Shrestha, R. (2019). Importance of orientation of structure in seismic performance. In Khwopa College of Engineering, *2nd International Conference on Earthquake Engineering and Post Disaster Reconstruction Planning.*

Gunes, B., Cosgun, T., Sayin, B., & Mangir, A. (2019). Seismic performance of an existing low-rise RC building considering the addition of a new storey. *Revista De La ConstruccióN*, *18*(3), 459–475. https://doi.org/10.7764/rdlc.18.3.459

Paul Pandian, A. V., Arunachalam, K. P., Alireza Bahrami, Lenin Miguel Bendezus Romero, Avudaiappan, S., & Awoyera, P. O. (2024). Unsymmetricity effects on seismic performance of multi-story buildings. *Discover Applied Sciences*, *6*, 476. https://doi.org/10.1007/s42452-024-06099-3s

Zaker, F. (2022). Study on Seismic Analysis of Multistorey RCC Building with Structural Irregularities. *IJERT*. https://doi.org/10.17577/IJERTCONV10IS06086

Bureau of Indian Standards. IS 1893 (Part 1): 2016—Criteria for Earthquake Resistant Design of Structures. Bureau of Indian Standards, 2016.