Investigation of Seismic Response of Irregular Steel Buildings: A Case Study of U-Shaped Structures

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Abstract. This paper presents a dynamic analysis focusing on the influence of plan shape on tall steel structures. The study specifically investigates the seismic behavior of two 22-story buildings, one with a square plan and the other adopting a U-shaped configuration. Utilizing OpenSEES platform for non-linear time history analysis, the research sheds light on the impact of plan irregularities on fundamental time periods, displacements, drift ratios, and base shear.Results reveal that the U-shaped building experiences higher dynamic response compared to the square shaped reference building. the U-shaped building experiences higher time periods across all modes due to increased mass and irregular stiffness distribution in the building's grid. Top story displacements reveal an increase in maximum displacement by 30% compared to the reference structure, showing a non-linear pattern. Inter-story drift ratios had peaks at the 8th and 18th floors showing increments of 43% and 117%, respectively. The time history response illustrates a higher response over time for the U-shaped building, indicating distinct behavioral differences. Base shear time history revealed higher values for the U-shaped building over time, including a 48% increase in maximum base shear compared to the reference building. These findings reveal the significant effect of plan regularity in tall steel building design on the seismic response and the importance of considering it in building design.

1 Introduction

The increasing concern for high-rise building safety in seismic regions is highlighted by recent earthquakes in the Middle East. In recent years, the vulnerability of high-rise buildings to earthquakes has become a significant concern, driven by their height and mass. Notably, earthquakes in the Middle East, such as the 7.8 magnitude event in Syria and Turkey in February 2023, have resulted in catastrophic damage and substantial casualties.

In the realm of seismic analysis, a series of studies spanning different years have contributed valuable insights into the behavior of structures under earthquake loads. Fajfar (2005)[1] proposed extensions to the response spectrum analysis N2 method, introducing a combined approach that incorporates pushover and linear dynamic analyses. This methodology was applied to a three-story reinforced concrete frame building, revealing the N2 method's conservatism in determining both target displacements and torsional effects.

Peres et al. (2020) [2] evaluated the effectiveness of Nonlinear Static Procedures (NSPs) for steel structures. They found that the Extended N2 method was suitable for torsional response in irregular structures. The study stressed the importance of considering higher modes in complex structural analyses.

And in 2007, Lu et al. [3] conducted a study on a high-rise building in China featuring unique architectural elements and large openings, subjecting it to shaking table testing and 3D finite element analysis to evaluate dynamic responses and structural behavior. Despite substantial openings in elevation, the structure exhibited reasonable stiffness design, with similar elastic frequencies and displacements in both X and Y directions. The design aimed to withstand seismic intensity 7 earthquakes without damage, frequent earthquakes with cracking, and rare earthquakes without collapse but with severe damages. Experimental natural frequencies matched analytical results, and the torsion period met code requirements.

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Rigid stories experienced a gradual increase in inertial force, causing abrupt inter-storey drifts. Recommendations included strengthening elements connected to rigid stories. Peak inter-storey drifts from time-history analysis closely matched experimental results under minor seismic levels but exceeded response spectral analysis, emphasizing the significance of considering higher modes in complex structural analyses. Limitations in shaking table testing were acknowledged, prompting a call for improvements in this method.

Richard et al. (2011) [4] delved into the seismic behavior of heavy industrial buildings, particularly those with irregularities in plan and vertical direction. This study emphasized the significance of the number of vibrational modes that the structure undergoes when subjected to dynamic loads considered in the analysis, showcasing that a sufficient number of modes in response spectrum analysis yielded good agreement with dynamic time history analyses.

Gerami et al. (2013) [5] took a comprehensive approach by assessing the seismic vulnerability of irregular steel buildings, considering the often-overlooked factor of panel zones. Their study, conducted in three dimensions, revealed differences in seismic resistance between low-rise and high-rise buildings, emphasizing the varying participation rates of energy and deformation in the damage.

Homaioon Ebrahimi et al. (2017) [6] investigated the impact of plan irregularities on progressive collapse in steel structures. Notably, they found that irregular structures under moderate seismic hazard were more prone to collapse, and seismic design under extreme seismic hazard resulted in reduced displacement and demand-to-capacity ratio (D/C).

Abdel Raheem et al. (2018) [7] explored the seismic response demands of L-shaped buildings, considering plan configuration irregularity. Their 3D finite element models demonstrated that increased irregularity made structures more susceptible to lateral-torsional coupling behavior and stress concentration.

Jia et al. (2022) [8] assessed the seismic performance of a 14-story office building, focusing on plan and vertical irregularities during frequent, moderate, and rare earthquakes. In instances of frequent seismic activity, all structural elements remain within elastic limits, exhibiting minimal horizontal drift. Moderate earthquakes result in a maximum horizontal displacement of 125.3 mm, occurring outside the podium building, while transfer columns and beams demonstrate desired elastic responses. Rare earthquakes lead to minimal damage in vertical members, meeting anticipated performance levels, and transfer beams and columns experience slight damage, aligning with seismic performance standards. Various structural strategies, particularly an effective beam transferring mechanism, are proposed for redistributing upper-story wall loading to lower-story columns. The recommended approach proves efficient, providing seismic and functional advantages in high-rise building design, particularly in seismic regions with composite structures.

Mohammadzadeh et al. (2021)[9] conducted a seismic response investigation on a twelve-story high-rise steel-frame building with stiffness irregularities. The building's design, created using SAP2000, featured different section profiles for various stories. ABAQUS software was employed for time-history analysis, utilizing seismic data from the Vrancea Earthquake in Romania. The study explored three irregularity scenarios: regular, plan irregularity involving torsional irregularity, and elevation irregularity with stiffness irregularity. The analysis, focusing on seismic acceleration peaks, revealed key findings. As irregularity degree increased, maximum drift steeply rose, with irregular stories exhibiting a higher rate of residual drift increase than regular ones. The regular building demonstrated superior seismic performance with lower deformation compared to irregular structures. Notably, among various irregularities, plan irregularity had the most adverse impact on seismic performance. In summary, Mohammadzadeh et al.'s study provides insights into the seismic behavior of buildings with stiffness irregularities, emphasizing their critical influence on seismic response.

showcase the evolving understanding of structural behavior under seismic loads, incorporating irregularity considerations, and the importance of different analysis methods. This study emphasizes the critical importance of designing tall steel buildings with earthquake resistance. Along with investigating the impact of plan irregularity on the seismic collapse behavior of these buildings, employing numerical modeling to enhance understanding and prevent future failures.

2 Methodology

In this study, a comparative seismic analysis of two high-rise steel building designs is undertaken, characterized by 22 stories, each with a height of 3m. The total height of the buildings is 66m. With one characterized by a square plan and the other featuring a U-shaped plan. The primary lateral load-resisting system of both buildings consists of a steel braced frame, with the specific configuration being inverted V-bracing around the periphery of the building.

The geometric properties include steel columns spaced at each 3.5m. The steel sections utilized are explained in Table (1).

Table 1. Distribution of steel sections used in building models.

Floor	U-shaped Building			Regular (reference) Building		
	Beams	Columns	Bracing	Beams	Columns	Bracing
1	W10x77	W14x99 W14x132	HSS6x5x1/8	W10x77	W14x99 W14x132 W16x100	HSS6x5x1/8
2	W10x77	W10x77 W14x99	HSS6x5x1/8	W10x77	W10x77 W16x100	HSS6x5x1/8
3	W10x77	W10x77 W14x99	HSS6x5x1/8	W10x77	W10x77 W16x100	HSS6x5x1/8
4	W10x77	W10x77 W14x99	HSS6x5x1/8	W10x77	W10x77 W16x100	HSS6x5x1/8
5 to 22	W10x77	W10x77	HSS6x5x1/8	W10x77	W10x77	HSS6x5x1/8

The plan view of the buildings is illustrated in **Figure (1)** and **Figure (2)** The selected buildings adhere to standard design parameters according to AISC-LRFD[10] method to withstand static loading.

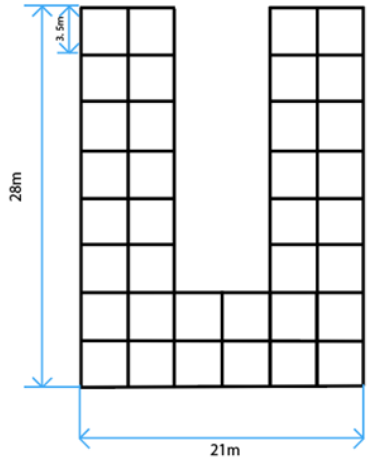

Fig. 1. Illustration of plan view of U-shaped building.

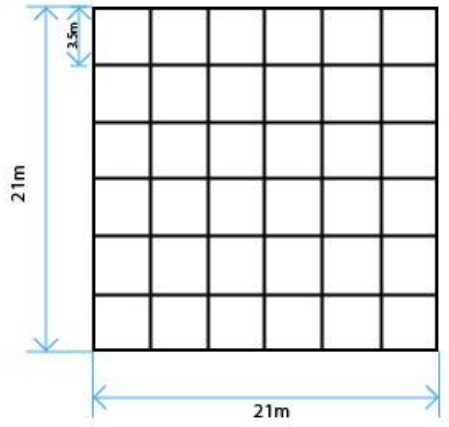

Fig. 2. Illustration of plan view of regular (reference) building.

Material properties of steel are defined as an elastic perfectly plastic material, as shown in **Figure (3)**.

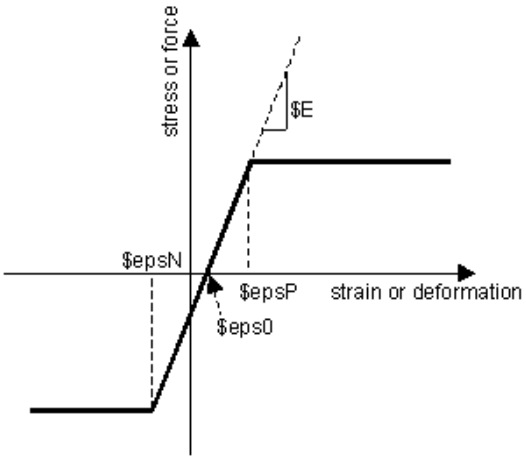

Fig. 3. Material properties of steel used in the model.[11]

Self-weight was applied as a uniformly distributed load along the members of the building, including superimposed dead load. After static-loading, time was reset to zero and a set of ground motion records, representative of regional seismic scenarios, is curated for the study. Time history analyses are undertaken to investigate the influence of plan irregularities, on seismic performance.

Validation against available experimental data from Bai (2021)[12] ensures the accuracy of the numerical models as shown in **Figure (4)** and **Figure (5).**

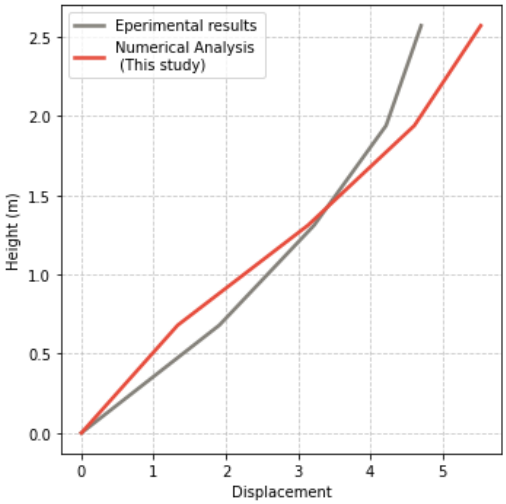

Fig. 4. Comparison between displacements of numerical and experimental model analysis results[12].

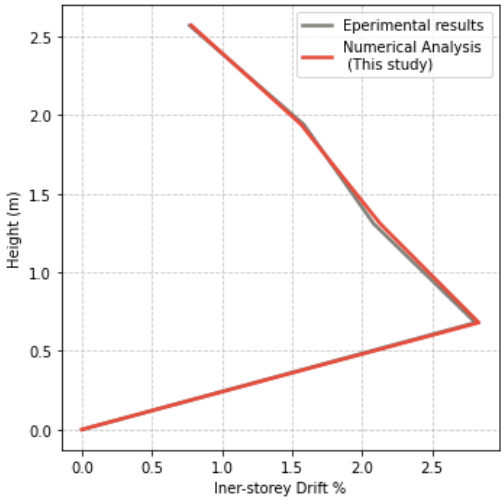

Fig. 5. Comparison between story drift of numerical and experimental analysis results[12].

3 Numerical Analysis

OpenSEES utilizes the finite element method (FEM) to conduct dynamic and seismic analyses by discretizing structures into interconnected elements at nodes with specified material properties. Nonlinear time history analysis is performed by applying dynamic load that consists of EL-Centro earthquake ground motion in **Figure (6)** uniformly to all supports. The peak ground accelerations (PGA) have been scaled to match the peak ground acceleration of Halabja earthquake in 2017 to convey regional earthquakes similarity. The analysis, centered on node displacement as the primary response, solves equations of motion incorporating mass, damping, and stiffness characteristics. Seismic analysis in OpenSEES accounts for the dynamic interaction with ground motion. The use of the reverse

Cuthill McKee (RCM) numberer to reduce the bandwidth of the stiffness matrix and Broyden–Fletcher–Goldfarb–Shanno (BFGS) algorithm aids in matrix construction and solution, ensuring convergence. Additionally, the Newmark method[13]serves as an integrator for incremental analysis, facilitating the consideration of both linear and nonlinear behaviors, encompassing effects such as yielding and plastic deformation. This comprehensive approach guarantees the accurate simulation of structural responses to seismic excitation.

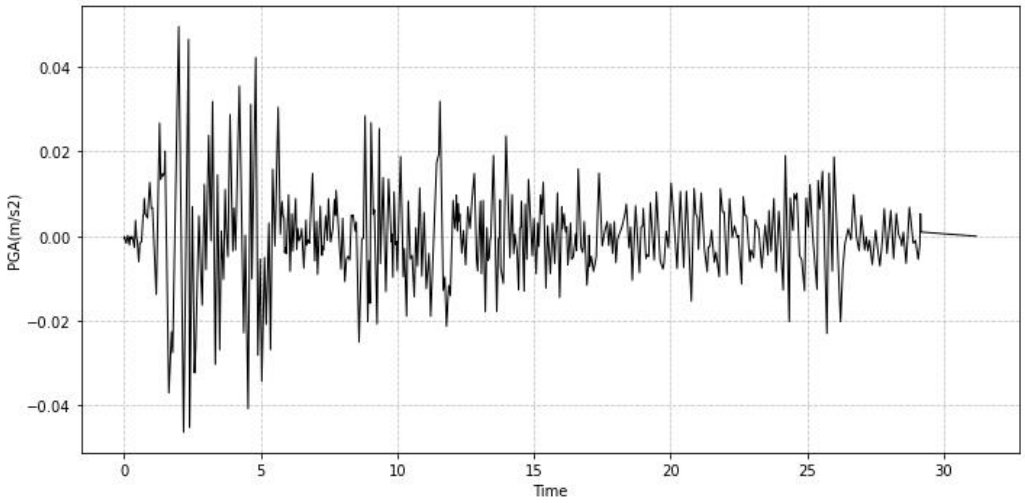

Fig. 6. Scaled EL-Centro ground motion used in this study.

4 Results and discussion

The selected node, as depicted in **Figure (7)** and **Figure (8)**, is a crucial point due to its role in abrupt changes in the building plan's cross-section, leading to variations in stiffness.

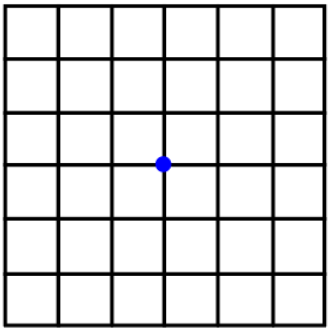

Fig. 7. Node selected for analysis of reference building.

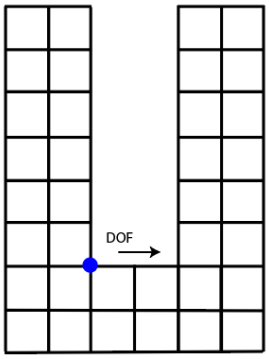

Fig. 8. Node selected for analysis of U-shaped building.

The fundamental time periods for each vibrational mode are shown in **Figure (9).** Each mode represents a failure scenario of the building. These modes correspond to the time periods of the building. The higher the time period, the more probable is the failure in this mode. It is clear that the U-shaped building experiences higher fundamental time periods across all vibrational modes. he due to its increased mass and irregular stiffness distribution in the building's grid.

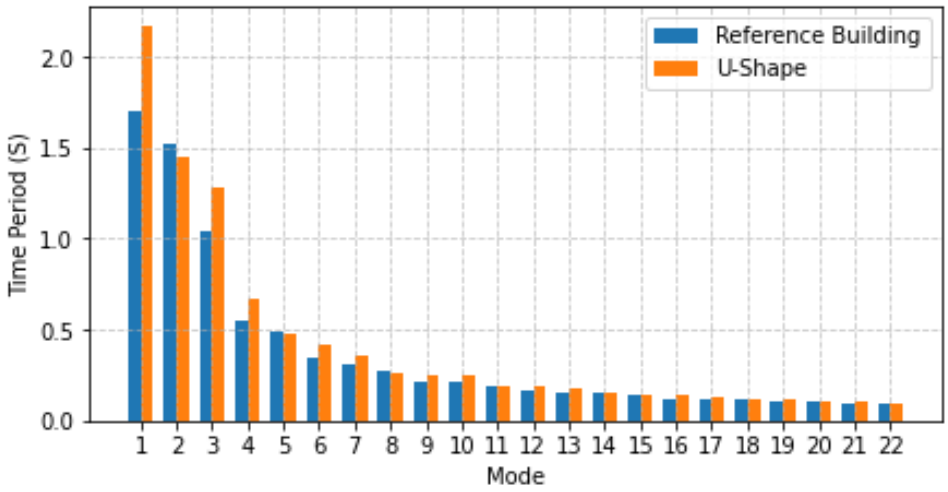

Fig. 9. Fundamental Time periods for 22 mode shapes of building models.

Examining the top story displacements in **Figure (10)**, it is evident that the U-shaped building demonstrates greater displacements compared to the reference building, with a non-linear pattern resembling that of the reference structure. The top story displacement increased by 30%. Regarding inter-story drift displayed in **Figure (11)**, the U-shaped building exhibits significantly high drift ratios within the first 15 meters of height, followed by a steady decrease until 50 meters, where a noticeable increase occurs. The peaks, notably at the 8th and 18th floors, show increments of 43% and 117%, respectively.

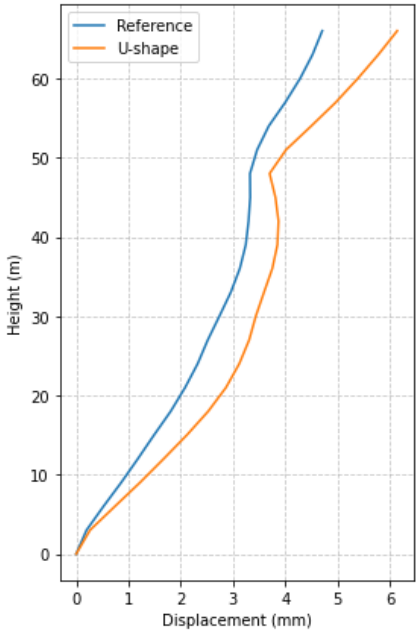

Fig. 10. Top story displacement over height for building models.

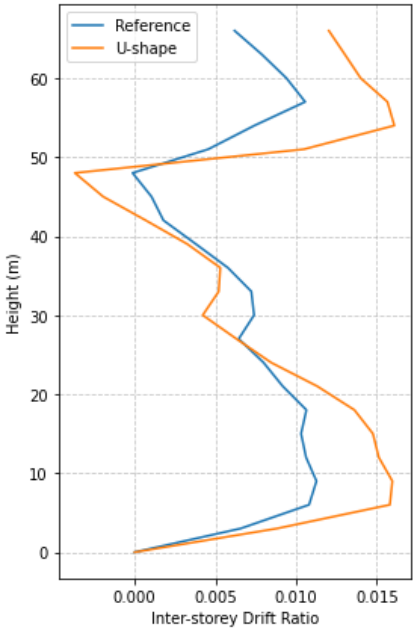

Fig. 11. Inter story drift ratio over height for building models.

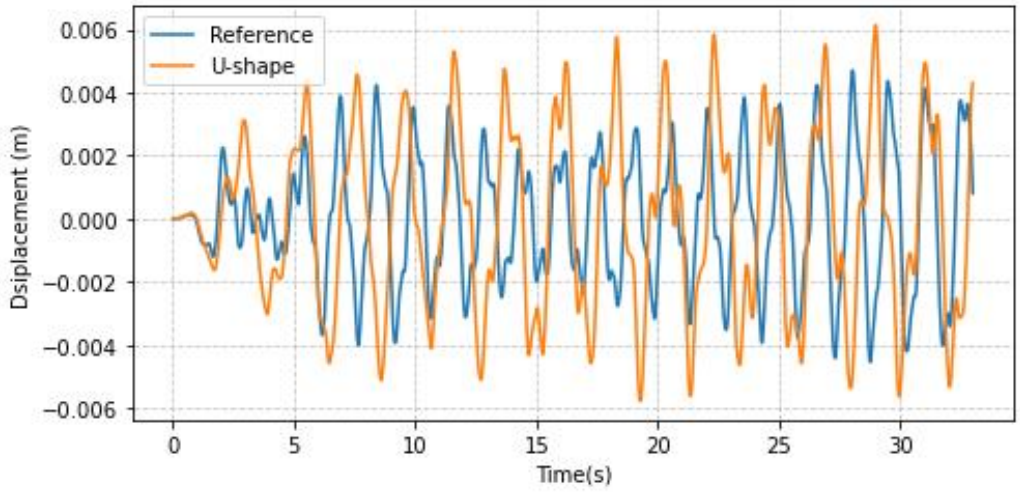

Fig. 12. Displacement Time-History of building models.

In **Figure (12)**, the time history response of both buildings is illustrated, revealing that the U-shaped building exhibits a higher response over time. The misalignment of most peaks with those of the reference building indicates distinct behavioral differences in response to the applied ground motions. **Table (2)** provides a summary of displacement time history values. The negative values indicate movement in opposite direction.

It is worth mentioning that the value of displacement of 4.705mm was achieved in the U-shaped building at 11.52 seconds instead of 28.04 seconds in the reference building. This highlights the effect of amplification in displacements due to the irregular distribution of stiffness across the grid of the building.

Table 2. Displacement Time-history data summary.

Building	Max. Displacement (mm)	Time (s)	PGA	Increment %
Reference Building	4.70255	28.04	-0.02044	0
U Shape	6.13591	28.98	0.00661	30.48

Base shear time history is illustrated in **Figure (13)** U-shaped building exhibits higher base shear values over time. The Reference Building exhibited a moderate base shear of 319.03 KN, accompanied by a peak ground acceleration (PGA) of -0.00469 m/s² occurring at 29.68 seconds. While U-shaped building exhibited 473.6282 KN at a peak ground acceleration of -0.00279 m/s^2 at a time of 30.28 seconds. **Table (3)** provides a summary of base shear time history values. The negative values indicate movement in opposite direction. The times at which both buildings reach the maximum base shear values are very close since both are subjected to the same ground motion. The base shear value was increased by 48% due to the increased torsional effect on the base of the building that results from the irregularity in plan shape.

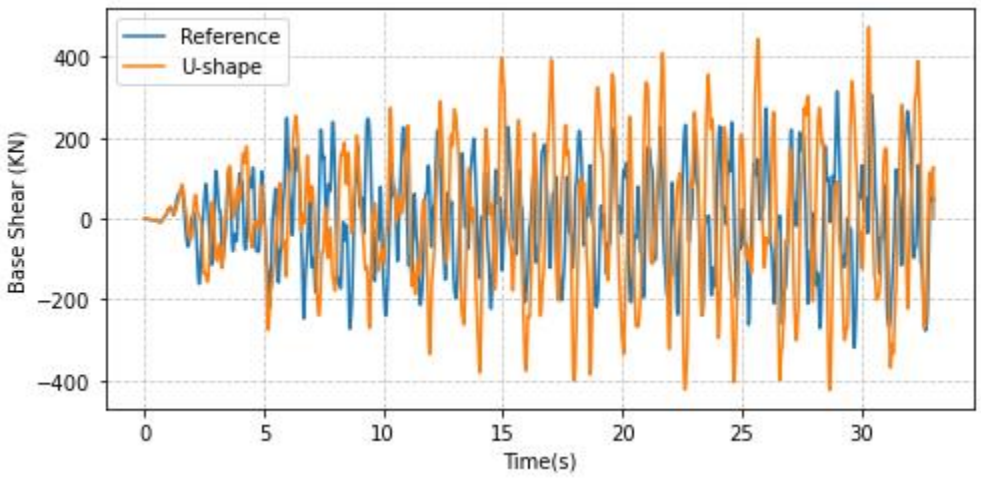

Fig. 13. Base shear time-history of building models.

Table 3. Base Shear Time-history data summary.

	Reference Building	**U Shape**
Time (s)	29.68	30.28
PGA (m/s²)	-0.00469	-0.00279
Base shear (KN)	319.03132	473.6282

5 Conclusions

In this study, nonlinear time history analysis was conducted to compare the seismic behavior of tall steel structures, specifically focusing on a regular and a U-shaped steel building. The effect of plan shape was investigated through non-linear time history analysis applying scaled EL-Centro ground motion.

It was concluded that the introduction of plan irregularity, as observed in the U-shaped building, resulted in a significant amplification of the seismic response. Increases of 30% in maximum displacement and 117% in maximum drift ratio were noted. The distribution of stiffness differences led to a notable rise in time periods, coupled with a 48% increase in maximum base shear.

recommendations for future research involve the exploration of the impact of earthquake direction, the assessment of soil-structure interaction, the construction of fragility curves, and the examination of mitigation strategies and economic losses across diverse plan shapes in buildings. These avenues of investigation are deemed crucial for the enhancement of seismic resilience in structural design.

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