International Journal of GEOMATE, Sep., 2025 Vol.29, Issue 133, pp.139-146
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2025.133.5048
Geotechnique, Construction Materials and Environment

SEISMIC PERFORMANCE EVALUATION OF STEEL BUILDINGS WITH STRUCTURAL MODIFICATION TECHNIQUES

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*Corresponding Author, Received: 14 May 2025, Revised: 09 June 2025, Accepted: 11 June 2025

ABSTRACT: Steel buildings are widely used as multi-story buildings due to their high strength and ductility. However, they remain vulnerable to seismic forces, especially in seismically active regions. This study conducted a 3D nonlinear time-history analysis using ABAQUS to evaluate the impact of structural modifications on the overall real-life constructed building. Every model was examined using the El Centro earthquake 0.32g. The results showed that weakened columns and higher ground floors exhibited longer natural time periods due to the decrease in stiffness. In contrast, strengthened columns decreased the time period, reflecting enhanced rigidity. Top floor maximum displacements were increased by 26.4% and 16.5% in the weakened column and higher ground floor, and reduced by 26.4% and 0.433% in the strengthened column and joint reinforcement, respectively. Inter-story drift was most pronounced in the model with weak column sections, while the higher ground floor showed soft-story behavior, and the stronger column sections showed a considerable decrease in drift. In weakened columns, strengthened columns, and ground floor height increased the timing of peak displacements by 1.8%, 15.4%, and 3.9%, respectively, while joint reinforcement experienced a reduction of 0.36%. Base shear was increased by 7.6% in thickening column sections, while weakening columns, joint reinforcement, and raising the ground floor experienced decreases of 8.0%, 0.99%, and 8.5%, respectively. Acceleration amplification was the largest at the roof in weakened columns and the smallest in the referenced model. Overall, column strengthening proved to be the most effective technique, while column weakening and increasing floor height significantly compromised seismic safety.

Keywords: Steel structures, Seismic loading, Fixed base, Strengthening methods

1. INTRODUCTION

Steel frame structures are widely used in multi-story buildings due to their high strength, ductility, and efficiency. Despite their advantages, these structures can be vulnerable to seismic forces, especially in regions prone to strong ground motions.

In the case of an earthquake or other natural disaster, a building often has multiple weaknesses that can be identified. Factors such as building type, materials, architectural design, and soil type are important variables that might affect the risk level. Weaknesses in buildings have a significant impact on the overall structure's vulnerability, which may lead to serious damage or the collapse of the structure. Vulnerabilities may arise from the weak connections between beams and columns or other connection parts within the framing system. It is essential to have well-planned and precise connections strong enough to withstand the stresses applied during an earthquake. As well as column buckling failure, in response to the 1985 Mexico City earthquake, designers ensured that seismic load-resisting systems had sufficiently strong columns to withstand the highest possible axial forces. Column failures were observed in Mexico City due to localized buckling, suggesting that insufficient column strength was the main reason [1].

Structural modifications are often required to ensure the safety and functionality of such buildings during and after earthquakes. Many researchers have studied the seismic behavior of steel structures and explored different types of modifications and retrofitting techniques using experimental and numerical approaches. The seismic collapse of multi-story buildings varies depending on several factors within the structure itself, the intensity of the ground motion, and the configurations of the buildings [2-5].

For steel structures retrofitting and modifications, bracing systems are a common way of retrofitting steel frame structures. Di Sarno and Elnashai investigated how concentrically braced frames (SCBFs), buckling-restrained braced frames (BRBFs), and mega-braces (MBFs) are effective in specific cases as retrofitting methods [6]. Another approach is using dampers. Masoud and Mehdi investigated the use of metal-yielding dampers, finding that rough-riding earthquake retrofitting of steel-frame buildings on soft soil can increase the safety and serviceability of deficient buildings, while reducing residual displacements and inter-story drifts. The use of engineering materials also gave promising results [7].

Advanced engineering materials also can be used Teng, Yu , and Fernando investigated the use of fiber-reinforced polymer (FRP) composites to enhance steel structures, with a focus on their high strength-to-weight ratio and corrosion resistance, and examines numerous strengthening methods, issues such as bonding and debonding failures, and the necessity for additional research into surface preparation and adhesive selection. Despite the obstacles, the main key findings are that FRP composites offer a viable approach for improving the performance of steel structures [8].

And for the reinforced concrete structures, Shirin, Mohammed J., and Mohammed show that using RC infill walls provides an alternative retrofit method that can be effective for the structure design only to carry gravity load by increasing overall strength and ductility and reducing structural deficiencies [9]. Fei, Zhiqiang, Shilong, Biao, Shitao, and Junbo study joint core hoop reinforcement, and they observed a significant improvement in the ductility of beam-column joints made of reinforced concrete (RC) when the joints are prone to shear failure [10]. Trung-Hieu evaluates how Ultra High-Performance Concrete (UHPC) impacts the seismic performance of reinforced concrete building exterior beam-column joints. The result shows retrofitting using UHPC significantly enhances load capacity, ductile strength, and energy dissipation [11].

A correct foundation embedment depth can be used as a suitable modification technique to modify the multi-story building's seismic response [12,13]. Previous research has covered many aspects of seismic retrofitting, such as base isolation, bracing systems, fiber-reinforced polymers, and material improvements. Nevertheless, few comparative studies concentrate exclusively on fixed-base steel structures with efficient yet straightforward strengthening measures.

The overall ability of buildings to resist seismic forces diminishes with age. Maintaining structural integrity under seismic stress depends critically on the strength and efficiency of specific modification methods. Although many studies have been conducted on retrofitting concrete frames, steel buildings remain under-researched. Further study on retrofitting techniques for steel structures, including cost, design efficiency, and performance comparisons, is required to improve the body of knowledge.

This study aims to evaluate the efficiency of four modification methods for steel structure buildings:

2. RESEARCH SIGNIFICANCE

This research explores the seismic behavior of steel buildings using methods of structural modifications, such as modifying column sections, reinforcing joints, and increasing ground level in comparison with the fixed-base model. The research also shows the effective use of site-specific retrofitting (joint reinforcement) for increased earthquake resistance. The comparison offers practical lessons for engineers and designers in search of cost-efficient measures to enhance structural safety. Finally, this study tends to reduce the gap between full-scale existing buildings by simulating the realistic behavior of structures and numerical modelling.

3. METHODOLOGY

In this study, a 3D nonlinear time-history analysis was conducted using ABAQUS-Finite Element Software to investigate the seismic performance of a steel structure building.

3.1 Geometry and Structural Configuration

A real-life constructed building was adopted and described as a low-rise 3D frame structure that has a 4-story and 2 bay by 2 bay configuration and was designed following the provisions of AISC Standard Manual for design of steel structures [14]

3.2 Material Properties

The modulus of elasticity (Ec) of slabs and shear walls was calculated using their compressive strength (fc′) and a Poisson's ratio (v) of 0.2. Table 1 summarizes the mechanical characteristics of the materials employed in the structure.

Table 1. Material properties.

Material	Property	Value
Concrete	Compressive strength fc′	28 MPa
	Young modulus EC	24800 MPa
	Poisson's ratio	0.2
Steel reinforcement bars	Yield Strength steel fy	420 MPa
	Ultimate Strength steel fu	620 MPa
	Young modulus ES	200,000 MPa
	Poisson's ratio	0.3
Steel Section	Yield Strength steel fy	275 MPa
	Ultimate Strength steel fu	500 MPa
	Young modulus ES	200,000 MPa
	Poisson's ratio	0.3

3.3 Loading Conditions

According to standard design principles, the structural analysis takes into account a variety of load types. All structural components' self-weight is included in dead loads, which are determined using a concrete density of 24 kN/m^3. Partition walls and floor finishing materials add an additional 1.0

kN/m2, and further superimposed dead loads are added at 1.5 kN/m². According to the Iraqi Code of Loads and Forces (301, 2015) [15], live loads were assigned with a value of 1.0 kN/m² for the roof level and 2.0 kN/m² for typical floors. In order to guarantee a precise representation of the total loading, conditions placed on the building, external wall loads are also included in the study.

3.4 Finite Element Modeling

The current study was done using Finite Element Method with ABAQUS 2019 to model and evaluate a steel structure under seismic loading. The S4R element was used to model beams, girders and columns. The S4R element is a four node doubly curved shell element that integrates with hourglass control and can enable finite membrane strain and is capable of operating under both thin and thick shell applications. Shear walls, pedestals and slabs were modeled with C3D8R element, which is an eight node linear brick element that is suitable for solids. Cross-rod steel bars were modeled with T3D2 element which is a two node truss element that has three degrees of freedom in translation motion, enabling modeling in three dimensions. All nodes in the model have three degrees of freedom in x, y, and z axes to enable movement. The structural analysis was performed in 2 steps through Dynamic Implicit method; the first imposing static and gravity loads as the second applying the El Centro earthquake ground motion as a seismic load. Figs (2-4) show the created parts and models in ABAQUS. The supports on the foundation are modelled as fixed by limiting the nodes.

To evaluate complete interaction, the steel bars are considered to be entirely embedded in concrete. The tie constraint option was used for joining two different surfaces together so that no relative motion exists between them. Also, the Tie constraint option was used for joining two different surfaces together. Finally, the Tie constraint option was used for joining two different surfaces together.

4. NUMERICAL RESULTS

This research analyzed four different scenarios, which are described below. Several key structural outcomes, including (natural period, Drift ratios and displacement, Displacement time history, Base shear time history, and Acceleration amplification), comprise the obtained results. The following cases will be utilized:

Case 1 illustrates the building's reference model, which includes all of the previously specified building characteristics and loads. In this case, fixed support was used to represent the foundations beneath the pedestal.

Case 2 represents the second model of the building, with one difference, which is weakening the column sections by reducing the thickness of the flange and web for all columns by half.

Case 3 represents the third building model, with one difference: it strengthens the column sections by doubling the thickness of the flange and web for all columns.

Case 4 represents the fourth model of the building, with the addition of strengthening the joints by connecting the columns and beams with additional steel sections at the joints.

Case 5 represents the fifth model of the building, with one difference: changing the ground floor's height from 4.3 to 5.3 m.

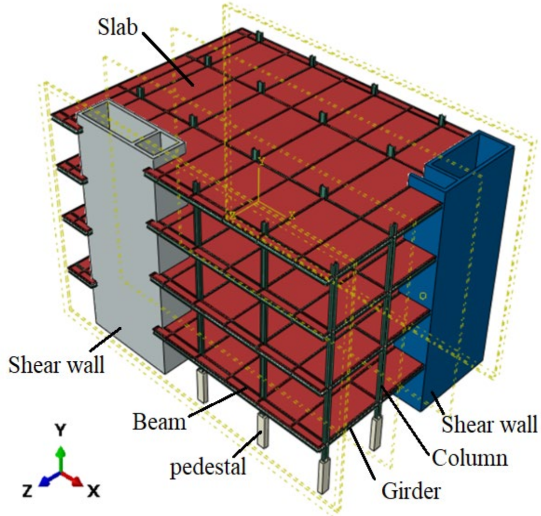

Fig. 2 Creating parts and assembly in ABAQUS

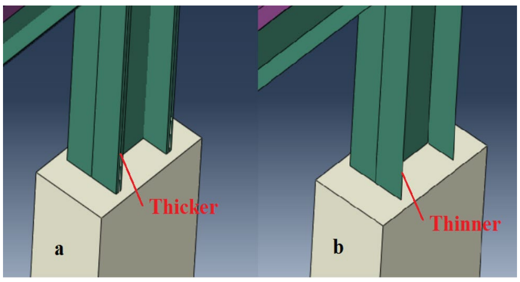

Fig. 3 a) Model with thicker column sections, b) Model with thinner column sections.

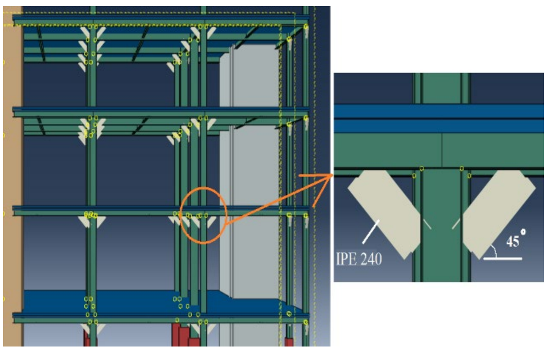

Fig. 4 Model with strengthening joints

The El-Centro 1940 NS earthquake was applied with a PGA of 0.32g as a base excitation. Which is represented in Fig. 5 below:

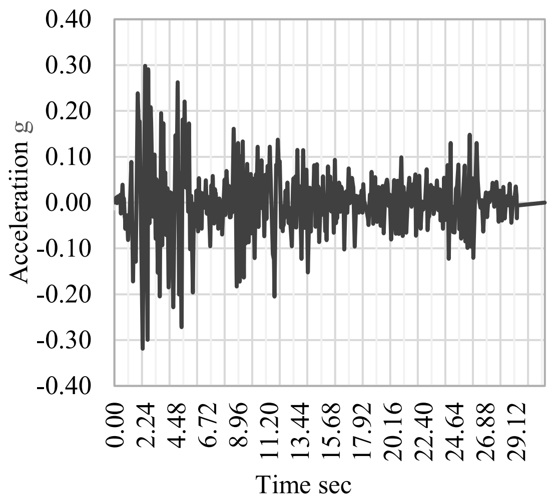

Fig. 5 El-Centro Earthquake 0.32g

The seismic performance of the steel structure under different scenarios was evaluated in this study using five key evaluation metrics: base shear, acceleration amplification, maximum displacement at the top floor, inter-story drift, and time to maximum displacement. Expected trends in structural stiffness and vulnerability are reflected in the clear and consistent variations across the cases of the metrics that are directly related to earthquake damage: maximum displacement and inter-story drift. However, because of the structure's dynamic behavior, which is dependent on several interrelated factors, including base shear, time to maximum displacement, and acceleration amplification, are more complicated. This section first describes the distinct patterns in the direct damage metrics before going into great detail about the more complex dynamic reactions that the indirect metrics showed.

4.1 Natural Time Period

The amount of time needed for a building to complete one full vibration cycle is known as the natural time period. Table 2 displays the natural time periods for each case.

Table 2. Fundamental time period (in seconds) for each case.

Mode	Case 1	Case 2	Case 3	Case 4	Case 5
1	2.294	2.538	2.11	2.288	2.833
2	1.567	1.715	1.473	1.565	1.98
3	1.473	1.637	1.353	1.471	1.745
4	0.671	0.76	0.583	0.667	0.741
5	0.548	0.549	0.547	0.548	0.652
6	0.53	0.531	0.529	0.53	0.618

5. ANALYSIS OF NUMERICAL RESULTS AND DISCUSSION

From the results reported in the figures and tables, the following were observed:

For the natural time period, Table 2 show how different structural alterations affect a building's natural time periods in six different vibration modes. case 2 results in longer time periods because of lower stiffness than case 1, but case 3 results in shorter time periods because of increased rigidity. In comparison to case3, case 4 have a moderate effect, slightly increasing the time period. However, the longest periods occur in case 5, indicating either a soft-story effect or a major decrease in overall structural stiffness. Less variations is seen in higher modes (4–6), suggesting localized dynamic behavior. As shown in Fig 6.

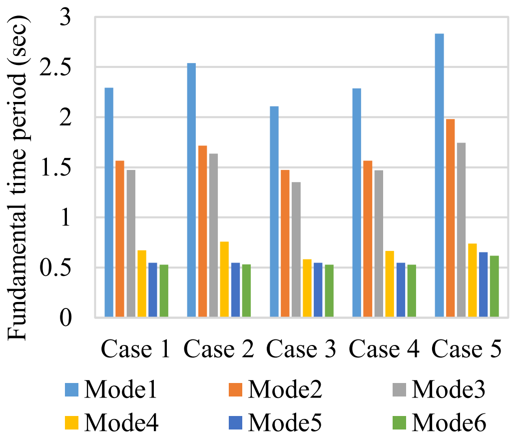

Fig. 6 A comparison of the fundamental time period according to modes.

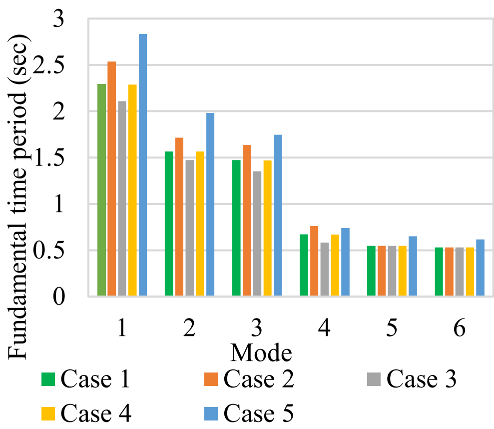

Fig. 7 A comparison of the fundamental time period according to cases.

5.1 Story Drift Ratios and Displacements

The maximum displacements at the top floors, as summarized in Table 3, increased by 26.4% and 16.5% for cases 2 and 5, respectively, since the smaller the dimensions of the column sections or the higher their height, the less stiff the building becomes. while the maximum displacements at the top levels are reduced by 26.4%, 0.433%, and case 3 and case 4. As shown in Fig 8.

And for the inter-story drift, Case 1 shows the typical drift distribution peaked at mid-height. case 2 produces much larger drift showing reduced lateral stiffness and increased vulnerability to damage. case 3, on the other hand, reduces drift by a large amount throughout the height, exhibiting increased stiffness and seismic safety. case 4 shows a modest improvement over the baseline with some reduction in drift. case 5 shows a soft-story behavior with large, concentrated drift at the lower and mid-levels, which may lead to a critical failure mechanism. As shown in Fig 9.

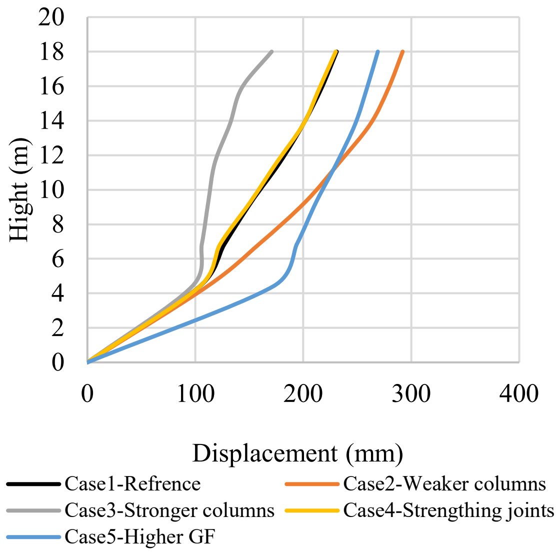

Fig. 8 Top node displacement over height.

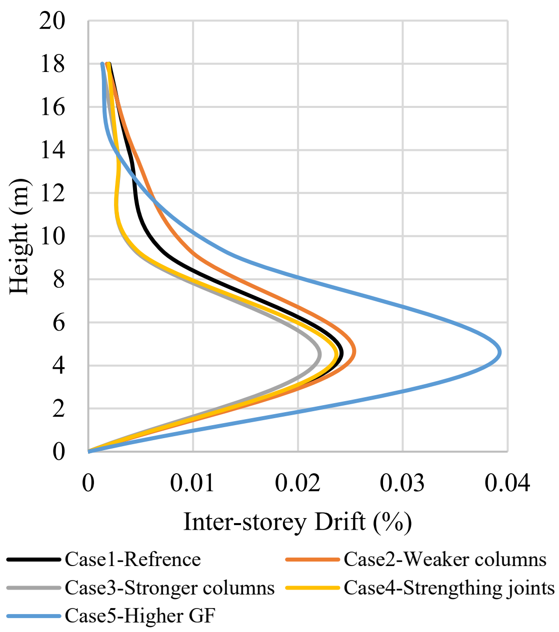

Fig. 9 Inter-story drift ratio over height.

Table 3. Percentage of change in Max. disp. At the top of the building with respect to the reference case.

Cases	Max. disp. At the top (mm)	Percentage of change in Max. disp. with respect to the reference
Case1	231	Ref.
Case2	292	26.4
Case3	170	-26.4
Case4	230	-0.433
Case5	269	16.5

5.2 Displacement Time-History

Figures 10-13 compare the displacement time-history results of each case to case 1 (reference). The time for Max. disp. rose by 1.8, 15.4, and 3.9% for case 2, case 3, and case 5 respectively, decreases by 0.36% for case 4. Table 4 summarizes the time history for each case.

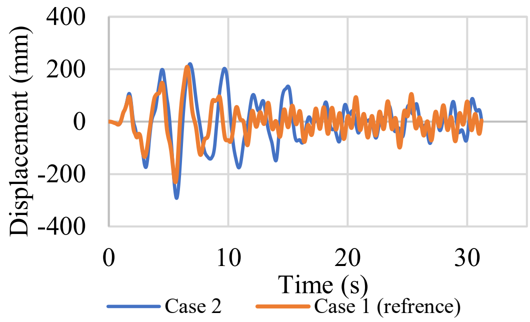

Fig. 10 A comparison in displacement time-history results between case 2 and case 1 (reference).

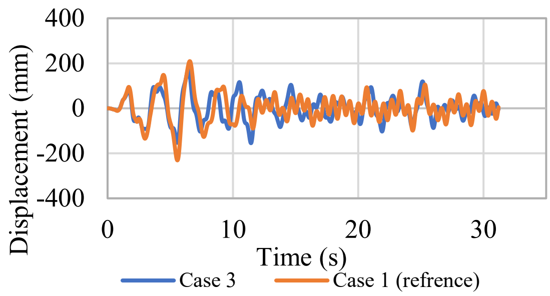

Fig. 11 A comparison in displacement time-history results between case 3 and case 1 (reference).

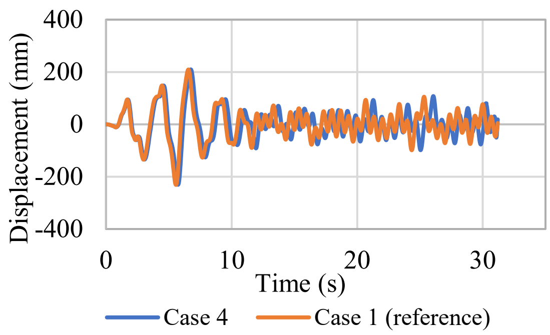

Fig. 12 A comparison in displacement time-history results between case 4 and case 1 (reference).

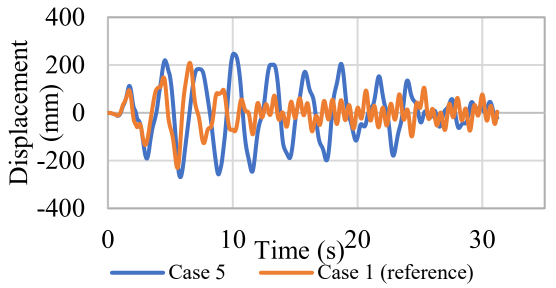

Fig. 13 A comparison in displacement time-history results between case 5 and case 1 (reference).

Table 4. Summary of displacement time history for each case

Case	Max. Displacement at the top floor (mm)	Time of Max. disp (s)	Percentage of change in time of Max. disp. with respect to the reference (%)	PGA (m/s^2)
1	231	5.58	Ref.	5.59
2	292	5.68	1.8	-3.15
3	170	6.44	15.4	4.77
4	230	5.56	-0.36	5.35
5	269	5.8	3.9	-3.37

5.3 Base Shear Time-History

Figures 14-17 show how the base shear changes for each case during the earthquake compared to the reference model. The max base shear rose by 7.6% for case 3, while the Max base shear decreased by 8%, 0.99%, and 8.5% for case 2, case 4, and case 5, respectively. Table 5 summarizes the base shear time history for each case.

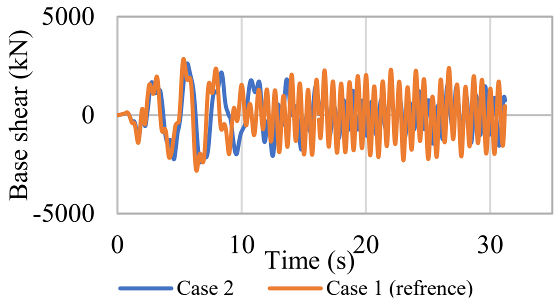

Fig. 14 A comparison in Base shear time-history results between case 2 and case 1 (reference).

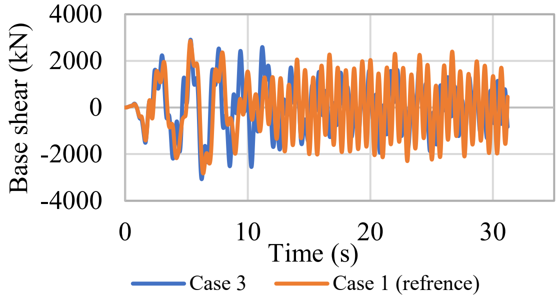

Fig. 15 A comparison in Base shear time-history results between case 3 and case 1 (reference).

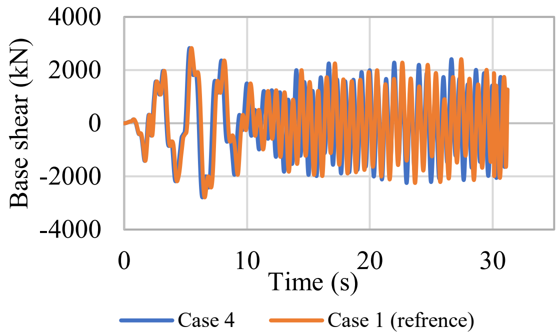

Fig. 16. A comparison in Base shear time-history results between case 4 and case 1 (reference).

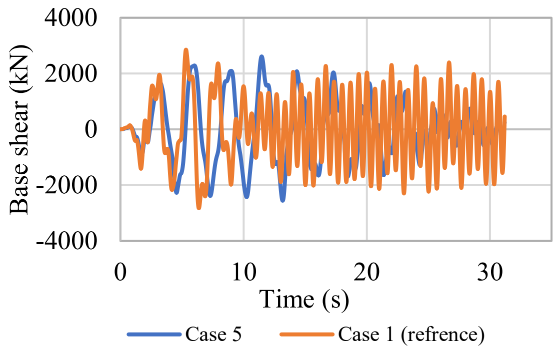

Fig. 17 A comparison in Base shear time-history results between case 5 and case 1 (reference).

Table 5. Summary of Base shear time history for each case.

Cases	PGA (m/s^2)	Time of Vmax (s)	Max Base shear, Vmax (kN)	Percentage of change in Vmax with respect to the reference (%)
Case 1	5.59	5.32	2856.9	Ref.
Case 2	-3.15	5.62	2628.2	-8
Case 3	4.77	6.24	3073.5**	7.6
Case 4	5.35	5.53	2828.7	-0.99
Case 5	-3.37	11.46	2612.8	-8.5

** Movement in opposite direction

5.4 Acceleration Amplification

Figure 18 illustrates the highest acceleration amplification factor across the height of the building for each case. All cases had similar values to the reference case at the top of the ground floor, but then the values began to vary. At the top of the building, case 2 shows the greatest value of Max. AAF, whereas the reference case shows the lowest value.

Acceleration amplification is computed using Eq. (1) by dividing the maximum acceleration at any given time by the peak ground acceleration applied to the building. [16]

$$\text{Max. AAF} = \frac{\text{Max.acceleration}}{\text{PGA}} \tag{1}$$

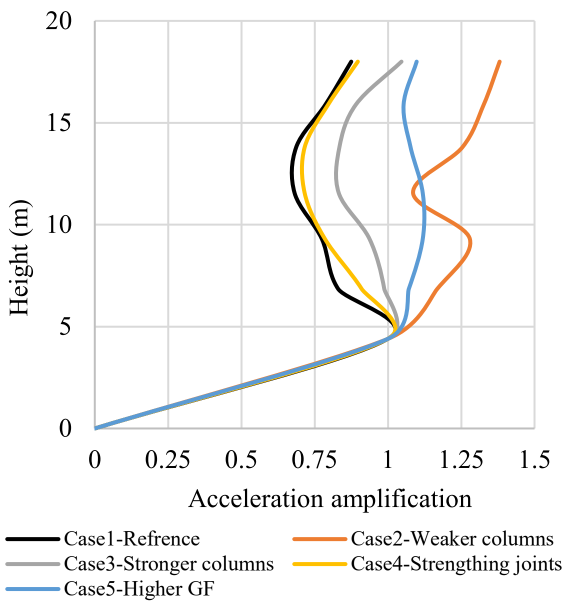

Fig. 18 Acceleration Amplification

6. CONCLUSION

Four structural modification methods were assessed in this study in order to enhance a multi-story steel building's seismic performance. The findings imply that the best option is to reinforce the column sections, which will greatly increase building stiffness, decrease drift and displacement, and increase base shear capacity, all of which are essential for maintaining structural integrity during seismic events.

In contrast, weakening column sections or raising the ground floor significantly reduced structural performance, resulting in soft-story effects, extended vibration periods, and increased displacements, all of which increase the possibility of structural failure during strong ground motions.

In existing buildings where complete replacement or section enlargement is not practical, joint strengthening provides a viable retrofit option and offers modest improvements. The differences in acceleration, amplification, and displacement between the models suggest that seismic modifications need to be chosen with careful consideration.

The primary finding is that seismic resilience can be significantly increased by straightforward but focused retrofitting interventions like joint reinforcement and column strengthening. It bridges the gap between numerical and full-scale real-life buildings.

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