Original Article

# Evaluating the Effect of Span Length on the Seismic Performance of a Steel Structure with a Chevron Brace by Finite Element Method

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## ABSTRACT

The seismic performance of a steel structure depends on various factors, such as the design, materials, and dimensions. One important aspect to consider is the span length of the structure, which can influence the seismic response and the overall performance of the structure. In this study, a 10-story steel structure with chevron bracing system was designed with ABAQUS software and finite element method. The structure was subjected to the El Centro earthquake for 25 seconds using the dynamic analysis method. Furthermore, the W index was defined equal to the span length to the story height, and the values of 0.67, 1.67, and 2.5 were considered for W. The results showed that the increase of the W index has direct relationship with the changes in the seismic parameters of the structure, including the displacement and acceleration, the von mises stress, the acceleration-time, and the displacement-time diagrams in the roof and the base shear force. Changing the index from 0.67 to 1.67 and 2.5 has caused an increase of 13.34% and 16.67%, respectively. Changing the index from 0.67 to 1.67 and 2.5 has caused an increase of 10.15% and 52.28%, respectively. Changing the index from 0.67 to 1.67 and 2.5 has caused an increase of 43.75% and 109.37%, respectively. Changing the index from 0.67 to 1.67 and 2.5 has caused an increase of 20.83% and 47.91%, respectively.

## Introduction

The effect of span length on the seismic performance of a steel structure can be influenced by various factors, such as the span-to-story height ratio, frame design, and the use of special moment resisting frames [1,2]. Some key findings from the search results include:

- A model frame with a span length to story height ratio of approximately 2 seems to maintain both performance and economy [3,4]. However, a ratio higher than 2.5 can result in relatively high deflections and high element plastic rotations in lower stories under seismic loads [5,6].

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- Low-rise long-span frames can provide good seismic performance, but their design and performance evaluation may depend on factors such as material, construction techniques, and detailing [5,7].

- Seismic design and performance evaluation of long-span special moment-resisting frames can be improved by considering some factors such as material properties, frame geometry, and structural system [8,9].

- The seismic performance of multi-span simply supported slab-on-girder structures can be affected by the design and detailing of the connections between the slabs and the girders [10,11].

- The use of post-tensioned connections can improve the seismic performance of steel frames under mainshock and aftershock sequences [12,13].

To sum up, the seismic performance of steel structures can be influenced by various factors, including the span length, frame design, and the use of special moment resisting frames. It is essential to consider these factors when designing and evaluating the seismic performance of steel structures to ensure their safety and reliability under earthquake loads [14,15].

Ding *et al.* [16] evaluated the seismic response of non-structural components in multi-story steel frames. In this study, 38 steel frames with different heights were investigated. Divya and Murali [17] did a comparative study on design of steel structures and RCC frame structures based on column span. In this project, the design and analysis of G+8 RCC structure and steel structure are done using ETABS software. Embaby *et al.* [18] evaluated Investigation of bevel-ended large-span soil-steel structures. The impact of the dimensions of the structure in this article is very high. Forcellini and Kalfas [19] carried out seismic isolation between story for tall buildings. Modelling with the finite element method and the structure had 20-story. The results showed that the story height has an effect on the performance of the structure. Ghamari and Shooshtari [20] investigated suitable intensity measures for 3D steel structures. In this study, the importance of element dimensions in each direction was considered. Gullu *et al.* [21] investigated the response of the structure under nonlinear forces. The results showed that the story height has a great impact on the performance of the building. Hou *et al.* [22] study of seismic vulnerability of steel frame structures on soft ground considering group effect. Jiang *et al.* [23] discussed experimental and numerical studies of seismic induced story-to-story and inter-story pounding. Kalapodis *et al.* [24] did Integration of peak seismic story velocities and accelerations into the performance-based design of steel structures. Kioumarsi *et al.* [25] investigated the effect of span length on MRF behaviour accompanied with CBF and MBF systems. The main objective of this study is to quantify the effects of variations of aspect ratio (span length to story height) and lateral resisting system on response of high-rise steel structures. The results show the effect of increasing the span length ratio on the high-rise steel structure. Legese *et al.* [26] evaluated composite structures. They investigated the effect of the number of story in the research. Li *et al.* [27] investigated large-span steel truss structures. Mai *et al.* [28] discussed nonlinear inelastic analysis for steel frame structure using Monte-Carlo modelling. In this modelling, the size of the structure is important. ManjoKumara *et al.* [29] investigated the behaviour and performance of steel frame structures with X-type concentric bracing system due to variations in comparison of span width to story height. In this study, structural modelling is done on 3D portals with levels of 3, 5, 8, and 10-story with different $\frac{L}{H}$ variations, including 1, 1.25, 1.5, 1.75, and 2. The results showed that the greater the displacement target produced. Mokhtari *et al.* [30] investigated Quasi-static cyclic tests on a half-scaled two-storey steel frame equipped with Crescent Shaped Braces at both storeys. Qian *et al.* [31] investigated the failure in steel structure. They consider the dimensions of the element to be the most effective factor in creating cracks. Qian *et al.* [32] evaluated the feasibility of two-storey substructures to equivalently investigate the behaviour of multi-storey steel frame. Ruiz *et al.* [33] dealt with Strengthening of historical earthen constructions with steel plates. They considered the effect of story height. Salem Milani and Dicleli [34] were able to reduce the drift of the low-height steel frame by installing dampers in the structure. Soleymani and Saffari [35] worked on strengthening the steel structure with different heights. They used dampers on the lower story. Topaloglu and Yanik [36] were able to investigate soil-structure interaction in a base and mid-story seismically isolated building. The effect of the dimensions of the classes has been included in the results of the article. Venneri *et al.* [37] were able to investigate the seismic performance of multi-storey steel frames with semi-rigid joints. The effect of the structural dimensions was considered in their article. Zhang *et al.* [38] evaluated the ventilation performance of solar chimney integrated into a multi-storey building. The effect of model height in their article is great. Zhang and Shu [39] discussed the optimal design of isolation devices for mid-rise steel moment frames using performance based methodology. In their research, the story height is effective on the performance of the structure. Zhang *et al.* [40] evaluated the steel modular structure. They considered the story height to be effective on the structure performance. Zhang *et al.* [41] analyzed the model of metal frame structures. In their modelling, the effect of structure height on seismic performance was considered. Zhang *et al.* [42] investigated the friction fatigue behaviour of steel composite structures. The effect of element dimensions on crack growth is one of the results of this article.

## Methodology

In the present study, a 10-story steel structure was designed with ABAQUS software. The models were modelled by finite element method. ST37 materials were used in modelling. The specifications of steel used in modelling, elastic and plastic sections are presented in Table 1. Johnson-Cook model was used for steel hardening section. The middle span has a variable size and the left and right span are equal to 5 meters. The middle opening has a chevron bracing system. Three ratios of span length to story height equal to 0.83, 1.67, and 2.5 were used in the modelling. The dimensions of the frames are listed in Table 2.

Figure 1 shows the accelerometer of the El Centro earthquake (period of seismic loading).

**Table 1** Characteristics of the elastic section of steel used in structural modelling

| Parameter / Unit | Elastic Section | | | Plastic Section | | |
|---|---|---|---|---|---|---|
| | Young's Modulus $\frac{Kg}{cm^2}$ | Density $\frac{Kg}{cm^2}$ | Poisson's Ratio | Melting Temp | Transition Temp | Rate Dependent |
| Numerical value | $210\times 10^9$ | 0.001 | 0.3 | 0.0915 | 1300 | 0.22 |

**Table 2** The specifications of the steel frames modelled by ABAQUS software

| Frame No. | Span Length L | Height Story h | $W=\frac{L}{h}$ |
|---|---|---|---|
| 1 | 2.5 | 3 | W1=0.83 |
| 2 | 5 | 3 | W2=1.67 |
| 3 | 7.5 | 3 | W3=2.5 |

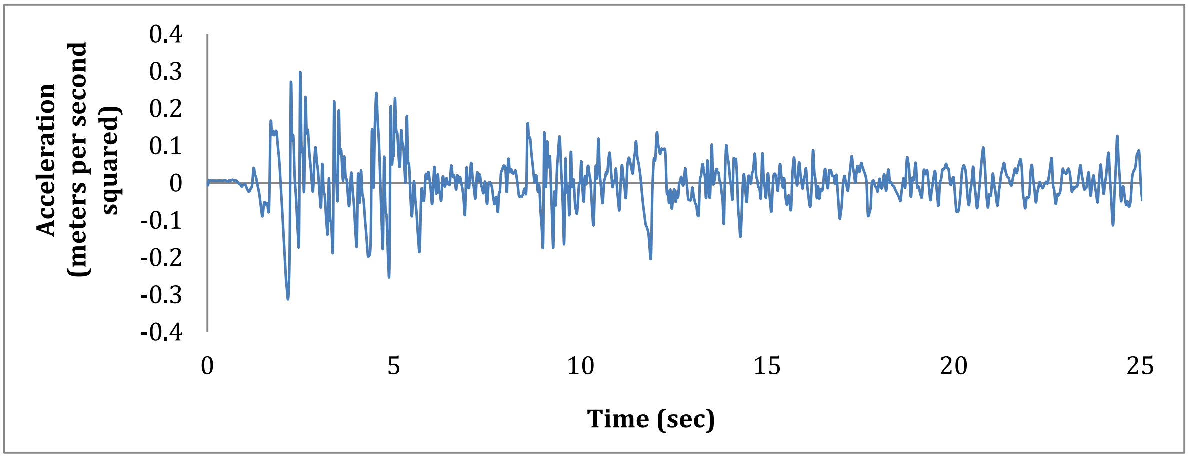


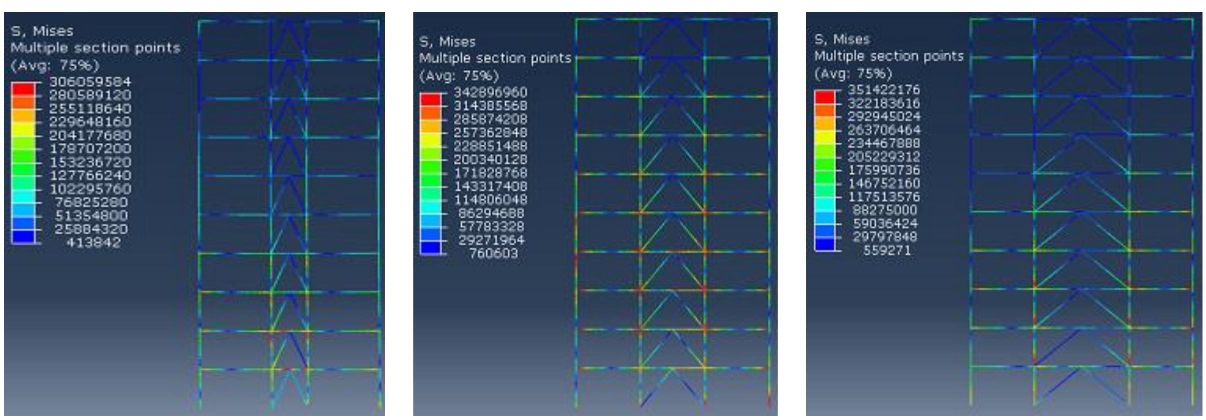

**Figure 1** El Centro earthquake accelerometer

## Results

### *Von Mises Stress*

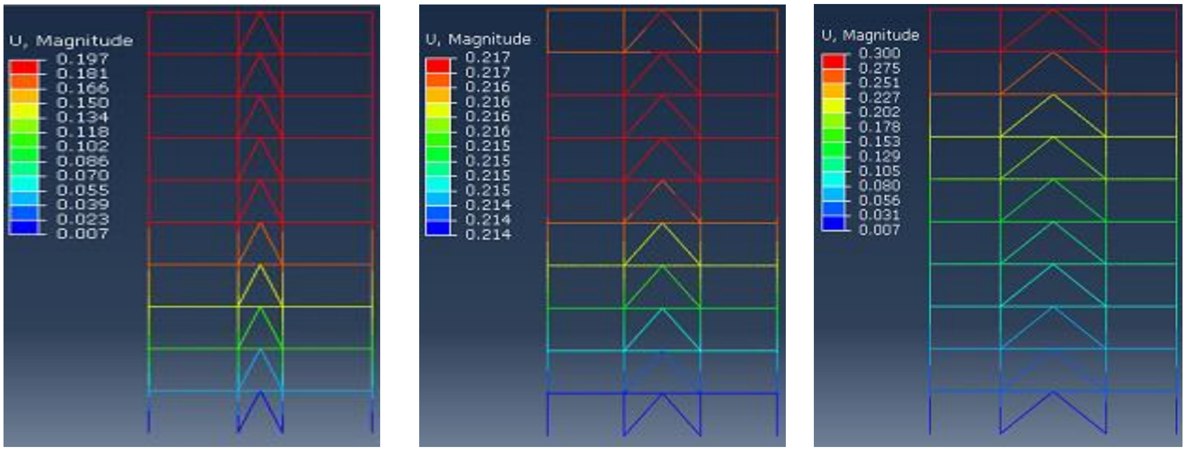
In this section, the stress resulting from seismic loading on the steel structure is presenting.

Figure 2 shows that the steel structure with W3 index has the highest von mises stress resulting from the El Centro earthquake. By increasing the W1 index to W2 index, the maximum von mises stress has increased to 13.34%. By increasing the W1 index to W3 index, the maximum stress has increased to 16.67%. In the structure with index W3, most of the beam-to-column connections have maximum von mises stress and plastic hinges are created in places close to the connections. Maximum stress is applied to the connections of the structure under an earthquake, and the probability of damage during an earthquake increases. Likewise, the maximum von mises stress in steel structure with W1 index is lower than other structures.




(a) (b) (c)

**Figure 2** The maximum von mises stress resulting from the El Centro earthquake in the steel structure with different ratios of W; (a) W1, (b) W2, and (c) W3




(a) (b) (c)

**Figure 3** The displacement resulting from the El Centro earthquake in the steel structure with different ratios of W; (a) W1, (b) W2, and (c) W3

### *Displacement*

In this section, displacement in steel structure under El Centro earthquake is provided.

Figure 3 reveals that the steel structure with W3 index has the highest displacement. The primary structure (with index W1) has the least displacement. Therefore, increasing the W index has caused an increase in displacement in the structure.

### *Displacement-Time Diagram*

In this section, the Displacement-Time diagram under the El Centro earthquake is presenting.

Figure 4 indicates that the steel structure with W3 index has the largest displacement during the earthquake. The difference between the structure displacement with W3 index and other structures is very large. Increasing displacement causes the structure to be subjected to greater lateral forces, including earthquakes and storms. In this situation, nonlinear forces are applied to the structural elements. Therefore, the structure may suffer damage during an earthquake.

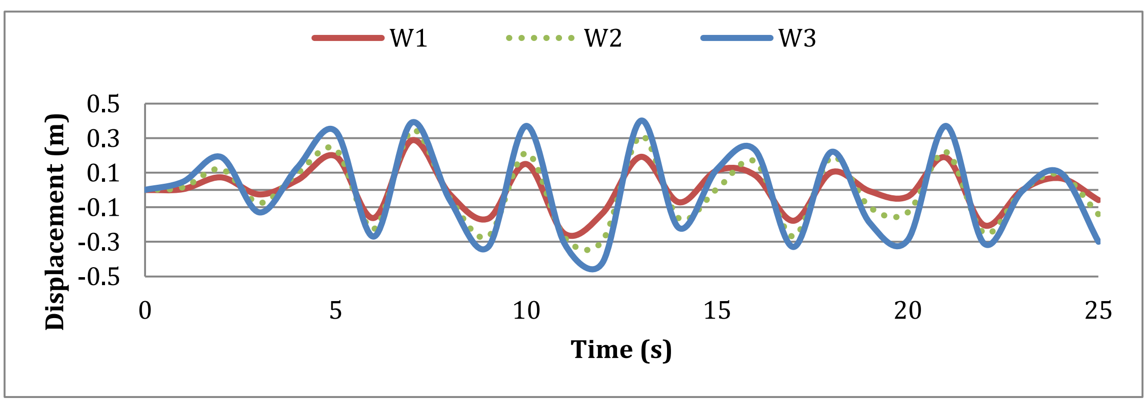



**Figure 4** The displacement-time diagram resulting from the El Centro earthquake in the steel structure with different ratios of W; (a) W1, (b) W2, and (c) W3

*Acceleration-Time Diagram*

In this section, the acceleration-time diagram under the El Centro earthquake is presented.

Figure 5 indicates that acceleration in steel structures with W1, W2, and W3 indexes is different. For the accurate evaluation of the acceleration, the numerical average of the acceleration is demonstrated in Figure 6.

Figure 6 demonstrates that the structure with W3 index has the highest average acceleration. The structure with W1 index has the lowest average acceleration. The results showed that increasing the value of the W index increases the average acceleration value in steel frame with chevron brace. Increasing the acceleration in structural elements increases the amount of nonlinear forces in them. Therefore, during an earthquake or storm, the probability of damage or collapse of the structure increases.

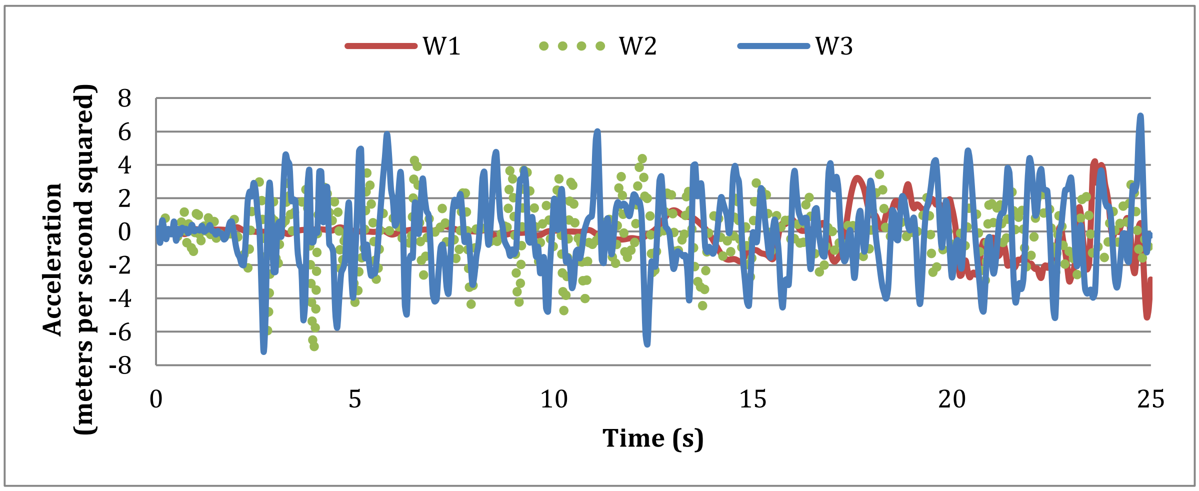



**Figure 5** The acceleration-time diagram resulting from the El Centro earthquake in the steel structure with different ratios of W; (a) W1, (b) W2, and (c) W3

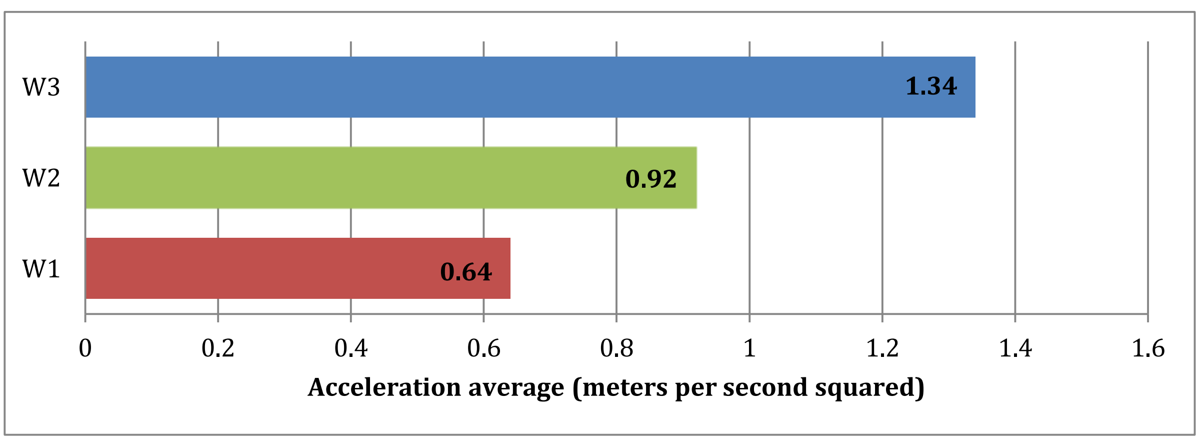



**Figure 6** The acceleration average resulting from the El Centro earthquake in the steel structure with different ratios of W; (a) W1, (b) W2, and (c) W3

*Base Shear-Time Diagram*

In this section, the base shear-time diagram under the El Centro earthquake is provided.

Figure 7 illustrates that the structure with W3 index has the maximum base shear force. The average base shear force in all structures is demonstrates in Figure 8.

Figure 8 shows the structure with W3 index with the highest average base shear force. Similarly, the structure with W1 index has the lowest base shear force. Increasing the W index has increased the base shear force. Changing the index from W1 to W2 and W3 has caused an increase of 20.83% and 47.91%, respectively.

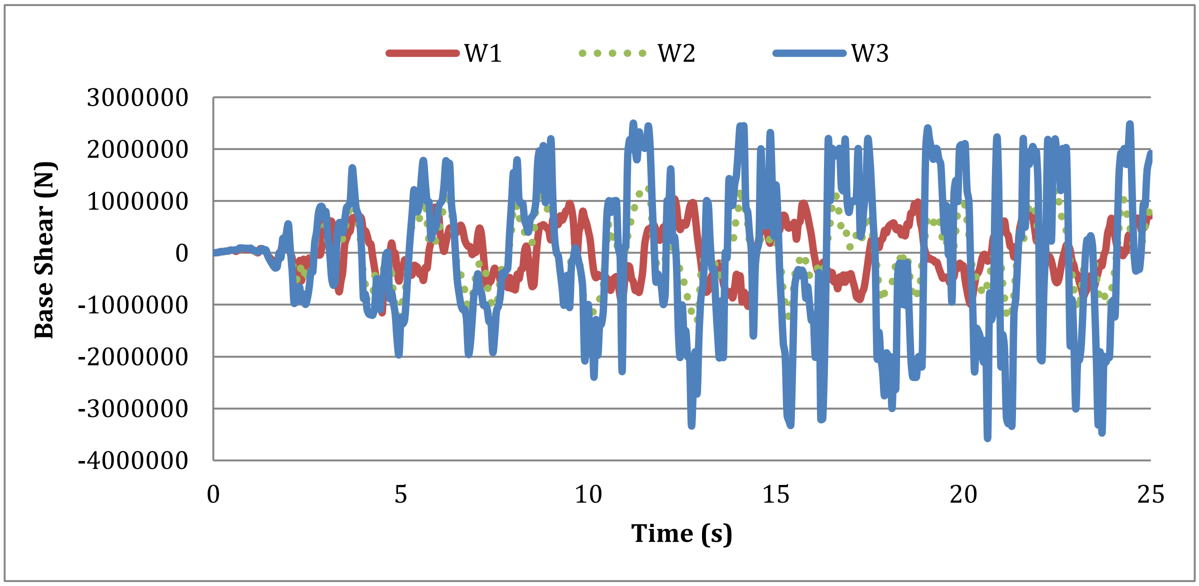



**Figure 7** The base shear-time diagram resulting from the El Centro earthquake in the steel structure with different ratios of W; (a) W1, (b) W2, and (c) W3

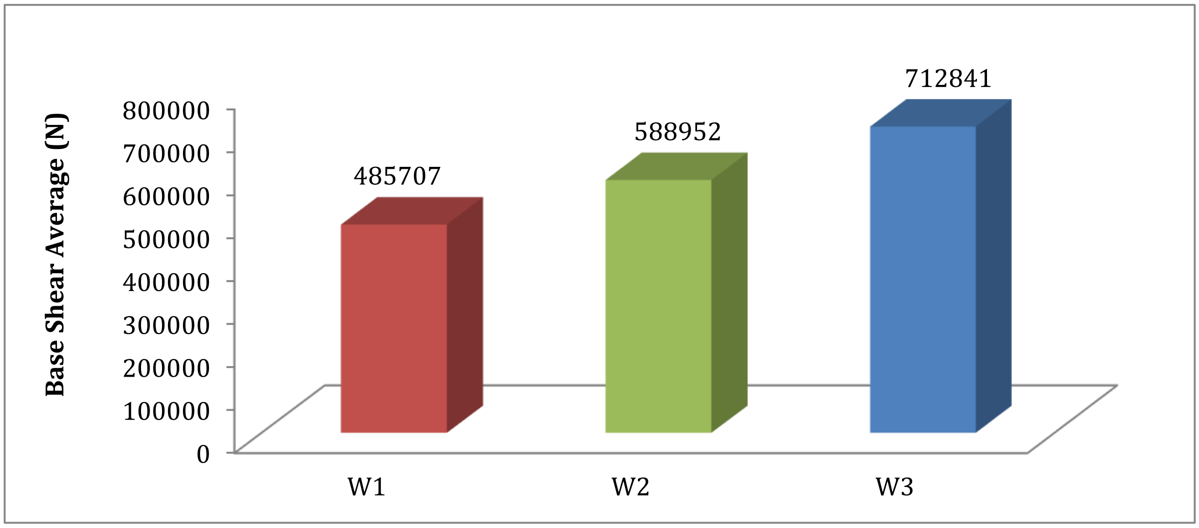



**Figure 8** The base shear average resulting from the El Centro earthquake in the steel structure with different ratios of W; (a) W1, (b) W2, and (c) W3

## Discussion

The effect of span length on story height in steel structures under earthquake is a complex topic that is extensively studied in the field of structural engineering. The relationship between span length and story height can impact the seismic performance of the structure. However, the specific impact can vary based on various factors such as the structural system, building codes, and seismic design parameters. Research in this area has focused on aspects such as the seismic performance of steel special moment resisting frames, analysis of steel structures with soft story, seismic resilient steel structures, and seismic behaviour of existing high-rise steel buildings. These studies often consider the influence of different structural parameters, including span length and story height, on the overall seismic response and collapse behaviour of steel structures under earthquake loading. While the search results provide a comprehensive overview of the study conducted in this field, they do not offer specific findings on the direct effect of span length on story height in steel structures under earthquake. In the present study, focusing on the structure with Chevron bracing system under the El Centro earthquake (far-fault), the effect of the span length on the story height has been investigated. So far, such a topic has been less discussed. Modelling has been done with ABAQUS software and finite element method (FEM). The W index is defined as equivalent to the span length to the story height. In the present study, W is equal to 0.83, 1.67, and 2.5. The results showed that the increase in the W index causes changes in the seismic parameters of the steel structure such as displacement, acceleration and base shear force. For example, increasing the value of W from 0.83 to 1.67 has caused increase in the structural displacement and acceleration. There are few studies on the effect of span length on story height in steel structures with chevron braces, but other types of structures have been investigated in studies such as [25,32] and confirm the results of the present study.

The research results show a direct relationship between the K index and the displacement and acceleration parameters. As the K index increases, the length of the beams in the story increases. Therefore, the dead load (weight of the structure) will increase. In the seismic calculations of the structure, the mass source is calculated based on the relationship of Dead+0.2Live. Therefore, with the increase of the dead load, the mass source in the seismic calculations of the building will increase. As a result, the simultaneous effect of increasing the mass source and increasing the beams length causes displacement and acceleration in nonlinear loading on the structure. Doubling or tripling the K index has caused a great increase in the displacement and acceleration of the structure. Therefore, it is important to accurately evaluate the K index in the design of the structure.

Increasing the K index in the steel structure increases the total effective weight. To calculate the total shear force and the shear force of the story caused by the earthquake, the total effective mass in the structure is used. Therefore, increasing the K index increases the total effective mass in the structure and increases the total shear force. As the value of K increases in the structure, the total mass increases and the probability of damage to the structure increases. In other words, the K index and the performance level of the structure have the invert relationship.

Researchers can use the results of this article. Seismic parameters investigated in the current research, including displacement, acceleration, performance diagrams and total shear force in the structure; show the general behaviour of the building. Therefore, the relationship between the K index and the structural performance is very dependent on each other. The effect of the K index on the behaviour of the structure in the nonlinear zone is important. This research can be done by researchers. Investigating the formation of plastic hinges in nonlinear static analysis is one of the topics suitable for researchers. In many researches about steel structures, the effect of K index has not been investigated. Therefore, this index can be introduced as the main criterion in evaluating the performance of the steel structure and be included in the engineering regulations.

## Conclusion

In the von mises stress index, increasing the W index has caused an increase in the von mises stress. Changing the index from W1 to W2 and W3 has caused an increase of 13.34% and 16.67%, respectively. The von mises stress is a scalar value used to predict yielding of materials under loading. It is computed from the Cauchy stress tensor and is particularly applicable for the analysis of plastic deformation in ductile materials such as steel, as it is independent of the hydrostatic component of the stress. The von mises stress is used to determine if a given material will yield or fracture and it is often the default stress output of most commercial finite element analysis codes. An increase in the K index causes an increase in the von mises stress. With the increase of stress in the structural elements, the possibility of partial and extensive damage increases during an earthquake. In the current research, the steel structure has a Chevron brace, but the increase in K has a great effect on the increase in von mises stress. This result can be much more in the steel moment frame (SMF). Therefore, it is very important to check the K index in the seismic design of the structure.

In the Displacement and Acceleration indexes, increasing the W index has caused an increase in displacement and acceleration in the structure. Changing the index from W1 to W2 and W3 has caused an increase of 10.15% and 52.28%, respectively. In acceleration parameter, changing the index from W1 to W2 and W3 has caused an increase of 43.75% and 109.37%, respectively. The stated numerical values are very high and indicate the effect of the K index on the performance of the steel structure. If the bracing system is changed or removed, the numerical values will change and maybe increase. A large increase in displacement or acceleration in the structure is very dangerous and must be controlled by various engineering methods. Many structural failures are caused by increased displacement. Also, these conditions are much more important during major earthquakes.

In the Displacement-Time and Acceleration-Time for the roof, there is direct relationship between the increase in the W index and displacement. W3 index has a very large displacement compared to other indexes. Therefore, there is direct relationship between the increase in the W index and changes in roof displacement and acceleration. The steel structure with K3 index had a larger displacement and acceleration than other structures during the entire seismic loading period (25 seconds). The structures had the same conditions in all the modelling and only the K index was changed. This result is very important and showed that the K index is very effective in increasing displacement and acceleration. Therefore, the importance of the K index in the design of the structure by designers is very high. In many construction projects, this index is not checked and it can have great effects on the building's performance. Structural designers should pay attention to these results.

In the base shear force parameter; there is direct relationship between the increase of the W index and the base shear force. W3 index has a higher average base shear force compared to other indexes. Changing the index from W1 to W2 and W3 has caused an increase of 20.83% and 47.91%, respectively. Increasing base shear in the structure has many effects. These effects will increase during an earthquake. The possibility of the total collapse of the structure during an earthquake is one of the effects of increasing base shear. Therefore, the K index should be checked during the design of the structure.

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