Study of the elastic stiffness factor of steel structures with different lateral load resisting systems

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ABSTRACT

Steel structures, like other types of structures, are exposed to different types of loads, including lateral loads such as earthquake and wind. To resist such loading, lateral stiffness has a significant role. In this paper, the elastic stiffness factor (K) for different models of steel structure with various bracing systems and different parameters are compared. The comparison has been performed by analysing and studying the formation of plastic hinges applying the pushover analysis. The results illustrate that the increase in the number of stories reduces the K value, while the increase of span length increases it. Besides, the usage of the bracing system significantly increases the K value.

1. INTRODUCTION

When designing a building, a lot of loads and combinations should be taken into consideration, including lateral loads like the wind, and earthquake that may result in a lot of life loss. Lateral loads are one of the riskiest events when it happens, and buildings need a special design to be able to withstand this kind of loads. A bare-frame model using centerline dimensions is more flexible and weaker than all other models (Foutch, 2002). The main advantage of the bracing system is that it increases the stiffness of the building with a minimum added weight and decreases the bending moment and shear forces in columns (Somasekharaiah, 2016). Considering lateral stiffness, the concentric X-bracing has been found the most suitable one for the steel building (Tafheem, 2013).

During lateral loads events, the building starts to bend, and the displacement begins to increase gradually in a linear elastic manner until reaching the occurrence of the first plastic deformation (plastic hinges occurred). After that, if the lateral base shear increases, the displacement starts to increase, and plastic hinges happen successively until the building's collapse. Every structure has different stiffness and capability to withstand the lateral loads depending on different variables such as the number of stories, span lengths, and the lateral load resisting system used to support the structure. A plastic hinge happens when the steel member reaches its yielding point and starts to bend, making a hinge. The plastic hinges are different from regular hinges because the bending moment does not equal to zero, but it has a plastic moment in it. The occurrence of the first plastic hinge shows the stiffness of the structure whereby calculating the ratio of the base shear over displacement or by finding the slope of the first linear portion of the pushover curve, which the elastic stiffness factor (K) can be calculated. The objectives of this study are to find the K factor for different buildings with different parameters to analyse and compare between them to find the effect of each parameter and the best bracing system to use. This paper will focus on steel structures. All models were created and analysed in ETABS 18.0.1 software using the American design code for steel structure, AISC 380-16. Besides, the analysis method used is the nonlinear static analysis (pushover analysis) because it is economical and gives a reliable simulation of what can occur in a real structure (Hassaballa et al., 2014).

1.1. Elastic stiffness factor

Elastic stiffness factor (K) is the measure of the building's ability to withstand the applied loads on it without the occurrence of plastic hinges). This factor can be used to calculate the natural period (T) of the buildings and allows the designers to have a deeper understanding of the building load capacity as well as the collapse mechanism of the building. Furthermore, K factor can be used to calculate the displacement under specific load resembling Hook's spring equation, where the building represents the spring, and the base shear represents the load.

$$V_s = D_s . K \quad (1)$$

where:

V_s: The base shear at the occurrence of the first plastic hinge

D_s: The displacement at the occurrence of the first plastic hinge

K: The elastic stiffness factor

1.2. Analysis methods

The occurrence of plastic hinges is directly related to the lateral loads applied to the building. The "plastic-hinge evaluation approach can describe the structure behaviour with high accuracy as far as with large displacement" (Hoang et al., 2015). Lateral loads can be wind load and seismic loads, which do damage to the structure. Therefore, every building must be designed to resist lateral forces; thus, four seismic analysis methods can be used to study the behaviour of a building under seismic events as described below. Fig. 1 shows the overall scheme for seismic analysis methods.

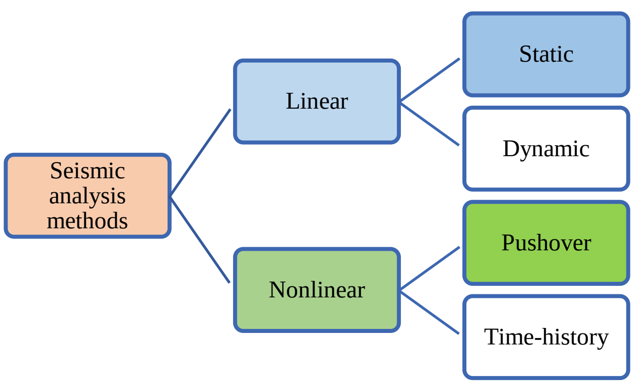

Fig. 1. Overall scheme for seismic analysis methods

- Linear analysis is an analysis where a linear relation holds between the applied force and displacement. This type of analysis is applied to structural problems where stresses remain in the linear elastic range; therefore; it is not useful for the study of plastic hinges. The linear static method was used to make and design the structural models before applying the pushover analysis.
- Nonlinear dynamic analysis (time-history) utilises the combination of ground motion records with the structural model; therefore, it is capable of producing results with relatively high accuracy. It should be noted that nonlinear pushover analysis has a higher speed of implementation than time-history analysis by several times (Alilou and Pouraminian, 2019).
- Nonlinear static analysis approach which also known as pushover analysis is a pattern of forces applied to a structural model which includes nonlinear factors like steel yielding as the resistance of concentrically braced steel frames to earthquake relies on the capacity of the bracing members to undergo several cycles of inelastic deformations including stretching and buckling (Tremblay, 2002). The total shear force is plotted against displacement (pushover curve). Also, "pushover analysis is a performance-based analysis procedure, usually consists of applying a distribution of lateral loads to a model of an existing or previously designed structure. These loads are increased until the peak response of the structure is obtained" (Dhileep et al., 2011).

1.3. Maximum base shear

Maximum base shear is the maximum applied load that the building can withstand before the failure occurs (global failure of the building). Also, the maximum base shear of the first plastic hinge is the amount of load that the building can withstand before the plastic deformation occurs (local failure). The study of maximum base shear is significantly essential to predict the buildings capabilities to withstand seismic events like an earthquake.

1.4. Lateral displacement

Lateral displacement is directly related to the building stiffness where the less stiff of the building, the more displacement we have, and it is one of the most sensitive parameters during design because every building must maintain some amount of flexibility to avoid brittle failure, but on the other hand the displacement must be limited to avoid having any serviceability issue in addition to the possibility of having a collision with the adjacent buildings.

2. APPLIED PROCEDURE

This study is based on pushover analysis to test and compare the structural models in terms of their stiffness by finding the elastic stiffness factor; their capability to withstand the maximum lateral load that can be applied, and the maximum displacement. In this approach, the structural model is subjected to a gradually increasing lateral load, and the building displacement is increasing progressively until reaching a targeted displacement where the failure will occur. In this paper, eighteen 3D models subjected to displacement control pushover were analysed, where all buildings were pushed up until failure occurrence. The obtained base shear-displacement pushover curve used to study the load capacity and to find the K values of the models. The procedure was as flow:

- All models were made and designed using ETABS 18.0.2 software according to AISC 360-16 code (ANSI, 2016).
- Hinges were assigned to all structural frame members (beams, columns, braces).
- Pushover analysis was defined, and the load patterns of the analysis were assigned to the x-direction. The lateral load pattern considered is the acceleration pattern where the lateral load is increased gradually until the structure reached the full capacity and collapse.
- ETABS draws pushover curve (base shear-displacement) up to failure, as shown in Fig. 2.
- Using ASCE 41-13 (2018), the base shear and displacement at the occurrence of the first plastic hinge, and K is calculated where its value is the ratio of the base shear to the displacement at the occurrence of the first plastic applying Eq. (2).

$$\mathrm{K} = V_s / D_s \quad (2)$$

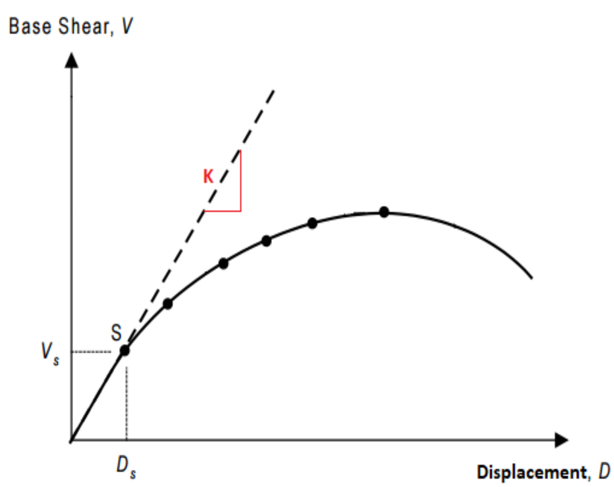

Fig. 2. K shown on the pushover analysis curve

3. MATERIAL PROPERTIES, FRAME SECTIONS AND LOADS

3.1. Material properties

The main materials used in this study are concrete with grade C30 which used for slabs, and steel grade A992F_y50 having a yield strength of 344.74 N/mm^2 which represent the main building members in the studied buildings (all beams, columns, and bracing members). All of the beams, columns, and braces used in the design was the wild flange section (W-section) using the AISC Steel Construction Manual 13th edition. Table1 summarises the properties of the materials used in the models of this study.

Table 1. Materials properties of models

Materials	Properties
F_y of steel sections	344.74 N/mm^2
F_u of steel sections	448.16 N/mm^2
f_c' of concrete	300 N/mm^2
Steel modulus of elasticity	200000 N/mm^2
Concrete modulus of elasticity	33000 N/mm^2
F_y of reinforcement steel	420 N/mm^2
Unit weight of concrete	25.5 kN/m^2

3.2. Studied structural models

Different types of 3D steel frame were selected to be analysed and designed, which include two types of bracing methods (X and Z bracings), in addition to the ordinary moment-resisting frame (OMRF), which consists of linear, horizontal members (beams) in a plane with linear vertical members (columns) by rigid or semi-rigid joints (Chandiwala, 2012). Where the braces placed in the external frames of the buildings. The bracing system has some advantages such as it is relatively cost-effective, does not significantly add the structural weight, is easy in application and can be customized with the necessary strength and rigidity (Kumar, 2016). The used yield strength of steel (F_y) is 240 N/mm2 during all analyses. The study takes into consideration different variables including the different types of bracing and other variables which are the span lengths (L) of 5.5 m and 6.5 m, and the number of stories (S) (4-, 7-, and 10-story). The height of stories (H) was taken 3.2 m for all buildings. The OMRF (shown in Fig. 3) is the most economical type of frame systems because of its lake of the additional steel bracing members. However, Taranath (1998), in his book "Steel, concrete, and composite design of tall buildings" stated that OMRF systems are not efficient for buildings higher than about 30 stories because the shear component of deflection produced by the binding of columns causes the building draft to be huge. On the other hand, this type of frame system is the most used for small and short buildings. Z bracing frame system (shown in Fig. 4) is less economical than OMRF, but it increases the building rigidity and stability. This type of bracing depends on either the tensile or normal compression force, therefore this kind of bracing exposed to high stress during seismic events. Because of that, this type of bracing may not perform properly. Moreover, it requires additional supporting members. X bracing frame system (shown in Fig. 4), is the least economical type, but this system is much more rigid than the OMRF and Z frames. This system applies both tensile and compression at the same time along with the bracing members; therefore, the stress can be shared between both members and allows the building to resist more lateral force applied to it. Steel-braced dual systems exhibit higher ductility and therefore, higher behaviour factors (Maddala, 2013). Therefore, this type of bracing system usually used for high-rise buildings. "The steel braces are usually placed in vertically aligned spans. This system allows obtaining a great increase of stiffness with a minimal added weight" (Viswanath et al. , 2010).

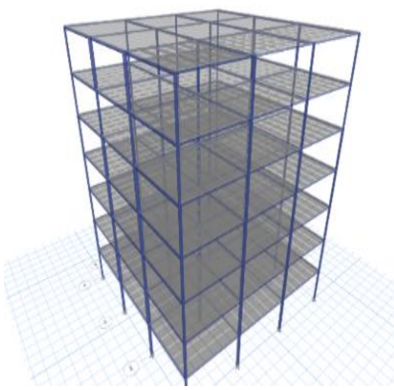

Fig. 3. Example of an OMRF

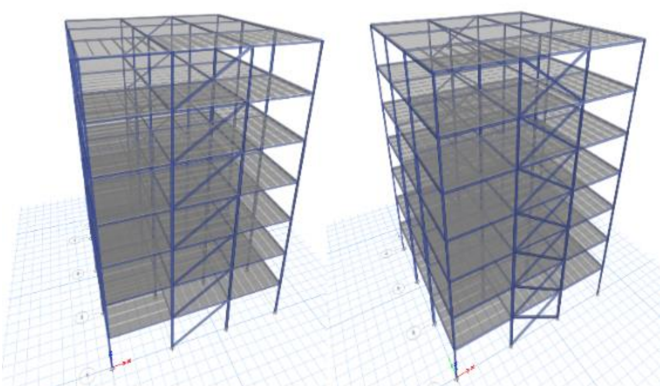

Fig. 4. Examples of Z and X braces

3.3. Applied loads

In all models, super dead load and live loads are fixed and considered to be the same for all models, while the dead load is the self-weight of the structure which automatically calculated by ETABS 18.0.1 software. The program automatically calculates the self-weight of the structure. On the other hand, live load and super dead load is defined and assigned to the program manually as follows. The live load was taken and designated as 3 kN/m^2, and the super deadweight was taken as 2.8 kN/m^2 for all slabs of the 3D structural models in this study. Also, pushover load as lateral base shear load simulating the earthquake was assigned and increased automatically by the program in a gradual manner until the displacement of the model reaches a specific pre-assigned distance.

4. RESULTS AND DISCUSSION

This section introduces and compares the results obtained in this study for the occurrence of plastic hinges in the buildings, and the elastic stiffness factor (K) of the 3D models created on ETABS 18.0.1 software. In this paper, the main comparison factors taken under consideration are the type of lateral resisting systems (X and Z bracings; OMRF), the number of stories (4,7 and 10) and the span lengths (5.5 m and 6.5 m).

- The number of spans (N) is fixed as three spans for all models.
- Yield strength of steel (F_y) is fixed as 240 kN/mm^2 for all models.
- Story high is fixed to (3.2 m) for all models.

4.1. Effect of the number of stories on the K factor

The number of stories represents one of the factors addressed in this paper, and one of the main factors related to the K factor of the buildings whereas the increase in the building height have a significant impact on it as the results show in Fig. 5, the rise in the number of stories (N) decreases the K value of the structural models for all types of bracing in this study. Fig. 5 shows the relation between the K factor and for N (4, 7 and 10) where the bracing type is fixed, and the span lengths are set as 6.5 m.

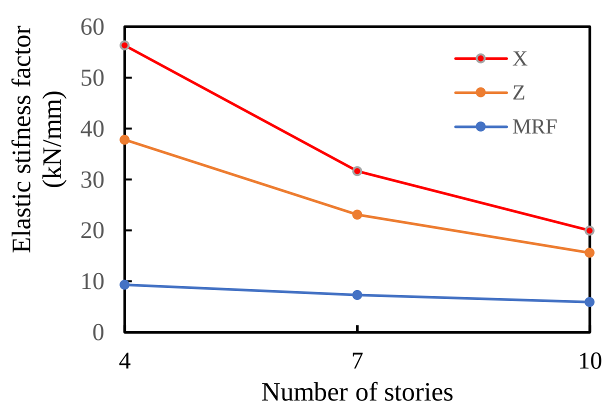

Fig. 5. K factor versus the number of stories for different types of bracing system

Also, the value of the K factor rate decrease when increasing the number of stories. In OMRF, the K value decreased by 30% when the number of stories increased from 4 to 10, which considered a small decrease when compared with models with the bracing system. Using a bracing system resulted in sharply increase the K value. When the number of stories increased from 4 to 10, K value decreased by 60% for Z-brace and 65% for X-brace.

4.2. Effect of span length on the K factor for different types of bracing system

The span length is a beneficial factor related to the K factor. According to the obtained results, the increase of span length is proportional to the K value where it increases with the rise of the span length. Fig. 6 shows the relation between the elastic stiffness factor and the span lengths (5.5 m, and 6.5 m) for different types of lateral resisting systems (X and Z bracings; OMRF) while the number of stories fixed to 4 stories. Also, increasing the span length increases the overall thickness of the building.

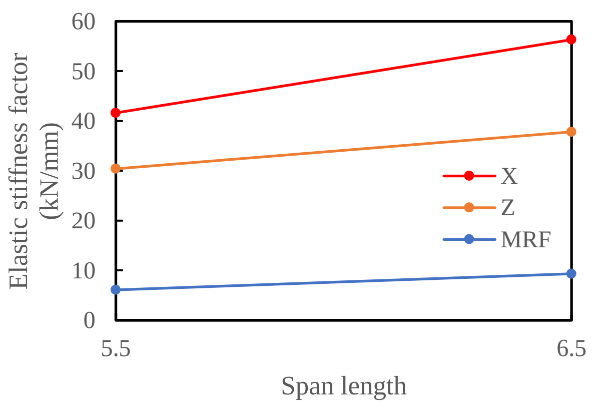

Fig. 6. K factor versus the span lengths of different types of bracing system

4.3. Effect of different bracing systems on the K factor

Bracing is a type of lateral resisting systems usually used to increase the stability of buildings, especially high-rise buildings. As the results of this study show, the existence of the bracing system in the structure increase the value of the elastic stiffness factor significantly. Moreover, the effect varies between the different types of lateral resisting system. In this paper, we compare the OMRF, Z brace, and X brace, as shown in Fig. 7, where the span length of 6.5 m is fixed.

As shown in the figure, the value of the elastic stiffness factor of the OMRF is the smallest, followed by Z bracing and X brace systems. Additionally, the results show that the difference between the bracing types and MRFs is enormous, especially for low-rise (4-story) buildings.

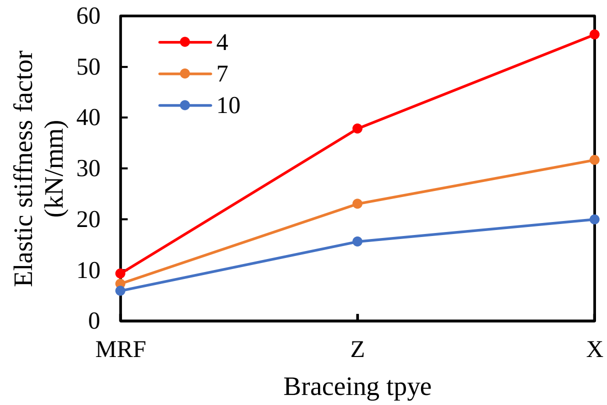

Fig. 7. K versus different types of bracing system for various number of stories

5. CONCLUSIONS

In this study, eighteen 3D steel models were made applying ETABS 18.0.1 software with different types of bracing system, and other various parameters like the number of stories and span length. Then, the pushover analysis was applied to determine the elastic stiffness factor (K) from the resultant pushover curve. The results were analysed and organised in charts to show the differences in each arrangement of parameters used in the structural models. The types of brace system used in the study are X and Z braces in addition to OMRF. Three different numbers of stories were studied, which are 4, 7, and 10 stories. While two different span lengths were used which were is 5.5 and 6.5 m, some other parameters were not varied in the study and fixed for all models like the number of spans, stories height, and yield strength of steel. Besides, all models were designed to have a uniform shape of plan view in the form of a regular square.

Summarising all the results of the elastic stiffness factor in the study are as follows:

- The increase of stories number resulting in decreasing the value of K value, as the number of stories number directly related to the displacement at the occurrence of the first plastic hinge.
- The increase of the span length resulting in increasing the K value, where it increases the overall thickness of the building and strengthens the structure's resistant to lateral loads.
- The presence of a bracing system in the 3D structural models increases the K value significantly, where X brace has the highest effect followed by Z brace when comparing with the OMRF models, which exposed to a significant displacement with small base shear value.

The decrease of the elastic stiffness factor will lead to larger displacement range, which leads to the need to use additional methods to increase the stiffness like using more bracings because the large displacement decreases the serviceability of the buildings. The value of elastic stiffness factor rate of decrease when increasing the number of stories in OMRF, the elastic stiffness factor value has a small decrease compared to the models with the bracing system.

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