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Comparing the performance of diagonal, A-Chevron, Gate, Knee, Rhombus and X braces with the finite element method

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ABSTRACT

The use of modern bracing systems is one of the common ways to increase the lateral stiffness of the structure. Evaluating and comparing the performance of new braces using different analytical methods can compare their advantages and disadvantages. Therefore, in the present paper, steel frames with Diagonal, A-Chevron, Gate, Knee, Rhombus and X braces are designed with a finite element method (FEM) and ABAQUS software. The braced frames are subjected to modal analyses in the frequency domain and 50 vibration modes are investigated. The modeling and results are validated by Li et al.'s paper (2022). The results show that in terms of modal performance parameters, including von mises stress, the beam displacement in the steel frame, eigenfrequency and generalized mass, Rhombus, Gate, Rhombus and Knee braces show the best performance, respectively. Steel frames have the best performance in the participation factor parameter of component type in x, y and z directions with diagonal, diagonal and knee braces, respectively. Moreover, the steel frames have the best performance in the participation factor parameter of rotational type in x, y and z directions with knee, diagonal and X braces, respectively.

Keywords: Steel structure, Structural Bracing System, Finite Element Method, Modal Analysis in the Frequency Domain, Abaqus Software.

1. Introduction

Steel braces are one of the most common systems used for increasing the lateral stiffness of the structure [1]. Engineers use different braces in the structure according to various factors including (a) the structure height, (b) intensity of the seismicity, (c) load combinations and (d) geometrical conditions [2]. Therefore, there are different types of braces in structural engineering and they can be used in the lateral bearing system of the building [3]. The comparison of new braces helps to know the advantages and disadvantages of different braces.

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Farheen and Akshara [4] investigated the performance of knee braces in steel frames with different dimensions. This research was conducted with nonlinear static and nonlinear time history analysis methods. The results showed that the knee braces had a good performance in steel frames with different dimensions. Mahdavi et al. [2] investigated ten types of braces in steel structures, including gate, v and knee braces. Modeling was done with Sap2000 software and nonlinear static analysis methods. The results showed that an increase in the structure height causes many changes in the performance of braces. Zheng et al. [5] investigated the performance of X braces in steel frames. The investigation was carried out with a finite element method (FEM). The results showed that the X braces cause a 20% increase in the bearing capacity of the structure. Hamidi and Soleimani [6] investigated and compared the seismic performance of X brace and steel moment frame. This investigation was conducted with 20 earthquake records and a nonlinear time history analysis method in OPENSEES software. The results showed that the x brace has a great effect on increasing the performance of the steel frame. Li et al. [7] investigated chevron braces with proposed beams. The results showed that the proposed chevron brace increases the seismic performance of the steel structure by 33%. Zheng et al. [8] investigated the seismic performance of chevron braced frames. In this investigation, three new structural systems including arched chevron braced frame (HZC), multi-line chevron braced frame (ZXC) and sidebar braced frame (ZCG) were proposed. The results showed that the seismic performance of ZCG is better than the other proposed braced frames. Nagy Kem [9] suggested a suitable rhombus bracing system. The proposed brace modeling is based on the one-dimensional tensile frame stiffness theory of Recski and Shai [10]. Mahdavi et al. [11] investigated and compared the performance of gate and inverted v braces. This research was conducted using ABAQUS software and the FEM method. The results showed that the inverted v brace has lower von mises stress (29.18% reduction) and displacement (16.69% reduction) as compared to the gate brace. Rangaraj et al. studied the behavior of 3, 7 and 10 storied steel structures with and without chevron bracing systems using STAAD Pro. [12] The results showed that Chevron brace improves the seismic performance of the structure. Honma et al. [13] proposed a knee brace with a damper. They showed that the experimental low-cycle fatigue life of the knee brace can be predicted using the fatigue curve of notched specimens of the steel and Miner's rule. Zhang et al. [14] investigated the seismic behavior of an X-deployed cable-braced bolt-assembly (CBBSF) steel frame. The results showed that the brace has a good performance. Ullah et al. [15] investigated the braced frame with Chevron braces equipped with replaceable sandwiched fused damper (SFD). The results of their study indicated that the ductile flexural-yielding of fuses governed the failure of SFD-braced frames. Besides, it was found that the ductility, energy dissipation, and deformation capacity of SFD-braced frames was respectively 2, 4.73 and 4.59 times larger than that of the conventional chevron-braced frame.

Other research studies [3,4,7–9,16–19] have compared two braces and there are few studies comparing several braces. Also, bracing systems have been investigated with common static or dynamic methods, and other methods have not been used to compare braces. Therefore, the innovations in the present paper, compared to other similar papers, are as follows:

- Comparing the performance of different braces including Chevron, Diagonal, Gate, Knee, Rhombus and X. In the present study, six different braces are examined, and this process has been done in very few papers.
- Using the modal analysis method in the frequency domain in modeling. Modal method for analysis is seen in very few papers about bracing systems.
- Modeling braces with the latest FE method;
- Determining various performance parameters in braces during the current research, including von mises stress, beam displacement, effective mass, participation factor (in x, y and z axes), generalized mass and eigenfrequency. Determining the modal parameters in the frequency domain makes the behavior of braced frames be fully revealed and the results are very complete.
- In similar studies, usually the six vibration modes are investigated and the effects of higher modes are not considered. In the present study, fifty vibration modes are investigated in braced frames, increasing the accuracy of the results.

2. Methodology

In the present paper, 1-story steel frames are modeled with ABAQUS software and FE method. The story height and span length are 3200 and 6600 mm, respectively. In Fig. 1, the FE model and meshing of the six braces examined in the present paper are shown. In software modeling, St37 steel is used and its specifications are presented in Table 1.

For software modeling, all elements, including column (3D element), beam (3D element), brace (3D element) and joint plate (2D element) are used. After FE modeling, steel sections are assigned to all elements. Then, the elements are assembled according to the type of the brace. In the step module, modal type analysis is then selected in the frequency domain. In the present paper, 50 vibration modes in braced frames are investigated. The values of vectors are considered as 58 and 30, respectively using per iteration and maximum number of iteration. Considering that the entire braced frame is made of St37 steel, interaction between the members is not considered. The bases of the columns are defined in a steel frame, joining to the ground by fixed supports (Fig. 2). Then the meshing of the model is done. In Fig. 3, the meshing of important parts in the braced frame is shown.

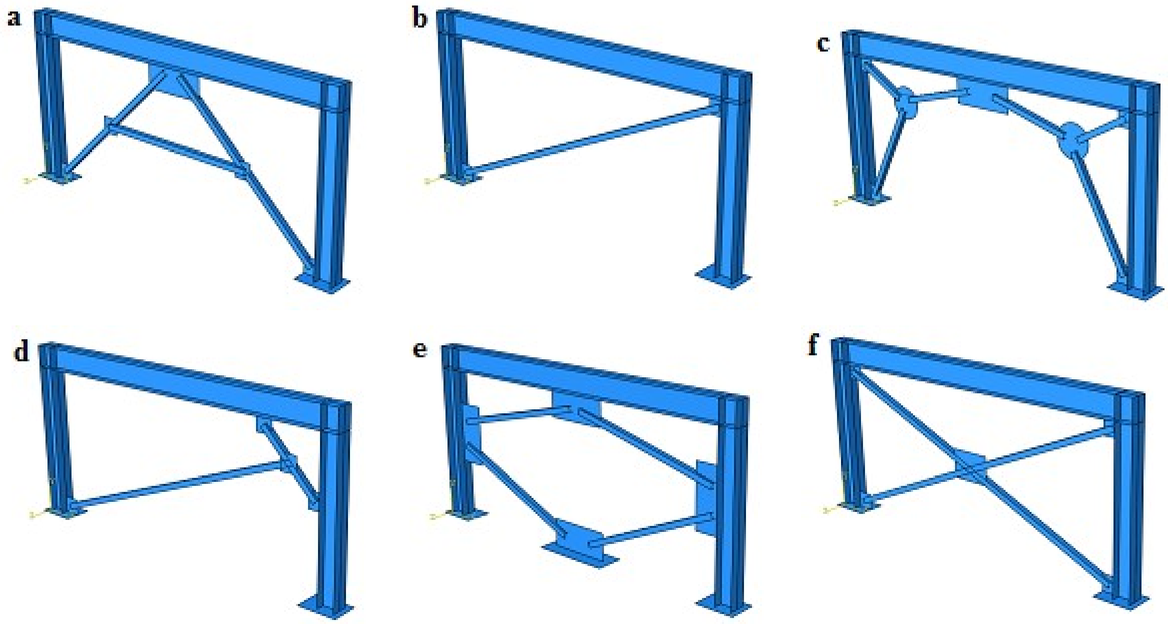


Fig. 1. FE modeling of steel braces in the present paper (a) A-Chevron; (b) Diagonal; (c) Gate; (d) Knee; (e) Rhombus; (f) X.

Table 1. Characteristics of St37 steel in modeling with FEM technique [11].

Parameter	Minimum yield stress	Minimum tensile stress	Effective tensile stress	Effective tensile stress	Poisson's ratio
Numerical value (Unit)	24×10^{6} $(\frac{Kg}{cm^{2}})$	27×10^{6} $(\frac{Kg}{cm^{2}})$	27.6×10^{6} $(\frac{Kg}{cm^{2}})$	42.55×10^{6} $(\frac{Kg}{cm^{2}})$	0.3

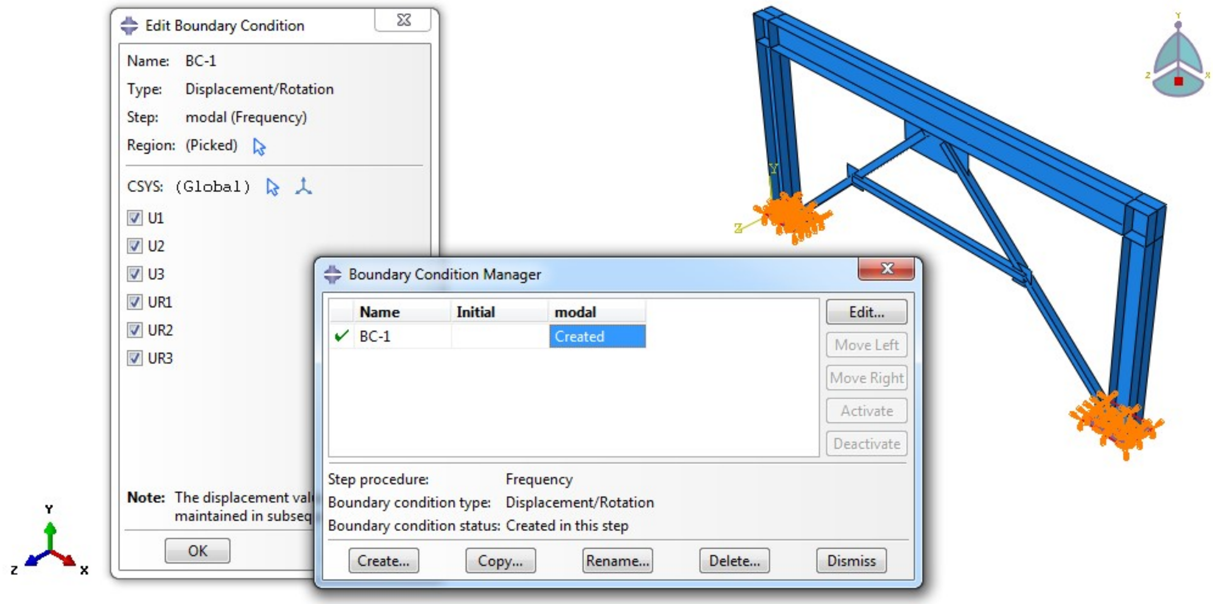


Fig. 2. Fixed supports in braced frames during software modeling.

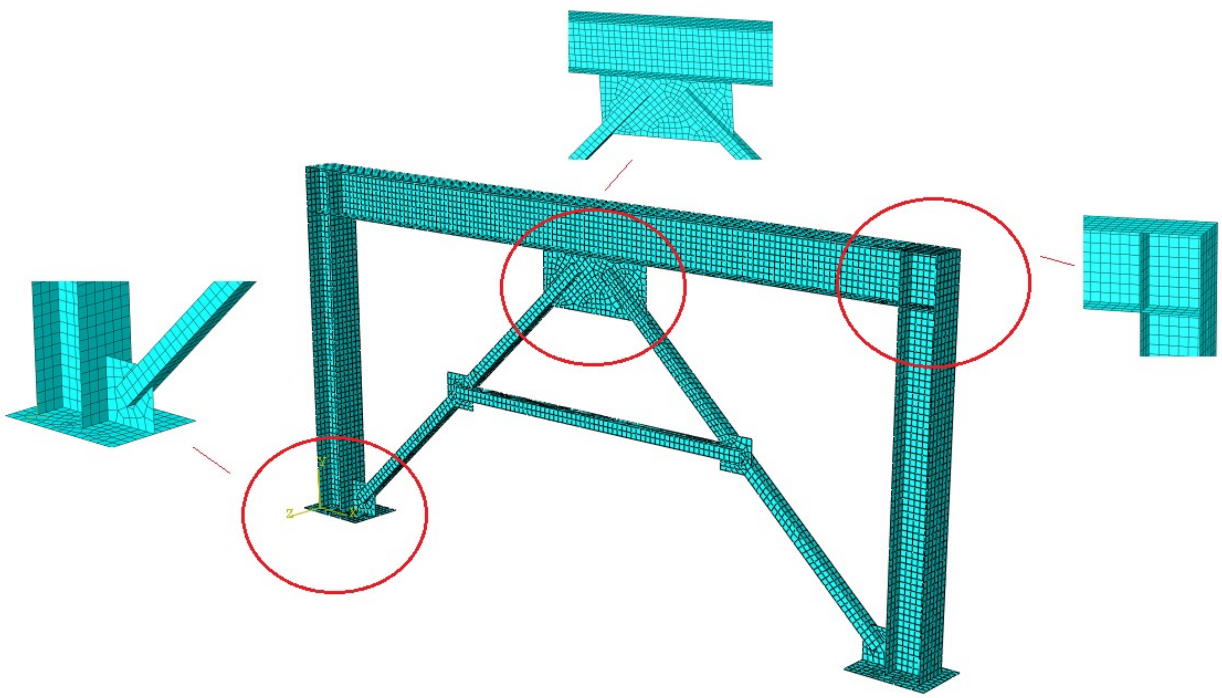


Fig. 3. Braced frame meshing in software modeling.

In general, modal analysis in the frequency domain for extracting modal parameters includes natural frequencies, damping coefficients and modal constants. Considering that the experimental data can be in the form of frequency response factor (FRF) or impulse response factor (IRF), different modal analysis methods are developed in the frequency and time domains [20].

Modal analysis in the frequency domain, based on the evaluation of laboratory data, is performed by the proposed mathematical model. The proposed model includes the degrees of freedom of the structure, damping model and number of vibration modes in the frequency domain. Assumptions in the proposed model (mathematical model) include curve optimization for modal response. Therefore, the main task in modal analysis is to create a curve optimization process to determine modal parameters (using laboratory results) [20,21].

In general, the accuracy of modal analysis does not depend on the quality of frequency curve optimization. Increasing accuracy in frequency responses will increase accuracy in optimizing the performance curve. By defining a suitable and complete mathematical model, we will achieve much better results in frequency response. Therefore, the accuracy of the results will increase [21].

In general, if damping in the system with one degree of freedom is representing by damping matrix, the equation of motion is as follows (1):

$$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}=\{0\} \tag{1}$$

Where:

M: The mass matrix,
C: The damping matrix,
K: The stiffness matrix,
x: The displacement vector,
$\dot{x}$: The velocity vector,
$\ddot{x}$: The acceleration vector [11].

The solution for Eq. (1) is in terms of eigenvalues and eigenvectors. Special vectors show vibration modes. The generalized mass matrix is defined as below:

$$\hat{m}=\varphi^{T} M\, \varphi \tag{2}$$

Where:

$\hat{m}$: The system's generalized mass matrix,
φ : The eigenvector matrix,
φ^{T} : Transducer of the matrix φ [11].

The influence vector examines a rigid body motion in all modes. Define a coefficient vector $\overline{L}$ as follows:

$$\overline{L}=\varphi^{T} M\, \bar{r} \tag{3}$$

Where:

$\overline{L}$: The coefficient vector,
$\bar{r}$: The influence vector [11].

The modal participation factor matrix Γ_i for mode i, is as below:

$$\Gamma_i=(\overline{L}_i/\hat{m}_{ii}) \tag{4}$$

Where:

Γ_i : The modal participation factor matrix.

The effective modal mass (m_{eff}), for mode i is:

$$m_{eff,i}=(\overline{L}_i{}^2/\overline{m}_{ii}) \tag{5}$$

Where:

m_{eff} : The effective modal mass [11].

3. Results

3.1. Von Mises Stress

In this section, von mises stress in braced frames will be presented and the results will be analyzed. It is mostly used for ductile materials, such as steel. The von mises yield criterion states that if the von mises stress of a material under load is equal to or greater than the yield limit of the same material under simple tension then the material will yield. Fig. 4, displays the stress contour in braced frames during the modal analyses.

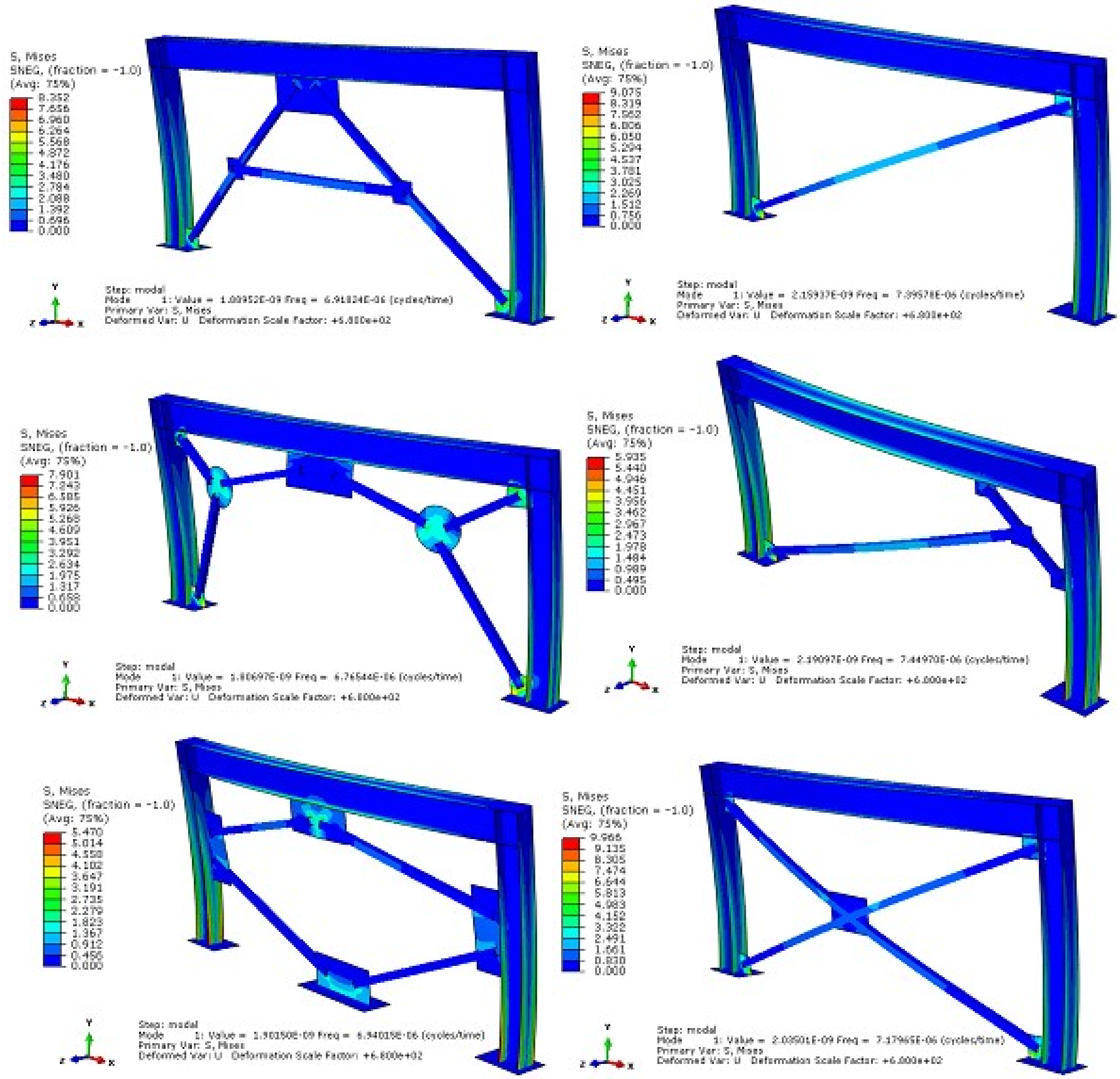


Fig. 4 Von Mises stress in braced frames in the first mode of vibration during modal analyses in the frequency domain.

As shown in Figure 4, the type of brace has a great effect on the von mises stress (in the first vibration mode) during modal analysis. The results of the analyses show that the steel frame with Rhombus brace has the lowest von mises stress (with a maximum stress of 5.47 MPa).

Also, the steel frame with X brace has the highest von mises stress with a maximum stress of 9.965 MPa. To evaluate the von mises stress in different vibration modes, the stress diagram under the column for different braced frames is presented in Fig. 5. In general, the numerical value of the compressive stress will be negative, but the von mises stress is always positive because it is a square-root of a sum of stress values squared. The results show that the changes caused by the change of bracing system are relatively large. The effect of brace type on von mises stress changes is very important in other types of software analysis such as nonlinear statics and time history dynamics. Von Mises stress in modal analysis indicates the amount of stress in vibration modes. Figure 5 shows the stress diagram in braced frames during modal analyses.

Figure 5 shows that the performance of braced frames under modal analyses is very different. By examining the von mises stress diagram in different vibration modes (in Fig. 5), it is not possible to get an accurate result. Therefore, the average von mises stress (under the column) for different vibration modes is shown in Fig. 6.

Figure 6 shows that steel frames with Rhombic and Diagonal braces have the lowest (13.4 MPa) and the highest (23.9 MPa) von mises stress in 50 vibration modes during modal analyses in the frequency domain, respectively. The application of Rhombus braces causes 24.29%, 43.93%, 10.07%, 28.72% and 24.29% reduction in von mises stress as compared to the use of A-Chevron, Diagonal, Gate, Knee and X braces, respectively.

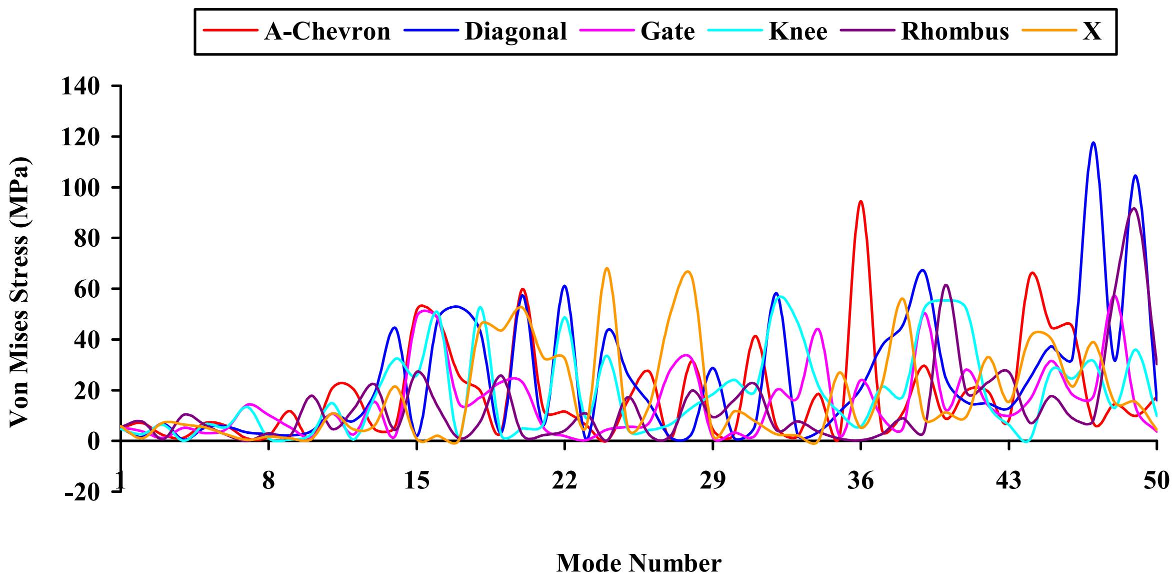


Fig. 5. Von Mises stress in different braced frames during modal analyses in the frequency domain.

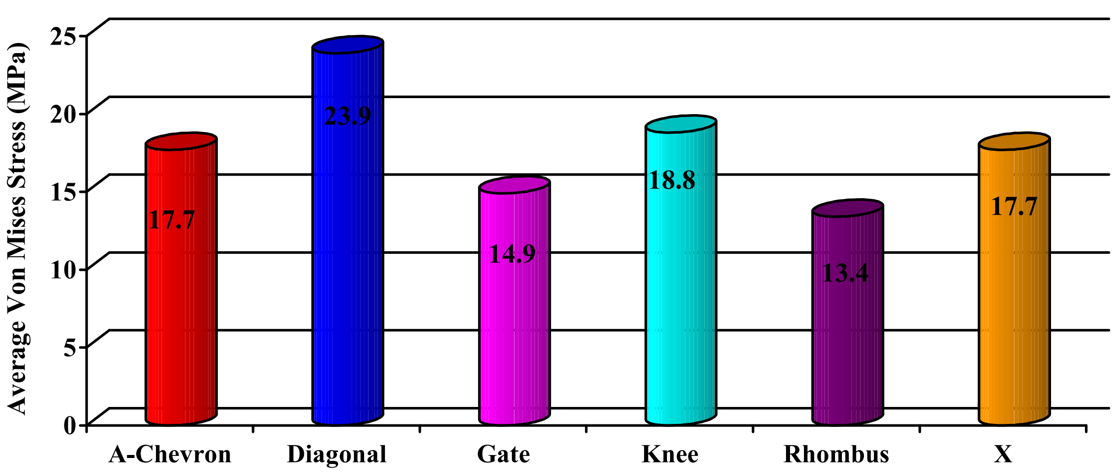


Fig. 6. Average von mises stress in different braced frames during modal analyses in the frequency domain.

3.2. Displacement

In this section, displacement in braced frames is shown and the results are analyzed.

Figure 7 shows that the maximum displacement is created in the beam. The maximum amount of displacement in braced frames is almost the same. Therefore, to numerically check the displacement of braced frames, the beam displacement diagram in vibration modes is presented in Fig. 8. Displacement parameter is the most appropriate criterion to check the dynamic performance of structures. This parameter shows the overall performance of the structure under nonlinear loading. For structures with distributed mass, the displacement is proportional to the spatial and temporal coordinates in the structure. Therefore, the proper bracing system in the structure will reduce the displacement of the structure and make the structure more stable.

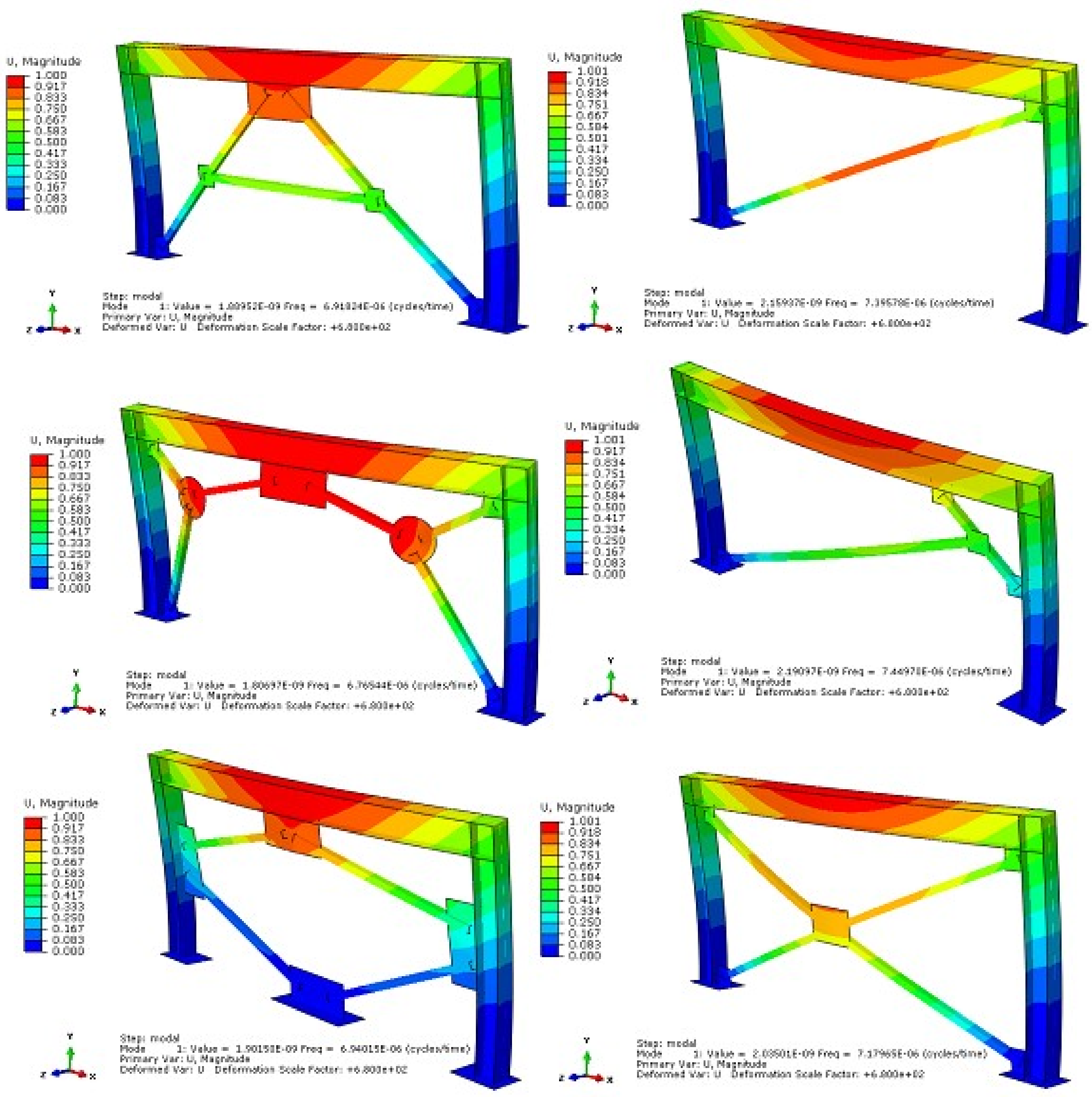


Fig. 7. Displacement in braced frames in the first mode of vibration during modal analyses in the frequency domain.

As shown in Figure 8, the braces differently affect displacement in the horizontal beam. For the numerical analyses of the results, the average beam displacement in vibration modes during the modal analysis is presented in Fig. 9.

Figure 9 shows that the steel frame with Gate brace has the least displacement in the horizontal beam (26 cm). Also, the steel frame with Diagonal brace has the largest displacement (38 cm). The use of Gate brace causes 7.14%, 31.58%, 29.73%, 10.34% and 18.75% reduction in the displacement of braced frames as compared to the use of A-Chevron, Diagonal, Knee, Rhombus and X braces, respectively,.

Generally, modal analysis can show large deformations in the structure. If nonlinear static or dynamic time history lading is performed on the structure, the actual performance of the structure is determined. Therefore, in the present paper, the determined displacement is general and the real performance of the structure is determined under static and dynamic analyses. Modal analysis determines the initial results for checking the strength of braces.

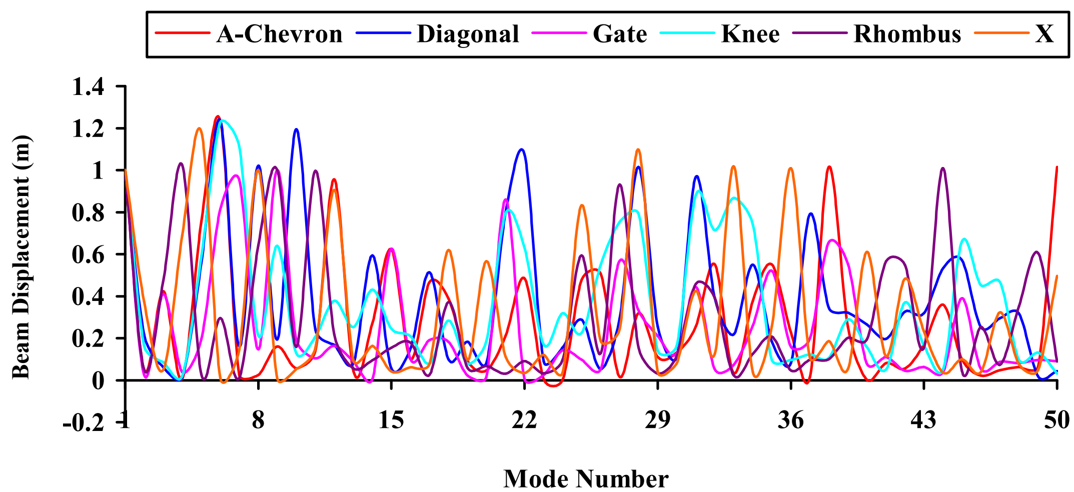


Fig. 8. Beam displacement in different braced frames during modal analyses in the frequency domain.

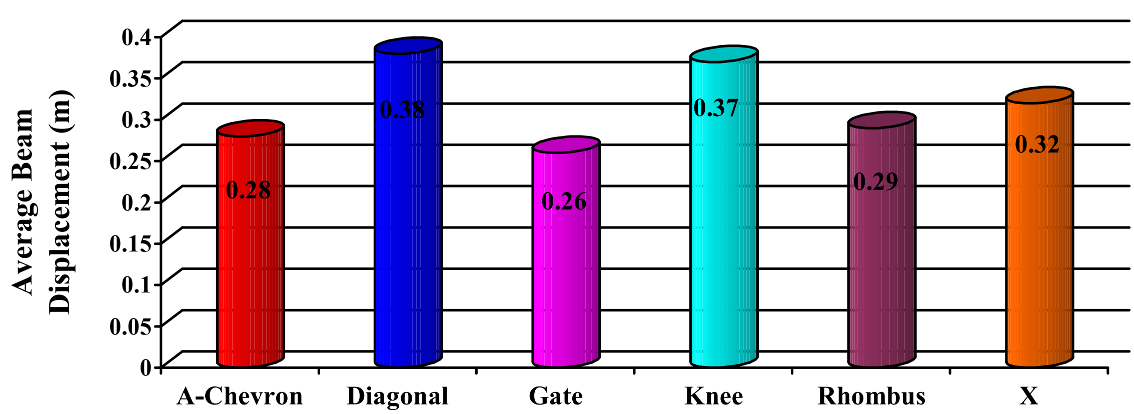


Fig. 9. Average beam displacement in braced frames in vibration modes during modal analyses in the frequency domain.

3.3. Eigen frequency

In this section, eigenfrequency in braced frames is presented and the results are analyzed.

Figure 10 shows that the effects of braces on eigenfrequency in braced frames are different. In Fig. 11, the numerical analyses of eigenfrequency in different braced frames are presented.

Figure 11 shows that the steel frame with Rhombus brace has the lowest eigenfrequency (142 Hz). Also, steel frames with Diagonal and Knee braces have the highest eigenfrequency (171 Hz).

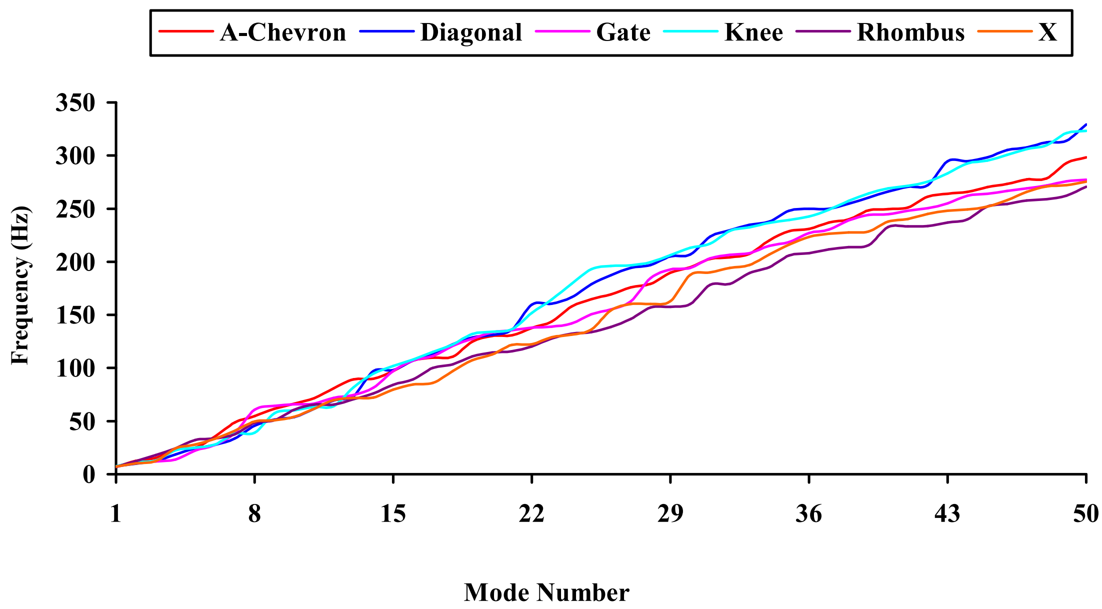


Fig. 10. Eigenfrequency in different braced frames during modal analyses in the frequency domain.

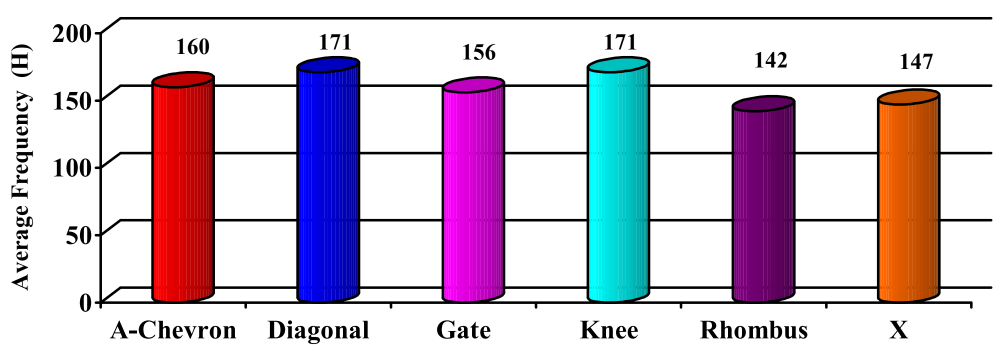


Fig. 11. Average eigenfrequency in different braced frames during modal analyses in the frequency domain.

3.4. Generalized Mass

In this section, the generalized mass in the braced frames are presented and the results are analyzed.

Figure 12 shows that the generalized mass in braced frames is different. For the numerical analyses of the results, the average generalized mass of the frames is presented in Fig. 13.

As shown in Fig. 13, the steel frame with X brace has the highest generalized mass (3.35×10^{11} Kg). Also, the steel frame with Knee brace has the lowest generalized mass (2.72×10^{11}Kg). In general, the generalized mass depends on the kinetic energy of the frame. The greater the generalized mass of the frame, the greater the total kinetic energy. Therefore, the kinetic energy in the X-braced frame is more than other braced frames.

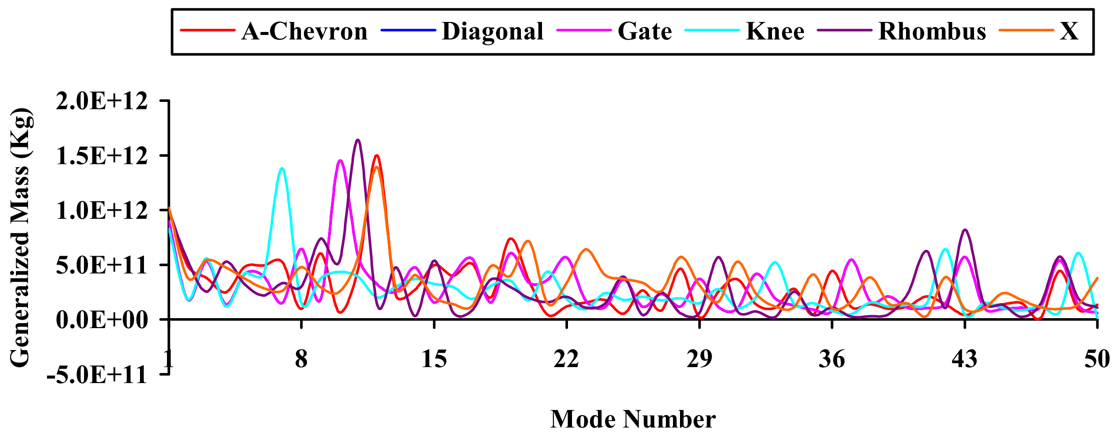


Fig. 12. Generalized mass in different braced frames during modal analyses in the frequency domain.

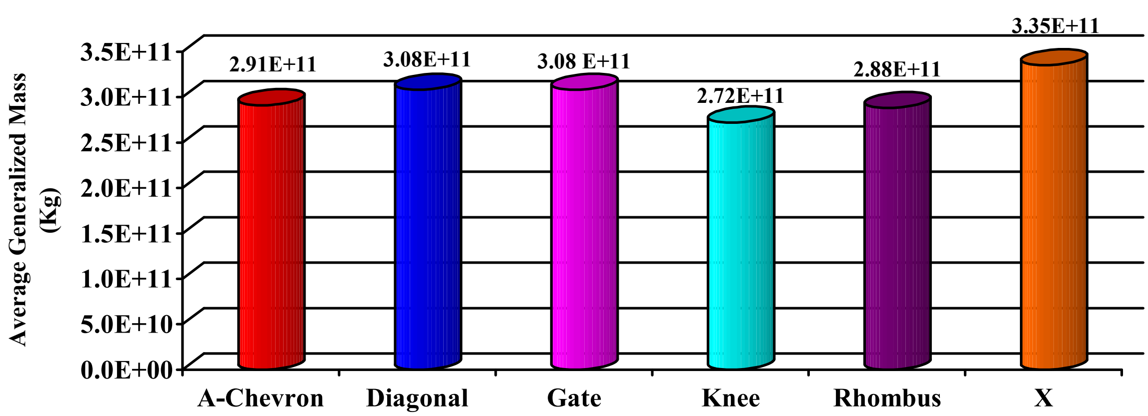


Fig. 13. Average generalized mass in different braced frames during modal analyses in the frequency domain.

3.5. Participation Factor

In this section, participation factor in braced frames is presented and compared. Figures 14 to 22 show that the type of bracing system has a great effect on the participation factor in the steel frames. Participation factors are non-dimensional scalars measuring the interaction between the modes and the state variables of a linear system. The modal participation factor is a measure of how strongly a given mode contributes to the response of the structure when subjecting to force-displacement excitation in a specific direction. In the x, y and z axes, different results are obtained, and the results and numerical analyses are presented in the graphs. In Figs. 23 and 24, the average participation factor (components and rotations) in braced frames during modal analyses in the frequency domain is presented for x, y and z axes. Modal participation factors are scalars that measure the interaction between the modes and the directional excitation in a given reference frame with larger values indicating a stronger contribution to the dynamic response. Figure 23 shows that steel frames in x, y and z components with Diagonal brace (0.051), Diagonal brace (0.088) and Knee brace (0.079) have the highest values (in average participation factors), respectively. Figure 24 shows that steel frames in x, y and z rotations with Knee brace (106), Diagonal brace (-367) and X brace (329) have the highest values (in average participation factors), respectively.

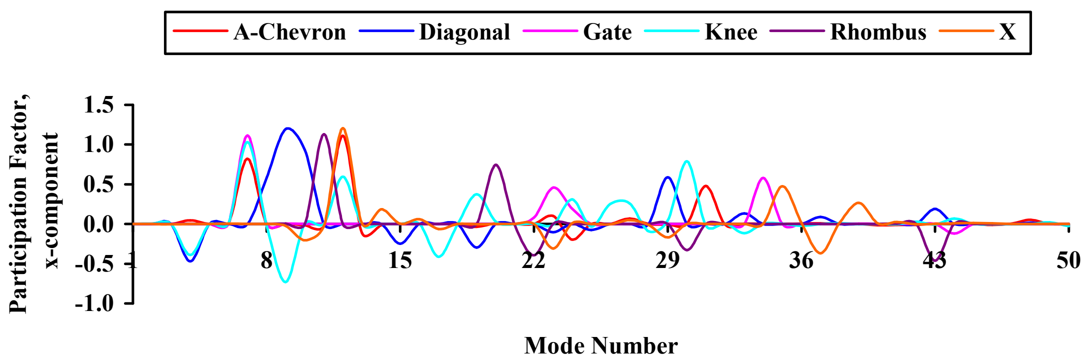


Fig. 14. Participation factor (x-component) in braced frames during modal analyses in the frequency domain

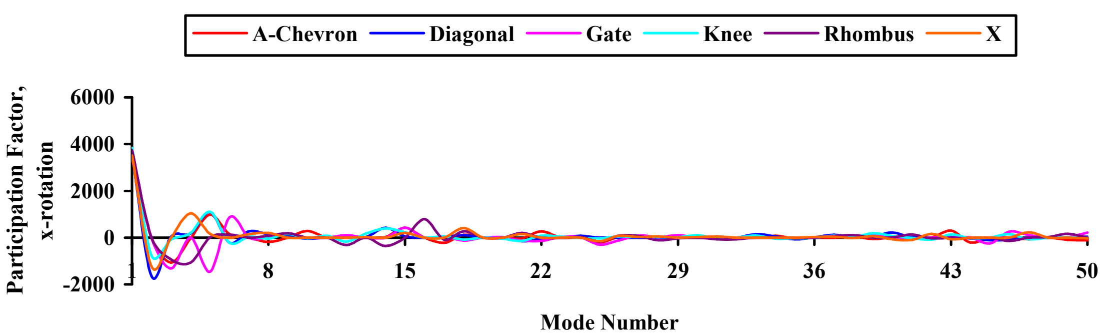
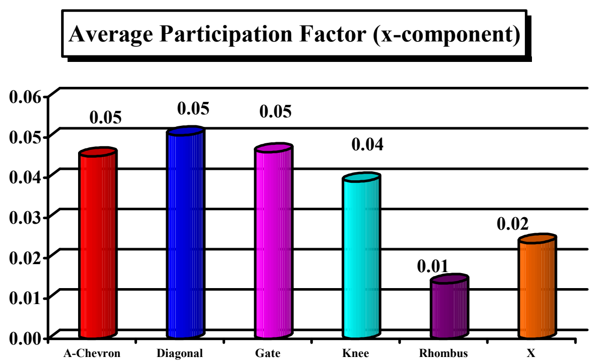
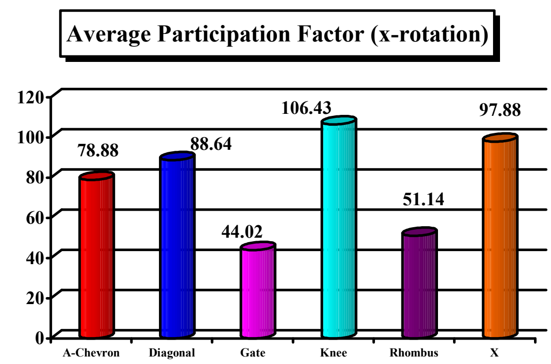


Fig. 15. Participation factor (x-rotation) in braced frames during modal analyses in the frequency domain



(a)



(b)

Fig. 16. Average Participation factor in braced frames during modal analyses in the frequency domain; (a) x-component; (b) x-rotation

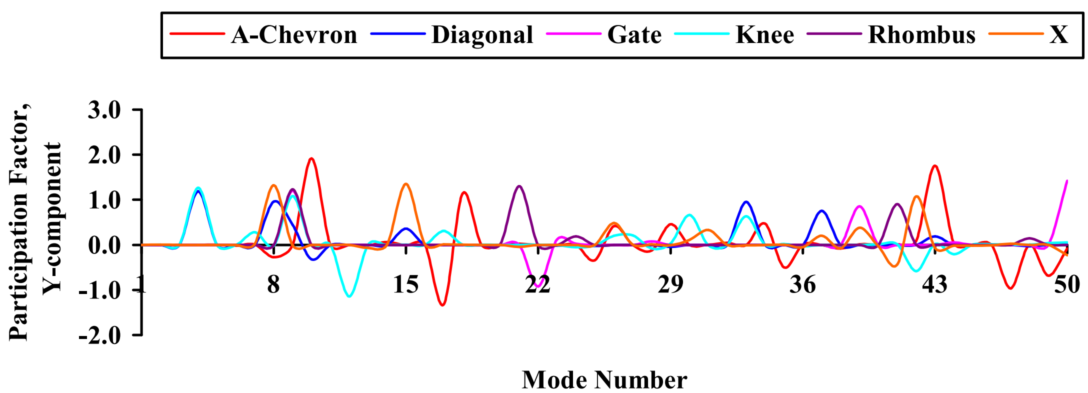


Fig. 17. Participation factor (y-component) in braced frames during modal analyses in the frequency domain

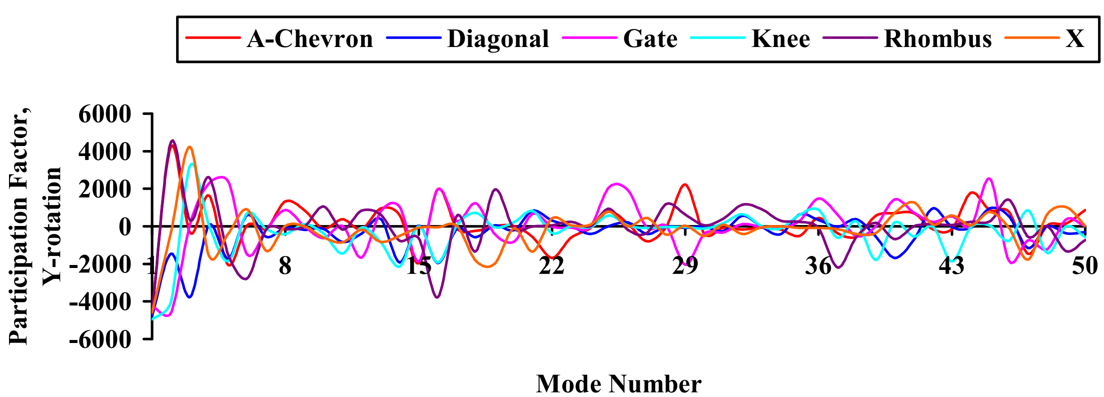
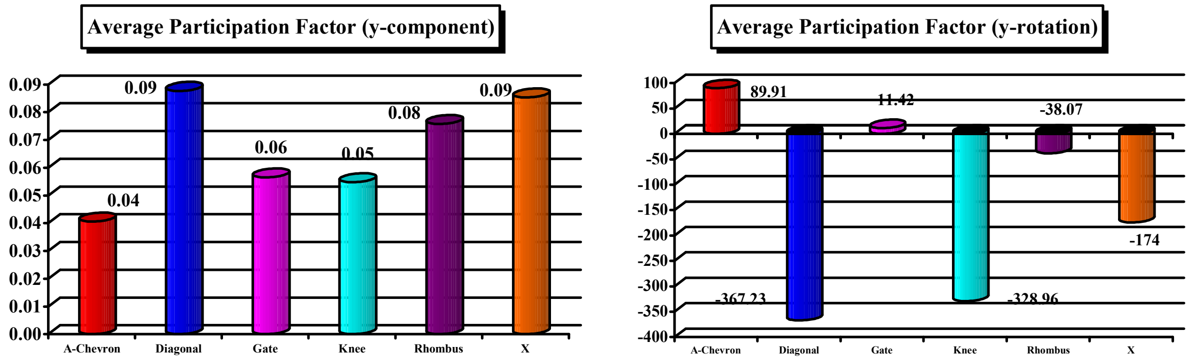


Fig. 18. Participation factor (y-rotation) in braced frames during modal analyses in the frequency domain



(a) (b)

Fig. 19. Average Participation factor in braced frames during modal analyses in the frequency domain; (a) y-component; (b) y-rotation

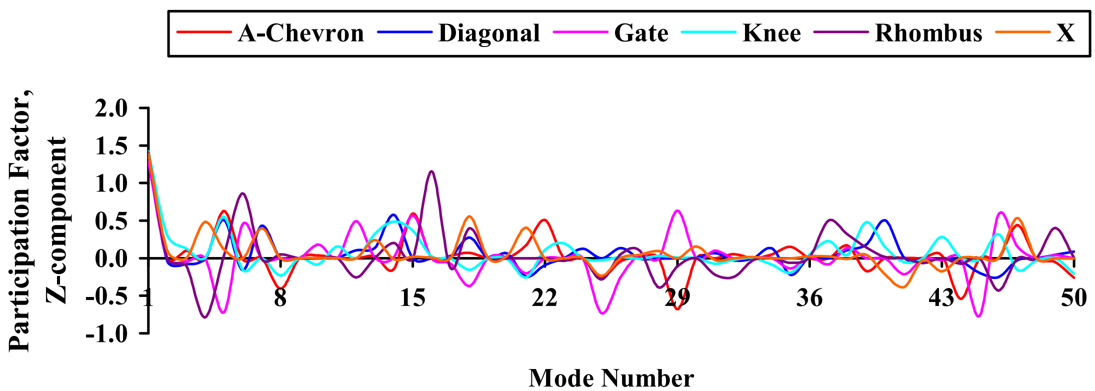


Fig. 20. Participation factor (z-component) in braced frames during modal analyses in the frequency domain

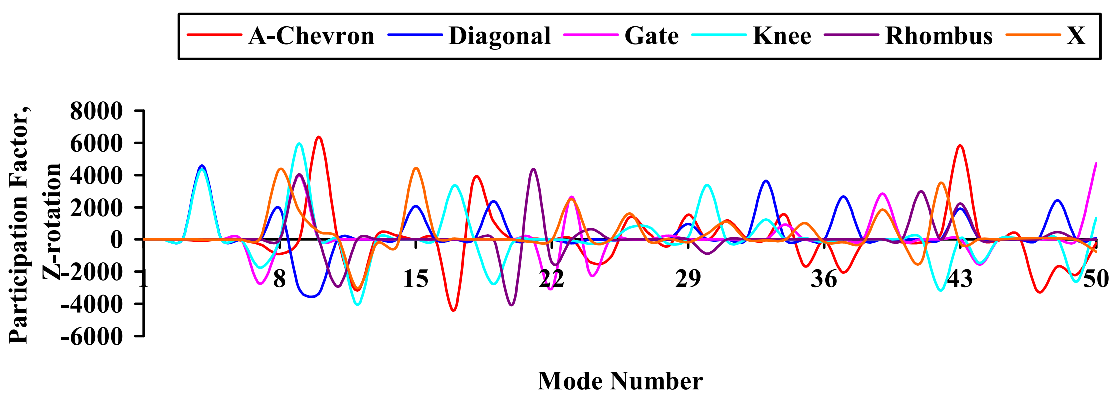
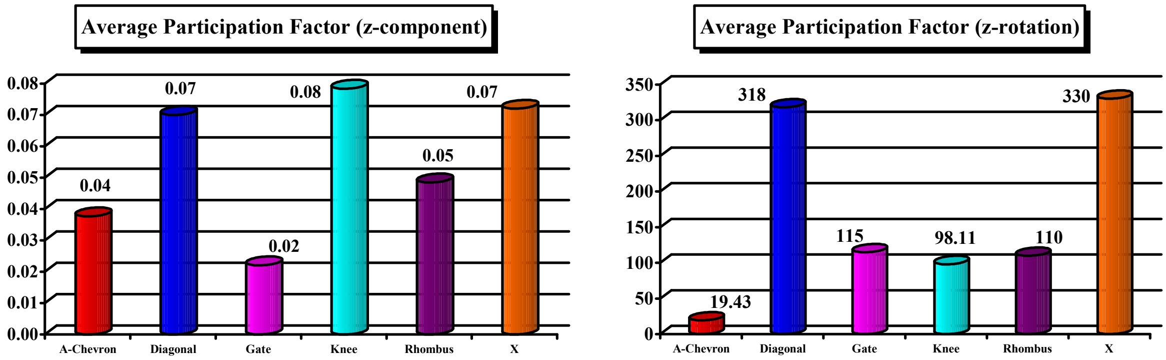
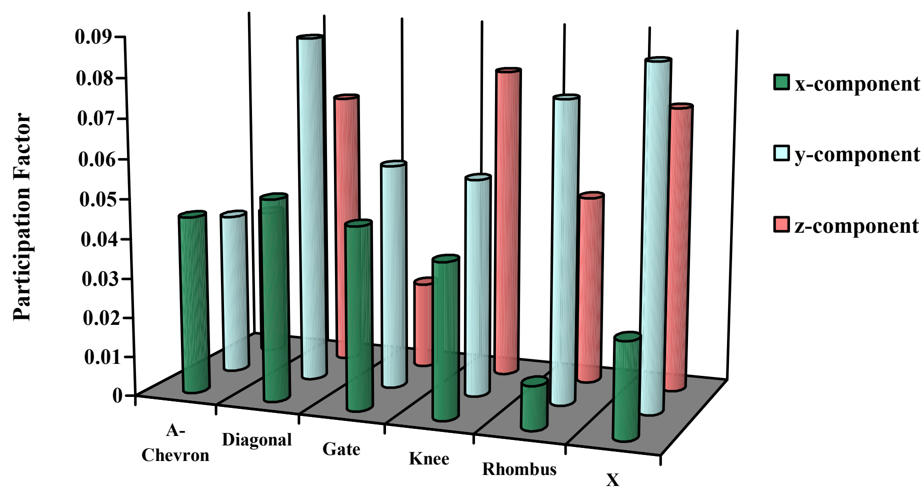


Fig. 21. Participation factor (z-rotation) in braced frames during modal analyses in the frequency domain



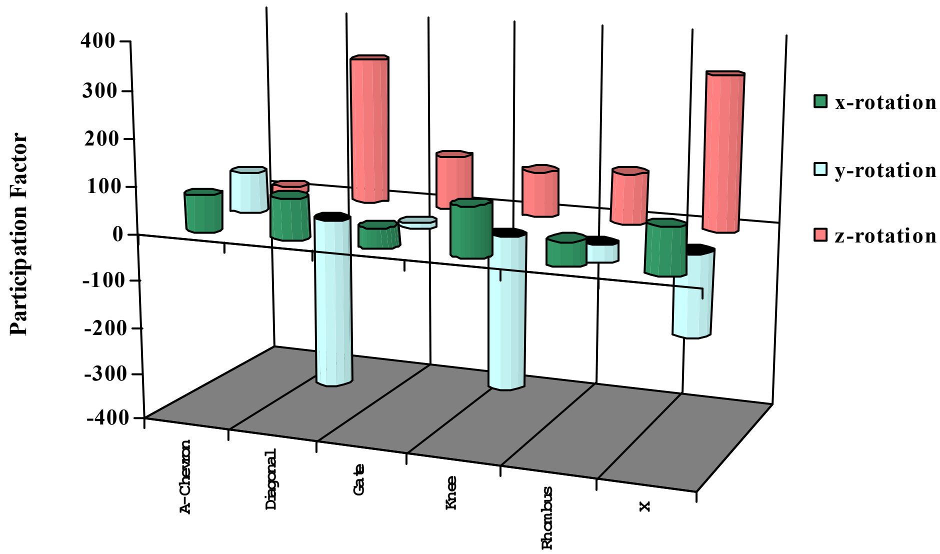
(a) (b)

Fig. 22. Average Participation factor in braced frames during modal analyses in the frequency domain; (a) z-component; (b) z-rotation



	A-Chevron	Diagonal	Gate	Knee	Rhombus	X
x-component	0.045	0.051	0.046	0.039	0.011	0.024
y-component	0.041	0.088	0.057	0.055	0.076	0.086
z-component	0.038	0.07	0.022	0.079	0.048	0.072

Fig. 23. Average participation factor for x, y and z components in braced frames during modal analyses in the frequency domain.



	A-Chevron	Diagonal	Gate	Knee	Rhombus	X
x-rotation	78	88	44	106	51	97
y-rotation	89	-367	11	-328	-38	-174
z-rotation	19	317	115	98	109	329

Fig. 24. Average participation factor for x, y and z rotations in braced frames during modal analyses in the frequency domain.

4. Validation

In the present paper, the validity of the results is done with the paper by Li et al. [22]. In [22], a 2-story steel frame with concentrically braced structure is subjected to concentrated load. In Fig. 25, the schematic of the FE model in [22] is shown. For verification in the present paper, the steel frame with geometric conditions similar to [22] (shown in Fig. 26), is modeled and subjected to concentrated static load with ABAQUS software. In Fig. 27, the results of validation are presented. The results showed that the modeling error of the results is less than 5%. Therefore, modeling and results are acceptable.

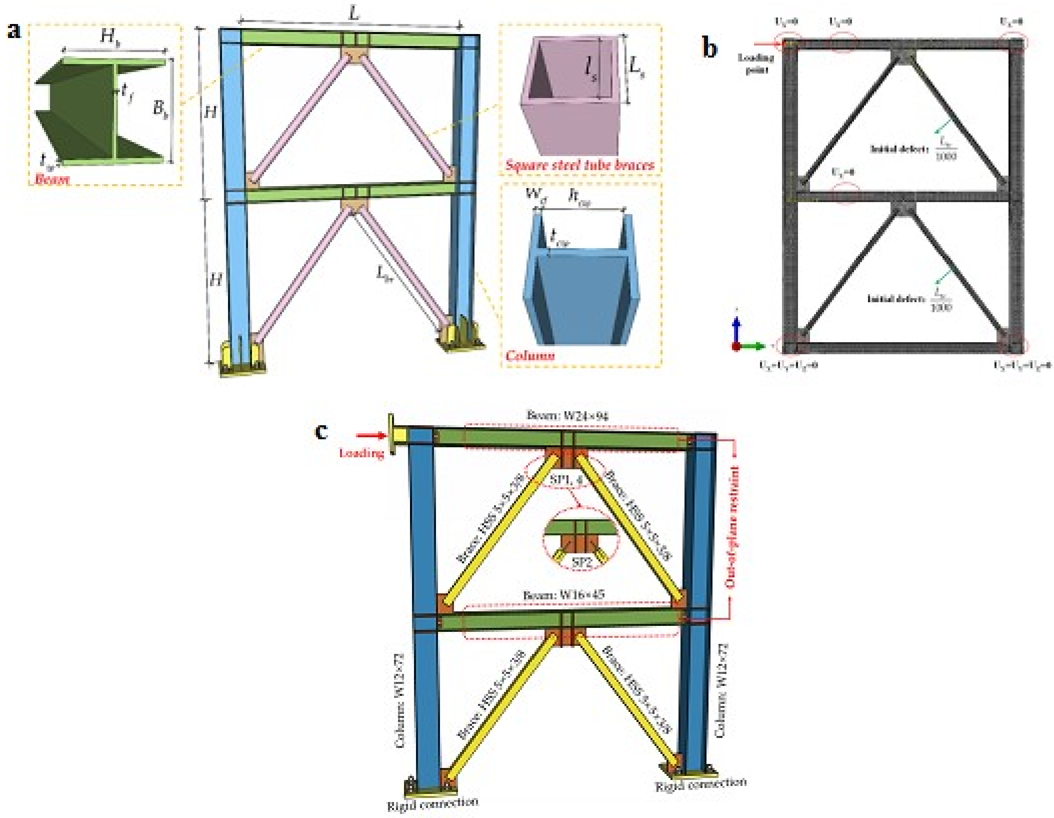


Fig. 25. (a) Schematic of FE model; (b) boundary conditions and loading; (c) test specimens in [22].

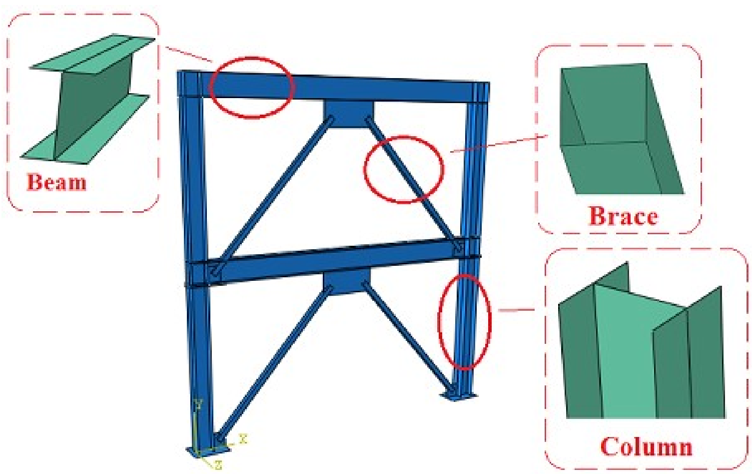


Fig. 26. Details of FE model for validation.

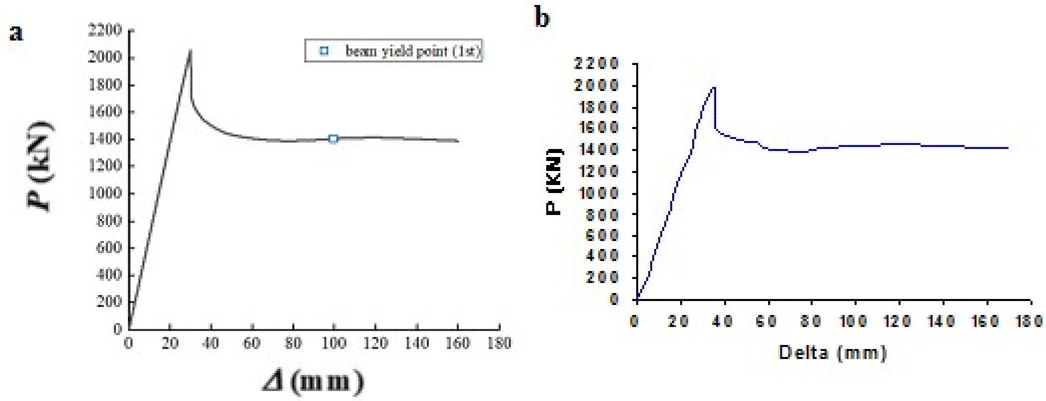


Fig. 27. (a) The predicted PEEQ distributions of concentrically-braced steel frames in [22]; (b) The output diagram from the FE modeling of the present paper for validation

5. Conclusions

Comparing the performance of bracing systems in steel structures is one of the important topics in structural engineering. Therefore, in the present paper, six new bracing systems in steel structure are examined and subjected to modal analyses in the frequency domain with the FEM and ABAQUS software. The most important results of the paper are as follows:

- In the von mises stress parameter, the Rhombus brace causes the steel frame to have the lowest average stress in 50 vibration modes, compared to other braces. The reduction of von mises stress causes the reduction of nonlinear forces on the steel frame during modal analysis. Therefore, the possibility of causing damage to the structure is reduced and the stability of the structure is increased. Also, the Diagonal brace causes the steel frame to have the most average stress during the modal analysis, in 50 vibration modes. The Rhombus brace geometry causes the nonlinear forces to be transferred to the columns in a more appropriate way, and the performance of the Rhombus brace is more suitable than the other braces.
- In the displacement parameter in the horizontal beam, the Gate brace causes the steel frame to have the lowest average displacement in 50 vibration modes. The Gate brace geometry causes the horizontal beam to have less displacement during modal analyses in the frequency domain, in 50 vibration modes. Therefore, the performance of the Gate brace is more suitable than other braces. Also, the performance of the Rhombus brace is appropriate.
- In the eigenfrequency parameter, the Rhombus brace causes the steel frame to have the lowest frequency content. Also, the X brace has (almost) the same performance as the Rhombus brace. However, Diagonal and Knee braces cause the highest frequency in steel frames.
- In the generalized mass parameter, the Knee brace causes the steel frame to have the lowest value. Also, the generalized mass in the Rhombus brace is (almost) equal to the Knee brace. However, the X brace causes the steel frame to have the most generalized mass. An increase in generalized mass during earthquakes or strong storms causes an increase in seismic forces.
- In the Participation factor (component) parameter, the Diagonal, Diagonal and Knee braces cause the steel frames to have the highest value in the modal response in the x, y and z axes, respectively. Also, the Knee, Diagonal and X braces cause the steel frames to be of the highest value in the modal response in the Participation factor (rotation) parameter, in the x, y and z axes, respectively.

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