Advanced Structural Mechanics 1 (2023) 199-209

Advanced Structural Mechanics

Journal homepage: https://asm.sku.ac.ir

Investigating the performance of modern concentric braces during modal analysis in the frequency domain with the finite element method

Masoud Mahdavi[a]*, Seyyed Reza Hosseini[b], Abbas Babaafjaei[b]

[a]*PhD Student, K. N. Toosi University of Technology, Tehran , Iran,*
[b]*MsC Student, K. N. Toosi University of Technology, Tehran , Iran.*
Article received:2024/03/07, Article revised: 2024/03/14, Article accepted: 2024/03/14

ABSTRACT

The use of steel braces in the structure is the most practical method to increase the lateral stiffness of the building. Today, all types of modern braces are used in steel structures. Gate and Inverted V braces are very common and modern. In the present paper, by using ABAQUS software and Finite Element Method (FEM), Gate and inverted V braces are modeled and compared. St37material is used for modeling. In the present paper, the structures are analyzed by modal methods in the frequency domain. The present paper is confirmed with the results of the paper by Mosalman et al. The results show that the Inverted V brace has a lower von Mises stress (equal to 29.18% reduction) and displacement (equal to 16.69% reduction) as compared to the Gate brace. Also, the Gate brace has a lower natural frequency and eigenvalue (equal to 19.46% attenuation) as compared to the Inverted V brace.
Keywords: Gate brace, Inverted V brace, Modal analysis in the frequency domain, structural bracing systems

1. Introduction

The bracing system in steel structures is the best method to increase the (lateral) stiffness of the building. Nowadays, all kinds of modern braces, including gate braces and inverted braces are used in buildings [1, 2]. Braces have special characteristics and an improvement in the performance of the brace increases the seismic performance of the structure [3]. Therefore, checking and comparing the performance of new braces are important and practical.

* Corresponding author at: K. N. Toosi University of Technology, Tehran , Iran.
E-mail address: M.Mahdavi@kntu.ac.ir
DOI: 10.22034/asm.2024.14720.1018: https://asm.sku.ac.ir/article_11600.html

Nomenclature

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
$\hat{m}$	The system's generalized mass matrix
$\underline{m}_{eff}$	The effective modal mass
$\bar{L}$	The coefficient vector
Γ_i	The modal participation factor matrix
φ	The eigenvector matrix
$\bar{r}$	The influence vector

In the present paper, the evaluation of new braces, including Gate and Inverted V with the Finite Element Method (FEM) is done. Modeling has been done with FE software to have new results for engineers. Ullah et al. [4] investigated the seismic performance of steel frame with chevron brace and damper. The results showed that the presence of the damper increases the performance of the brace. Behnamfar et al. [5] evaluated the performance of concentrically braced frames with dampers. This paper has been done on 4, 8 and 12-story structures with CBF brace. The results showed that the proposed brace has reduced the story drift. Qiu et al. [6] evaluated the seismic performance of steel frames with Knee brace. This study was done on 3 and 6-story structures. The results showed that the presence of the brace reduces the story drift. Ghiasvandan et al. [7] investigated the experimental and numerical analyses of new braces to improve the seismic performance. This study was done with ABAQUS software. The results showed that the Knee brace increases the durability of the structure against lateral loads. Mokhtari et al. [8] investigated the seismic performance of braced frames. This study was done with the incremental dynamic method. Li et al. [9] investigated the stiffness in steel structures with eccentrically braced frames (EBF). The results showed that the EBF braces increased the performance. Zhang et al. [10] investigated the seismic performance of eccentrically braced steel structures based on plastic design. In this paper, 6 and 9-story structures were modeled and analyzed with SAP2000 software. The results showed that the elastoplastic performance of structures is suitable. Mata et al. [11] investigated the seismic performance of eccentrically braced frames with IDA analyses (under Chile earthquake). In this paper, 8, 12 and 16-story structures were modeled and analyzed. In this study, more than 15000 analyses have been performed. The results showed that structures with greater stiffness (braced frames) have a lower probability of collapsing in earthquakes. Mahdavi [12] investigated steel structures with different types of CBF and EBF braces. In this paper, 4 and 8-story structures were modeled and analyzed with SAP2000 software. They investigated 10 types of braces with nonlinear static analyses. The results showed that the concentrically braced frames (4-story) and the zipper brace (8-story) have the highest capacity in creating plastic hinges. Gao et al. [13] investigated concentrically braced structures. This research has been done using the time history analysis method. Bradley et al. [14] designed a CBF with low ductility. The results showed that the proposed brace can be a good alternative to the modern braces. Haji Mazdarani et al. [15] were able to optimize concentrically braced steel structures. In this paper, reliability-based design optimization (RBDO) for 4, 5 and 9-story steel structures has been performed using the new algorithm.

In the present paper, two new concentrically braced structures have been modeled. In very few papers, modern concentrically braced structures have been subjected to modal analysis. Therefore, the modal analysis of the Gate and Inverted V braces will yield new results, which are reviewed in the present paper. This research returns many results such as von Mises stress, displacement, natural frequency, etc. Therefore, there are many innovations in the present paper.

The Gate brace is similar to the Chevron brace, except that brace members are not straight. Gate brace has advantages such as increasing the geometric space [16–18]. Figure 1-a. shows the Gate brace. In the Inverted V brace, that is a type of concentrically braced structure, the brace members under gravity loads have maximum tension. Also, bracing members have compressive forces under lateral loads and overcome tensile forces. Therefore, this factor causes the behavior of the Inverted V brace to be better than Chevron brace [17,18]. Figure 1-b. shows the Inverted V brace.

2. Validation

The present research has been validated using the study by Mosalman et al. [19]. In [19], the Gate brace is subjected to nonlinear static loading. Modeling in [19] has been done with ABAQUS software and Finite Element Method (FEM). In the present paper, the loading of the model was done based on [19]. The validation results of the present research are presented in Fig. 2. Based on the results, the error is less than 5%, and therefore, the modeling is confirmed.

3. Methodology

In the present study, steel frames are designed with ABAQUS software. Gate and Inverted V braces are located in the structures. The frames modeled in the present research are shown in Fig. 3.
The story height and the span length are equal to 3.2 and 6.6 meters, respectively. In the modeling, ST37 steel is used and material specifications are presented in Table 1.

Fig. 1. (a) Gate brace [15]; (b) Inverted V brace [17].

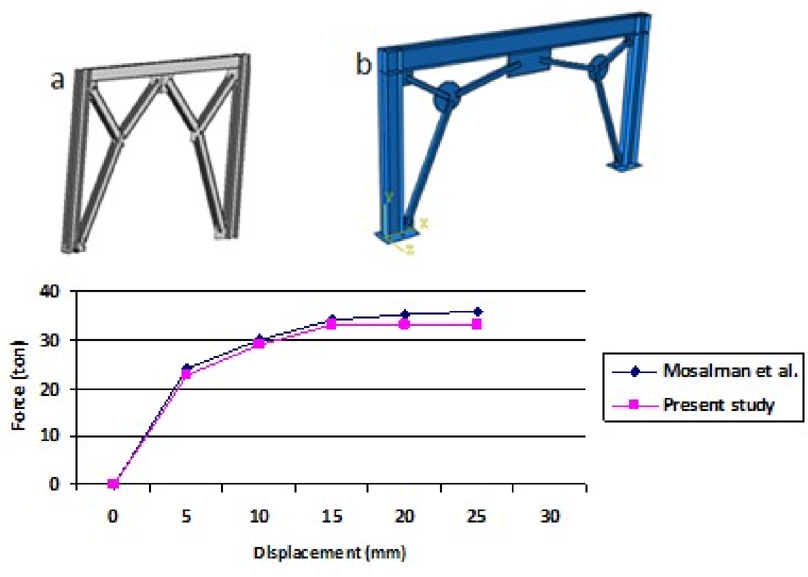


Fig. 2. (a) Modeling in [19]; (b) The present study modeling for validation; (c) Comparison between present study and [19].

In the present study, modal analysis in the frequency domain has been used to analyze structures. The 10 vibration modes in structures have been investigated. In the eigensolver section, the subspace method is used. The maximum number of iteration in the analysis is 30 times. In general, in finite element modeling, the mesh size should be according to Table 2. Meshing criteria are established in this study.

In general, if damping in the system with one degree of freedom is represented by the damping matrix, the equation of motion is according to Eq. (1):

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

Where:

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

The solution (for the homogeneous model) for Equation (1) is in terms of eigenvalues and eigenvectors. Special vectors show vibration modes. The generalized mass matrix is defined in Eq. (2) [21]:

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

Where:

$\hat{m}$: system's generalized mass matrix,
φ : eigenvector matrix,
φ^{T} : transducer of the matrix φ .

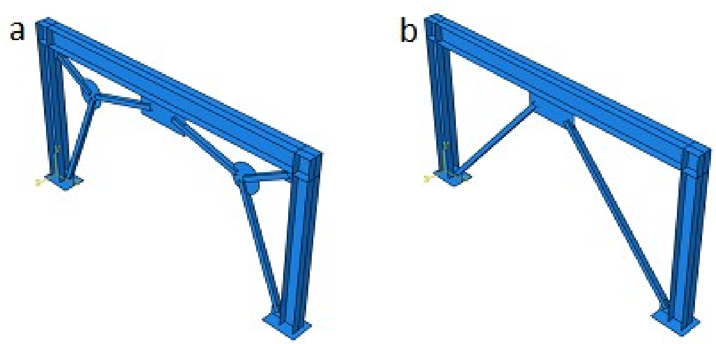


Fig. 3. (a) Gate brace; (b) Inverted V brace in the present paper

Table 1. Characteristics of steel (St37) used in modeling by ABAQUS software [17]

Parameter (Unit)	Minimum Yield Stress (Kg/cm × cm)	Minimum Tensile Stress (Kg/cm × cm)	Effective Tensile Stress (Kg/cm × cm)	Effective Tensile Stress (Kg/cm × cm)	Poisson's Ratio
Numerical value	24×10^{6}	27×10^{6}	27.6×10^{6}	42.55×10^{6}	0.3

Table 2. Maximum element dimension in nonlinear analysis [20]

Row	Type	Minimum Yield Stress
1	2D Model	Min (L/50 and B/5)
2	3D Model	Min (L/50, B/5 and H/5)
Note: The element dimensions include L: Length, B: Width and H: Height.		

The influence vector examines a rigid body motion in all modes. Define a coefficient vector $\overline{L}$ as [21]:

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

Where:

$\overline{L}$: coefficient vector,

$\overline{r}$: influence vector.

The modal participation factor matrix Γ_i for mode i is [21]:

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

Where:

Γ_i : modal participation factor matrix.

The effective modal mass (m_{eff}), for mode i is [21]:

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

Where:

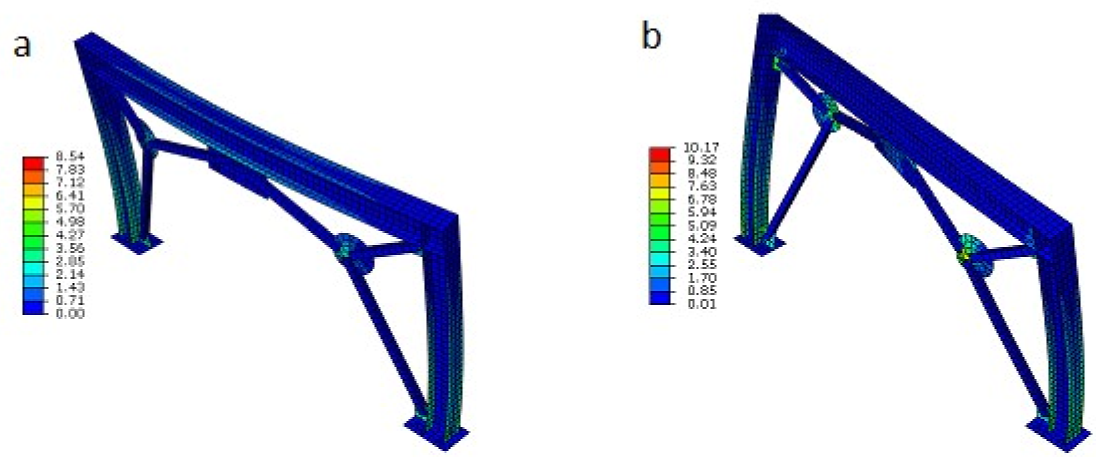
m_{eff} : effective modal mass

In the present study, ABAQUS software is used for modeling braces. The elements included columns, beams, connecting plates (3 types), plate under the column and connecting rods. The braces are of steel type. Therefore, by assigning steel materials (Table 1) to elements, materials and sections are defined. Then by assembling the elements, the complete brace is created. The step is then defined as frequency type. In the present research, 10 vibration modes are investigated in braces. Next, the supports are assigned to the sub-columns. In the brace meshing section, an approximate global size equal to 100 is considered. The mesh Control is Quad dominated. Finally, frequency analysis is performed in the modal domain.

4. Presentation and Analysis of Results

4.1. Von Mises Stress

In this section, the von Mises stress in the four vibration modes of the structures, which are separated by type of brace, is presented and compared (Figs. 4 and 5).



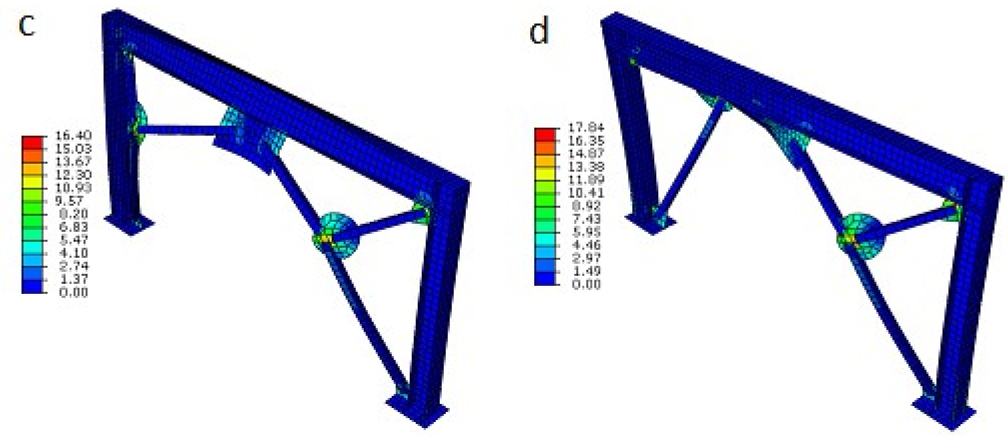


Fig. 4. Von Mises stress (a) 1st mode; (b) 2nd mode; (c) 3rd mode and (d) 4th mode in Gate braces under modal analysis of frequency domain.

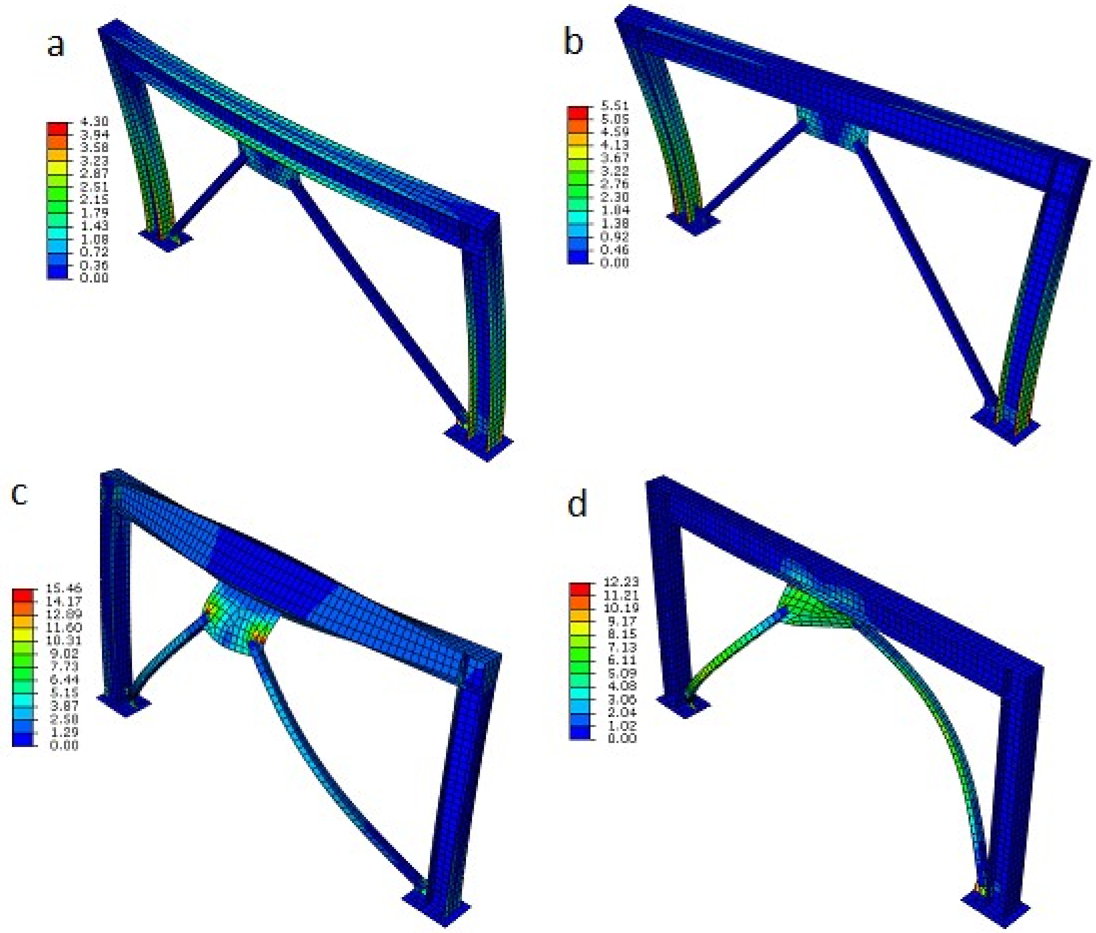


Fig. 5. Von Mises stress (a) 1st mode; (b) 2nd mode; (c) 3rd mode and (d) 4th mode in Invert V braces under modal analysis of frequency domain.

Figure 4 and Figure 5 show that the maximum stress in the 1st to the 4th vibration modes is lower in the Inverted V brace. Reducing the stress in the structure causes less compressive forces to be applied to the structure in an earthquake or storm. Therefore, the probability of damage to the structure will be reduced. In Fig. 6, the numerical analysis of the deformations in the 1st to the 4th vibration modes are presented.

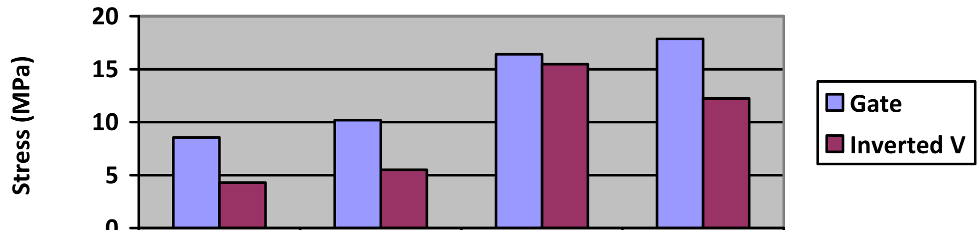
4.2. Natural Frequency

In this section, a numerical analysis of the natural frequencies resulting from the modal analysis, separated by the type of brace and vibration modes, is presented (Fig. 7).

Figure 7 shows that the natural frequency in the Gate and Inverted V braces is almost equal. The sum of the natural frequencies in ten vibration modes in the Gate and Inverted V braces is equal to 0.0003231723 and 0.00032317233 MHz, respectively. Therefore, the natural frequency in the Gate brace is lower.

4.3. Displacement

In this section, the displacement caused by the modal analysis in the frequency domain, separated by the vibration modes and the type of brace, is presented (Figs. 8 and 9).



Mode No.	1	2	3	4
Gate	8.54	10.17	16.4	17.84
Inverted V	4.3	5.51	15.46	12.23

Fig. 6. Analytical diagram of the maximum stress in the 1st to the 4th vibration modes in Gate and Inverted V braces

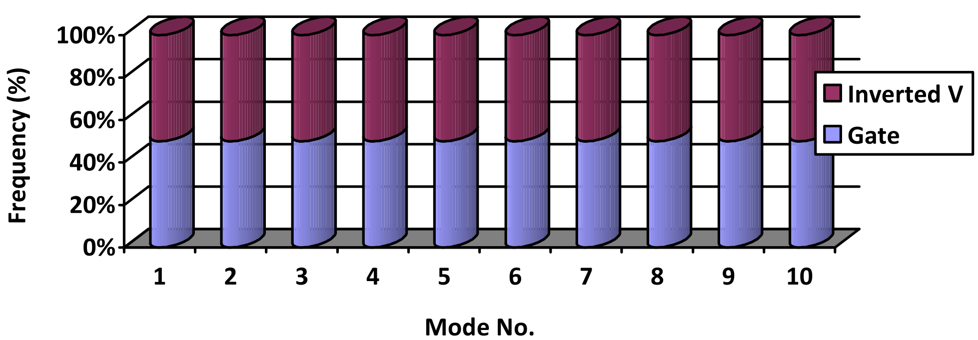


Fig. 7. Natural frequency in Gate and Inverted V braces under modal analyses in the frequency domain

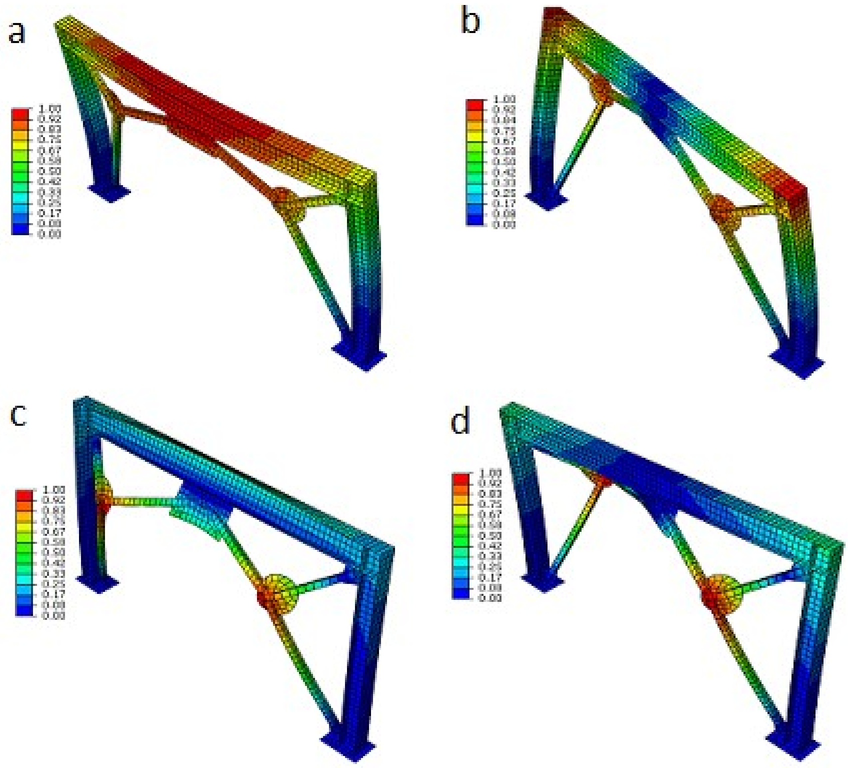


Fig. 8. Displacement in the (a) 1st mode; (b) 2nd mode; (c) 3rd mode and (d) 4th mode in Gate braces under modal analyses

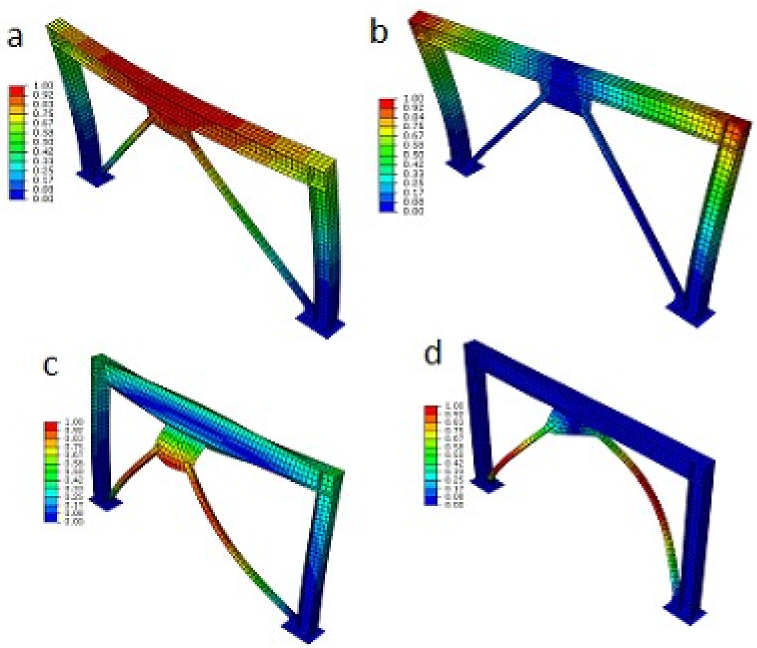


Fig. 9. Displacement in the (a) 1st mode; (b) 2nd mode; (c) 3rd mode and (d) 4th mode in Inverted V braces under modal analyses

In order to perform numerical analyses, a comparison diagram for the Gate and Inverted V braces, in the horizontal beam of the steel frame, is presented in Fig. 10.

Figure 10 shows that the horizontal beam in the frame with Inverted V brace has less displacement. The Inverted V brace has a better structure than the Gate brace. Therefore, the force movement is better in the Invert V brace.

4.4. Eigenvalues

In this section, the eigenvalue, which represents the critical load during buckling, is presented and compared (Fig. 11). Figure 11 shows that the probability of buckling in an earthquake or storm is higher in an Inverted V brace. Therefore, the stiffness of the Gate brace is higher in the modal analysis.

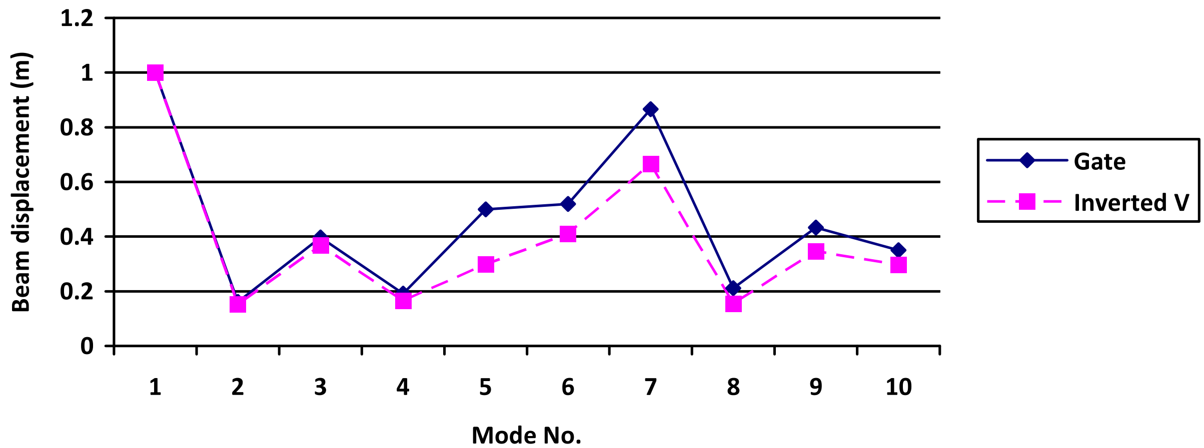


Fig. 10. Beam displacement in Gate and Inverted V braces under modal analysis in the frequency domain.

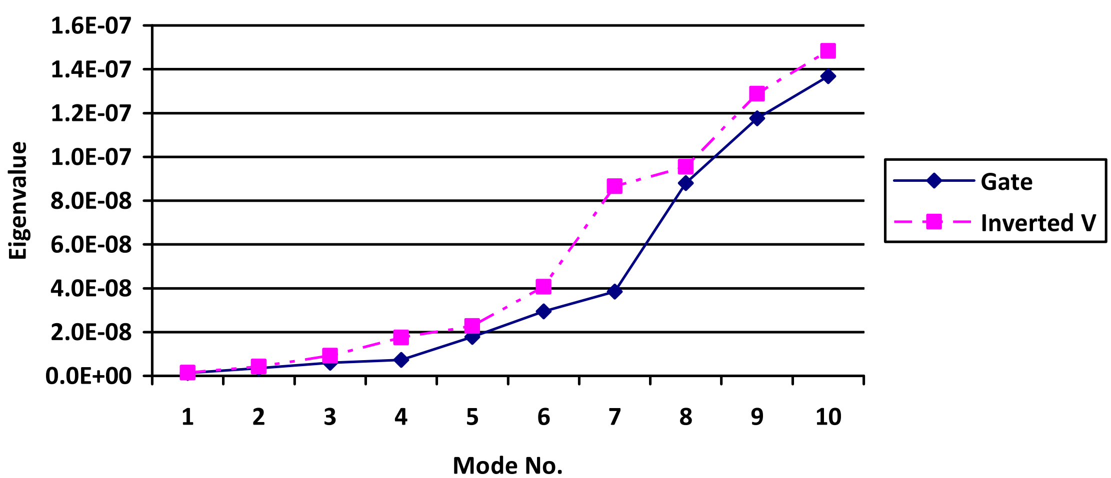


Fig. 11. Eigenvalue in (a) Gate brace; (b) Inverted V brace under modal analysis in frequency domain.

5. Conclusion

The most important results of the present study are as follows:

- In the von Mises stress parameter, the Inverted V brace outperformed the gate brace. The Inverted V brace has 29.19% less tensile force. The Inverted V brace is capable of better transferring the compressive forces and establishes the balance in the structure. Therefore, less stress is created in the members of the structure. The reduction of von Mises stress causes the structure to be subjected to smaller forces. Therefore, less damage is caused in the structure. When large earthquakes occur, high stresses cause damage to beams and columns. So, reducing the von Mises stress increases the stiffness and stability of the structure.

- In the Natural Frequency parameter, the Gate brace has lower values (by a very small difference) compared to the Inverted V brace. Due to the same frequency in the Inverted V and Gate braces, the modal performance in this parameter is almost the same during earthquakes or severe storms. Reducing the brace vibration increases the static performance. By increasing the static forces, the dynamic forces are decreased. Therefore, the structure performance during an earthquake is improved.

- The results show that the displacement of the Inverted V brace is less than that of the Gate brace. The inverted V brace has better geometry (compared to the gate brace) in power transmission. Therefore, the forces are transferred faster to other members and finally to the ground, and less damage is thus caused to members during the earthquake in the inverted brace. The reduction of the displacement in the steel structure causes the structure to have more static performance during nonlinear loading. The reduction of dynamic behavior in the structure reduces the dynamic forces. Therefore, smaller forces are applied to the inverted brace.

- The results show that the Inverted V brace has a higher eigenvalue than the Gate brace. The eigenvalue is checked in the structure when there is buckling. Therefore, the results show that the Inverted V brace has a higher probability of buckling in nonlinear loads (such as nonlinear statics (pushover) and nonlinear time history). Buckling of the brace causes its load capacity to decrease. Excessive buckling of the brace and its members completely destroy the brace and leave the structural equality system.

References

[1] Zhao, J., Qiu, H., 2024. Numerical and analytical studies for a novel steel brace retrofit system, Journal of Construction Steel Research. 212, 108284.

[2] Mahdavi, M., Hosseini, S., Babaafjaei, A., 2023. Modelling and Comparison of Plastic Performance in Ten Types of New Steel Braces under Pushover Analysis. Computatinal Engineering and Physical Modeling. 6(2), 79-97.

[3] Liu, T., Zhu, L., Luo, J., Dong, Y.R., Li, Z., 2023. Experimental, mathematical model and simulation of a dual-system self-centering energy dissipative brace equipped with SMA and variable friction device. Journal of Construction Steel Research. 211(1), 4660-4680.

[4] Ullah, R., Vafaei, M., Alih, S.C., Waheed, A., 2024. Investigating the seismic response of chevron braced frame equipped with a replaceable sandwiched fused damper. Journal of Building Engineering. 86, 108928.

[5] Behnamfar, F., Ahmadi, A., Anaraki, A.M.G., Mazrouei, V., 2023. Performance evaluation of concentrically braced frames equipped with pure bending yielding damper. Structures. 58, 105650.

[6] Qiu, C., Jiang, T., Liu, J., Du, X., 2023. Seismic performance of knee-braced frames equipped with NiTi BRBs. Journal of Construction Steel Research. 197, 107480.

[7] Ghiasvandan, M., Alirezaei, M., Mohammad Mirhosseini, S., Zeighami, E., 2022. Experimental and parametric study of a novel braced system to improve seismic performance. Structures. 45, 229–42.

[8] Mokhtari, M., Islam, A., Imanpour, A., 2022. Development, seismic performance and collapse evaluation of steel moment-resisting knee braced frame, Journal of Construction Steel Research. 193, 107262.

[9] Li, S., Xu, T., Li, X., Liang, G., Xi, H., 2023. Elastic stiffness and bearing mechanism of eccentrically braced steel frames. Structures. 55, 818–33.

[10] Zhang, X., Ma, X., Zhang, S., 2023. Seismic performance of eccentrically braced precast reinforced concrete columns-steel beams

frame with replaceable shear links based on plastic design. Journal of Building Engineering. 76, 107027.

[11] Mata, R., Nunez, E., Calo, B., Herrera, R., 2023. Seismic performance of eccentrically braced frames with short-links: IDA approach using chilean earthquakes. Journal of Building Engineering. 76, 107186.

[12] Mahdavi, M., 2020. Evaluation and Comparison of Seismic Performance of Structural Trusses under Cyclic Loading with Finite Element Method. World Academy of Science, Engineering and Technology, Open Science Index 166, International Journal of Civil and Environmental Engineering. 14(10), 341 - 348.

[13] Gao, X., Li, J., Qiu, C., Hou, H., Chen, C., 2023. Quantification of material modeling uncertainty on seismic performance of SMA-based self-centering concentrically braced frames. Structures. 56, 105028.

[14] Bradley, C.R., Fahnestock, L.A., Hines, E.M., 2021. Dual system design for a low-ductility concentrically braced frame with a reserve moment frame. Structures. 34, 3315–3328.

[15] Haji Mazdarani, M.J., Hoseini Vaez, S.R., Hosseini, P., Fathali, M.A., 2022. Reliability-based layout optimization of concentrically braced in 3D steel frames. Structures. 47, 1094–1112.

[16] Mahdavi, M., Babaafjaei, A., Hosseini, S., Aghababaei Mornani, B., Tavakoli, M., 2023. Investigating the Effects of Increasing the Span Length to the Story Height of the Bracing Frame under Near-Fault and Far-Fault Earthquakes. Journal of Civil Engineering Material Application. 7, 225–242.

[17] Mahdavi, M., Azizzadeh, R., 2020. Structural Bracing Systems. LAP Lambert Academic Publishing. 1, 80.

[18] Fanaie, N., Ezzatshoar, S., 2014. Studying the seismic behavior of gate braced frames by incremental dynamic analysis (IDA). Journal of Construction Steel Research. 99, 111–120.

[19] Mosalman, M., Mosalman, A., Mosalman Yazdi, H., 2011. On the connection behavior of gate bracing system. Scientiffic and Research Essays. 6, 241–256.

[20] Bomers, A., Schielen, R.M.J., Hulscher, S.J.M.H., 2019. The influence of grid shape and grid size on hydraulic river modelling performance. Enviromental Fluid Mechanics. 19, 1273–1294.

[21] Modak, S.V., 2023. Analytical and Experimental Modal Analysis, Boca Raton: CRC Press. 2, 136.