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A Study on Improving the Vibration Performance of the Smart Moment Frame (Produced by PACO Company in USA) using the Proposed Brace under Modal Analyses in the Frequency Domain

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ABSTRACT

Reducing the vibration of the steel structure is one of the most important issues in evaluating its dynamic performance. There are various methods to reduce the vibration of the structure such as structural bracing systems. Modern concentrically braced systems are among the latest methods used to reduce structure vibration. In the present paper, with the finite element method and ABAQUS software, the steel frame is improved with rhombus and Super X braces. The smart steel frames are manufactured by PACO Engineering Company in the USA. The smart braced frames are investigated using modal analyses in the frequency domain. The results show that the rhombus bracing system improves the vibration performance in the PACO smart frames with the Super X bracing system. The proposed rhombus bracing system in the smart moment frame reduces von Mises stress by 8.04%, displacement by 30.02%, natural frequency by 10.64%, and eigenvalue by 10.95% compared to the smart moment frame equipped with a Super X bracing system. The results of the present paper are suggested to PACO Company in the USA and engineers in Iran as a means to improve the vibration of the steel moment frame.
Keywords: Vibration Performance, Smart Moment Frame, Modal analysis, PACO Engineering Company, rhombus Brace.

1. Introduction

Evaluation of the performance of steel structures is one of the most important activities of structural engineers [1]. Earthquakes and strong storms cause damage to structures [2]. There are different ways, such as braces, to improve the structures performance [3]. Engineers choose the best structural strengthening method by performing various engineering analyses [4]. One of the structural analysis methods is the modal method in the frequency domain. This method can determine the vibration performance of the structure. Different vibration modes are investigated in modal analyses [5,6]. Zhang et al. [1] investigated the seismic performance of X-braced steel frames. The results showed that

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the brace has increased the capacity of the structure by 20%. Zhao and Qiu [2] reinforced the steel structure with new steel braces. In this paper, a new bracing system (GESB) was proposed. The results showed that the proposed brace has reduced the inter-story drift. Therefore, it reduces the vibration of the structure. Yang et al. [7] strengthened the seismic performance of the structure with BRB brace. This paper proposed a two-time brace system. The results showed that the proposed brace results in a 17%-23% reduction in structural damage. Chou et al. [8] investigated finite element analysis in steel frame with K bracing system. They reinforced a 24-story building in Taipei city. Soleymani and Saffari [9] strengthened the seismic performance of the steel frame with the proposed system. They designed new shear fuses within the structure. Li et al. [10] could increase the elastic stiffness in the eccentrically braced steel frames. In this paper, eccentric braces of K, D and V types were proposed. Wang et al. [11] investigated the performance of dual self-centering steel braced frames. Khan et al. [12] investigated steel braced frames of the RC type using SEISMOSTRUCT software. The results showed that improving the steel structure reduces fragility. Li et al. [13] investigated steel frames with irregular buckling braces. The method proposed in this paper was applied on a 15-story structure. Imanpour et al. [14] carried out the seismic stability of braced steel frames. Rangaraj et al. [15] compared steel structures with inverted V braces and without braces. In this paper, 3, 7 and 10-story structures were modeled. The results showed that the presence of braces improves the seismic performance of structures. Yan et al. [16] investigated the seismic performance of braced steel frames. The brace proposed in this paper is a disk spring-based viscous damper. The steel brace reduces the structure's vibration during an earthquake or storm, resulting in enhanced dynamic performance. Figure 1 shows new steel braces in the steel structure.

In the present paper, the smart moment frame [17-27] made by PACO Engineering Company in the United States of America (USA) [28], one of the new technologies in building construction, is seismically improved. Some of the innovations of the present paper, compared to investigations with a similar topic, are as follows:

- PACO smart moment frame system features distinct detailing in its components, including connections and auxiliary components to the steel frame (such as wooden beams). Therefore, the investigated frame is one of the newest structural engineering technologies in the world, which is improved in the present paper with the proposed bracing system, and the results of the paper may contribute to optimizing the PACO smart frames. Finally, the paper is submitted to the PACO Engineering Company in the USA.
- By studying the design flowchart in [28], it is concluded that the vibration improvement of this frame is necessary. In the present paper, the rhombus bracing system is proposed as a solution. The Super X brace is sometimes used in PACO and the rhombus brace is presented as an innovative method.
- The present paper improves the performance of the new structural system. All findings are original as no study has been done on this subject so far.

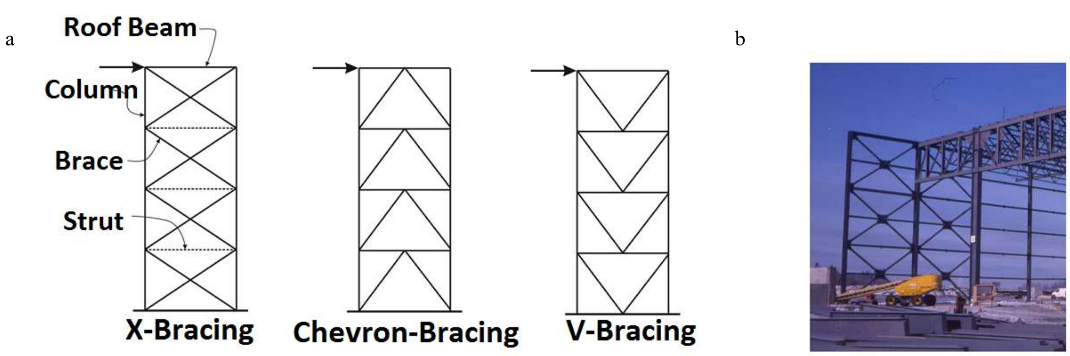


Fig. 1. (a) Types of concentrically braced frames; (b) Concentrically bracing systems in Canada [11].

2. Smart Moment Frame (Manufactured by PACO Company)

In this section, some of the most important details related to the steel frame manufactured in PACO Engineering Company in the USA are presented.

2.1. PACO Smart Moment Frame System

PACO Engineering Company has developed a state-of-the-art, pre-engineered, pre-fabricated and cost-effective Special Moment Frame to resist both lateral and gravity loads. Special Moment Frames allow the architect to design large clear openings while providing the Engineer of Record a frame capable of maintaining structural integrity. Using PACO Steel's lightweight section for the Special Moment Frame enables fast installation by a standard framing crew. The system fits into standard 2x4 or 2x6 wood walls and is less expensive than site-built wide flange moment frames. PACO Moment Frames are compatible with wood, LGS or heavy structural framing systems. PACO provides the calculations, submittal documents and detail drawings for the moment frames and their attachments to the foundation. This reduces design time for the engineer and offers a cost-effective solution for large, clear span openings [28]. Figure 2 presents the schematic models of the SMF used in PACO.

2.2. Smart Moment Frame Connections

PACO unstiffened extended end plate connection features an end plate that extends beyond the outside of the connecting PACO beam flanges. The end-plate is shop-welded to the end of a PACO beam and is then field-bolted to a PACO column flange with four rows of high-strength bolts using a total of eight bolts.

The excellent inelastic response capacities of the PACO Special Moment Frame beam-column connections have been validated through numerous tests conducted at Virginia Polytechnic Institute and State University (Virginia Tech) utilizing the testing protocol per Appendix S of 2005 AISC Seismic Provision. Test results for the PACO SMF beam-column connection configuration indicate that the connection is capable of sustaining an inter-story drift angle of more than 0.04 radians, exceeding code requirements. The measured flexural resistance of the connection, determined at the column face, is greater than 0.80Mp, where Mp = ($1.1R_y.Z_x.F_y$), for the connected PACO beam at the inter-story drift angle of 0.04 radians [28].

Where:

R_y: equal to the expected yield stress (F_{ye}) divided by the value of the minimum yield limit (F_y),

Z_x: The plastic section modulus [28].

2.3. Design Provisions

1. The clear span-to-depth ratio of the beam shall be limited as follows:

a. For SMF, 7 or greater,

b. For Intermediate Moment Frame (IMF), 5 or greater [18].

2. Lateral bracing of beam shall be provided as follows:

a. For SMF system, both flanges of beams shall be braced, with a maximum spacing of:

$$L_b = \frac{0.086 R_y.E}{F_y} \tag{1}$$

Where:

L_b: The distance between the side braces in the bending steel frame,

E: Modulus of elasticity [28].

b. For IMF system, both flanges of the beams shall be braced, with a maximum spacing of:

$$L_b = \frac{0.17 R_y.E}{F_y} \tag{2}$$

3. Protected zones shall comply with the following:

a. The portion of the beam between the face of the column and a distance either equal to the depth of the beam or three times the width of the beam flange, whichever is less, shall be designated as the protected zone.

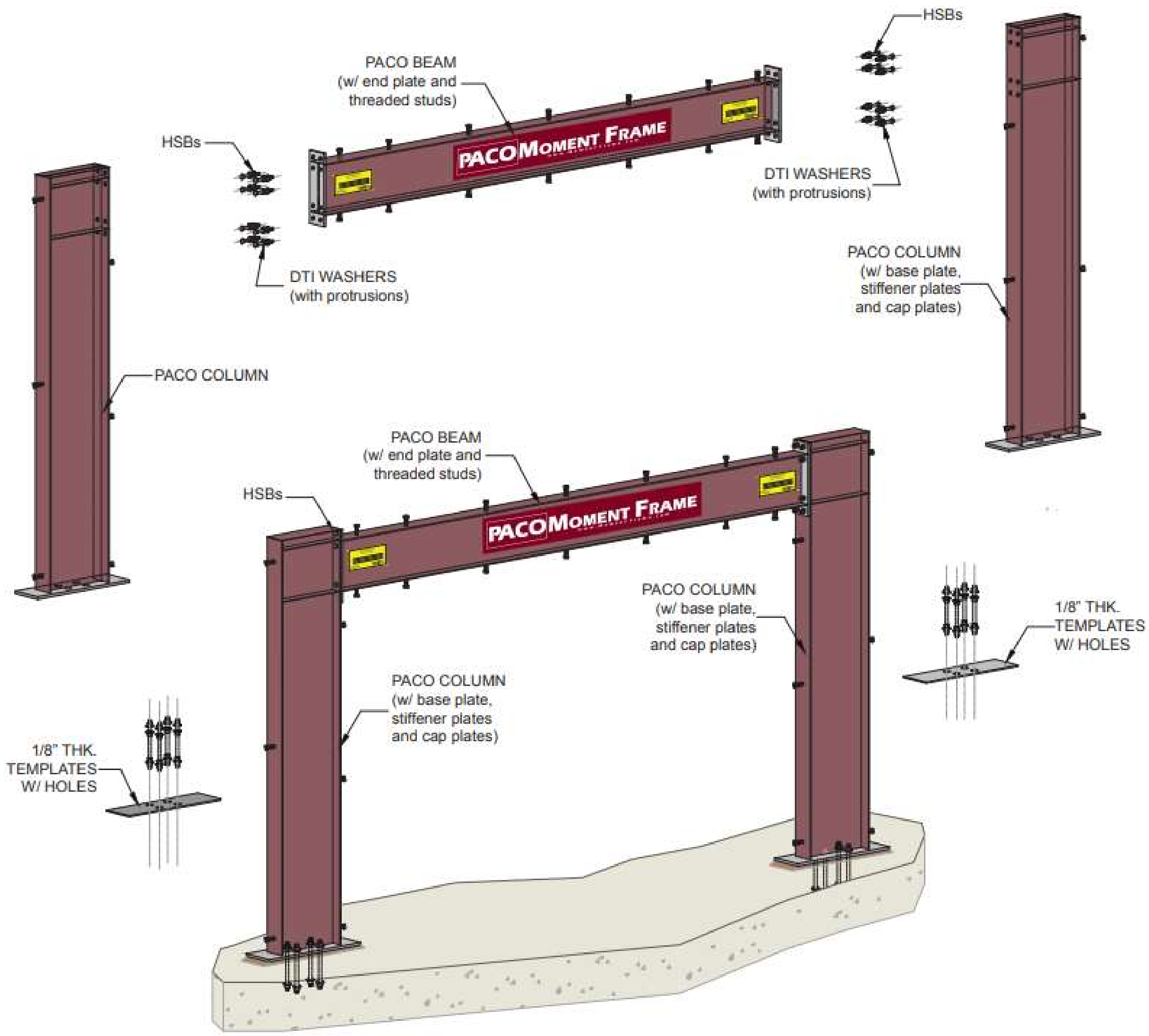


Fig. 2. Smart moment frame manufactured by PACO Engineering Company (a) schematic [28].

b. Within the protected zone, holes, tack welds, erection aids, air-arc gouging and unspecified thermal cutting from fabrication or erection operations shall be repaired as required by the engineer of record.
c. Steel headed stud anchors and decking attachments that penetrate the beam flange shall not be placed on beam flanges within the protected zone. Arc spot welds as required to secure decking shall be permitted.

d. Welded, bolted, screwed or shot-in attachments for perimeter edge angles, exterior facades, partitions, duct work, piping or other construction shall not be placed within the protected zone [28].
4. There shall be no transverse loading between the column supports in the plane of bending and the beams framing into the column weak axis shall be pin connected and produce a negligible moment [28].
5. The values of effective length factor, K, for columns are approximated as follows:
a. The effective length factor (along Y axes K_y), for column type buckling about the member's weak axis is taken as 1.2.
b. The effective length factor K_x (along X axes), for column type buckling about the member's strong axis is approximated based on the recommended design values for frames with side sway uninhibited of Table C-A-7.1 of the AISC 14th Edition Manual [28].
6. Design of PACO Moment Frames is governed by drift requirements [28]. In Fig. 3, the hysteresis curve of the smart moment frame made by PACO Engineering Company is presented.

3. Methodology

3.1. Geometry of Frames and Materials

In the present paper, a braced frame sample designed and tested in the laboratory of [28] is seismically improved. The span length and the frame height are 3.3 and 6.3 meters, respectively. The type of steel in SMF production in PACO Company is St37, whose specifications are presented in Table 1. Finite Element Model (FEM) has been done with ABAQUS software. The FE model of the SMF (for PACO Company) is presented in Fig. 4.

3.2. Software modelling

To improve the vibration performance of a braced frame with Super X, a proposed bracing system (rhombus) is used. Figure 5 shows the proposed concentrically braced frame (rhombus) used in the present paper. In software modelling, the elements include columns, beams, braces and connecting plates. The elements are the assembled (dependent-mesh on part). Also, to perform structure analyses, modal analysis method in the frequency domain is used. In the present paper, 10 vibration modes in braced frames are simulated. The value of vector using per iteration and maximum number of iteration are taken as 18 and 30, respectively. In modal analyses, eigensolver of subspace type is selected. All supports of the frames are modelled as fixed and degree of freedom is 0 in all directions. Finally, the meshing of the frames is done. In meshing, the approximate global size of 100 is considered for all models. Figure 6 shows the meshing of rhombus and Super X models in ABAQUS software.

Table 1. Specifications of St37 steel in SMF structure in PACO Company [25-27].

Parameter	Minimum yield stress	Minimum tensile stress	Modulus of elasticity	Effective tensile stress	Effective tensile stress	Poisson's ratio
Numerical value (Unit)	24×10^{6} ($\frac{Kg}{cm^2}$)	27×10^{6} ($\frac{Kg}{cm^2}$)	$2.039\times\times10^{10}$ (GPa)	27.6×10^{6} ($\frac{Kg}{cm^2}$)	42.55×10^{6} ($\frac{Kg}{cm^2}$)	0.3

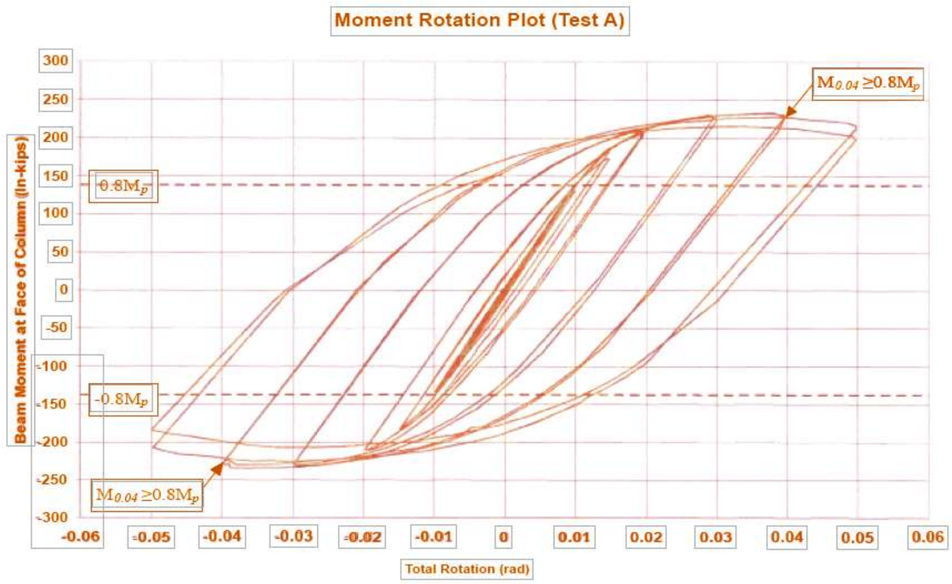


Fig. 3. Hysteresis curve of smart moment frame made by PACO engineering company in USA [28].

a b

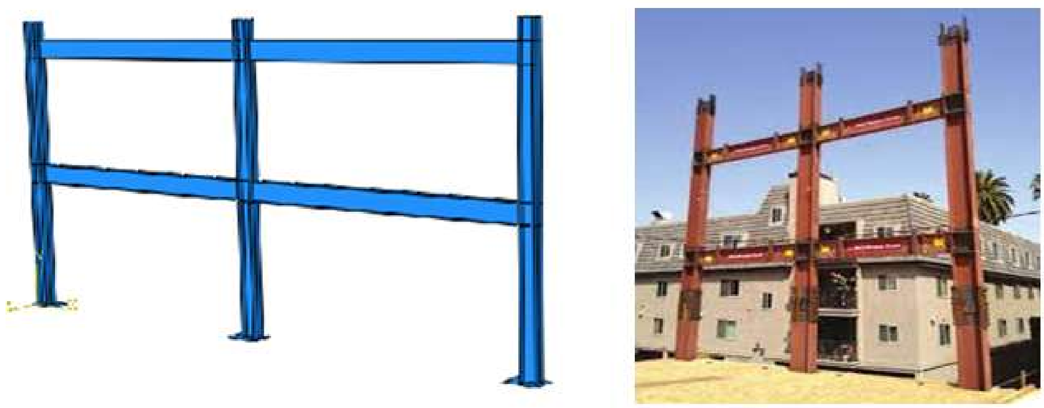


Fig. 4. (a) FE model in the present paper with ABAQUS software; (b) SMF manufactured by PACO Engineering Company [28].

4. Results

4.1. Von Mises Stress

As shown in Fig. 7, the von Mises stress in the rhombus brace is the lowest. The Super X brace experiences less stress as compared to the SMF model. The presence of the brace has reduced the stress of the structure. In Fig. 2, the maximum stress resulting from modal analyses is presented in SMF, rhombus and Super X models.

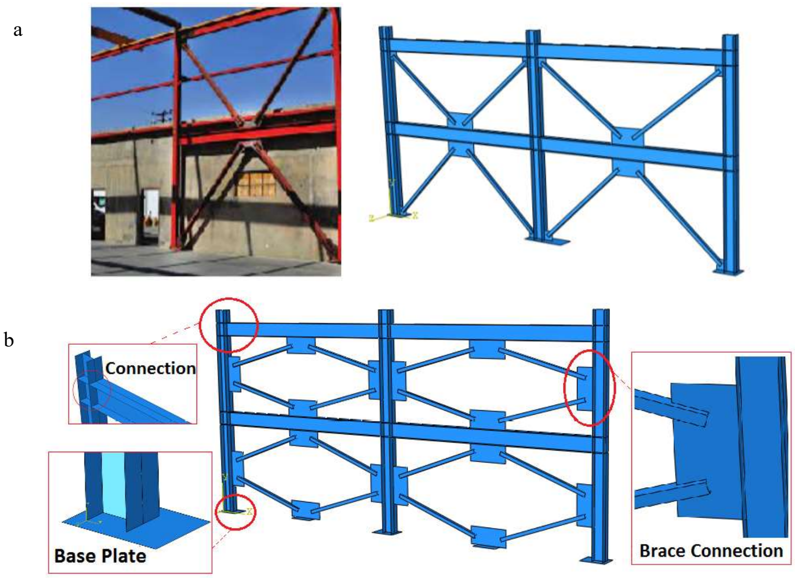


Fig. 5. FE models in ABAQUS; (a) Braced frame produced by PACO Company [28]; (b) Proposed brace (Rhombus) in the present paper.

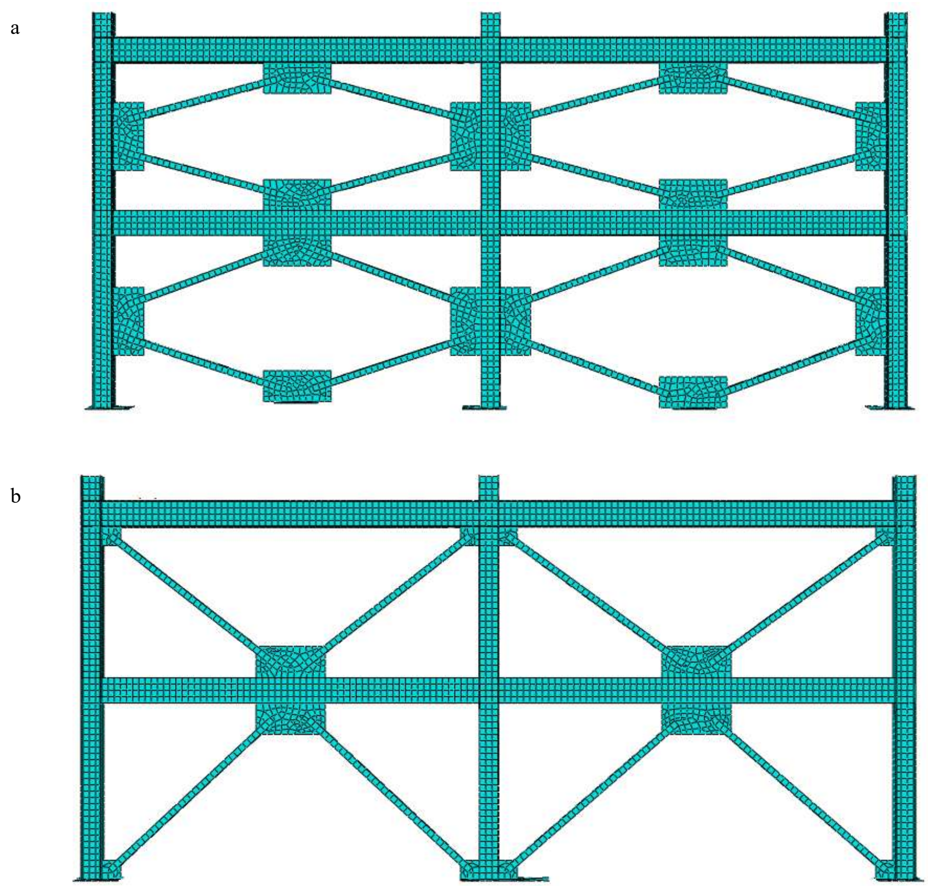
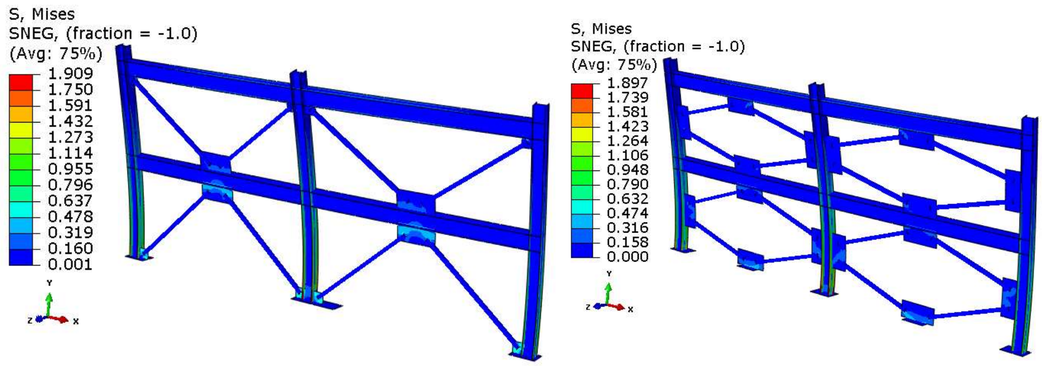


Fig. 6. Meshing models in ABAQUS (a) Rhombus; (b) Super X.

a



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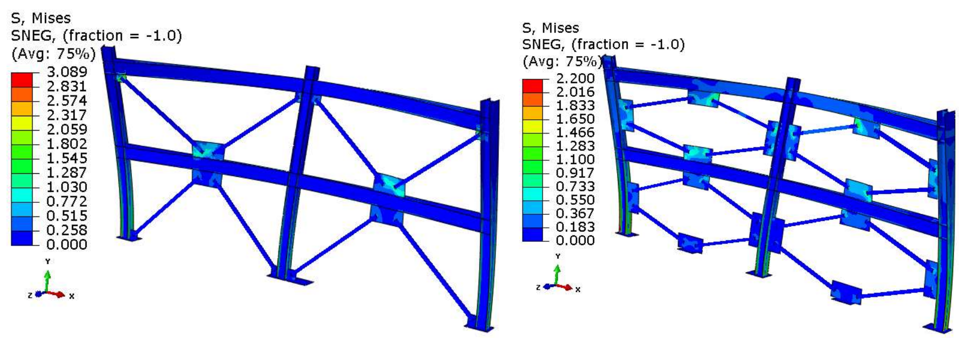

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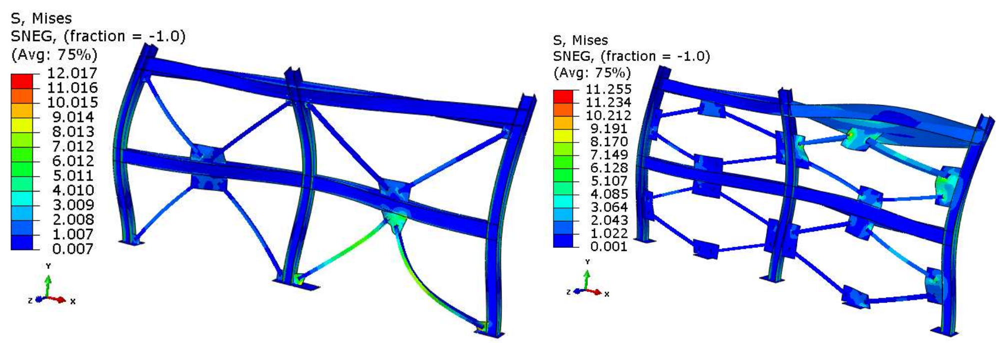

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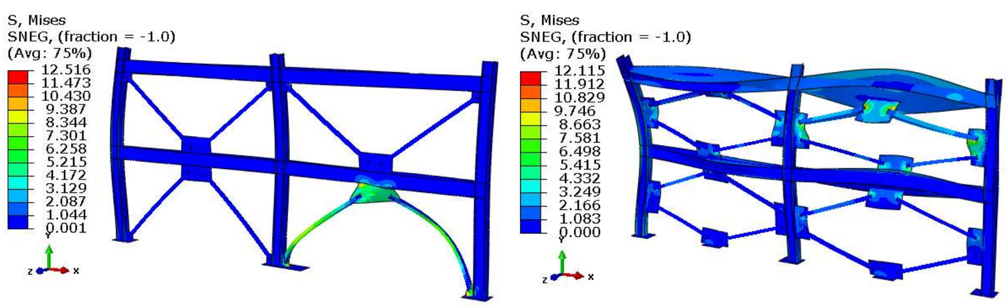


Fig. 7. Von Mises stress in Super X and rhombus models during modal analyses in the frequency domain (a) 1st mode; (b) 3rd mode; (C) 9th mode; (d) 10th mode.

Figure 8 shows that the presence of braces in the steel structure has reduced the von Mises stress in the majority of vibration modes. Moreover, the rhombus brace outperforms the Super X brace.

As illustrated in Fig. 8, the average von Mises stress in Super X and rhombus models is 5.001 and 4.599 MPa, respectively. Therefore, the use of rhombus bracing system has caused an 8.04% reduction in the von Mises stress of the smart braced frame produced by PACO Engineering Company.

4.2. Displacement

In this section, the displacement of steel structures is separated by the structure's load-bearing system. Figure 9 shows that the use of rhombus brace in the smart braced frame reduces displacement in all vibration modes. Figure 9 shows that the average displacement (in 10 vibration modes) is 0.433 and 0.303 meters in Super X and rhombus models, respectively. Therefore, the use of rhombus bracing system has caused a 30.02% reduction in the von Mises stress of the smart braced frame produced by PACO Engineering Company.

4.3. Natural Frequency

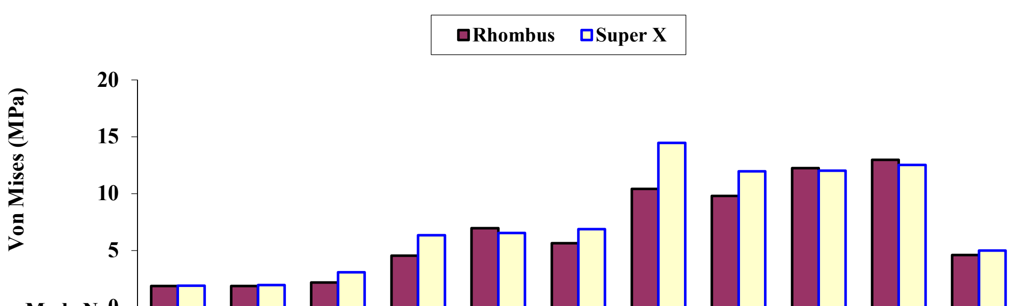
In this section, the natural frequency of steel structures is separated by the structure's load-bearing system.

Figure 10 shows the presence of rhombus is reduced the natural frequency. Numerical analysis shows that the average natural frequency in Super X and rhombus models is equal to 12.5 and 11.17 Hz, respectively. Therefore, the rhombus brace causes a 10.64% decrease in the structure’s frequency. Reducing the frequency of the structure is equivalent to reduce its vibrations during loading. Therefore, with the presence of a rhombus brace, the possibility of damage to the members of the smart moment frame will be reduced. The decrease in frequency means the decrease in the structure’s vibration, which shows the greater stiffness of the structure.

4.4. Eigenvalue

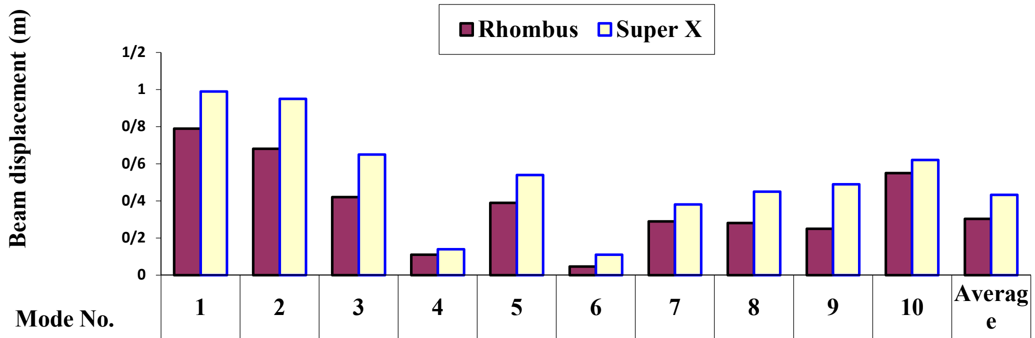
In this section, the eigenvalue of steel structures is separated by the structure's load-bearing system.

The eigenvalue index examines the probability of the frame buckling. Numerical analysis in Fig. 11 shows that the average eigenvalue in Super X and rhombus models is equal to 8.13×10^{-9} and 7.24×10^{-9}, respectively. Therefore, the rhombus brace causes a 10.95% decrease in the structure’s eigenvalue. A reduction in structure buckling increases its stability during loading. Therefore, the rhombus model has a higher stiffness compared to the Super X model.



Mode No	1	2	3	4	5	6	7	8	9	10	Average
Rhombus	1/89	1/88	2/2	4/55	6/96	5/65	10/42	9/81	12/26	12/99	4/599
Super X	1/91	1/97	3/09	6/34	6/54	6/87	14/46	11/97	12/02	12/52	5/001

Fig. 8. Maximum von Mises stress in Super X and rhombus models during modal analyses in the frequency domain.



Mode No.	1	2	3	4	5	6	7	8	9	10	Average
Rhombus	0/79	0/68	0/42	0/11	0/39	0/047	0/29	0/28	0/25	0/55	0/303
Super X	0/99	0/95	0/65	0/14	0/54	0/11	0/38	0/45	0/49	0/62	0/433

Fig. 9. Beam displacement of Super X and rhombus models during modal analyses in the frequency domain.

4.5. Validation

In the present paper, the models are developed based on the study by Shen et al. [29]. In [29], the 2-story steel frame with double-X brace is modelled with ABAQUS. In Fig. 12, the models in [29] are presented. Also, Fig. 13 presents the von Mises stress in the FE models under loading as reported in [29].

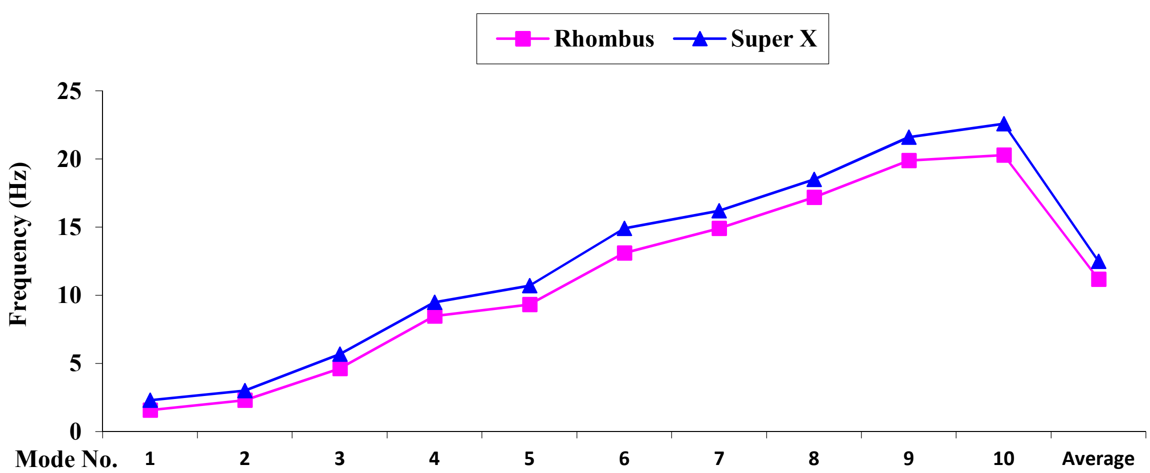


Fig. 10. Natural frequency of Super X and rhombus models during modal analyses in the frequency domain.

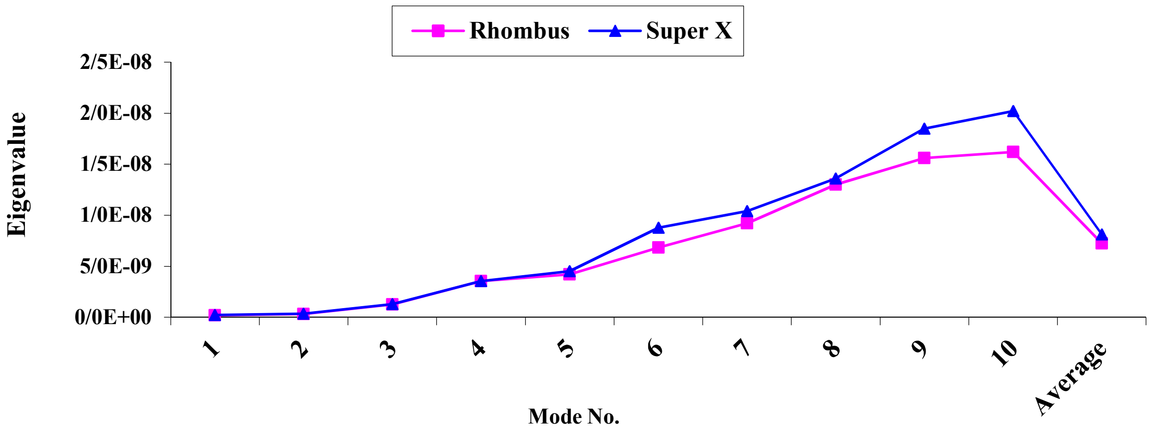


Fig. 11. Eigenvalue of Super X and rhombus structures during modal analyses in the frequency domain.

Using the assumptions outlined in [29] (as illustrated in Fig. A in **Appendix**), the FE model is developed in ABAQUS. Figure 14 shows the difference between software modelling in the present paper and that in [29] is less than 3.4%. Therefore, the modelling of the present paper is confirmed and the results are acceptable.

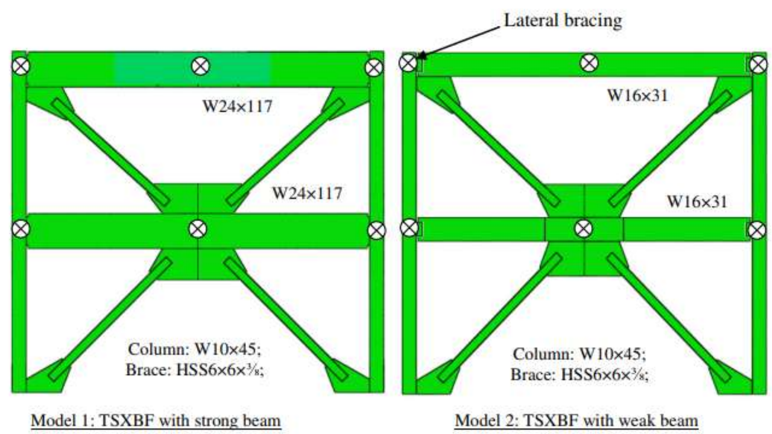


Fig. 12. Schematic of the models in [29].

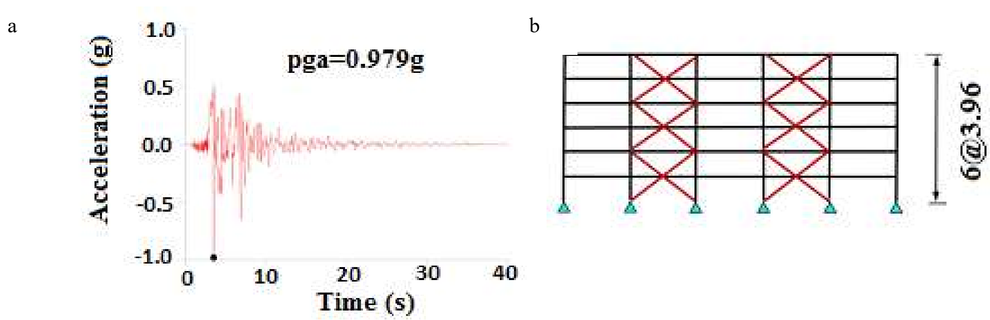


Fig. 13. (a) GM record for analysis; (b) Elevation for frames with 2-story X bracing system in [29].

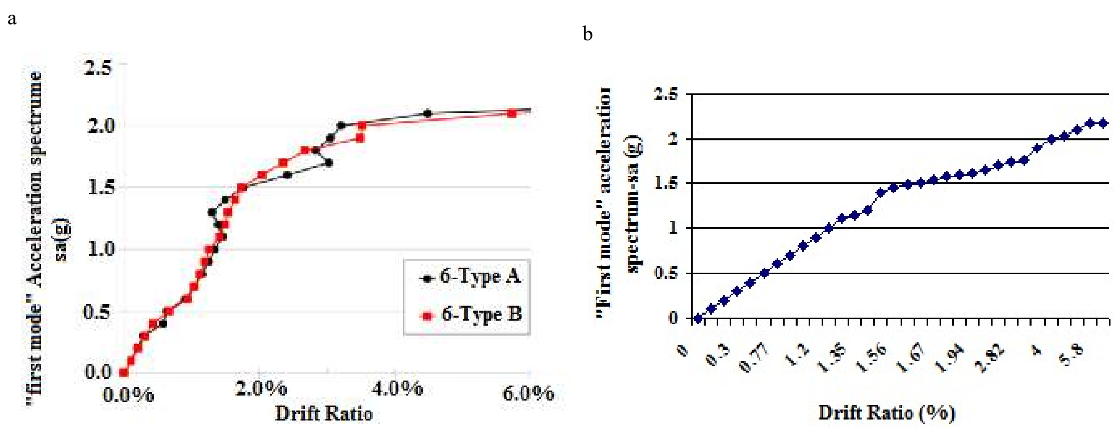


Fig. 14. Drift Ratio-Acceleration Spectrum diagram of FE models (a) in [29] and (b) in the present paper.

5. Conclusion

In the present paper, the smart moment frame produced by PACO Engineering Company in the USA is improved with rhombus and Super X braces using the FEM. PACO Company usually improves the manufactured smart frames by Super X braces. In the present paper, the proposed rhombus brace is used to improve the PACO smart frames. Software modelling is performed using ABAQUS. The results of the present paper are as follows:

- The von Mises stress of the smart steel frame with rhombus brace is lower than that as compared to the frame with Super X brace. The proposed rhombus bracing system reduces the von Mises stress by 8.04% compared to the PACO smart frame with Super X bracing system. Reducing the von Mises stress in the structure reduces the compressive forces on the members. Therefore, during an earthquake or storm, the probability of damage to the structure is reduced.
- The displacement of the smart steel frame with rhombus bracing system is lower than that of the frame with Super X bracing system. The proposed rhombus brace reduces the displacement by 30.02% of the PACO smart frame with Super X brace.
- The natural frequency of the smart steel frame with rhombus brace is lower than that of the frame with Super X brace. The proposed rhombus bracing system reduces the natural frequency by 10.64% of the PACO smart frame with Super X bracing system.
- The eigenvalue of the smart steel frame with rhombus bracing system is lower than that of the frame with Super X bracing system. The proposed rhombus brace reduces the eigenvalue by 10.95% compared to the PACO smart frame with Super X brace.

Appendix: Smart Steel braced frame manufactured by PACO Engineering Company

a

b

c

d

Fig. A. Smart Steel Braced Frame by PACO Engineering Company in USA [29] (a) column-ground connection; (b) brace-frame connection [29]; (c) beam-column connection[29]; (d) brace-beam connection [29].

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