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# Theoretical Assessment of the Behavior of a Cable Bracing System with a Central Steel Plate

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**ABSTRACT:** The large displacements and lack of sufficient lateral stiffness are the main problems of moment resisting frames (MRFs). In this research a system of four cable bracings connected to a square steel plate located in the center of them has been studied to solve MRF's mentioned problems. The theoretical behavior of the system was derived under a lateral static load. The purpose of this study is to demonstrate the efficiency of the system, in which all cables have tensile forces under the lateral load and cables are not slackened. The cables diameter and plate dimensions were investigated. It was observed that the variation of cable diameter had a significant effect on the frame lateral displacement; while the variation of dimensions of the plate did not have much effect on the obtained values. The results showed that the proposed system had the same characteristics of the MRF for its appropriate ductility, at the same time it had its high stiffness. Adding a steel plate in the center of bracings causes all cables to involve against the lateral load and all cables remain in tension. Therefore, using the central steel plate improves the performance of the structure against the applied lateral load.

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## 1- Introduction

The moment resisting frame (MRF) is a desirable system due to its appropriate ductility and high energy absorption. The main problems of this system are the large displacements and insufficient lateral stiffness of the frame. In order to solve this problem, different bracing systems have been proposed. One of the proposed bracing systems is the cable bracing. The advantages of cable bracing system are the high tensile strength, the ability to apply pre-stressing forces, and consequently high lateral stiffness of the frame, light weight of cable bracing and the elimination of the local buckling of bracing element. One of the disadvantages of cable bracing system is that both bracing elements are not involved against lateral loads, meaning that one of bracing always endures tensile force and the other one does not.

## 2- Brief literature review of the cable bracing

A research project (1998-2002) named SPIDER (Strand Prestressing for Internal Damping of Earthquake Response) was conducted which dealt with the effects of a cable bracing system with a damper in a three-story concrete building. Sorace and Terenzi [1] studied about that building and concluded that although the damped cable system was not flexible enough to be able to take the advantage of the special benefits of damped bracings, it had the required abilities to be utilized in the retrofitting of buildings. Maghsoudpour and Barghian [2] studied the range of the prestressing force and the optimum route for cables in an integrated cable system. The optimum route for the integrated cable was determined utilizing the step by step method by the modeling of concrete structures with integrated cable bracings and the comparison of the stiffness and resistance of the system. Their results showed that the integrated cable systems had a positive effect on the economy of the design by the means of reducing the shear forces and bending moments of frame elements. Khalili Majd [3] modeled the slip joint of the cable bracing. The results showed a reduction in the displacement of short structures by the utilization of integrated bracings. Phocas and Pocanschi [4] conducted a research on the simultaneous involvement of all cables against the lateral load. In their research, a kind of disc-shaped joint was introduced, by using of it, all cables were under tension during the cyclic loading process. A hysteretic damper was used in the studied frame between the horizontal cable and the frame to increase the energy dissipation. Hossein Zadeh et al. [5] assessed the reinforcement of a steel MRF using an eccentric cable bracing and concluded that the eccentric cable bracing had more appropriate behavior regarding ductility and the amount of axial force of frame columns in comparison with cable

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cross bracing. Hou and Tagawa [6] proposed a new method for the reinforcement of a steel MRF with the cable bracing. In their system, the cables passed through the cylinder in their interaction point. The cylinder, either soft or stiff, could cause a delay in the performance of the bracings and thus caused the high ductility of the braced frame and more energy dissipation. The results of that experiment showed that the system increased the lateral resistance of the story without reducing ductility.

Moreover, in the proposed bracing system, both cables were under tension, and none of them would loosen unless one of the cables was totally straightened. Therefore, the impulse caused by cable loosening was removed. Fanaie et al. [7] studied the behavior of the cable bracing system with a central steel cylinder, at cables' crossing point, and presented the equations. They studied the effects of the cylinder dimensions and the prestressing of the cables. The steel cylinder had high stiffness and very low elastic deformation and could be considered rigid for the simplicity of calculations. According to the results, the initial stiffness of the cylinder-cable bracing system was proportional to the prestressing force. Following the previous research, they studied the seismic behavior of MRFs braced with cables and a central steel cylinder [8]. According to the results, although the displacement of the frame in their system was more compared with the cable cross bracing system, the system distributed the relative displacement of stories in the frame height and prevented the concentration of damages in a particular story of a building as well as the formation of soft story. Fanaie and Zafari [9] studied the behavior of a cable-cylinder bracing under near field records. The overstrength factor, ductility factor and response modification factor of the cable-cylinder bracing system were computed by using a two-dimensional model. Based on the results, cable cylinder bracing worked better than the cable bracing, regarding its higher response modification factor. Razavi and Sheidaii [10] studied the improvement of the performance of inverted V concentric bracing by using a zipper bracing. They considered that by using a zipper bracing in higher stories caused those sections to experience large tensile forces. They concluded that using sections with larger cross-sections were required. Considering that, they suggested to use cables instead of steel sections in the zipper bracing. Barghian and Najafi [11] proposed a new kind of cross bracing with a steel plate and compared the proposed model with the unbraced frame and cross-braced frame. Adding the steel plate caused all cables to be under tension, while in the cross bracing, only one of the cables was under tension. By adding the square plate in the center of the frames, the lateral displacement of the frame was increased. The results showed that by adding a steel plate in the center of bracings in each story, the lateral displacement of the frame was increased compared with a cross-braced frame, but it was less than the unbraced frame. Kurata et al. [12] proposed a cable bracing system with a central damper to involve all the cables against applied loads. All cables were under tension with the lateral motion of the frame and the rotation of damper plates.

Fateh et al. [13] proposed a new cable bracing system with a spring with variable stiffness. The system was designed to protect structures against vibrations and severe earthquakes. The proposed system included a spring which was made up of four layers of curved steel and had a nonlinear behavior and provided variable stiffness in different displacements of the frame. Another study was done by Mousavi and Zahrai [14] on the behavior of frames with cable bracings. In that research, a model was proposed in order to reduce the residual damages in frames, which showed inappropriate seismic behavior, and also caused an increase in the lateral resistance capacity of the frames with low ductility. The effect of the cable bracing arrangement on the seismic response of 2D steel frames was studied by Kuh-Kamari [15]. Different arrangements of cable cross bracings were studied in that research in different spans to determine the coefficient of 2D steel frames. Hejazi [16] proposed a combination of a concentric cable bracing system with a horizontal element. According to the results, the proposed system caused an increase in stiffness in comparison with the MRF, but experienced larger displacement compared to other concentric bracing system because of the delay in the performance of the bracings against lateral loads.

Giaccu [17] used a displacement-based approach to examine the non-linear behavior of a building system with the cable cross bracing. Giaccu studied the dynamic behavior of the system, using mode by mode. In the present research, a type of bracing arrangement in a 2D concrete MRF is studied, in which a steel plate is located in the center of the frame and the cables are connected to it. In this system, the cables and the plate are used in such a way that the cables reach their ultimate strength at the larger displacements of the frame. Therefore, the system covers the low ductility defects of the cable braced MRF. The behavior of this bracing system depends on the dimensions and thickness of the plate, as well as the axial stiffness and pre-stressing of cables. In this research, the theoretical behavior of the cable bracing system with central steel plate is assessed. Also, the effect of the variation of the cable diameter and plate dimensions and thickness on the behavior of this system is studied.

## 3- Determination of equations

In this research the theoretical behavior of the cable bracing system with the central steel plate against lateral loads was assessed. In order to simplify, the bending and shear of the beam and column were ignored in determining the equations. The beam and column were considered as truss members. The steel plate with high stiffness and low elastic deformation characteristics was considered to be rigid for simplicity of calculations. Figure 1 shows the deformed shape of cable braced frame with the central steel plate when the lateral load is applied to the frame. The cables are connected to each other by the plate, all four cables are prestressed. According to initial assumptions, the plate is located at the center of the frame, which suggests that the slopes of AE and GC and the slopes of BF and HD are equal, respectively. Equations 1 and 2 express the coordinates of the frame points, before and after the lateral displacements of the frame, respectively.

$$\begin{aligned} &A:\begin{bmatrix}0\\0\end{bmatrix}, B:\begin{bmatrix}l_b\\0\end{bmatrix}, C:\begin{bmatrix}l_b\\h_c\end{bmatrix}, D:\begin{bmatrix}0\\h_c\end{bmatrix}, O:\frac{1}{2}\begin{bmatrix}l_b\\h_c\end{bmatrix},\\ &E:\frac{1}{2}\begin{bmatrix}l_b-a\\h_c-b\end{bmatrix}, F:\frac{1}{2}\begin{bmatrix}l_b+a\\h_c-b\end{bmatrix}, G:\frac{1}{2}\begin{bmatrix}l_b+a\\h_c+b\end{bmatrix}, H:\frac{1}{2}\begin{bmatrix}l_b-a\\h_c+b\end{bmatrix} \end{aligned} \tag{1}$$

Where A, B, C and D are the joints of the mentioned frame and E, F, G and H are the steel plate joints and O is the center of the steel plate, before the lateral displacements of the frame. Figure 2 shows the free body diagram of steel plate.

$$A':\begin{bmatrix}0\\0\end{bmatrix}, B':\begin{bmatrix}l_b\\0\end{bmatrix}, C':\begin{bmatrix}l_b+\delta\\h_c\end{bmatrix}, D':\begin{bmatrix}\delta\\h_c\end{bmatrix}, O':\frac{1}{2}\begin{bmatrix}l_b+\delta\\h_c\end{bmatrix},$$
$$E':\frac{1}{2}\begin{bmatrix}l_b+\delta-a\cos\theta+b\sin\theta\\h_c-a\sin\theta-b\cos\theta\end{bmatrix}, F':\frac{1}{2}\begin{bmatrix}l_b+\delta+a\cos\theta+b\sin\theta\\h_c+a\sin\theta-b\cos\theta\end{bmatrix},$$
$$G':\frac{1}{2}\begin{bmatrix}l_b+\delta+a\cos\theta-b\sin\theta\\h_c+a\sin\theta+b\cos\theta\end{bmatrix}, H':\frac{1}{2}\begin{bmatrix}l_b+\delta-a\cos\theta-b\sin\theta\\h_c-a\sin\theta+b\cos\theta\end{bmatrix} \quad (2)$$

Where A′, B′, C′ and D′ are the joints of the mentioned frame and E′, F′, G′ and H′ are the steel plate joints and O′ is the center of steel plate, after the lateral displacements of the frame.

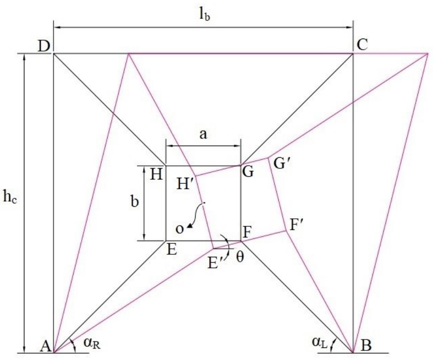



**Figure 1. Deformation of the cabled braced frame with the central steel plate**

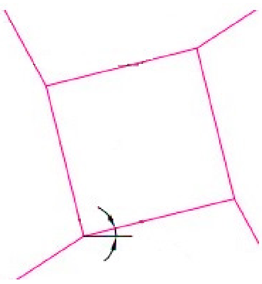


**Figure 2. Free body diagram of steel plate**

Under the lateral static displacement of the frame (δ) - toward the right - the center of the steel plate moves as "1" /"2" "δ" and rotates as θ. The displacement of the plate center in the vertical direction is 0. According to Figure 2, the plate should rotate in such a way that the applied moment from the cables to the plate center becomes equal to 0. In other words, the equilibrium equation of the plate must be satisfied ($\Sigma M_{O'}$ = 0) according to Equation 3.

$$\overset{+}{\leftarrow} \sum M_{O'}=0 \rightarrow F_R\times d=F_L\times d' \rightarrow 1/2\, F_R\times|(AE')\times(E'G)|/|AE'| =1/2\, F_L\times|(BF')\times(F'H')|/|BF'| \rightarrow F_R\times|(AE')\times(E'G')|/|AE'| =F_L\times|(BF')\times(F'H')|/|BF'| \quad (3)$$

d and d′ represent the distance from FR and FL to the center of the plate (O′) after the the plate rotation, respectively. According to Equations 4 and 5, the projection of forces distance from the center of the plate, which is a half of the diameter, is calculated by multiplying by sin θ. Sin θ is required for the determination of d and d′, and it is calculated according to the Equations 4 and 5, by cross product.

$$\begin{cases} d=\dfrac{|E'G'|}{2}\sin\theta \\ a\times b=ab\sin\theta \end{cases} \Rightarrow |\overline{AE'}\times\overline{E'G'}|=|AE'||E'G'|\sin\theta \rightarrow$$
$$\sin\theta=\frac{|\overline{AE'}\times\overline{E'G'}|}{|AE'||E'G'|} \rightarrow d=\frac{|E'G'|}{2}\cdot\frac{|\overline{AE'}\times\overline{E'G'}|}{|AE'||E'G'|}=\frac{1}{2}\frac{|\overline{AE'}\times\overline{E'G'}|}{|AE'|} \quad (4)$$

$$\begin{cases} d'=\dfrac{|F'H'|}{2}\sin\theta \\ a\times b=ab\sin\theta \end{cases} \Rightarrow |\overline{BF'}\times\overline{F'H'}|=|BF'||F'H'|\sin\theta \rightarrow$$
$$\sin\theta=\frac{|\overline{BF'}\times\overline{F'H'}|}{|BF'||F'H'|} \rightarrow d'=\frac{|F'H'|}{2}\cdot\frac{|\overline{BF'}\times\overline{F'H'}|}{|BF'||F'H'|}=\frac{1}{2}\frac{|\overline{BF'}\times\overline{F'H'}|}{|BF'|} \quad (5)$$

$$F_R=EA/L_{AE}\times\Delta_{AE} \quad (6)$$

$$F_L=EA/L_{BF}\times\Delta_{BF} \quad (7)$$

Considering the equal lengths and axial stiffness values for both right and left cables, the equilibrium equation of the plate (Equation 3) is expressed as follows:

$$\sum M_{O'}=0 \rightarrow \frac{EA}{L_{AE}}\times\Delta_{AE}=\frac{EA}{L_{BF}}\times\Delta_{BF}$$
$$\xrightarrow{L_{AE}=L_{BF}} \Delta_{AE}\times\frac{|\overline{AE'}\times\overline{E'G'}|}{|AE'|}=\Delta_{BF}\times\frac{|\overline{BF'}\times\overline{F'H'}|}{|BF'|} \quad (8)$$

The unknown variables of Equation 8 - written based on the initial and secondary lengths of cables - are obtained from Equations 9 to 18. The vectors and lengths are shown with arrows and absolute values, respectively.

$$\overline{AE'}=\frac{1}{2}\begin{pmatrix}l_b+\delta-a\cos\theta+b\sin\theta\\h_c-a\sin\theta-b\cos\theta\end{pmatrix} \quad (9)$$

$$\overline{E'G'}=\begin{pmatrix}a\cos\theta-b\sin\theta\\a\sin\theta+b\cos\theta\end{pmatrix} \quad (10)$$

$$\overline{F'H'}=\begin{pmatrix}a\cos\theta+b\sin\theta\\a\sin\theta-b\cos\theta\end{pmatrix} \quad (11)$$

$$\overline{BF'}=\frac{1}{2}\begin{pmatrix}l_b-\delta-a\cos\theta-b\sin\theta\\-h_c-a\sin\theta+b\cos\theta\end{pmatrix} \quad (12)$$

$$|(AE')\times(E'G')|=1/2|(l_b+\delta)(a\sin\theta+b\cos\theta)-h_c(a\cos\theta-b\sin\theta)| \quad (13)$$

$$|(BF')\times(F'H')|=1/2|(l_b+\delta)(a\sin\theta+b\cos\theta)-h_c(a\cos\theta-b\sin\theta)| \quad (14)$$

$$|(AE')|=1/2\sqrt{(((l_b+\delta)-a\cos\theta+b\sin\theta)^2+(h_c-a\sin\theta-b\cos\theta)^2)} \tag{15}$$

$$|(BF')|=1/2\sqrt{(((l_b+\delta)-a\cos\theta+b\sin\theta)^2+(h_c-a\sin\theta-b\cos\theta)^2)} \tag{16}$$

$$\begin{cases}\Delta_{AE}=\left|\overrightarrow{AE'}\right|-\left|\overrightarrow{AE}\right| \\ \left|\overrightarrow{AE}\right|=\frac{1}{2}\begin{bmatrix} l_b-a \\ h_c-b\end{bmatrix}\end{cases} \Rightarrow \frac{1}{2}\sqrt{((l_b+\delta)-a\cos\theta+b\sin\theta)^2+(h_c-a\sin\theta-b\cos\theta)^2} -\frac{1}{2}\sqrt{(l_b-a)^2+(h_c-b)^2} \tag{17}$$

$$\Delta_{BF}=1/2\sqrt{(((l_b-\delta)-a\cos\theta-b\sin\theta)^2+(-h_c-a\sin\theta+b\cos\theta)^2)}-1/2\sqrt{((l_b-a)^2+(h_c-b)^2)} \tag{18}$$

Equation 19 is obtained by inserting the Equations 13 to 18 in the Equation 8. With this equation, a direct relationship between the steel plate rotation and the frame lateral displacement is established.

$$\left[1-\sqrt{((l_b-a)^2+(h_c-b)^2)}/\sqrt{(((l_b+\delta)-a\cos\theta+b\sin\theta)^2+(h_c-a\sin\theta-b\cos\theta)^2)}\right]\times|(l_b+\delta)(a\sin\theta+b\cos\theta)-h_c(a\cos\theta-b\sin\theta)|=\left[1-\sqrt{((l_b-a)^2+(h_c-b)^2)}/\sqrt{(((-l_b+\delta)+a\cos\theta+b\sin\theta)^2+(h_c+a\sin\theta-b\cos\theta)^2)}\right]\times|(-l_b+\delta)(-a\sin\theta+b\cos\theta)+h_c(a\cos\theta+b\sin\theta)| \tag{19}$$

$\alpha'_R$ and $\alpha'_L$ are the angles between the right and left cables and the horizontal axis after the frame lateral displacement that are expressed in Equations 20 and 21, respectively.

$$\cos\alpha'_R=\cos\alpha_{AE'}=((l_b+\delta)-a\cos\theta+b\sin\theta)/\sqrt{(((l_b+\delta)-a\cos\theta+b\sin\theta)^2+(h_c-a\sin\theta-b\cos\theta)^2)} \tag{20}$$

$$-\cos\alpha'_L=\cos\alpha_{BF'}=-((-l_b+\delta)+a\cos\theta+b\sin\theta)/\sqrt{(((-l_b+\delta)+a\cos\theta+b\sin\theta)^2+(h_c+a\sin\theta-b\cos\theta)^2)} \tag{21}$$

According to Equation 22, by writing the resultant of horizontal components of cable forces, Equation 23 is obtained to determine the P load (the applied lateral load to the frame) in terms of the steel plate rotation and frame lateral displacement.

$$\sum F_x=0\rightarrow P-F_R\cos\alpha'_R+F_L\cos\alpha'_L=0 \rightarrow P=F_R\cos\alpha'_R-F_L\cos\alpha'_L=EA/L_{AE}\times\Delta_{AE}\cos\alpha'_R-EA/L\_BF\times\Delta\_BF\cos\alpha'_L\rightarrow(L_{AE}=L_{GC}=0.5l_t@L_{BF}=L_{HD}=0.5l_t))) \; P=2EA/l_t(\Delta_{AE}\cos\alpha'_R-\Delta_{BF}\cos\alpha'_L) \tag{22}$$

$$P=\frac{2EA}{l_t}\left[\begin{array}{l}\Delta_{AE}\times\dfrac{(l_b+\delta)-a\cos\theta+b\sin\theta}{\sqrt{((l_b+\delta)-a\cos\theta+b\sin\theta)^2+(h_c-a\sin\theta-b\cos\theta)^2}} \\ +\Delta_{BF}\times\dfrac{(-l_b+\delta)+a\cos\theta+b\sin\theta}{\sqrt{((-l_b+\delta)+a\cos\theta+b\sin\theta)^2+(h_c+a\sin\theta-b\cos\theta)^2}}\end{array}\right] \tag{23}$$

Equations 24 and 25 can be used to plot the strain curves of cables versus the lateral displacement of the frame.

$$\varepsilon_R=\Delta_{AE}/L_{AE} \tag{24}$$

$$\varepsilon_L=\Delta_{BF}/L_{BF} \tag{25}$$

The obtained equations are valid until one of the cables is totally straightened. At that moment, the other cable starts to loosen and the force of it becomes 0, since the equilibrume equation of $\Sigma MO' = 0$ should be satisfied. In other words, the other cable is not involved against lateral load anymore.

## 3- 1- Determination of the equations considering the prestressing of cables

One of the factors that affect the behavior of the cable bracing system with a steel plate is, prestressing of the cables. If the prestressing force is assuemed to be Fp in the cables, concerning the equality of axial stiffness and cables lengths, the equations change, and the new P and ε are expressed as follows:

$$F_P=2EA/l_t\times\Delta_P \rightarrow \Delta_P=(2l_t)/EA\,F_P \tag{26}$$

$$(l_t/2EAF_P+\Delta_{AE})\times|((AE')\times(E'G'))/(AE')|=(l_t/2EA\,F_P+\Delta_{BF})\times|((BF')\times(F'H'))/BF'| \tag{27}$$

Equation 28 is obtained by inserting the Equations 13 to 18 in the equilibrium equation of the steel plate (Equation 27). With this equation, a direct relationship is achieved between the steel plate rotation and the frame lateral displacement.

$$l_t\times[F_p/EA+\sqrt{(((l_b+\delta)-a\cos\theta+b\sin\theta)^2+(h_c-a\sin\theta-b\cos\theta)^2)}-1]\times|(l_b+\delta)(a\sin\theta+b\cos\theta)-h_c(a\cos\theta-b\sin\theta)|/\sqrt{(((l_b+\delta)-a\cos\theta+b\sin\theta)^2+(h_c-a\sin\theta-b\cos\theta)^2)}=l_t\times[F\_P/EA+\sqrt{(((-l_b+\delta)+a\cos\theta+b\sin\theta)^2+(h_c+a\sin\theta-b\cos\theta)^2)}-1]\times|(-lb+\delta)(-a\sin\theta+b\cos\theta)+h\_c(a\cos\theta+b\sin\theta)|/\sqrt{(((-l_b+\delta)+a\cos\theta+b\sin\theta)^2+(h_c+a\sin\theta-b\cos\theta)^2)} \tag{28}$$

According to Equation 29, by writing the resultant of horizontal components of cable forces, equation 32 is obtained regarding the prestressing effects to determine the P load in terms of the steel plate rotation and frame lateral displacement.

$$\sum F_x=0\rightarrow P=F_R\cos\alpha'_R-F_L\cos\alpha'_L \tag{29}$$

$$F_R=EA/l_t\,\Delta_R+F_P\rightarrow(\Delta R=2\Delta_{AE}))\;F_R=2EA/l_t(\Delta_{AE}+(F_P l_t)/2EA) \tag{30}$$

$$F_L=EA/l_t\,\Delta_L+F_P\rightarrow(\Delta L=2\Delta_{BF}))\;F_L=2EA/l_t(\Delta_{BF}+(F_P l_t)/2EA) \tag{31}$$

$$P=\frac{2EA}{l_t}\left[\begin{array}{l}(\Delta_{AE}+\dfrac{F_P l_t}{2EA})\times\dfrac{(l_b+\delta)-a\cos\theta+b\sin\theta}{\sqrt{((l_b+\delta)-a\cos\theta+b\sin\theta)^2+(h_c-a\sin\theta-b\cos\theta)^2}} \\ +(\Delta_{BF}+\dfrac{F_P l_t}{2EA})\times\dfrac{(-l_b+\delta)+a\cos\theta+b\sin\theta}{\sqrt{((-l_b+\delta)+a\cos\theta+b\sin\theta)^2+(h_c+a\sin\theta-b\cos\theta)^2}}\end{array}\right] \tag{32}$$

Equations 33 and 34 can be used to plot the strain curves of cables versus the lateral displacement of the frame.

$$\varepsilon_R=(2\Delta_{AE})/l_t+F_p/EA \tag{33}$$

$$\varepsilon_L=(2\Delta_{BF})/l_t+F_p/EA \tag{34}$$

he obtained equations are valid as long as the forces have counter-clockwise rotational effects. Otherwise, some modifications should be made. The analyzed models were 2D problems, therefore, the out of plane plate behavior was not considered.

## 4- Numerical validation

To verify the obtained equations, two one-story steel frames with one span and the same dimensions were chosen and modeled in SAP2000. One of the chosen frame had pinned supports (Figure 3) and the other had fixed supports (Figure 4) together with cable bracing system with a central steel plate. A lateral load of 100,000 kgf - applied to joint 2 - was considered for both frames. The results of software analysis and the obtained equations in both simple supports and fixed supports are shown in Tables 2 and 3, respectively. A steel box section with the dimensions of 100×100×8 [mm] was used for the beams and columns, and a wire towing rope with the diameter of 2 mm was used for the cable bracing. The defined materials for the beam, column, and plate are ST37, according to Table 1. The defined material for wire towing rope has the density, elastic modulus, Poisson ratio, yield stress, and the ultimate strength of 7850 kgf/m$^3$, 2.04×106 kgf/cm$^2$, 0.3, 2400 kgf/cm$^2$, and 3700 kgf/cm$^2$, respectively. The span and height of the frames are 80 mm, and the dimensions and thickness of the plate are 4×4 mm$^2$ and 1 mm, respectively.

According to the obtained equations, the plate should rotate in such a way that the applied moment from the cables to the plate center becomes equal to 0. In other words, θ should have the value that the equilibrium equation of the plate must be satisfied (ΣMO′ = 0); however, the condition was so complicated that it was not possible to obtain θ from equations. For this reason, the angle of rotating plate modeled in SAP2000 was used to calculate equation values.

**Table 1. Steel material properties**

| E (kgf/cm$^2$) | $F_y$ (kgf/cm$^2$) | $F_u$ (kgf/cm$^2$) | υ | γ (kgf/m$^3$) |
|---|---|---|---|---|
| 2.1×106 | 2400 | 3700 | 0.3 | 7850 |

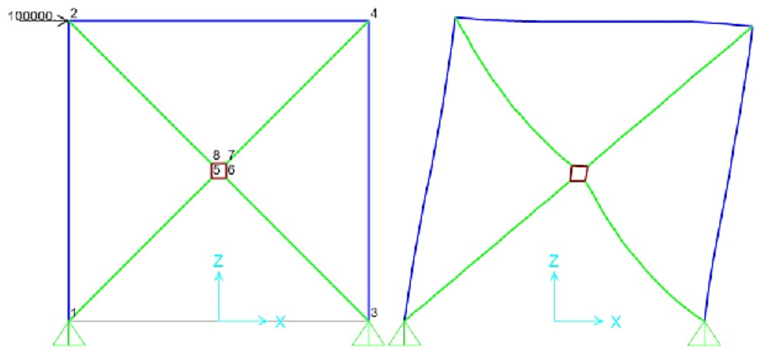



**Figure 3. Cable braced steel MRF with the central steel plate together with pinned supports**

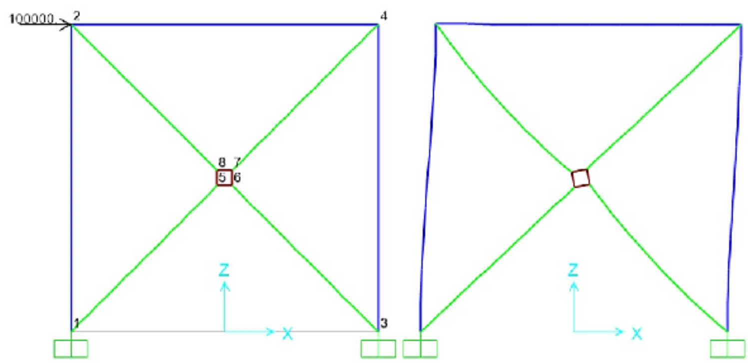



**Figure 4. Cable braced steel MRF with the central steel plate together with fixed supports**

**Table 2. Displacement of plate joints in the steel frame with pinned supports**

| Frame lateral displacement (δ) = 1.29765 mm & Plate rotation (θ) = - 0.00789 Rad = - 0.45206° | | | | |
|---|---|---|---|---|
| Plate Joints | Initial Coordinates (cm) | Joints coordinates after applying the lateral load (cm) | | Percentage of Difference |
| | | Calculated by equation (2) | Calculated by SAP2000 Modeling | |
| 5 | 3.8<br>3.8 | 3.86331<br>3.80158 | 3.86175<br>3.79306 | - 0.04040<br>- 0.22462 |
| 6 | 4.2<br>3.8 | 4.26330<br>3.79843 | 4.26284<br>3.79194 | - 0.01079<br>- 0.17115 |
| 7 | 4.2<br>4.2 | 4.26645<br>4.19842 | 4.26803<br>4.19302 | 0.03702<br>- 0.12879 |
| 8 | 3.8<br>4.2 | 3.86647<br>4.20157 | 3.86694<br>4.19415 | 0.01215<br>- 0.17691 |

**Table 3. Displacement of plate joints in the steel frame with fixed supports**

| Frame lateral displacement (δ) = 0.35913 mm & Plate rotation (θ) = 0.01909 Rad = 1.09378° | | | | |
|---|---|---|---|---|
| Plate Joints | Initial Coordinates (cm) | Joints coordinates after applying the lateral load (cm) | | Percentage of Difference |
| | | Calculated by equation (2) | Calculated by SAP2000 Modeling | |
| 5 | 3.8<br>3.8 | 3.82181<br>3.79621 | 3.82136<br>3.79492 | - 0.01178<br>- 0.03426 |
| 6 | 4.2<br>3.8 | 4.22174<br>3.80385 | 4.22163<br>3.80315 | - 0.00261<br>- 0.01841 |
| 7 | 4.2<br>4.2 | 4.21410<br>4.20378 | 4.21461<br>4.20341 | 0.01210<br>- 0.00880 |
| 8 | 3.8<br>4.2 | 3.81418<br>4.19615 | 3.81434<br>4.19518 | 0.00419<br>- 0.02312 |

By comparing the results of Tables 2 and 3, it can be seen that the difference between the values calculated by the equations and determined by the software analysis is less than 5% in every case and that is acceptable. The difference of values in the fixed supports is less than in those with pinned supports.

### 4- 1- Comparison of the results of equations with numerical modeling in a concrete frame

For a better comparison of the results of equations with numerical modeling, a one-story concrete frame with one span and with the length and height of 3 m was selected. A lateral load of 30,000 kgf was subjected to joint 2. Concrete sections of 20×30 cm$^2$ and 20×20 cm$^2$ were used for the beams and columns, respectively. A cable was used for cable bracing with the diameter of 2 cm (Figure 5). The properties of steel, concrete, and cable materials are shown in Tables 1, 4 and 5, respectively. The dimensions and thickness of the plate are 25×25 cm$^2$ and 1 cm, respectively.

By comparing the results of Table 6, it can be seen that the difference between the values calculated by the equations and determined by the software analysis is less than 5% in every case and that is acceptable.

**Table 4. Concrete material properties**

| E (kgf/cm$^2$) | $f'_c$ (kgf/cm$^2$) | υ | γ (kgf/m$^3$) |
|---|---|---|---|
| 218820 | 210 | 0.2 | 2400 |

**Table 5. Cable material properties**

| E (kgf/cm$^2$) | $F_y$ (kgf/cm$^2$) | $F_u$ (kgf/cm$^2$) | υ | γ (kgf/m$^3$) |
|---|---|---|---|---|
| 1.97×106 | 16000 | 17000 | 0.3 | 8000 |

**Table 6. Displacement of plate joints in the concrete frame braced with the cable and steel plate**

| Frame lateral displacement (δ) = 3.35345 cm & Plate rotation (θ) = - 0.00575 Rad = - 0.32945° | | | | |
|---|---|---|---|---|
| Plate Joints | Initial Coordinates (cm) | Joints coordinates after applying the lateral load (cm) | | Percentage of Difference |
| | | Calculated by equation (2) | Calculated by SAP2000 Modeling | |
| 5 | 137.5<br>137.5 | 139.10506<br>137.57208 | 139.11212<br>137.48330 | 0.00508<br>- 0.06458 |
| 6 | 162.5<br>137.5 | 164.10464<br>137.42833 | 164.12024<br>137.35524 | 0.00951<br>- 0.05321 |
| 7 | 162.5<br>162.5 | 164.24839<br>162.42792 | 164.27982<br>162.36328 | 0.01913<br>- 0.03981 |
| 8 | 137.5<br>162.5 | 139.24881<br>162.57167 | 139.27170<br>162.49132 | 0.01644<br>- 0.04945 |

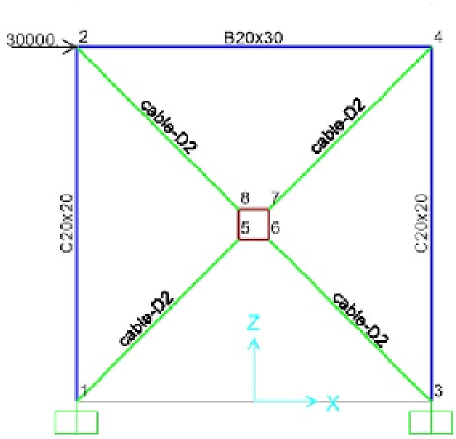
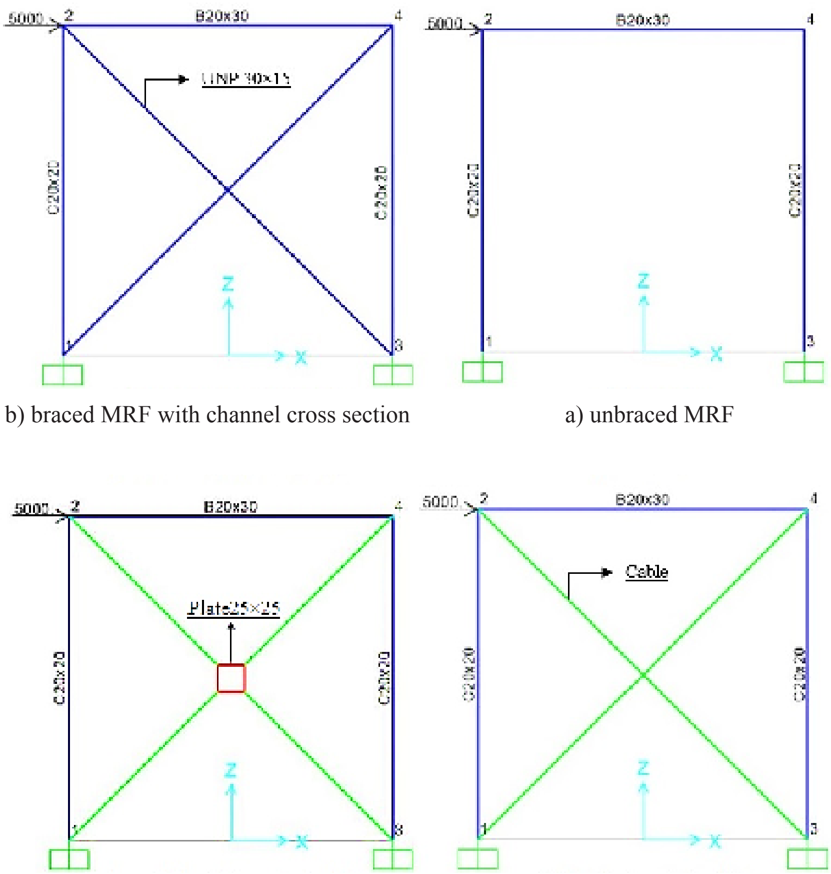



**Figure 5. Concrete MRF braced with the cable and a central steel plate**

In order to verify the obtained equations, the model of ref. [6] was used. In the ref. [6] a 2D steel frame with pinned supports was studied. Next, the pinned supports were changed into fixed ones. Finally, in the next step, a concrete frame with fixed supports was analyzed.

## 5- Studying the behavior of four MRFs with different bracings subjected to lateral loads

Four one-span 2D concrete frames were studied, as shown in Figure 6. The first one was an unbraced MRF (Figure 6a), the second one was a braced MRF with the channel cross section (Figure 6b), the third one was a cable cross bracing MRF (Figure 6c) and the fourth one was a cable braced MRF with a central steel plate (Figure 6d). The frames were modeled in SAP2000 and compared with each other. A lateral load of 5,000 kgf was subjected to joint 2 in four frames, as shown in Figure 6. The frame dimensions were the same in all frames with the length and height of 3 m. The concrete sections of 20×30 $cm^2$ and 20×20 $cm^2$ were used for the beams and columns, respectively. The dimensions and thickness of the plate were 25×25 $cm^2$ and 1 cm, respectively. A channel bracing with a section of UNP 30×15 was used for the second frame, and a cable brace with the cross-section of 2 $cm^2$ was used for the third and fourth frames. A prestressing force of 300 kgf was applied to the cables. The criterion for choosing these sections as bracing elements was the approximate similarity of their cross-sections for a better comparison in the modeling. The properties of steel, concrete, and cable materials are shown in Tables 1, 4 and 5, respectively. Static analysis was used to analyze the frames, considering the nonlinear geometrical effects. The lateral displacements of joint 4 were 3.54, 0.41, 0.80 and 0.75 in the x- direction and -0.03, -0.01, -0.02 and -0.02 in the z- direction for the unbraced MRF, frame with the channel section bracing, frame with the cable cross bracing and frame with the cable bracing and the steel plate, respectively. So, the unbraced MRF had a large lateral displacement. By comparing the lateral displacements of the intended joint in the braced and unbraced frames, it was realized that, by adding the bracing elements, the displacement of the frame had decreased. In fact, the lateral stiffness of the frame had increased. As it is seen from displacements, in the cable bracing system with the central steel plate, because of the delay in the performance of the bracings against lateral loads, the frame has larger displacements in comparison with the channel section braced MRF.




b) braced MRF with channel cross section a) unbraced MRF

c) cable cross bracing MRF d) cable braced MRF with a central steel plate

**Figure 6. Braced and unbraced frames**

## 6- Studying the behavior of the MRF braced with cables and a central steel plate

In this section, one-span 2D concrete MRFs braced with the cable and central steel plate were studied, considering the variation of cable diameters, plate dimensions, and plate thicknesses. A lateral load of 5,000 kgf was subjected to joint 2 in all frames, as shown in Figure 7. The frames dimensions were the same in all of them with the length and height of 3 m. The concrete sections of 20×30 cm$^2$ and 20×20 cm$^2$ were used for the beams and columns, respectively. The dimensions of the used plates were 25×25, 30×30, 35×35, 40×40, 45×45, and 50×50 cm$^2$ with the thicknesses of 1, 1.5, and 2 cm. Cables with the diameters of 1, 2, and 3 cm were used. The prestressing force of 300 kgf was applied to the cables. Again the geometric nonlinearity was considered in the static analysis. The properties of steel, concrete, and cable materials are given in Tables 1, 4 and 5, respectively. As shown in Figure 8, when the cable diameter increases, the lateral displacements decrease significantly. By increasing the plate dimensions and thickness, the values decrease, but this decrease is negligible compared with the cable diameter, and the values are very close to each other. This indicates that the thickness of the plate does not have much effect on the displacement of the joints.

The maximum axial forces of the bracing cables are given in Tables 7 to 10. It is realized that, when the cable diameter increases, the cables axial force increases significantly but, increasing the plate dimensions and thickness do not have much effect on the values, and the values are very close to each other. This indicates that the dimensions and the thickness of the plate do not have much effect on the amount of the applied forces to the cables. However, the dimensions and thickness of the plate should be checked for a design purpose. In a frame with the cable cross bracing system when the load is applied, one of the cables starts to loosen, and the axial force of it becomes 0. Therefore, one of the cables is not involved against lateral loads anymore. But as it is seen from Tables 7 to 10, in the frame with the proposed bracing system (cables and the central steel plate) cables do not slack. In this system, the cables are connected to each other by the plate. All four cables have tensile axial forces and are involved against the lateral loads and none of them loosens. This is the best advantage of this system.

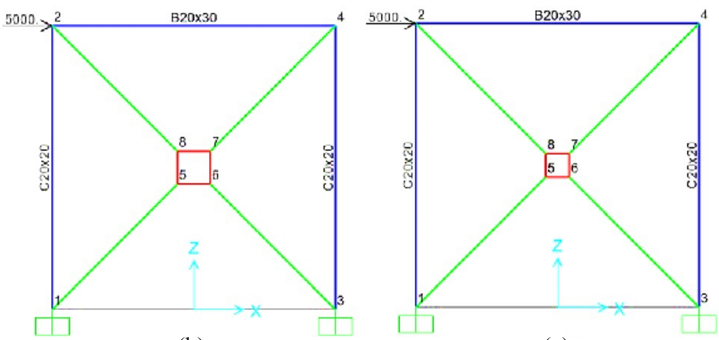



**Figure 7. MRF braced with the cable and central steel plate with different dimensions**

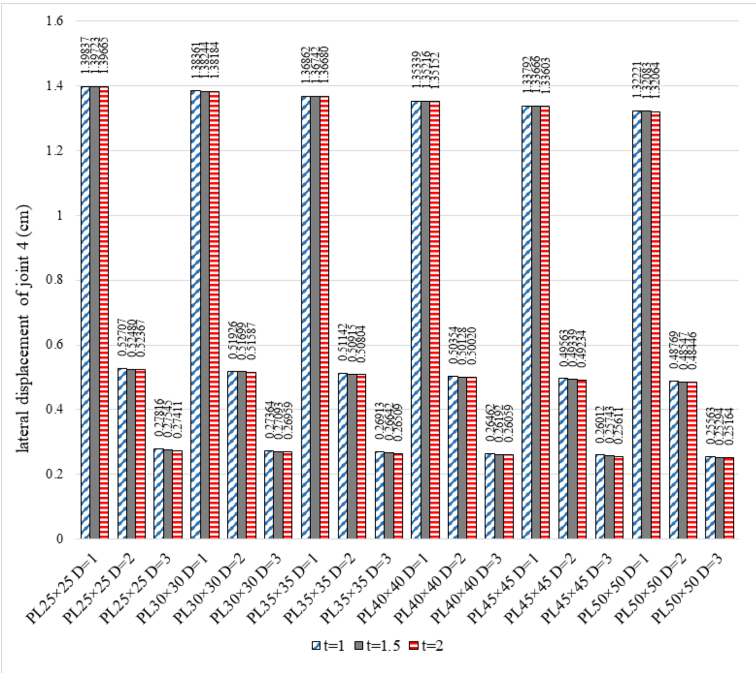



**Figure 8. Displacement of joint 4 in the cable braced frame with the steel plate (cm)**

**Table 7. Maximum axial force of cable AE in the cable braced frame with the steel plate (kgf)**

| Cable Diameter | Plate Thickness | PL25×25 | PL30×30 | PL35×35 | PL40×40 | PL45×45 | PL50×50 |
|---|---|---|---|---|---|---|---|
| D=1 | t=1 | 4294.83241 | 4323.49978 | 4352.51414 | 4381.89702 | 4411.67209 | 4441.86572 |
| | t=1.5 | 4296.31687 | 4324.72109 | 4353.45130 | 4382.54616 | 4412.04678 | 4441.76632 |
| | t=2 | 4296.70605 | 4324.86162 | 4353.34345 | 4382.19211 | 4411.46486 | 4441.44242 |
| D=2 | t=1 | 6049.22635 | 6063.78344 | 6078.35239 | 6092.95024 | 6107.59519 | 6122.30559 |
| | t=1.5 | 6053.20789 | 6067.57110 | 6081.94662 | 6096.36658 | 6110.86173 | 6125.45956 |
| | t=2 | 6054.92689 | 6069.11814 | 6083.33764 | 6097.63103 | 6112.03816 | 6126.59510 |
| D=3 | t=1 | 6589.37574 | 6596.54768 | 6603.63646 | 6610.65368 | 6617.61253 | 6624.52752 |
| | t=1.5 | 6594.39481 | 6601.35027 | 6608.20600 | 6614.98542 | 6621.71399 | 6628.41794 |
| | t=2 | 6596.62958 | 6603.38198 | 6616.61019 | 6616.61019 | 6623.16150 | 6629.72000 |

**Table 8. Maximum axial force of cable GC in the cable braced frame with the steel plate (kgf)**

| Cable Diameter | Plate Thickness | PL25×25 | PL30×30 | PL35×35 | PL40×40 | PL45×45 | PL50×50 |
|---|---|---|---|---|---|---|---|
| D=1 | t=1 | 4300.02070 | 4330.18085 | 4360.96513 | 4392.39510 | 4424.49448 | 4457.28988 |
| | t=1.5 | 4303.23710 | 4333.89617 | 4365.29700 | 4397.47845 | 4430.48327 | 4464.21865 |
| | t=2 | 4305.35822 | 4336.53075 | 4368.58413 | 4401.56188 | 4435.51043 | 4470.72001 |
| D=2 | t=1 | 6059.54433 | 6075.50488 | 6091.75445 | 6108.31010 | 6125.19005 | 6142.41263 |
| | t=1.5 | 6065.25958 | 6081.78869 | 6098.74592 | 6116.16338 | 6134.07177 | 6152.49848 |
| | t=2 | 6068.71170 | 6085.83123 | 6103.53340 | 6121.86375 | 6140.86196 | 6160.56390 |
| D=3 | t=1 | 6607.54481 | 6615.98567 | 6624.61599 | 6633.44845 | 6642.49718 | 6651.77748 |
| | t=1.5 | 6614.27253 | 6623.24473 | 6632.52799 | 6642.14723 | 6652.12922 | 6662.50123 |
| | t=2 | 6618.20679 | 6627.72398 | 6637.68545 | 6648.13040 | 6659.09865 | 6670.62782 |

**Table 9. Maximum axial force of cable BF in the cable braced frame with the steel plate (kgf)**

| Cable Diameter | Plate Thickness | PL25×25 | PL30×30 | PL35×35 | PL40×40 | PL45×45 | PL50×50 |
|---|---|---|---|---|---|---|---|
| D=1 | t=1 | 3.79066 | 3.63147 | 3.31230 | 3.31230 | 3.15807 | 3.01060 |
| | t=1.5 | 3.69780 | 3.51448 | 3.16193 | 3.16193 | 3.00127 | 2.83394 |
| | t=2 | 3.61351 | 3.41284 | 3.04298 | 3.04298 | 2.88436 | 2.78702 |
| D=2 | t=1 | 22.34517 | 21.60235 | 20.07643 | 20.07643 | 19.31952 | 18.58226 |
| | t=1.5 | 22.03542 | 21.19310 | 19.51962 | 19.51962 | 18.72845 | 17.98673 |
| | t=2 | 21.73955 | 20.82368 | 19.07751 | 19.07751 | 18.29391 | 17.85992 |
| D=3 | t=1 | 67.25657 | 65.51850 | 61.87953 | 61.87953 | 60.00346 | 58.10814 |
| | t=1.5 | 66.96639 | 65.03947 | 61.00993 | 61.00993 | 58.95533 | 56.90714 |
| | t=2 | 66.58856 | 64.49330 | 60.14963 | 60.14963 | 57.97386 | 55.84063 |

**Table 10. Maximum axial force of cable HD in the cable braced frame with the steel plate (kgf)**

| Cable Diameter | Plate Thickness | PL25×25 | PL30×30 | PL35×35 | PL40×40 | PL45×45 | PL50×50 |
|---|---|---|---|---|---|---|---|
| D=1 | t=1 | 4.64883 | 4.71588 | 4.83001 | 5.00605 | 5.26829 | 5.65770 |
| | t=1.5 | 4.86154 | 5.05946 | 5.37578 | 5.87856 | 6.71931 | 9.18468 |
| | t=2 | 5.10570 | 5.48548 | 6.12719 | 7.37391 | 10.41133 | 13.34234 |
| D=2 | t=1 | 29.54980 | 29.75215 | 30.13769 | 30.73050 | 31.55969 | 32.65985 |
| | t=1.5 | 30.49397 | 31.16732 | 32.17037 | 33.55958 | 35.40204 | 37.76897 |
| | t=2 | 31.46970 | 32.66876 | 34.37898 | 36.70001 | 39.73069 | 43.46952 |
| D=3 | t=1 | 83.98229 | 83.38121 | 82.96903 | 82.75866 | 82.76477 | 83.00355 |
| | t=1.5 | 85.27626 | 85.17562 | 85.38484 | 85.93076 | 86.84274 | 88.15128 |
| | t=2 | 86.47115 | 86.89451 | 87.76428 | 89.11856 | 91.00791 | 93.47429 |

## 7- Conclusion

In this research, a one-story two-dimensional (2D) concrete frame with one span was subjected to a specified static lateral load. A cable bracing system connected to a square steel plate in the center of the frame was studied. The following conclusions were made in the range of the conducted studies for this case under nonlinear static analyses:

1. Unbraced moment-resisting frame (MRF) has more displacement compared with braced ones. By adding the cable bracing to the frame, the lateral stiffness of the frame increases. Consequently, the lateral displacement of the frame decreases. In the frame braced with cables and the central steel plate, because of the delay in the performance of the bracings against lateral loads, the

frame has larger displacements in comparison with the ordinary bracing. By adding a steel plate in the center of bracings, the lateral displacement of the frame increases. In this case, the lateral displacement of this frame is larger than the frame with the channel bracing and is smaller than the unbraced MRF. By changing the plate dimensions and thickness, as well as changing the cable diameter, it is possible to increase/decrease the lateral displacement of the structure, considering the required design.

2. In this research the theoretical behavior of the cable bracing system with a central steel plate is assessed.
3. By studying the results of non-linear static analysis, it was observed that the variation of cable diameter had a significant effect on the lateral displacement of the frame, the stresses in the plate and internal forces of beams and columns; while the variation of dimensions and thickness of the plate did not have much effect on the values. Studying the thickness of the plate is only required for the design accountability.
4. Adding a steel plate in the center of cable bracings, causes all four cables to involve against the lateral loads. Therefore, all four cables are under tension. In other words, adding the steel plate improves the performance of the structure against applied lateral loads. This is the advantage of the cable bracing system with a central steel plate in comparison with the normal bracings and cable bracing.

## Nomenclature

The following symbols were used in this paper

$l_b$ the length of the frame
$h_c$ the height of the frame
a the length of the steel plate
b the width of the steel plate
$\delta$ the lateral displacement of the frame
$\theta$ the rotation of the plate
$F_R$ the force of the right cable
$F_L$ the force of the left cable
$F_P$ the prestressing force
$F_y$ yield stress
$F_u$ ultimate strength
t the plate thickness
E modulus of elasticity
A cables cross section
EA axial stiffness of each cable
D the cable diameter
$\Delta_{AE}$ the elongation of the cable AE
$\Delta_{BF}$ the elongation of the cable BF
$L_{AE}$ the lengths of the cable AE
$L_{BF}$ the lengths of the cable BF
$\varepsilon_R$ the strain of the right cable
$\varepsilon_L$ the strain of the left cable
$\upsilon$ poisson ratio
$\gamma$ density
d the distance from FR to the center of the plate after the the plate rotation
d' the distance from FL to the center of the plate after the the plate rotation
$\alpha'_R$ the angle between the right cable and the horizontal axis
$\alpha'_L$ the angle between the left cable and the horizontal axis
$\Delta_P$ the elongation of cables caused by prestressing force
$f'_c$ the specified compressive strength of concrete
$l_t$ the total length of right and left cables

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