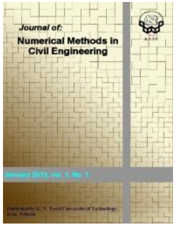
Numerical Methods in Civil Engineering, 6-4 (2022) 47-58



Numerical Methods in Civil Engineering

Journal Homepage: https://nmce.kntu.ac.ir/

Seismic behavior of cable braces strengthened with a central steel plate

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ARTICLE INFO

RESEARCH PAPER

Article history:
Received:
November 2021.
Revised:
January 2022.
Accepted:
January 2022.

Keywords:
Cable bracing
Steel plate
Plate stress
Retrofitting of structures
Rehabilitation systems

Abstract:

This research suggests a novel method to use steel cables as a structural bracing system. The Moment Resisting Frame (MRF) works in tandem with the cable bracings when this method is used. The suggested bracing model can address the fundamental problem of current cable bracing methods, namely the lack of flexibility while keeping costs to a minimum. This approach requires no additional equipment, and despite the minor alterations to the structure, it uses MRF's full flexibility by delaying the brace action while minimizing substantial and undesirable displacements. This bracing method combines the major advantages of MRFs with cable bracing. For 1, 3, and 6-story 2D frames, the performance of frames that use the provided bracing mechanism was investigated. The numerical results of the dynamic analyses done for this study reveal that the proposed bracing approach was successful for the seismic protection of the structure. The relative displacement of the floors is substantially decreased when using the suggested method, yet the designer may make the structure's behavior predictable by adjusting the model specifications. The fluctuations in axial forces and moments transferred to the beams and columns, as well as the forces applied to the structural cables, and most importantly, the stresses subjected to the central plate, are investigated in this study. Another advantage of this research is that it demonstrates how this method may lead all cables to share a considerable portion of the load-bearing capacity.

1. Introduction

The growth of engineering science necessitates the adoption of appropriate and cost-effective technologies that work reliably. Engineers attempt to make progress in this direction by improving existing rehabilitation systems and creating new ones. Buckling-restrained braces (BRBs) are one type of solution that may be used to suit this viewpoint. In this field, Qiang Xie [1] proposed a BRB model, and Bartera and Giacchetti [2] examined the use of energy absorption devices such as dampers in bracing systems. In this regard, Tamai and Takamatsu [3] proposed non-compression braces, while Golafshani et al. [4] introduced a semi-active bracing approach. Steel cables linked to the main structure are one of the most recent MRF rehabilitation options, and researchers have introduced many types of cable bracings in recent years.

The following are some of the benefits of employing steel cables as bracings: flexibility, great capacity in sustaining tensile stresses, simple design, quick and easy construction and installation, no heavy machines required for installation, and little noise during installation. However, due to their low compressive strength, cables can only be used as tension components in structures [5]. As a result, cables have mainly been employed in cable bridges in recent years. Matteo et al. [6] conducted the earliest research on cable braces and suggested an assessment method to investigate the residual load-bearing capacity of the main cables in the Williamsburg Bridge. In this regard, cable corrosion became the primary research topic [7, 8]. Xu and Chen [9] provided an improved model based on earlier research to create corrosion tests on removed cables. Cable bracing systems can also be used to increase a building's dynamic performance [10-13]. It was proposed that non-linear constitutive effects (such as unilateral effects caused by buckled braces) should be addressed when evaluating the performance of bracing

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[DOI: 10.52547/nmce.6.4.47]

systems [14-17]. Any proper brace construction and distribution of internal pre-tension forces applied to the main structure are directly related to the unilateral behavior of the braces, which may have an influence on the system's dynamic performance [10, 13]. Giaccu and Caracoglia [10] developed a novel method for studying the non-linear unilateral behavior of the braces, which might prevent a total loss of pre-tension force applied to the bracing cables. They also offered a novel way for directly simulating the effect of an alternative loss of initial pre-tensioning in bracing cables on structural systems.

Cable bracing methods have two problems. The first is that cables have limited ductility and energy dissipation capabilities due to the small amount of inelasticity in their stress-strain curve [5]. The second challenge is the lack of simultaneous engagement of all cables used in the system to generate lateral system resistance. The cable bracing research approach is divided into two parts to eliminate these issues: (1) Systems with pre-stressed or continuous monolithic cables. Here, cables pass through casings or special connections on the floors and are secured at the final or any defined story. The most notable example in this regard is the SPIDER (Strand Pre-stressing for Internal Damping of Earthquake Response) project, which was implemented in several European countries [18, 19]. (2) On all floors and unique bays, X-shaped cable braces, similar to ordinary steel bracings, are installed for the second set. Lotfollahi and Alinia [20] investigated the effects of failure and ductility on the non-linear response of Tension Braced Moment Frames (TBMFs). In this kind of bracing, because lateral forces are two-way, half of the bracings constantly operate and contribute to the resistance capabilities of frames. As a result, Phocas et al. [21, 22] devised a unique disk-like connection capable of keeping all connections functioning. Hou and Tagawa [23, 24] established a permanent cable link by connecting them via a cylindrical component at the cable junction to keep all cables active in stress. Kurata and Kurata et al. [25, 26] presented a cable bracing system with a central damper to include all cables against applied loads. With the lateral movement of the frame and the rotation of damper plates, all cables were under strain in this approach.

It is worth mentioning that a disadvantage of the aforementioned rehabilitation techniques is their high cost due to the specialized connections and equipment required. Another disadvantage is that they must be assembled by a professional. Creating a device with a constant presence of stiffness without buckling is a novel approach in which the device absorbs input energy to the full capacity of the members [4]. Fanaie et al. [27] researched and published the governing equations for a cable bracing system with a central steel cylinder at the crossing point of the cables. They investigated the effects of cylinder size and cable pre-stressing. For simplicity, the steel cylinder had a high rigidity and minimal elastic deformation, and it could be considered rigid. The pre-stressing force was found to be proportional to the initial stiffness of the cylinder-cable bracing system. They also used previous research [28] to analyze the seismic behavior of MRFs supported by cables and a central steel cylinder. According to the results, even though the displacement of the frame in the system was greater than in the cable cross bracing system, the system distributed the relative displacement of stories in the frame height and prevented the concentration of damage in a particular story as well as soft-story formation. Fanaie and Zafari [29, 30] investigated the behavior of a cable-cylinder bracing in near-field conditions. A two-dimensional model was used to calculate the cable-cylinder bracing system's overstrength, ductility, and response modification factors. Due to its larger response modification factor, the cable-cylinder bracing outperformed the cable bracing in the results. Abhari and Barghian [31] investigated the theoretical behavior of a cable bracing system with a central steel plate and proposed the governing equations for lateral static loads. It was discovered that changing the cable diameter had a substantial influence on the lateral displacement of the frame, while changing the plate dimensions did not affect the measured values. The results demonstrated that the suggested system had the same properties as MRFs in terms of exhibiting acceptable ductility while simultaneously possessing high stiffness.

This method prompted the authors to investigate a revolutionary cable bracing system with central steel plates installed in each story to create a tensile brace force, preventing the braces from buckling and reducing story drifts by using this specifically constructed system. The current study focuses on a bracing configuration in a 2D MRF where a steel plate is situated in the middle of the frame, and the cables are connected to it. The advantage of cable bracing strengthened by a central steel plate is that all four used cables participate in load-bearing. This is caused by the central plate rotating under the force of lateral loads, allowing for the most effective use of cables. In this strategy, the cables and plate are used in such a way that the cables achieve their optimum strength at the larger displacements of the frame. As a result, this method compensates for the cable braced MRFs' deficiencies in ductility. Another advantage of the proposed system is that basic steel plates are less expensive than other devices and mechanisms, and because the plates are smaller in dimensions – as opposed to tubes – the designer may simply put them inside the walls, which is an excellent advantage from an architectural viewpoint. On the other hand, the stated system preserves the same ductility as the primary MRF frame due to the delay in brace action. Because the central plate does not rotate sufficiently in minor displacements, the cables endure

[DOI: 10.52547/nmce.6.4.47]

a minor amount of external stress. Additional displacements of the frame cause more rotation of the plate, and the four cables come into contact with each other. As a result, all four cables engage in the load-bearing with the highest potential. Furthermore, cable pre-tensioning has a considerable impact on the overall system's load-bearing capability. While the proposed bracing method does not affect the loads exerted on the structure reinforced by typical cable braces, it does reduce the cable bracing method's fundamental shortcoming, namely the braced structure's poor ductility. The size and thickness of the plate, as well as the axial stiffness and pre-stressing of the cables, all affect the behavior of this bracing system. With this in mind, this study investigates the dynamic behavior of a cable bracing system with a central steel plate. Changes in plate size and thickness, as well as cable diameter, are also investigated in this study. Furthermore, assessing the non-linear time-history analysis of the cable bracing technique is beneficial, as scholars consider that non-linear time-history analyses are the accurate approach to evaluate structural models [32-36]. This research compares unbraced and cross-braced frames to a unique method of cross-bracing employing a steel plate. When the steel plate was added, all cables were put under tension, whereas just one cable was under tension in the conventional cross-bracing method. Employing a square plate in the center of the frames increased the lateral displacement of the frame. The results also showed that using a steel plate in the center of the bracings in each story increased the lateral displacement of the frame when compared to a cross-braced frame. However, the lateral displacement was not as much as that of the unbraced one. Fig. 1 depicts the distorted shape of the suggested bracing system for the case study of a one-story structure. The central steel plate in this arrangement increases load-bearing capability while also preventing excessive displacements of the overall system. As a result, it may simultaneously compensate for the primary disadvantages of cable braces (insufficient ductility) and bare MRFs (very high displacements).

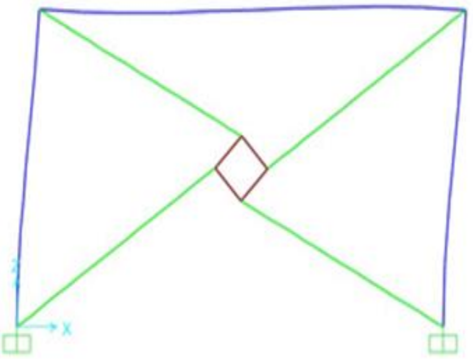
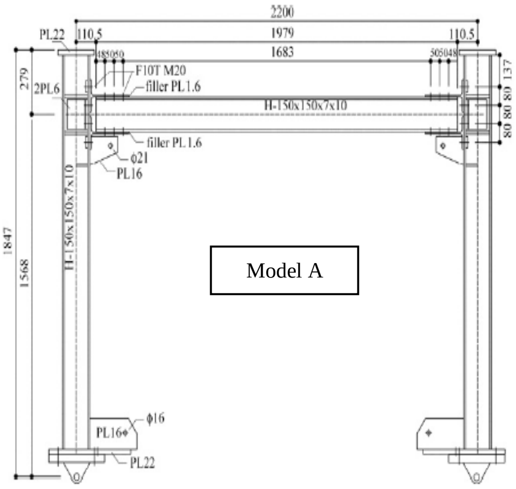
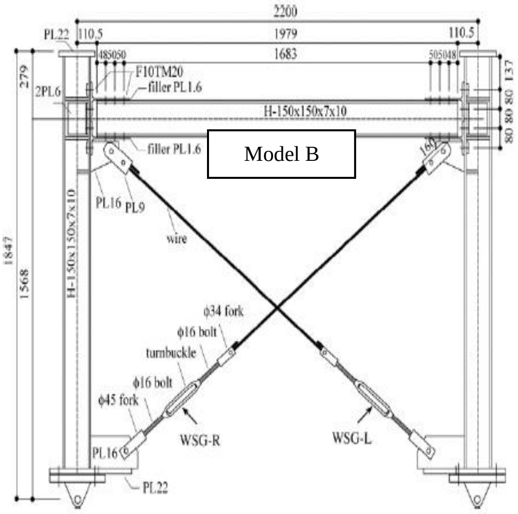


Fig. 1: Deformed configuration of the system

2. Verification of the models

Before analyzing the models, it is critical to ensure that the models and software are sufficiently robust. The experimental model developed by Tagawa and Hou [23] was applied to do this task. As a result, the modeled frames were as shown in Fig. 2 (The column and beam members were of H-150×150×7×10 sections and the bracing members of the wire rope were 8mm diameter steel cables). Model A depicts an MRF, Model B represents an MRF frame with X-shaped cables, and Model C represents a reinforced model with cables and a cylindrical component. These three frames were modeled in SAP2000 [37] using the same specs and materials as Tagawa and Hou's model. It should be emphasized that Model C was modeled in the shape of a truss, and the axial stiffness of the cylinder and its inner cables was 1500 times that of the outer cables (see references [23, 24] for more details). The loading pattern was the linear static time history shown in Fig. 3.





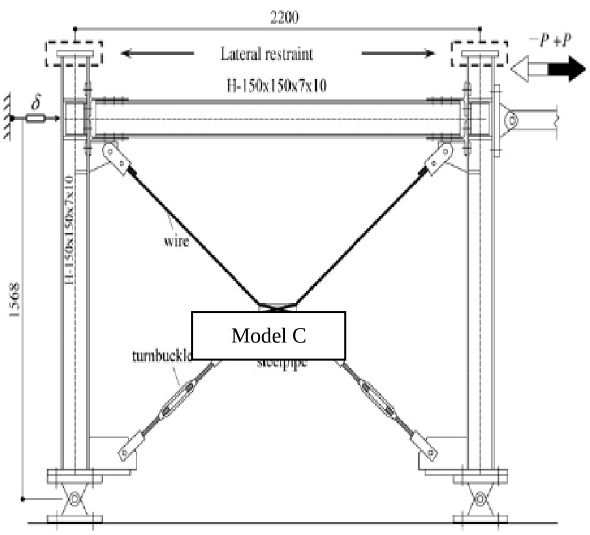


Fig. 2: Verified models [23]

After the models were examined, the highest internal forces and maximum displacements were compared to the results provided in reference [23]. The findings of the investigation are depicted in Fig. 4 and Table 1. According to the figures, the data collected from the Finite Element (FE) model corresponds to that of Tagawa and Hou [23]. This finding validates the modeling and material choices. For more details about the models, see Fig. 2 and reference [23].

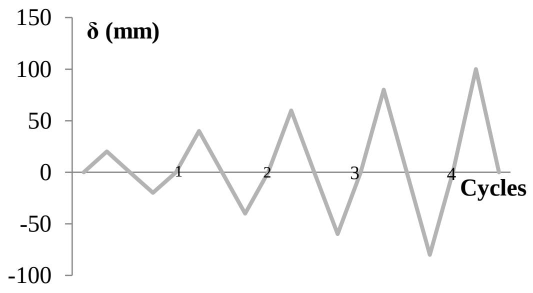


Fig. 3: Loading pattern

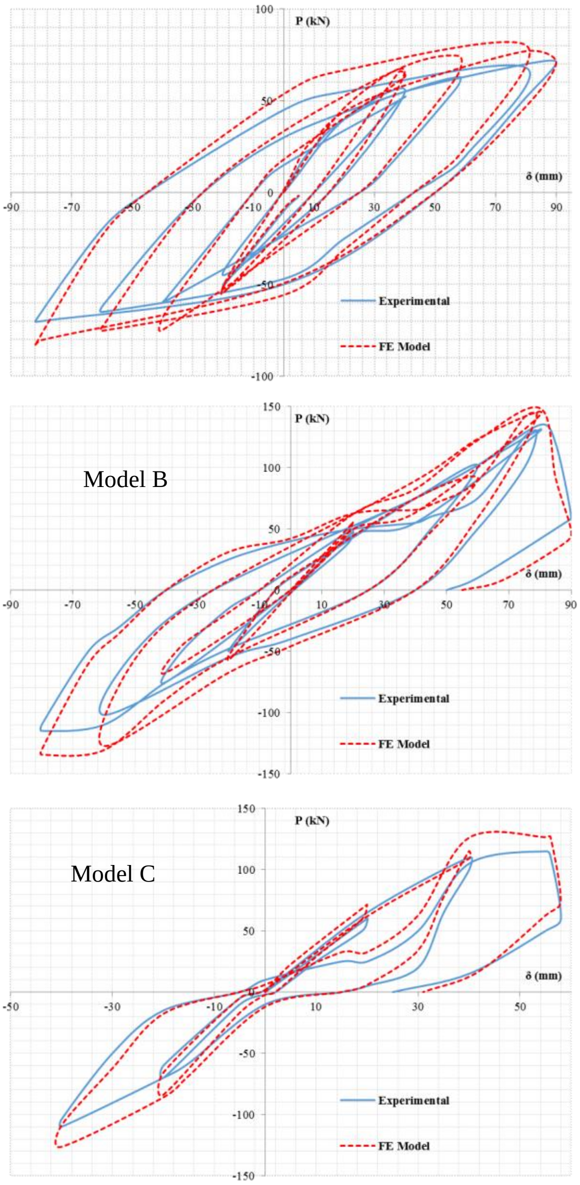


Fig. 4: Comparison of the hysteresis curves (FE and Experimental data)

Table 1: Comparison of FE and Experimental data

	P_{Max} (kN)			δ_{Max} (mm)		
	F.E.	Exp.	Diff %	F.E.	Exp.	Diff %
Model A	80.1	85.2	6.4	89.05	93.5	4.99
Model B	115.5	120.6	4.41	50.1	52	3.65
Model C	125.8	133.7	6.28	82.2	86.6	5.35

[DOI: 10.52547/nmce.6.4.47]

3. Specifications of the models

After ensuring that the software and modeling were robust, the models were modified to meet the objectives of this paper. A steel MRF with moderate ductility, located in a region with type III soil in Tehran, Iran, was chosen as the lateral load-bearing system. The model had a 2-D frame with a 5 m span and 1, 3, and 6 stories, each with a 3 m height. Three alternative sets of models were explored to investigate the bracing effect: an MRF, an MRF with standard X-shaped cable braces, and an MRF with an X cable bracing system strengthened by a central steel plate. In the current study, the central plate is a square, and due to the general nature of cable braces, the steel plate is attached to the cables through four holes in the corner of the plate and the hoop and U-shaped connection at the end of a cable (Fig. 5 shows the schematic view).

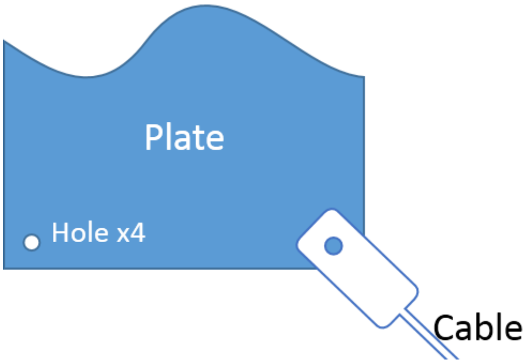


Fig. 5: Schematic view of the connection

The members were represented as beam elements for beams and columns and truss (wire) elements for cables to save analysis time and simplify the model. The beam and column materials were considered non-linear (elastoplastic), whereas the cable material was considered linear (elastic). To account for steel's strain hardening, the bilinear stress-strain curve was assumed to have the yield stress of 240 MPa for the ST-37 construction steel and the postyield branch slope of 2% elastic modulus (0.02 E). The density of steel was assessed to be 7800 kg/m^3. Non-linear dynamic analyses were used to analyze the models to investigate the seismic behavior of the system. Seven distinct earthquake data sets were used for non-linear dynamic time-history analysis [38], and these records were scaled according to the Iranian Code, considering all the criteria mentioned in the Iranian seismic design code, Standard 2800 [39] (PGA = 0.35 g). In this regard, Fig. 6 shows the normalized ground motion along with the code prescribed spectrum.

Table 2: Ground motion properties

Record	Year	M	Station	PGA (g)
NewZealand	1987	6.6	Matahina Dam	0.592
Tabas	1978	7.35	9102 Day hook	0.305
Northridge	1994	6.69	Old Ridge Route	0.689
Point Mugu	1973	5.65	Port Hueneme	0.128
Lytle Creek	1970	5.33	Hollywood Store	0.568
Park field	1966	6.19	Shandon Array	0.346
Erzican	1992	6.68	Erzican	0.495

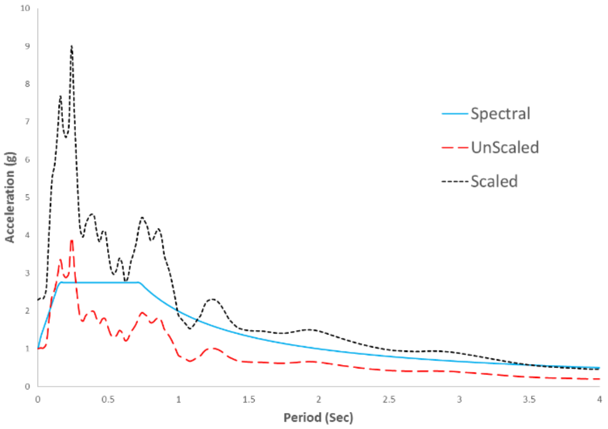


Fig. 6: Normalized ground motion

Non-linear dynamic analyses were carried out on both conventional braces and an equivalent one created by equipping the conventional braces with a central steel plate. The records' results were averaged and provided as the research's findings. All columns and beams were allocated the double IPE 180 (2IPE 180) sections. According to the Iranian design code [39], dead and live loads were considered equal to 400 and 200 Kgf, respectively. The models were analyzed using P-δ analysis and large displacements. The central plate in this study was square-shaped, and its dimensions ranged from 10×10 cm to 60×60 cm in 10 cm increments, with the thickness of the plate chosen as 1, 2, and 3 cm to investigate the thickness effect. In addition, the diameter of the cable was decided to be 1, 2, and 3 cm in various models. All bracing cables were pre-tensioned with a force of 3000 Kgf. This load level was chosen to prevent the cables from buckling [5]. The steel and the cables' specifications were considered according to Table 3. It should be mentioned that in this paper, "D" represents the cable diameter, and "T" reflects the plate thickness. As an illustration, D1 stands for X-shaped cable braces with 1 cm cable diameter, and 10-D1T2 denotes a cable bracing system with a diameter of 1 cm that is reinforced by a central steel plate with dimensions of 10×10 cm and a thickness of 2 cm.

[DOI: 10.52547/nmce.6.4.47]

Table 3: Steel and cable specifications

	Modulus of Elasticity (Kgf/cm^2)	Yield Stress (Kgf/cm^2)	Ultimate Stress (Kgf/cm^3)	Poisson's ratio	Density (Kg/cm^3)
Steel	2.1E5	2400	3700	0.3	7850
Cable	1.85E5	14000	17000	0.3	7800

In this regard, Fig. 7 displays the Modeled frames for the 6-story case study.

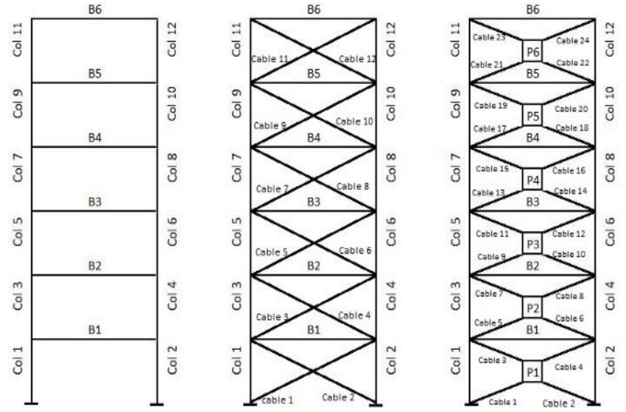


Fig. 7: Modeled frames (6-Story)

4. Discussion and Results

The axial forces and moments of the columns, beams, and cables in the MRF, the frame braced with standard X type cable bracing, and the frame with X braces coupled with a central steel plate were calculated using dynamic analyses, and the results were compared to each other. The central plate's stress analysis results were also examined. Another outcome investigated in the current paper was relative displacement (drift). The results showed that the variations in internal forces were not substantial as plate thickness increased. The findings also showed that changing the diameter of the cables had a more significant influence on the structure's behavior than changing the plate thickness. Except in the case of plate stress, this property is not examined further due to the insignificant influence of plate thickness.

4.1 Period of the first mode

As seen in Fig. 8, the MRF has the greatest changes in its period compared with the other models, which is related to the introduction of cable braces. This image also illustrates that adding X-shaped bracing cables to the MRF significantly decreases the structure's period due to the stiffness increase created by the cables. When a 3 cm cable is utilized, the period is lowered by about 79.1% compared to the plain MRF. To overcome this issue, Fig. 8 indicates that adding a central steel plate can increase the period of the structure. A central plate with 20 cm in dimension can increase the period of the structure by approximately about 20% in comparison with the same X-shaped cable bracing, which is the most significant advantage of the proposed system.

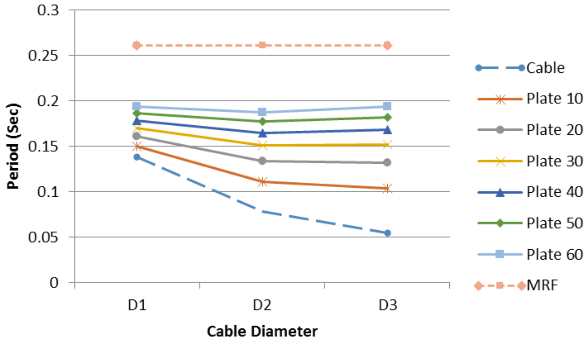


Fig. 8: Period (for the first mode)

4.2 Drifts

Fig. 9 depicts the one-story frame drift. As can be observed, the MRF exhibits the most drift of any model, indicating the system's ductility. By adding typical X-shaped cable bracing to the frame, the structure's drift is significantly reduced, and the system becomes substantially stiffer. Fig. 9 further shows that adding the central steel plate to the junction of cable braces increases the drift of the floor by around 20% compared to the cable braces. Enlarging the plate dimensions produces the same effect, as illustrated in this figure. In the extreme case, a plate of 10 cm, the data demonstrated that increasing the cable diameter reduced frame drift by approximately 41.3% compared to a lower diameter cable. It should be noted that when using larger plates, this impact drops to 6.2% when using a 60 cm plate.

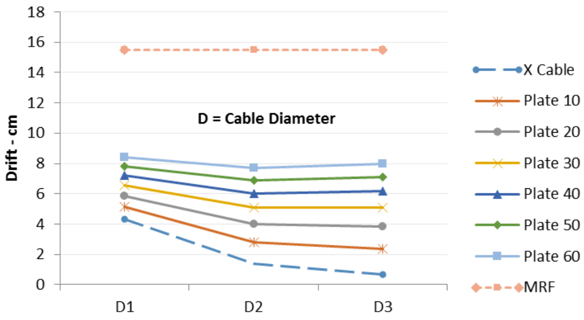


Fig. 9: Inter-story drift

In the case of the three-story building, as illustrated in Fig. 10, the MRF has the greatest drift of all models, but utilizing X-shaped cable braces significantly reduces the drift. In comparison with the MRF, a 1-cm-diameter cable can reduce drift by around 85%. Using a steel plate at the junction of cables, on the other hand, might increase drift and make the structure softer. As illustrated in this figure, increasing the plate magnitude causes an increase in joint

[DOI: 10.52547/nmce.6.4.47]

displacement. Employing a 50 cm plate instead of a 10 cm plate with identical parameters can raise the structure's drift by around 69.9%. This condition tends to happen in all stories. This fact demonstrates how employing cable braces reinforced with steel plates may assist the designer in predicting the behavior of the structure; and how by selecting the proper configurations, the overall structure can have a desirable behavior between the MRF and basic cable bracing system.

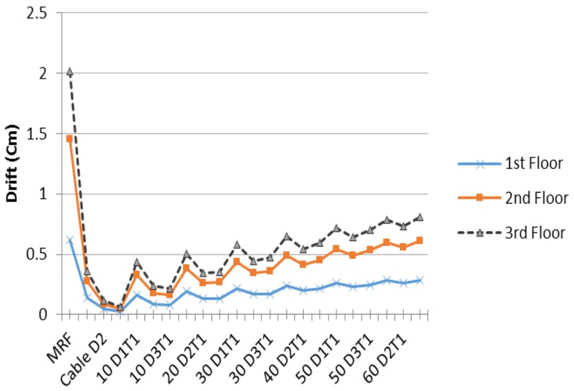


Fig. 10: Inter-story drift (3-Story)

In this regard, Fig. 11 depicts the dynamic response of the three-story frame's top right joint (roof) for the Northridge record. According to this diagram, the proposed system's displacement is between the MFR and X-shaped wires. Another benefit of the suggested approach is that it behaves the same way for the 6-story building.

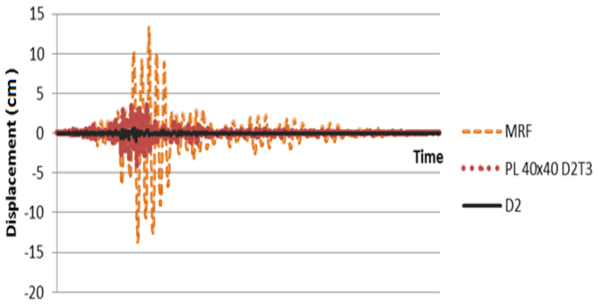


Fig. 11: 3-story drift - Northridge

Fig. 12 shows the drift of the 6-story frame in this regard. The relative displacement of the MRF is the greatest when compared to other bracing systems. However, by adding X-shaped steel cables to the frame, the drift of the structure was significantly reduced, around 49.7% maximum. Adding a central plate, unlike X-shaped cables, can increase the drift of the floor, and by modifying the plate size and thickness, the designer can adjust the drift of the entire frame to the MRF or X-shaped cable bracing system.

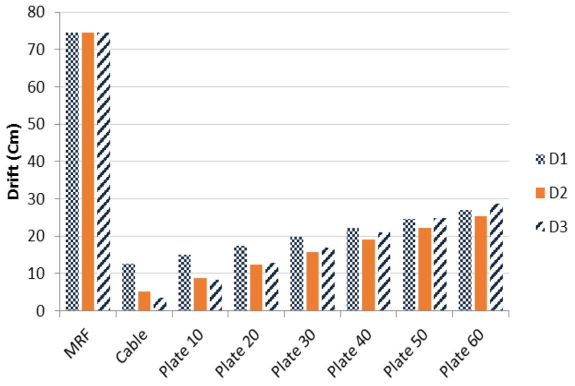


Fig. 12: Inter-story drift – 6-story

4.3 *Axial Forces and Moments of the Beams*

Table 4 depicts the maximum axial force of a beam in a one-story building. The examination of the beam's axial force (P) results shows that the MRF frame has the least amount of internal force among all types. Due to the brace action, the X-shaped cables create a significant increase in axial force. This table also shows that adding a central steel plate to the middle of the braces increases the beam's axial force by roughly 0.5%, whereas increasing the cable diameter decreases the axial force by around 7%.

Another significant finding from Table 4 is that the employed bracing system does not alter the behavior of the typical cable bracing system (1.32% uttermost), but, as previously stated, it can aid in the seismic protection of the overall system by preventing unexpected displacements.

Table 4: Axial forces of the beams

	D1	D2	D3
Cable	6,114	6,818	7,376
Plate 10	6,327	7,789	8,291
Plate 20	7,145	8,003	8,365
Plate 30	8,326	8,819	9,302
Plate 40	8,709	8,961	10,317
Plate 50	9,224	9,864	11,021
Plate 60	10,254	10,873	11,817
MRF	698		

Fig. 13 displays the axial force in the three-story frame's beams. This graph illustrates that, like in the previous case, X-shaped cable bracing may elevate internal force by around 12 times compared to the MRF. When a central steel plate is employed at the cables' intersection, the applied force increases by 0.11% when compared to the X-shaped brace system, demonstrating that the recommended system's mandated adjustments are quite minimal. However, for the 6-story building, cable diameter has the reverse effect and can reduce internal force by approximately 20%.

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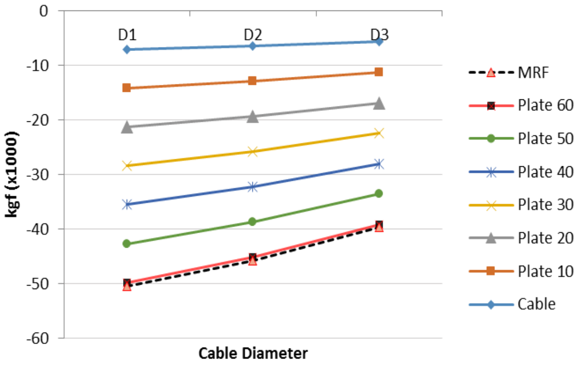

Fig. 13: Axial forces of the beams (3-Story)

Attaching X-shaped cable braces to the MRF reduces the moment of the beams; however, connecting the middle steel plate to the braces somewhat increases it (see Fig. 14). In this case, the moment is likewise raised by increasing the size of the central steel plate. The beams in the three and six-story structures react similarly. In contrast, Fig. 15 shows that the moment of the beams is significantly reduced in typical cable braces compared to MRF. The moment is limited to 30% of that in the MRF, as shown in Fig. 15, by using X-shaped cables 1 cm in diameter.

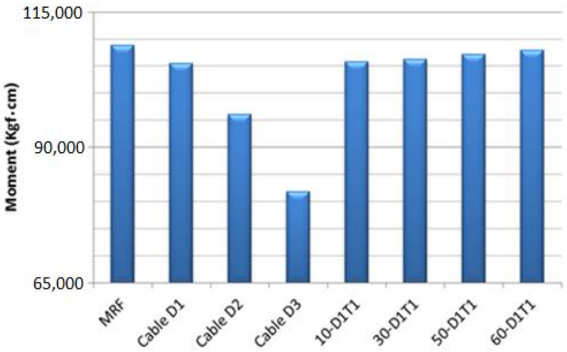

Fig. 14: Bending moments of the beams

Fig. 15 also shows that in the bracing with the central plate, increasing the plate size increases the beam’s moment. This change is around 33.5%.

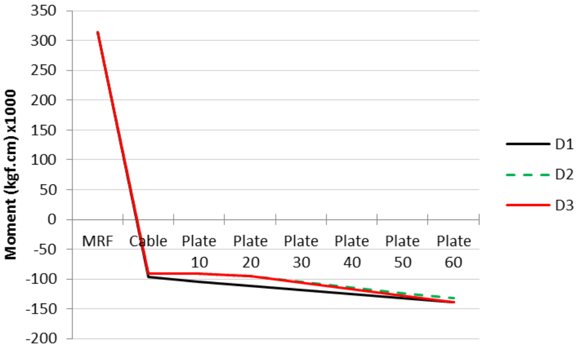

Fig. 15: Bending moment (6-story structure)

4.4 *Internal forces of the columns*

The axial forces of the columns of the one-story frame are shown in Table 5. This table indicates that adding cross-shaped cable bracing to the MRF increases the axial force of the columns significantly. It is also demonstrated that adding a central steel plate to the center of the braces may have the reverse effect of lessening the axial forces of the columns. A similar effect may be obtained by increasing the size of the central plate. In the same way, increasing the cable diameter decreases the axial force in cable bracing with the central plate.

Table 5: Axial forces of the columns

	D1	D2	D3
Cable	6,962	5,596	5,829
Plate 10	5,808	5,403	5,325
Plate 20	5,364	4,294	4,172
Plate 30	4,718	4,127	4,026
Plate 40	4,270	4,098	3,873
Plate 50	3,720	4,006	3,618
Plate 60	3,687	3,501	3,261
MRF	1,603		

According to the values in Table 6 for the three-story building, adding conventional X-shaped cables to the frame increases the axial force by around 53%. As can be observed, placing a central steel plate at the intersection of the cables can reduce this force marginally; by up to 1%. The increase in thickness has the same effect.

Table 6: Axial forces of the columns (3-story structure)

	D1	D2	D3
Cable	6,258	6,086	5,829
Plate 10	6,208	5,013	4,925
Plate 20	5,164	4,967	4,673
Plate 30	5,118	4,909	4,626
Plate 40	4,078	4,008	3,873
Plate 50	4,001	3,916	3,512
Plate 60	3,917	3,761	3,268
MRF	1,603		

4.5 *Bending moments of the columns*

The bending moments of columns are presented in Table 7. It can be observed that when the cross-shaped cable bracing is used, the moments of all columns increase in comparison to the MRF. However, by using larger-diameter cables, the column moment is somewhat increased. As shown in Table 7, the use of the central steel plate reduced the moment in the columns compared to cross-shaped bracing. Furthermore, increasing the plate size has the same effect on the behavior of the columns, which is a benefit of the suggested system.

[DOI: 10.52547/nmce.6.4.47]

Table 7: Bending moments of the columns

	D1	D2	D3
Cable	89,281	90,488	91,501
Plate 10	93,379	94,487	95,498
Plate 20	94,429	95,487	95,569
Plate 30	94,539	96,487	96,799
Plate 40	95,679	96,487	97,683
Plate 50	95,788	97,487	97,513
Plate 60	96,389	98,486	98,638
MRF	87,470		

For columns in the three and six-story frames, the MRF has the greatest bending moment (Table 8). By attaching typical X-shaped cables to these frames, the bending moment of the columns is reduced by approximately 32%. This table demonstrates that the middle plate, the increase in cable diameter, and the plate thickness all have a minor rising influence on the bending moment, around 0.95% at most.

Table 8: Bending moments of the columns (6-story structure)

	D1	D2	D3
Cable	88,068	89,178	91,001
Plate 10	90,479	91,326	93,245
Plate 20	91,351	91,294	96,571
Plate 30	95,163	96,328	97,631
Plate 40	96,279	97,487	98,500
Plate 50	98,678	99,654	100,643
Plate 60	99,037	99,814	101,852
MRF	86,193		

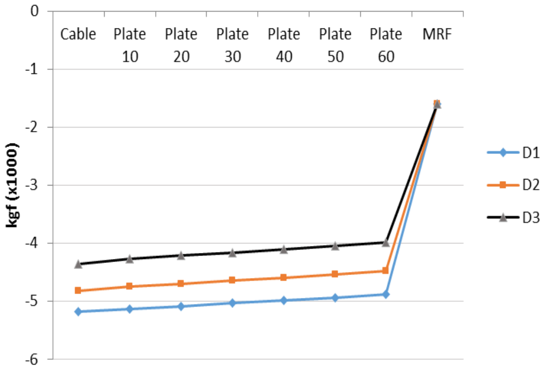

Fig. 16: Axial forces of the columns (6-story structure)

4.6 *The axial forces of the cables*

Being an important component of the bracing system, the cables significantly influence the structure's total load-bearing capability. Fig. 17 depicts the axial forces imparted to the cables. This diagram illustrates that using the cross-shaped cable braces system decreases the axial force by approximately 7%. According to this figure, the connection of a central steel plate resulted in a decrease in the axial forces of the cables, which was less than 10% in all cases.

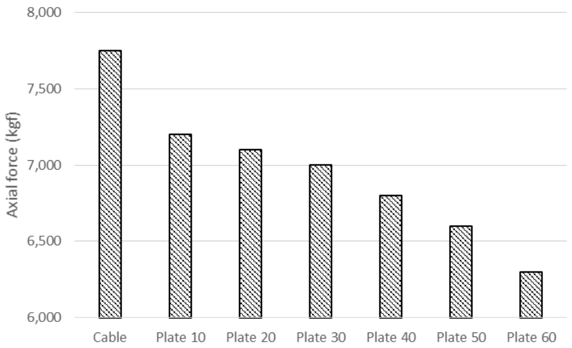

Fig. 17: Cables' axial force

The axial forces of the cables is displayed in Fig. 18 for the New Zealand earthquake data.

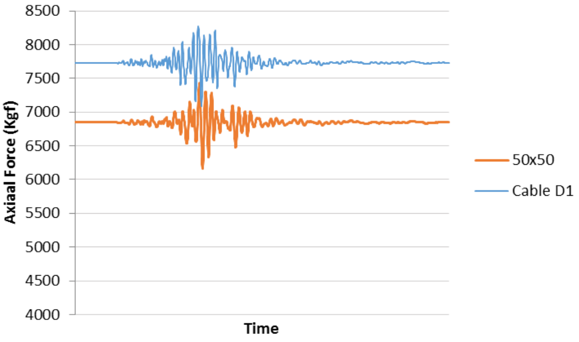

Fig. 18: Cables' axial force - New Zealand record

Changes in plate size and thickness have a minor influence on force alteration of the final floor's cables in a cable bracing system supported by a central steel plate; however, increasing cable diameter has a significant effect on lowering this force. This difference is 29% when a 3 cm cable diameter is used instead of a 1 cm diameter, as seen in Fig. 19.

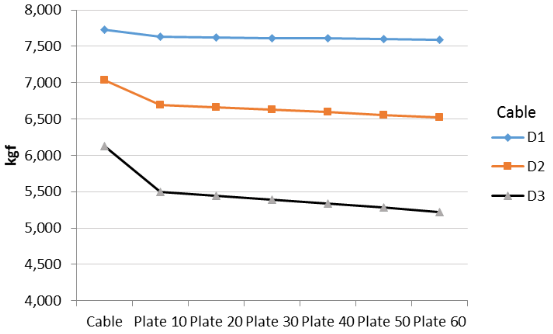

Fig. 19: Cables' axial force (6-story structure)

4.7 *Stress in the central plate.*

Fig. 20 shows the central plate's maximum internal stress. This graph indicates that increasing the plate size decreases internal tension, albeit the reduction becomes less effective as the plate size grows. Using a 30 cm plate instead of a 10 cm plate, for example, may reduce stress by roughly 32%,

[DOI: 10.52547/nmce.6.4.47]

while using a 60 cm plate instead of a 50 cm plate can reduce stress by around 12.3%. It was discovered that plate thickness affects plate stresses; hence, increasing the plate thickness lowered internal stress, with the highest reduction being around 60%.

Increasing the plate size in such instances reduced the effectiveness of the plate thickness. Increasing the diameter of the cables generated the same result, albeit with less intensity, as seen in Fig. 20. Keeping this in mind, an increase in cable diameter lowered stress by around 11% at most.

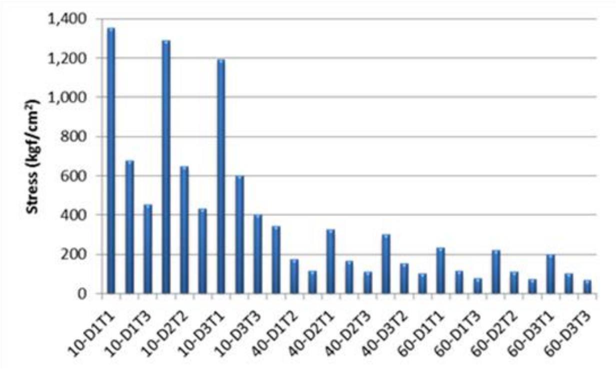

Fig. 20: Stress in the central plate

Fig. 21 depicts the time-history internal stress of the central steel plate of the frame during the Tabas earthquake.

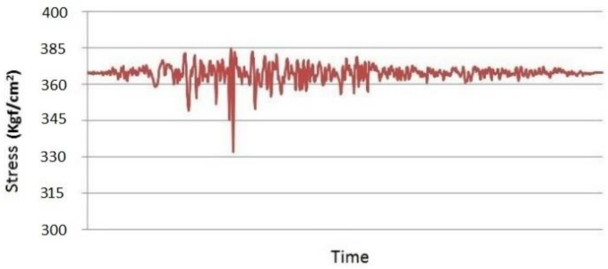

Fig. 21: Internal stress of the central plate – Tabas record

Fig. 22 depicts the internal tension of the three-story model. This graph demonstrates that the behavior of this model is similar to that of a one-story structure.

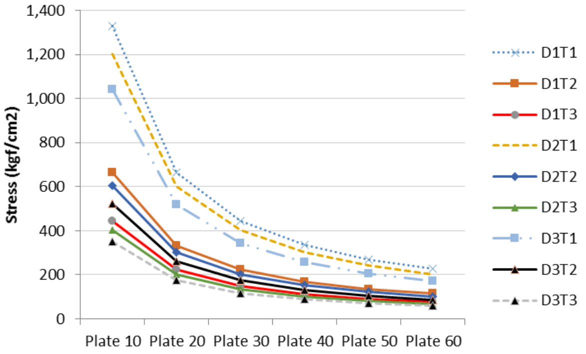

Fig. 22: Internal stress of the plate in the 3-story frame

When the results of the three-story frame are compared, it is clear that the bracing system with the central plate does not significantly change the internal forces of the conventional cable braces, but it can help to improve the seismic behavior of the entire system, which is a significant advantage in lateral bracing of structures.

As seen in Fig. 23, the smallest plate in the 6-story model has the highest stress of all models. Nonetheless, by increasing the plate size, the tension in the plate lowers. For example, by doubling the plate size, as shown in this figure, the internal stress falls by 49.8% when utilizing a 20 cm plate instead of a 10 cm plate. Internal stress, as anticipated previously, has an inverse relationship with plate size and is lowered by increasing plate dimensions.

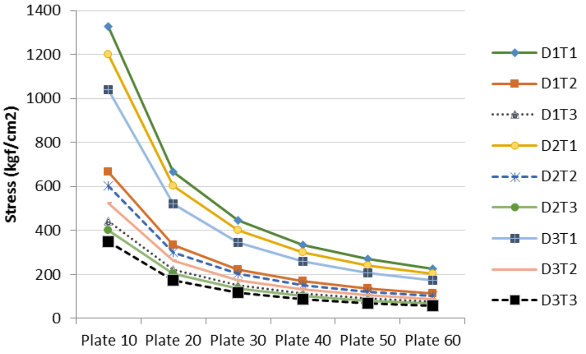

Fig. 23: Plate stress (6-story structure)

5. Conclusion

The goal of this research was to investigate a unique method of lateral bracing for buildings and structures. This method consists of four cables connected by a square steel plate at their connecting point. This approach can address the issues with the MRF and ordinary X-shaped cable bracing systems. Because of the rotation of the central plate, the cables face each other in this method and simultaneously participate in load-bearing at their maximum capacity. The results indicate that by using cable braces strengthened by a central steel plate, the designer may construct a unique ductile system that can also use the MRFs' maximum ductility by delaying the brace action. The researched bracing method, which is strengthened with a central plate, does not require any special equipment and, although having a minor influence on the forces exerted to the structure when compared to cross-shaped cable bracing, it makes the design more economical and considerably simpler. Due to the benefits of both the MRF and traditional cable bracing systems, this specific bracing design may enhance lateral resistance of the structure, even in significant displacements, and the numerical results illustrate the usefulness of the utilized technology for the seismic protection of the structure. When adopting this technology, displacements and drifts are

[DOI: 10.52547/nmce.6.4.47]

limited to acceptable levels, but internal forces are not significantly affected. The designer may adjust the system to have a preferred behavior, somewhere between the MRF and X-shaped cable braces, by selecting the appropriate cable diameter and plate size and thickness. It should be noted that this bracing method does not operate for minor displacements; hence it is not suggested for constructions that are sensitive to small displacements. This demonstrates that there is still room to research this bracing strategy.

The current findings add to a growing body of literature on the impacts of steel cable braces, and taken together, these findings suggest a role of positioning of these elements in promoting the behavior of the entire structure. However, it is essential to emphasize the need to interpret the results with caution and consider them tentative, given the obvious limitations. In fact, this study has several limitations that need to be considered when making generalizations about the findings. The most important ones are as follow:

1) The research is conducted on a 2D frame. Thus, the effects of 3D modeling, such as irregularity, are not investigated. In addition, the study does not consider frames with the soft-story irregularity.

2) The frames are not seismically designed and detailed, and uniform sections are considered for the entire beam and columns.

Further research investigating the effects of steel cable braces may provide insight into better understanding the behavior of these elements. There is clearly much room for future research in this respect.

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