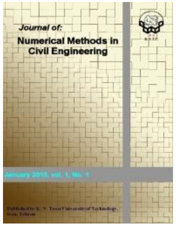
Numerical Methods in Civil Engineering, 7-4 (2023) 24-34



Numerical Methods in Civil Engineering

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

Diamond cable bracing with rings for steel structures

Ardalan B. Hussein * and Majid Barghian**

ARTICLE INFO

RESEARCH PAPER

Article history:
Received:
March 2022.
Revised:
September 2022.
Accepted:
September 2022.

Keywords:
Cable bracing system
Ring
Retrofitting
Steel frames
Cable configuration

Abstract:

This paper presents cable bracing with a new configuration so that all cables remain in tension. For this purpose, a diamond cable bracing system comprising cables and rings is proposed for steel frames. The use of cable bracing is due to its advantages, such as high tensile strength and lack of buckling in evaluation with traditional braces. The proposed method can be installed easily for existing structures. Also, the cable is lightweight, and it has delicate dimensions. Sap2000 software was used to model the cables and rings. It was found that the proposed system eliminated the main weakness of the x-shaped cable bracing system. Increasing or reducing the diameter of the cables can control the displacement. Among the studied models, MRF has the least amount of axial force applied to the beams . A large amount of axial force is added to the floor beams by adding steel cable braces to the frame. In this case, by increasing the diameter of the cables, the amount of this force can be reduced.

1. Introduction

Bracing systems play a significant role in dissipating seismic energy in steel structures. The braced frame structure requires lateral loading of tensile and compressive members. Buckling is one of the main issues in compressive members, causing a sharp decline in the drift control and ductility of structural system and its improper earthquake output. Different types of bracing have been used, such as ordinary bracing with angles or channels, BRB (Buckling Restrained Brace). Tension braces or cables were used to eliminate the issues involved with the inelastic buckling of bracing structures and utilize the initial configuration with minor changes.

In Mexico City, cable bracings were used efficiently to upgrade undamaged low to medium-rise buildings that had to be renovated for the higher strength standard required by the codes. In order to achieve an appropriate systemic response, the cable system and the current structure had to be connected. The axial loads produced by the cables needed the columns to be reinforced in several instances [1].

In 2016, S. M. Zahrai and S. A. Mousavi [2] researched on a new cable-pulley brace system to improve the story drift distribution of MRFs with large openings. Their design enabled it to brace big MRFs with broad openings. Two opposite corners of the frame were bound by the pre-tensioned cable elements using a bilinear direction that turned around the opening(s). Although the MRF would have the requisite energy dissipation, the cable braces would increase lateral stability and greatly enhance the self-centering capacity of the system. In 2016, N. Fanaie et al. [3] studied a bracing system in which a pair of cables passed through a cylinder at their point of intersection (a bracing cable system with a central cylinder). Their work focused on the seismic behavior of moment-resistant frames which were reinforced with cable-cylinder bracing. In 2017, N. Fanaie and N. Zafari [4] researched on the sensitivity analysis on the reaction adjustment factor of the new cable-cylinder crossing system. The over-strength, ductility, and reaction adjustment factors of this bracing device were measured using a two-dimensional model for the first time in current research. The outcome demonstrated that, compared with the cross-cable bracing system, the ductility of the cable-

---

* *MSc, Department of Civil Engineering, University of Tabriz, Tabriz, Iran. Email: ardalan.burhan93@gmail.com.*

** *Corresponding author: Professor, Department of Civil Engineering, University of Tabriz, Tabriz, Iran. Email: barghian@tabrizu.ac.ir.*

https://doi.org/10.52547/NMCE.2022.412

cylinder bracing system is stronger. In 2019, L. Xie et al. [5] studied cable bracing, which consisted of a pair of bracing cables, a pair of conductor plates (flywheels), and a shaft. A couple of cables were pre-tensioned, diagonally connecting the structural frame and shaft. When inter-story drift occurs in structures, one of the cables would shorten and drive the shaft into rotation. The low-speed translational movement of the system could be converted into a high-speed rotational motion of the conductor plates by cable bracing. Their new configuration had the advantages of relaxation of deformation at the joining joints, simple installation, and an adaptive structure for implementing nonconsecutive tales. The findings revealed that their system was an efficient mitigating mechanism for structural response to minimize the reaction of earthquake excitation structural systems. S. Bagheri et al. [6], in 2019, studied an energy-dissipative cable bracing device. A new frictional energy dissipation lateral load-resisting system comprising a pre-stressed cable and a drum has been proposed. An analytical approach had been developed for the force-displacement reaction of the system. The cable was pre-stressed with a force of friction, and the drum, limited from vertical rotation and acceleration, was displaced Δ in the horizontal direction due to the lateral loading of the system. The efficacy of the suggested method was tested in minimizing seismic responses of an idealized form of the building frame. In 2018, M. H. Mehrabi et al. [7] researched on X-cable braced frames packaged with a pre-compressed spring. Their research provided evidence demonstrating the efficacy of the proposed bracing system in improving structural reaction to maximum displacement and inter-story drift. Shamivand and J. Akbari [8] studied on the ring-shaped lateral bracing method for steel structures in 2019. The tensile and compression members were separated from the frames, and the circular rings were attached to them in that bracing system. During significant deformation, although the suggested bracings were not very rigid, they were very ductile, and the structure stayed intact when it was broken during a severe earthquake. The planned system consisted of a beam frame, main and secondary columns, and a ring-shaped element as a lateral bracing element. The key resisting factor against the lateral motions of the mechanism was the circular member in their system. Initially, their device displayed a bending behavior, and the behavior changed from pure bending to flexural and tensile conduct with increasing lateral deflection. In 2019, M. Naghavi [9] researched on retrofitting steel moment frames using cable bracing. With the aid of Abaqus software, finite element models were produced with moment frame only and moment frame retrofitted with cable brace passed through a cylindrical steel sheath, cross bracing with angles, and cross brace with cable. A combination of numerical analysis effects and experimental findings demonstrated the accuracy of finite element models. In 2019, S. Abhari and M. Barghian [10] investigated the behavior of a bracing cable system with a central steel plate.

This research studied a system of four cable bracings connected to a square steel plate located in their center. The theoretical behavior of the system was derived under a lateral static load. The authors demonstrated the efficiency of the system, in which all cables had tensile forces under the lateral load and were not slackened. The diameter of the cables and plate dimensions were investigated. It was observed that the variation in cable diameter significantly affected the lateral displacement of the frame. In contrast, the variety of sizes of the plate did not have much effect on the obtained values. The results showed that the proposed system had the same characteristics as the MRF for its appropriate ductility; at the same time, it had high stiffness. Adding a steel plate in the center of the bracings caused all cables to involve against the lateral load, and all cables remained in tension. Therefore, using the central steel plate improved the performance of the structure against the applied lateral load. In 2019, M. Ismail [11] presented a new elastoplastic bracing method called AR-Brace for passive structural vibration control. It consisted of five deformable elastoplastic components, which were four arcs in tangential contact with a central ring. In addition to being an excellent alternative to displacement-based and velocity-based damping mechanisms, the AR-Brace was designed to be an effective and inexpensive substitute for conventional cross-bracing mechanisms. H. Mirjalali et al. [12] studied the effect of bracing form on progressive collapse resistance of eccentrically braced frames in 2019. Results showed that the frame with two braced bays had more progressive failure resistance in specific element removal scenarios than the one with three braced bays under just gravity loads. A. Shamivand and J. Akbari [13] introduced ring-shaped lateral bracing for steel structures. The present research aims to use cable bracing with a new configuration in a way that all cables will remain in tension. For this purpose, a new cable bracing system consisting of rings and cables with a diamond arrangement shape for steel frames has been proposed for the first time. Remaining all cables in tension is the advantage of the new configuration offered. N. Fanaie et al. [3] used a cylinder in the center of a frame as a practical method. The proposed ring is similar to a cylinder with a small height, and it is attached to beams or columns rather than in the center of the frame. Therefore, the authors believe that it is a practical method.

2. Comparing moment resistant frames with angle and cable braced frames

For a case study, a 2D steel frame consisting of two floors with a height of 3 m for each floor and a width of 5 m was considered. In this frame, Europe Sections were used. All beams consisted of IPE 140; all columns consisted of IPE 160, and steel bracings consisted of L30×6.

Since the model had already been modeled in the references [10,14,15], this example was chosen. The authors used the same frame in this research to compare the results of the mentioned reference. Almost equal sectional areas were chosen for both angle and cable sections to compare the results of the angle section bracing with the cable bracing. The points marked with letters A to D (Figure 1) are the points where the cables are connected. The Points marked with the letter E are the applied load locations. The displacement will be considered at joint F. The diameter of the cables was chosen as 2 cm. The cables were pre-tensioned. Pre-tensioning force amount was selected between its limits, according to the relation given by M. Barghian and G. Zamani Ahari [16]. i.e.,

$$ {wl^2}/{8f} < cable\ pre-tensioning\ force < 0.45 f_{y,cable} \quad (1) $$

where, w, *l*, f, and $f_{y,cable}$ are the cable weight per unit length, cable length, the vertical deflection of cable, and the yield stress of cable, respectively.

First, a moment-resistant frame (MRF) - similar to the frame shown in Figure 1 without bracing - was analyzed by both ETABS and SAP2000 programs to compare the results. The self-weight of the frame members was considered a dead load. Geometric non-linearity was considered, and material non-linearity was ignored. This was done by selecting the "Non-linear plus large displacement" option for the cable bracing model and by selecting the "Non-linear" option based on SAP manual. Equal horizontal loads were applied as lateral loads at joints E. A target displacement of 0.01h was assumed for the joint F, where h is the total height of the frame. Equal lateral loads were chosen by trial and error to reach a target displacement of 60 mm at joint F, i.e., 0.01h.

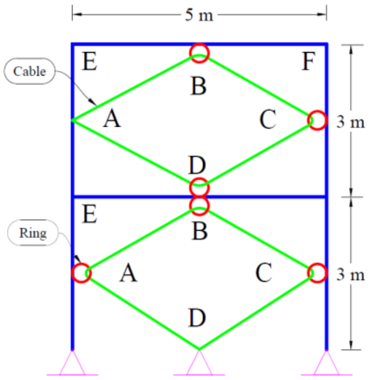


Fig. 1: A 2D frame with cables and rings -the proposed diamond cable bracing in this research

Both lateral forces causing the target displacement were found to be 3.28083 kN. Both programs found displacements in the x and z directions to be 60 mm and -0.0584 mm for joint F, respectively. Next, X-shaped angles were added as a bracing system (Figure 2). The same loads of (3.28083 kN) were applied at joins E. The displacement at joint F was 0.6379 mm in the x-direction. For all cases below, the loads of (3.28083 kN) were applied at joins E.

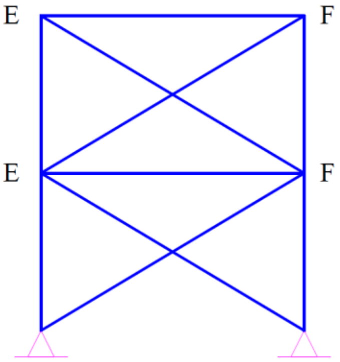


Fig. 2: Steel angle bracing (X - shaped bracing)

Then, X-shaped angle bracings were replaced by cables. Displacement results are compared and shown in Table 1. Next, Λ-shaped angle bracing was added (Figure 3). Figure 4 shows the axial forces of the Λ-shaped angle bracing. In each story, the Λ-shaped angle consists of two members. As seen in Figure 4, one member is in tension while the other is in compression. A designer should design them for tension and compression. However, when two cables are in tension, they withstand the lateral force in the cable bracing. Therefore, there is no need to design them for compression. Thereafter, Λ-shaped cables were added as a bracing system (Figure 5). Since both cables have been pre-tensioned, they are in tension. If the pre-stressing force is not enough, then one of the pair cables may be slacked. Figure 6 shows the axial forces of cables. However, the values of adjacent cables are not identical. This is because/Since the cables are not continuous. They have only been attached to the center of each beam. This kind of bracing is better than angle bracing; however, it will be ideal if the axial forces in adjacent cables are equal or close.

Table 1: Displacement of joint F according to Lateral Force (L.F.)

Types of bracing	Max. horizontal displacement [mm]
Unbraced (MRF)	60.00013
Angle racing	0.63792
Cable Bracing	0.11745

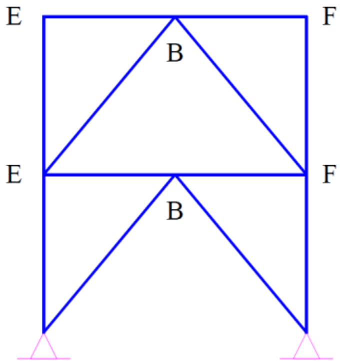


Fig. 3: Λ - shaped angle bracing

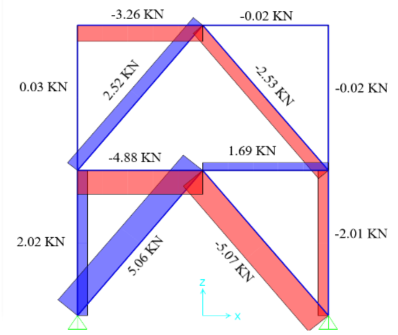


Fig. 4: Axial forces of the Λ-shaped angle bracing

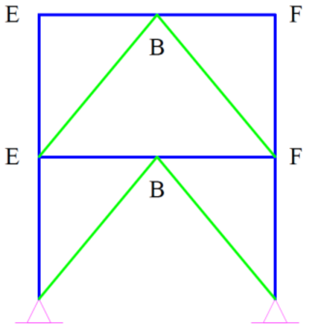


Fig. 5: Λ - shaped cable bracing

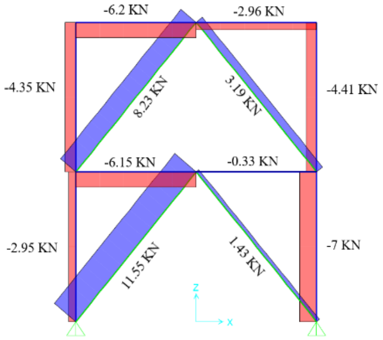


Fig. 6: Axial forces of the Λ - shaped cable bracing

Then, Λ-shaped cables were added as a bracing system. Two cables were connected with the frame at two joints on the first and second floors. The adjacent cables were connected, and at the connection point, they passed through a steel ring (Figure 7). All cables were in tension (Figure 8). The axial force at both cables was very close to each other.

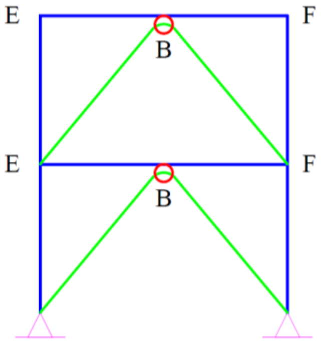


Fig. 7: Λ - shaped cable bracing

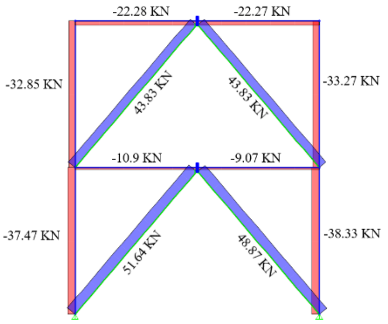


Fig. 8: Axial forces of Λ - shaped cable bracing

A diamond bracing was used for the first and second floors of the frame. For this purpose, four angles were placed for each floor, each of these angles is connected by a beam through one joint, and also, by a column through the other joint (Figure 9). In this case, half of the angle bracings were in tension while the other half were in compression (Figure 10).

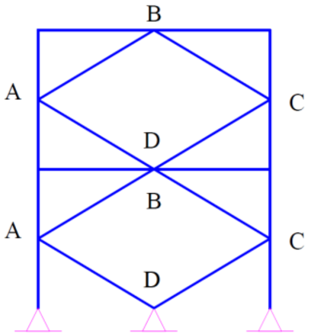


Fig. 9: Diamond-shaped angle bracing

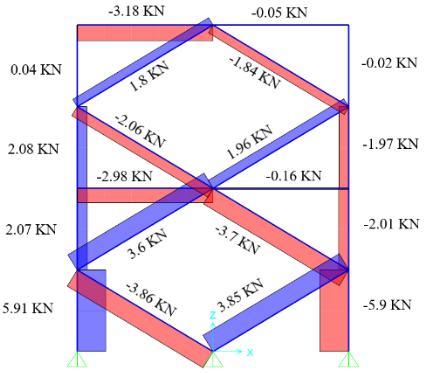


Fig. 10: Diamond-shaped angle bracing axial forces

Diamond bracing with four cables was used for both the first and second floors of the frame (Figure 11). In this case, all of the cables were in tension (Figure 12). Details of the modeling of the cable and ring in SAP2000 are shown in Figure 13. The cable is connected to the ring by link elements to allow the movement of the cable separately (Figure 13 (a) and (b)). Inside the ring, three rods were added to prevent deformation of the ring. Figure 13 (c) shows the detail and location of rings and cables. The movement of the cable passing the ring has been done using links between the cable and the ring.

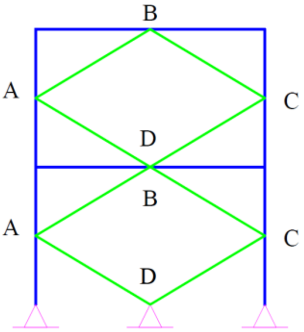


Fig. 11: Diamond cable bracing

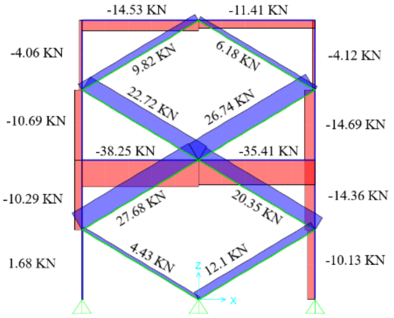


Fig. 12: Diamond cable bracing axial forces

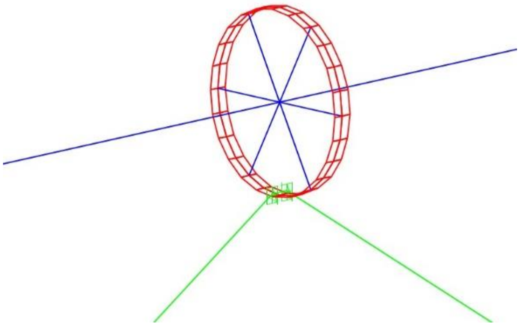
Table 2: Displacement of joint F in x-direction subjected to Lateral Force (L. F.)

Types of bracing	Horizontal displacement [mm]
Λ-shaped angle	0.7515
Λ-shaped cable	0.7356
Λ-shaped cable with a ring	6.8800
diamond-shaped angle bracing	0.6608
diamond cable bracing	0.59331

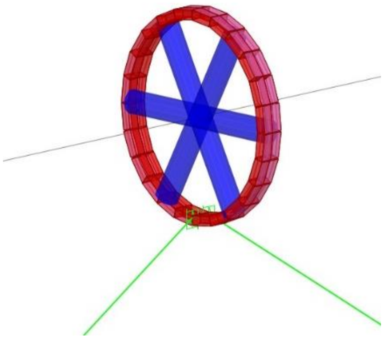
In the model, links were added between the ring and cable, as shown in Figure 14.

3. Analyzing frames with diamond bracings with different patterns of rings and cables

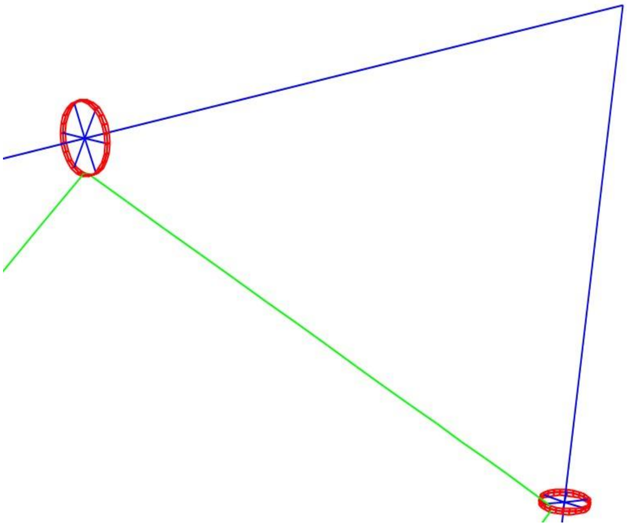
Different frames with diamond bracings having different patterns of rings and cables were analyzed to determine which one is more appropriate, as shown in Figure 15 by numbers (1) to (14), respectively, and their axial forces are shown in Figure 15. The red circles in the following pictures are rings and cables that pass through the shown rings without discontinuity. It was realized that all cables were in tension for all frames in Figure 16. The displacements at joint F are given in Table 3. Considering that, in this Table, two of the values are negative, it can be interpreted that there is tension in the cable.



(a)



(b)



(c)

Fig. 13: Details of the modeling of the cable and ring

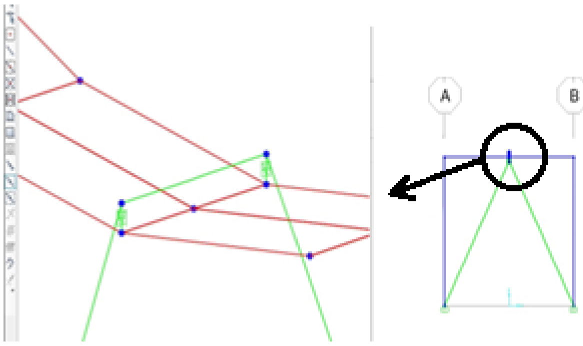
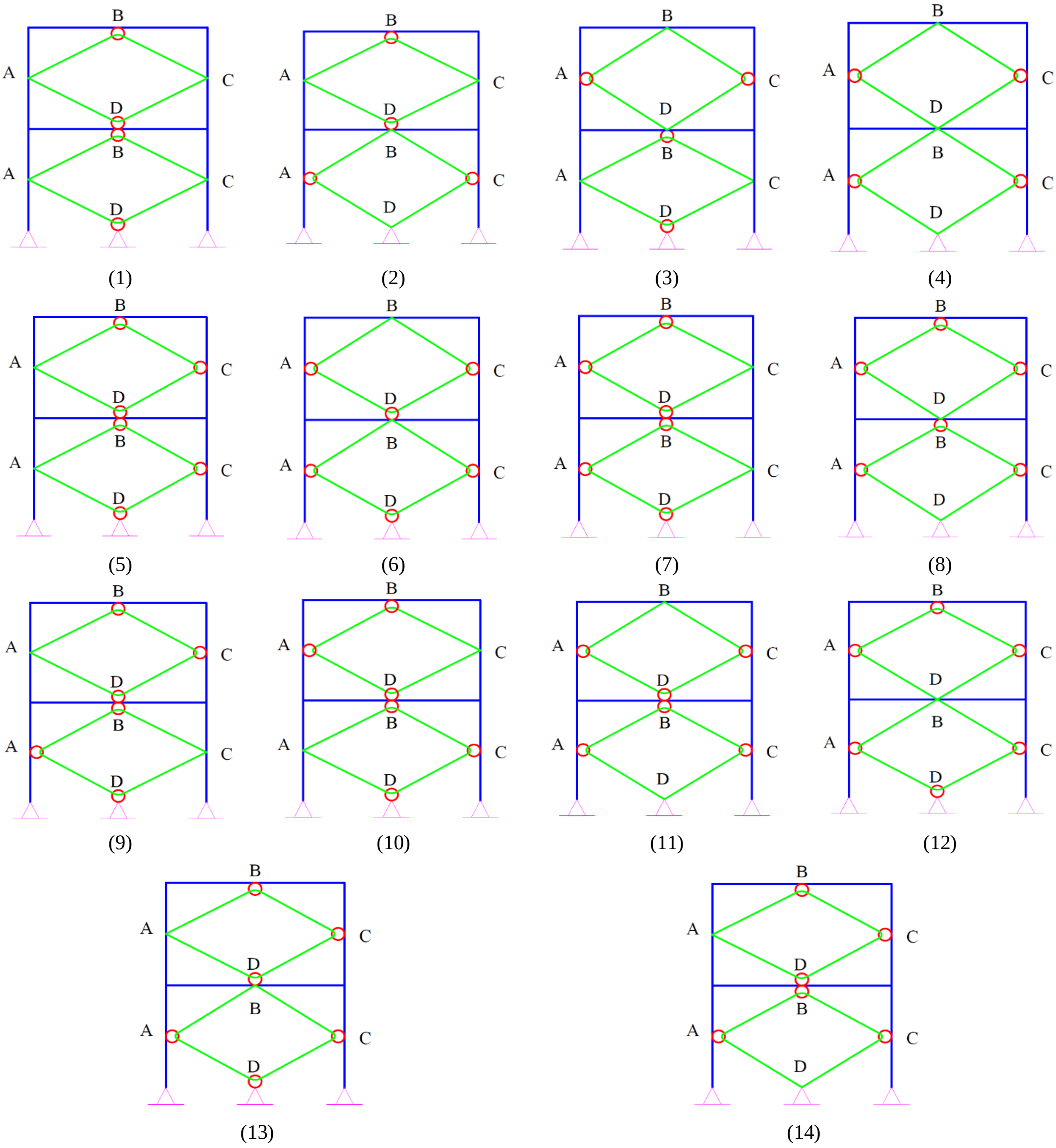


Fig. 14: The links between the ring and cable

It has a horizontal component toward the left-hand side, which is the result of bending the beam above the bracing; hence, it is the result of the negative value.

It is worth mentioning that when cable bracing is continuous, a ring is used to connect it to a beam or column. If the cable bracing is not continuous in its connection to a beam or a column, a ring is not used. Based on the results, frame number 14 was chosen as appropriate. Then frame number 14 was subjected to three earthquakes: a) Kobe (Japan) earthquake, 1995, recording station: Kobe University

b) Northridge (USA) earthquake. 1994, recording station: Alhambra - Fremont School



(1) (2) (3) (4)

(5) (6) (7) (8)

(9) (10) (11) (12)

(13) (14)

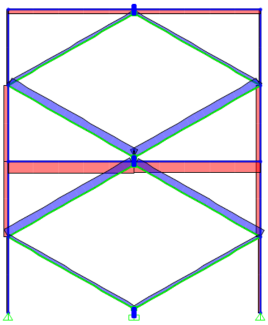
Fig. 15: Frames with different arrangements of cables and rings

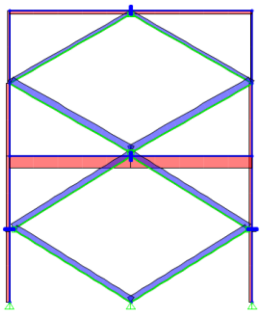
c) The Imperial Valley (USA) earthquake 1979, recording station: El Centro Array #9

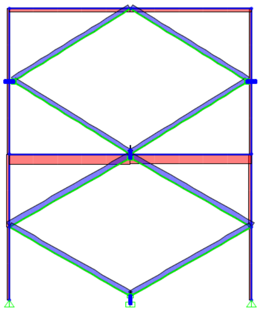
Appendix 1 gives the detail of the used records.

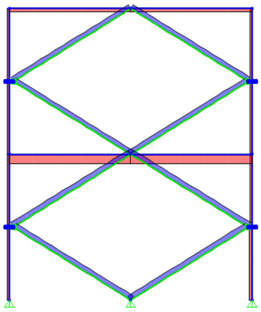
Table 3: Displacements of frames at joint F

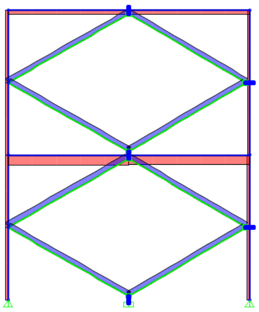
Frame number	in x-direction [mm]
(1)	12.0381
(2)	1.8862
(3)	3.5449
(4)	13.5347
(5)	-0.7550
(6)	2.0053
(7)	26.2480
(8)	12.6011
(9)	11.6437
(10)	-10.1188
(11)	3.1900
(12)	2.7569
(13)	14.2568
(14)	0.7116

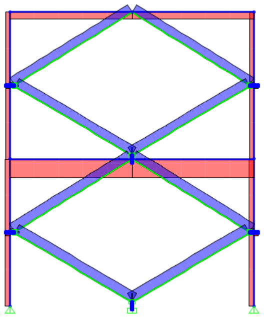

(1)

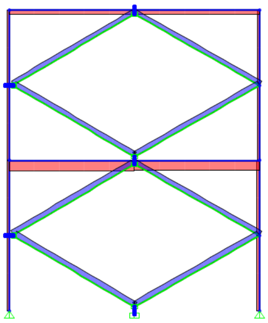

(2)

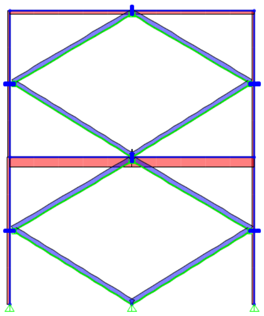

(3)

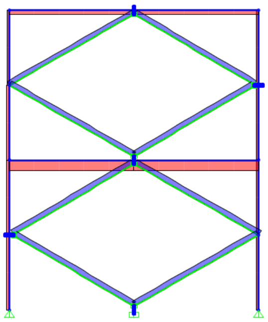

(4)

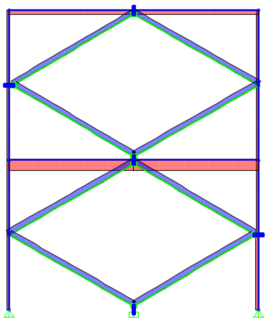

(5)

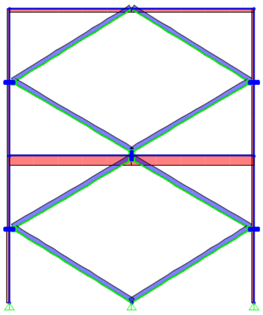

(6)

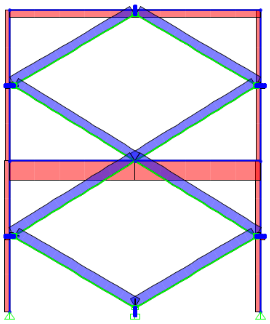

(7)


(8)


(9)


(10)


(11)


(12)


(13) (14)

Fig. 16: Axial forces of frames (related to frames in Fig. 14)

The results of the chosen frame were compared with MRF results. A damping ratio of 0.05 was considered for the frame. The results of the selected frame were compared with MRF results. The SAP2000 program is can calculate and plot the response spectrum. This capability was used.

3.1 Results of the Kobe earthquake

The response spectrum for the MRF is shown in Figure 17. The response spectrum for the diamond cable braced frame is shown in Figure 18. When the earthquake was considered as a time history type, the max horizontal displacement in the unbraced frame (MRF) was 155.377 mm, so that the frame vibrated several times between 155.377 mm and -122.080 mm and moved to the right and left in a harmonic vibration. The frame had high frequency, high wave height, and low wavelength (Figure 19). However, the max horizontal displacement in diamond cable bracing was -2.383 mm. The displacement of the frame moved between -2.383 mm and 0.102 mm. The frame had low frequency, low wave height, and high wavelength (Figure 20).

3.2 Results of the Northridge earthquake

The response spectrum for the MRF is shown in Figure 21. The response spectrum for the diamond cable braced frame is shown in Figure 22. When the earthquake was considered as a time history type, the max horizontal displacement in the unbraced frame (MRF) was 5.440 mm, so that the frame vibrated several times between 5.440 mm and -5.419 mm and moved to the right and left in a harmonic vibration. The frame had high frequency, high wave height, and low wavelength (Figure 23). However, the max horizontal displacement in diamond cable bracing was -2.271 mm. The displacement of the frame moved between -2.271 mm and 0.210 mm. The frame had low frequency, low wave height, and high wavelength (Figure 24).

3.3 Results of the Imperial Valley earthquake

The response spectrum for the MRF is shown in Figure 25. The response spectrum for the diamond cable braced frame is shown in Figure 26. When the earthquake was considered as a time history type, the max horizontal displacement in the unbraced frame (MRF) was -106.226 mm, so that the frame vibrated several times between -106.226 mm and 70.411 mm and moved to the right and left in a harmonic vibration. The frame had high frequency, high wave height, and low wavelength (Figure 27). However, the max horizontal displacement in diamond cable bracing was -2.274 mm. The displacement of the frame moved between -2.274 mm to 0.206 mm. The frame had low frequency, low wave height, and high wavelength (Figure 28).

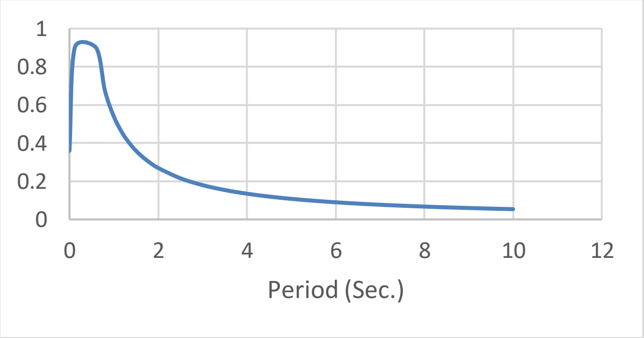


Fig. 17: Response spectrum of MRF

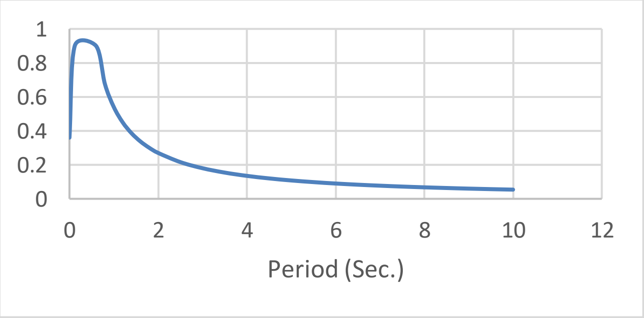


Fig. 18: Response spectrum of diamond cable bracing frame

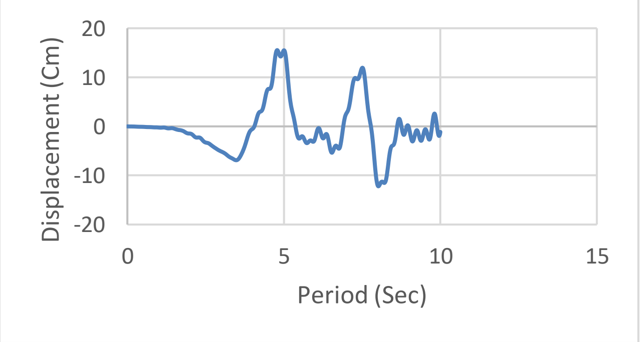


Fig. 19: Time history of MRF

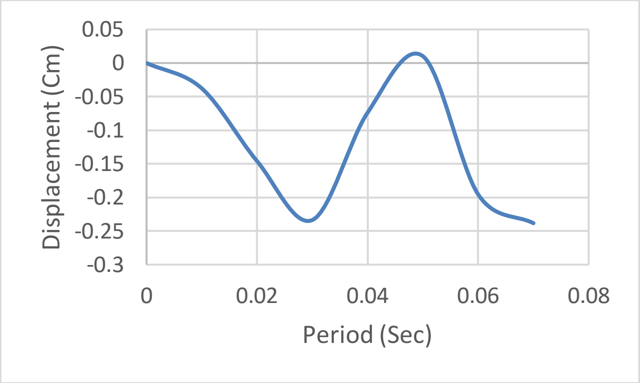


Fig. 20: Time history of diamond cable bracing frame

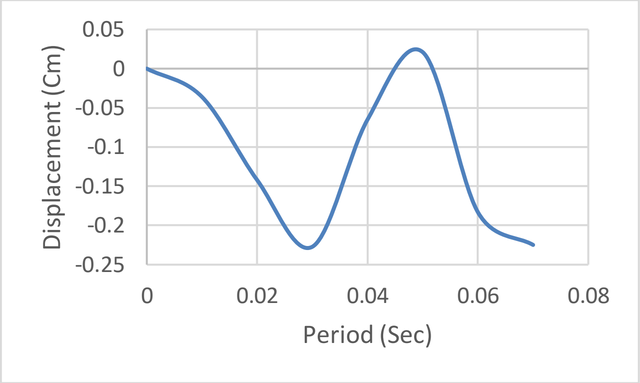


Fig. 24: Time history of diamond cable bracing frame

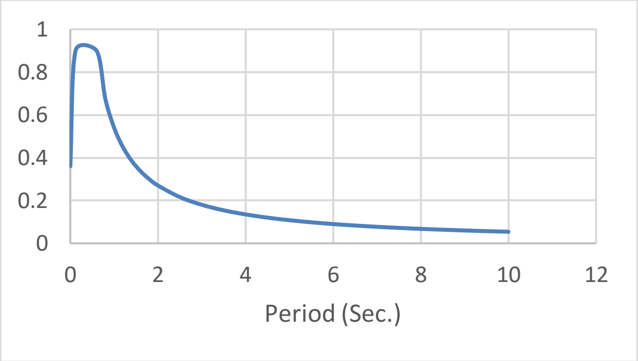


Fig. 21: Response spectrum of MRF

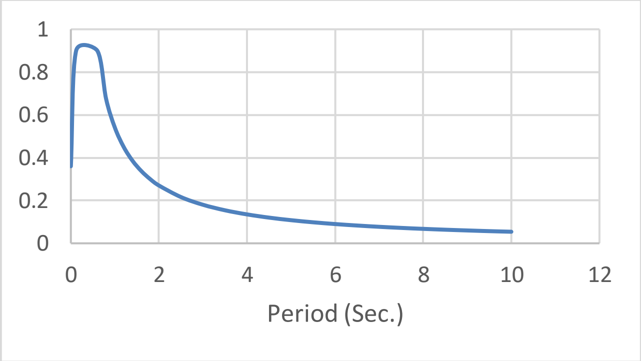


Fig. 25: Response spectrum of MRF

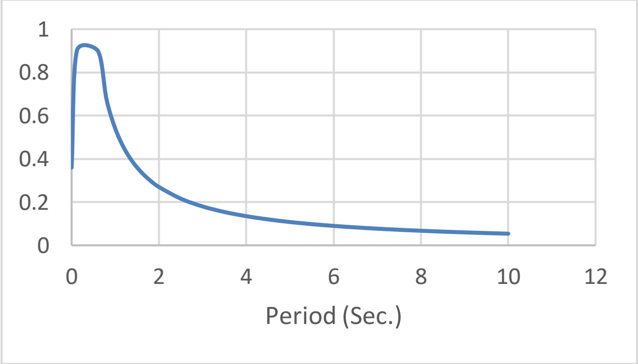


Fig. 22: Response spectrum of diamond cable bracing frame

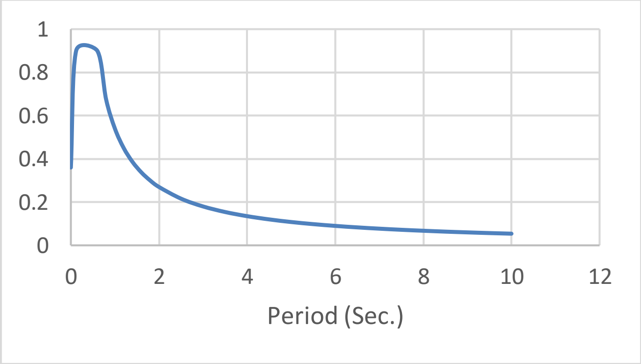


Fig. 26: Response spectrum of diamond cable bracing frame

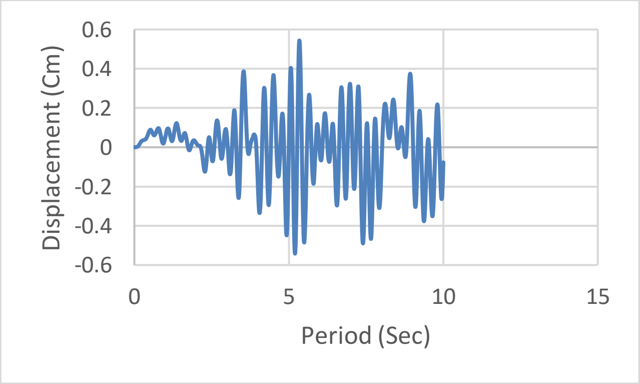


Fig. 23: Time history of MRF

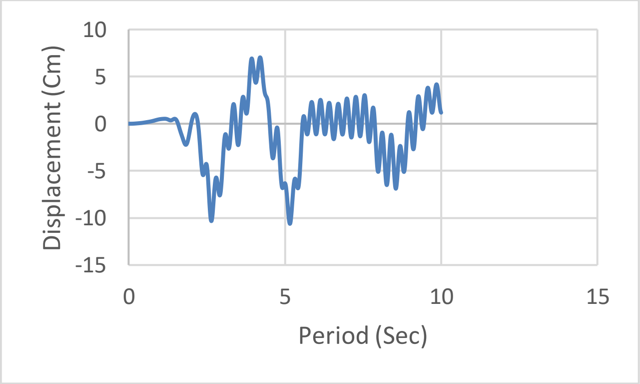


Fig. 27: Time history of MRF

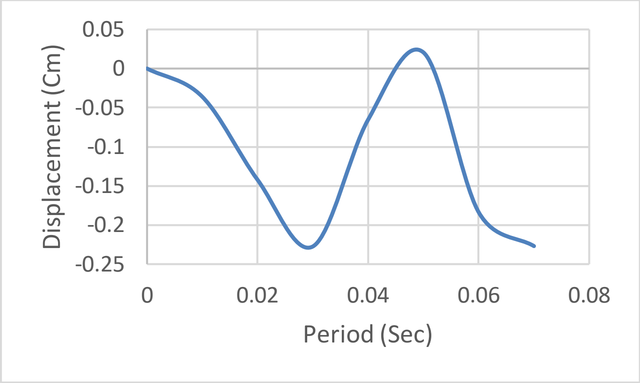


Fig. 28: Time history of diamond cable bracing frame

4. Conclusion

Considering a two-story one-bay portal frame and proposing a new idea for a diamond cable bracing with rings, the following results were obtained:

This system eliminates the main weakness of the x-shaped cable bracing system. Also, good ductility and reducing the base shear and axial force of the columns, which leads to a reduction in consumables and dimensions of the frame members, are the advantages of this type of brace. Furthermore, the ability to install for existing structures, easy installation and repair, and lightweight and delicate dimensions are the features of this bracing, which makes its use in the field of reinforcement significant. In MRF, there is the most displacement compared to braced frames. The displacement can be significantly reduced using the steel structure system. Increasing or decreasing the diameter of the cables can control the amount of displacement. MRF has a minor axial force applied to the beams among the studied models. A large amount of axial force is added to the floor beams by applying steel cable braces to the frame. Using the proposed system for steel structures is relatively low cost. Moreover, it improves structural performance against the applied lateral loads applied.

References

[1] S. T. Wasti and G. Ozcebe, *"Advances in Earthquake Engineering for Urban Risk Reduction"*, Springer, 66, 552 p., (2006).

[2] S. M. Zahrai and S. A. Mousavi, *"Cable-Pulley brace to improve story drift distribution of MRFs with large openings"*, Steel Compos. Struct., 21(4), pp. 863–882, (2016), doi: 10.12989/scs.2016.21.4.863.

[3] N. Fanaie and N. Zafari, *"Seismic study of cable-cylinder bracing under near field records"* 7th national and 2nd international conference of Steel and Structure, February, p. 13, (2017).

[4] N. Fanaie and N. Zafari, *"Sensitivity Analysis on Response Modification Factor of New Cable-Cylinder Bracing Systems*", J. Earthq. Eng., 23(4), pp. 648–668, (2019), doi: 10.1080/13632469.2017.1326419.

[5] L. Xie, X. Ban, S. Xue, K. Ikago, J. Kang, and H. Tang, *"Theoretical study on a cable-bracing inerter system for seismic mitigation"*, Appl. Sci., 9(19), pp. 1–17, (2019), doi: 10.3390/app9194096.

[6] S. Bagheri, S. S. Shishvan, M. Barghian, and B. Baniahmad, *"A new energy dissipative cable bracing system,"* Adv. Struct. Eng., 22(14), pp. 3134–3146, (2019), doi: 10.11**[6]** 77/1369433219858726.

[7] M. H. Mehrabi, Z. Ibrahim, S. S. Ghodsi, and M. Suhatril, *"Seismic characteristics of X-cable braced frames bundled with a pre-compressed spring"*, Soil Dyn. Earthq. Eng., 116, November, pp. 732–746, (2019), doi: 10.1016/j.soildyn.2018.10.014.

[8] A. Shamivand and J. Akbari, *"Ring-Shaped Lateral Bracing System for Steel Structures"*, Int. J. Steel Struct., 20(2), pp. 493–503, (2020), doi: 10.1007/s13296-019-00299-z.

[9] M. Naghavi, *"Retrofitting steel moment frames by using the cable bracing"*, J. Build. Mater. Sci., 1(1), pp. 10–17, (2019), doi: 10.30564/jbmr. v1i1.786.

[10] S. Abhari, M. Barghian, *"Theoretical Assessment of the Behavior of a Cable Bracing System with a Central Steel Plate"*, AUT Journal of Civil Engineering, 3(1), pp. 37-48, (2019), DOI: 10.22060/ajce.2018.15249.5527.

[11] M. Ismail, *"An elastoplastic bracing system for structural vibration control"*, Eng. Struct., 200(1), pp. 1-17, (2019), doi: 10.1016/j.engstruct.2019.109671.

[12] H. Mirjalali, M. Ghasemi, and M. S. Labbafzadeh, *"Effect of Bracing Type and Topology on Progressive Collapse Resistance of Eccentrically Braced Frames"*, Int. J. Steel Struct., 19(5), pp. 1–14, (2019), doi: 10.1007/s13296-019-00225-3.

[13] A. Shamivand and J. Akbari, *"Ring-shaped lateral bracing system for steel structures",* Int. J. Steel Struct., 20(2), pp. 493–503, (2020), doi: 10.1007/s13296-019-00299-z.

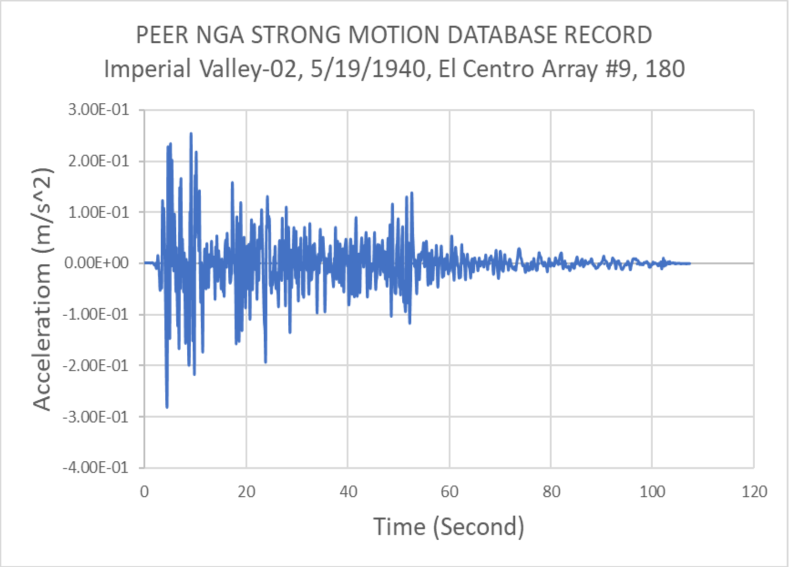
[14] M. Najafi and M. Barghian, *"Proposing a new cable bracing to retrofit steel* frames", Sharif Civil Eng., 30-2(4.1), pp. 121–127, (2014), [in Persian].

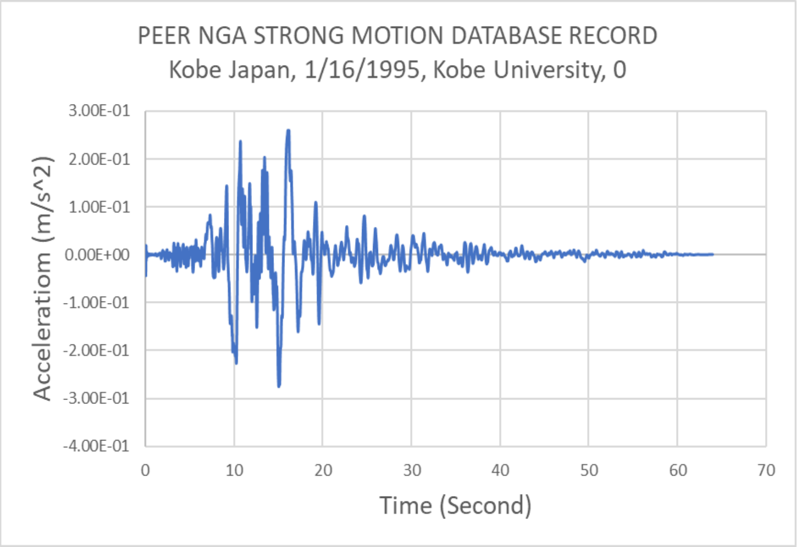
[15] K. Khorraminia, *"Investigation of cable bearing to retrofit steel moment resistant frames with continuous or discontinued cable connection"*, MSc. dissertation, Islamic Azad University

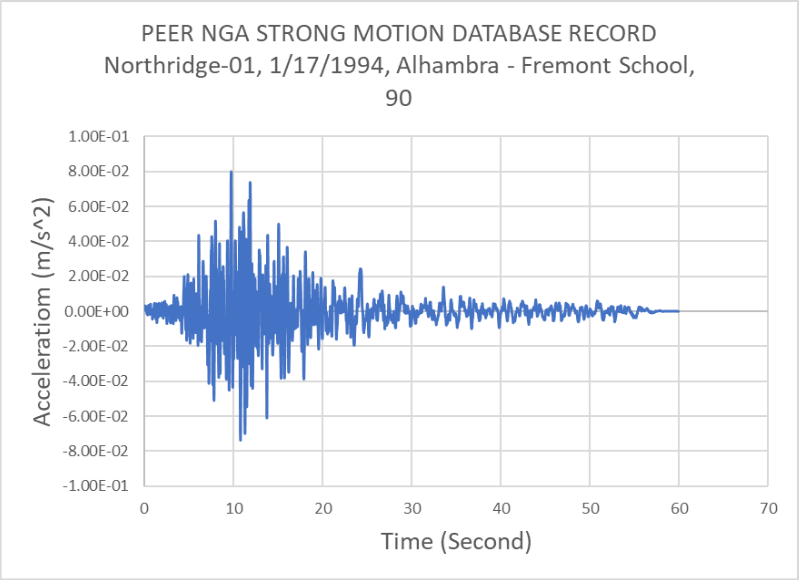
Ahar Branch, (2015).

[16] M. Barghian and G. Zamani Ahari, *"The theory of suspension bridges",* Ahar Azad University Publication, 221 p., (2005).

Appendix 1


PEER NGA STRONG MOTION DATABASE RECORD
Imperial Valley-02, 5/19/1940, El Centro Array #9, 180
Acceleratiom (m/s^2)
3.00E-01
2.00E-01
1.00E-01
0.00E+00
-1.00E-01
-2.00E-01
-3.00E-01
-4.00E-01
0
20
40
60
80
100
120
Time (Second)


PEER NGA STRONG MOTION DATABASE RECORD
Kobe Japan, 1/16/1995, Kobe University, 0
Acceleratiom (m/s^2)
3.00E-01
2.00E-01
1.00E-01
0.00E+00
-1.00E-01
-2.00E-01
-3.00E-01
-4.00E-01
0
10
20
30
40
50
60
70
Time (Second)


PEER NGA STRONG MOTION DATABASE RECORD
Northridge-01, 1/17/1994, Alhambra - Fremont School, 90
Acceleratiom (m/s^2)
1.00E-01
8.00E-02
6.00E-02
4.00E-02
2.00E-02
0.00E+00
-2.00E-02
-4.00E-02
-6.00E-02
-8.00E-02
-1.00E-01
0
10
20
30
40
50
60
70
Time (Second)