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Strengthening of moment-resisting frame using cable–cylinder bracing

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Abstract

Cable–cylinder bracing (cable bracing system with central cylinder) is one of the modern bracing systems in which a pair of cables passes through a cylinder at their point of intersection. This research focuses on the seismic behaviour of moment-resisting frames which have been strengthened using cable–cylinder bracing. For this purpose, steel moment-resisting frames, with different numbers of storeys, were strengthened with two different types of cable bracing: cable cross-bracing and cable–cylinder bracing, and their seismic performances were compared. After performing verification, the original moment-resisting frames and those strengthened with cable–cylinder bracings and cable cross-bracings were subjected to the scaled records of six well-known earthquakes. The hysteresis, drift distribution and column axial force variation curves were plotted for the storeys at the height of the strengthened frames and compared to those of moment-resisting frames. Moreover, the energy dissipation values were also derived from the mentioned records. Based on the obtained results, the moment-resisting frames strengthened with cable–cylinder bracings performed much better compared to those strengthened by cable cross-bracing.

Keywords

cable cross-bracing, cable–cylinder bracing, drift, moment-resisting frame, strengthening

Introduction

Strengthening or upgrading may be defined as improving the performance level of an existing structural member. This is particularly significant considering the critical facilities (such as hospitals) that should remain operational even after the occurrence of earthquakes. As such, the concern is not only on structural damage but also on controlling the seismic drifts and floor accelerations. One important aspect, especially for the buildings of moderate heights (over 15 storeys), is the development of P–δ effects that may lead to large residual displacements in the earthquakes (Bruneau and Bhagwagar, 2002). One or more upgrading methods may be used to meet improved performance levels. These methods are as follows: refined calculation methods, strengthening, improved durability and aesthetic appearance. The performance level can also be increased by replacing the existing member with a new one. Different methods are used for strengthening of structures (Nordin, 2005). Adding braces or shear walls to an existing structure is a retrofit approach normally used by engineers to mitigate the problem of excessive drifts in steel frames during earthquakes (Bruneau and Bhagwagar, 2002). Bracing systems can increase the stiffness and strength of storeys. Some researchers have assessed the application of braces for retrofitting and upgrading the existing building frames (Bartera and Giacchetti, 2004; Sarno, 2006). Moreover, many researches have been conducted to evaluate the effectiveness of different added damping systems in reducing the seismic response of buildings (Aiken et al., 1993; Hanson, 1993; Kurata et al., 2012; Soong and Dargush, 1997; Sorace and Terenzi, 2012).

In recent years, researchers have been motivated to study the application of cables in buildings through different approaches with respect to their advantages. Several researchers have focused on applying the cables in tall buildings for controlling frame lateral displacement (Saleem and Saleem, 2010). Some others have been concerned about applying the cables instead of shear reinforcement in reinforced concrete beams (Keun-Hyeok et al., 2011). Cables are used as bracings with the advantages of flexibility, high capacity in supporting tensional forces, simple design and fast and

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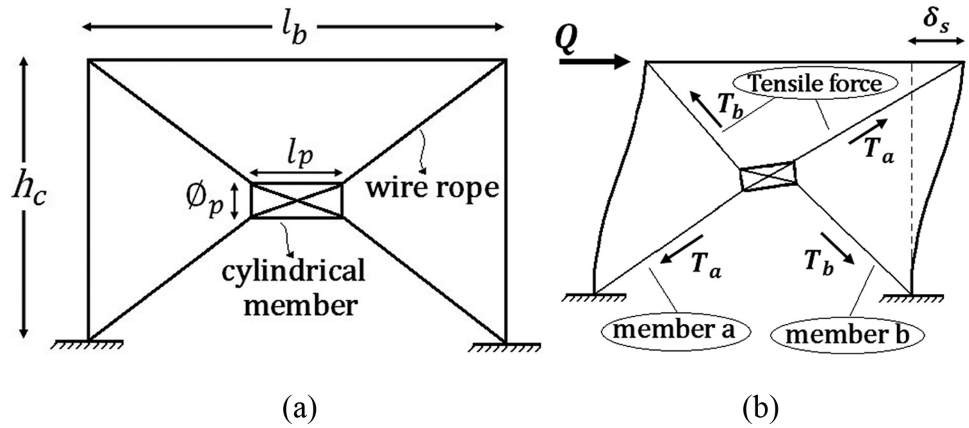

Figure 1. Cable bracing system with central cylinder: (a) dimensions and (b) deformation at δ_s.

easy construction and installation. They do not need heavy devices for installation and they make the least noise during installation (Kurata et al., 2012).

Cable bracing system with central cylinder (called cable–cylinder bracing) is one of the modern bracing systems in which a pair of cables passes through the cylinder at their point of intersection. In such systems, the cables and cylinder are used in such a way that the cables meet their final strengths at higher lateral displacements of the frame and therefore cover their ductility defects. Cylinder dimensions are effective parameters in the behaviour of cylinder–cable bracing. These dimensions should be selected in such a way to make the cable crooked. The application of a high-stiffness cylindrical member to a cable bundler induced an early strain increase in the bracing members, see Figure 1 (Hou and Tagawa, 2009). Hou and Tagawa (2009) used this bracing system for seismic retrofitting of steel moment frames. They believed that this retrofitting method can increase the lateral strength of storeys without reducing the moment frame ductility. Moreover, the storey drift is kept within a specified range.

The behaviour of cable–cylinder bracing system depends on the dimensions of the cylinder, the axial rigidity and prestressing of the cables. The theoretical behaviour of this system has been studied in the case of using soft cylinder (Fanaie et al., 2012). The behaviour of the mentioned system has also been assessed along with the effect of cylinder dimensions and prestressing of cables in the case of using a stiff cylinder such as steel cylinder by the authors and presented in Fanaie et al. (2016). As mentioned, some previous relevant studies focused on the advantages of such systems and others on the effect of cylinder characteristics. Ordinarily, cross cables are used for strengthening the moment-resisting frames (MRFs). So far, nothing has been found in the literature about using cable–cylinder bracing system for strengthening existing MRFs and comparing its effects on the seismic performance of MRFs to that of cross cables. The aim of this study is as follows: (1) to strengthen steel MRF with cable–cylinder bracing considering two-, four- and six-storey frames, (2) to also use the conventional cable bracing (i.e. cross-cable bracing) to strengthen MRFs and (3) to compare the results obtained from frames strengthened with cross-cable bracing to those frames strengthened with cable–cylinder bracing.

Nonlinear finite element modelling of the studied frames

In this research, the already existing two-, four- and six-storey (previously designed) MRFs were used. The geometry of the studied frames is shown in Figure 2. The considered frames were designed according to AISC360-05/IBC2006 code. All studied frames are located on a seismic site in Tehran. Dead and live loads of 6 and 2 kN/m^2, respectively, were applied to all storeys. The equivalent lateral force procedure, represented in ASCE7-10, was considered in order to estimate seismic design loads. A horizontal rigid diaphragm was supposed for all storeys. All load combinations of Load and Resistance Factor Design (LRFD) are considered according to ASCE7-10.

To perform nonlinear time history analysis, one derived frame of each structure (B-axis frame of Figure 2(a)) was modelled two-dimensionally in the well-known commercial finite element (FE) software package, ABAQUS. The reasons for this simplification (i.e. two-dimensional (2D) modelling) are as follows:

1. Reducing the analysis time of structure, considering the numerous numbers of analyses as well

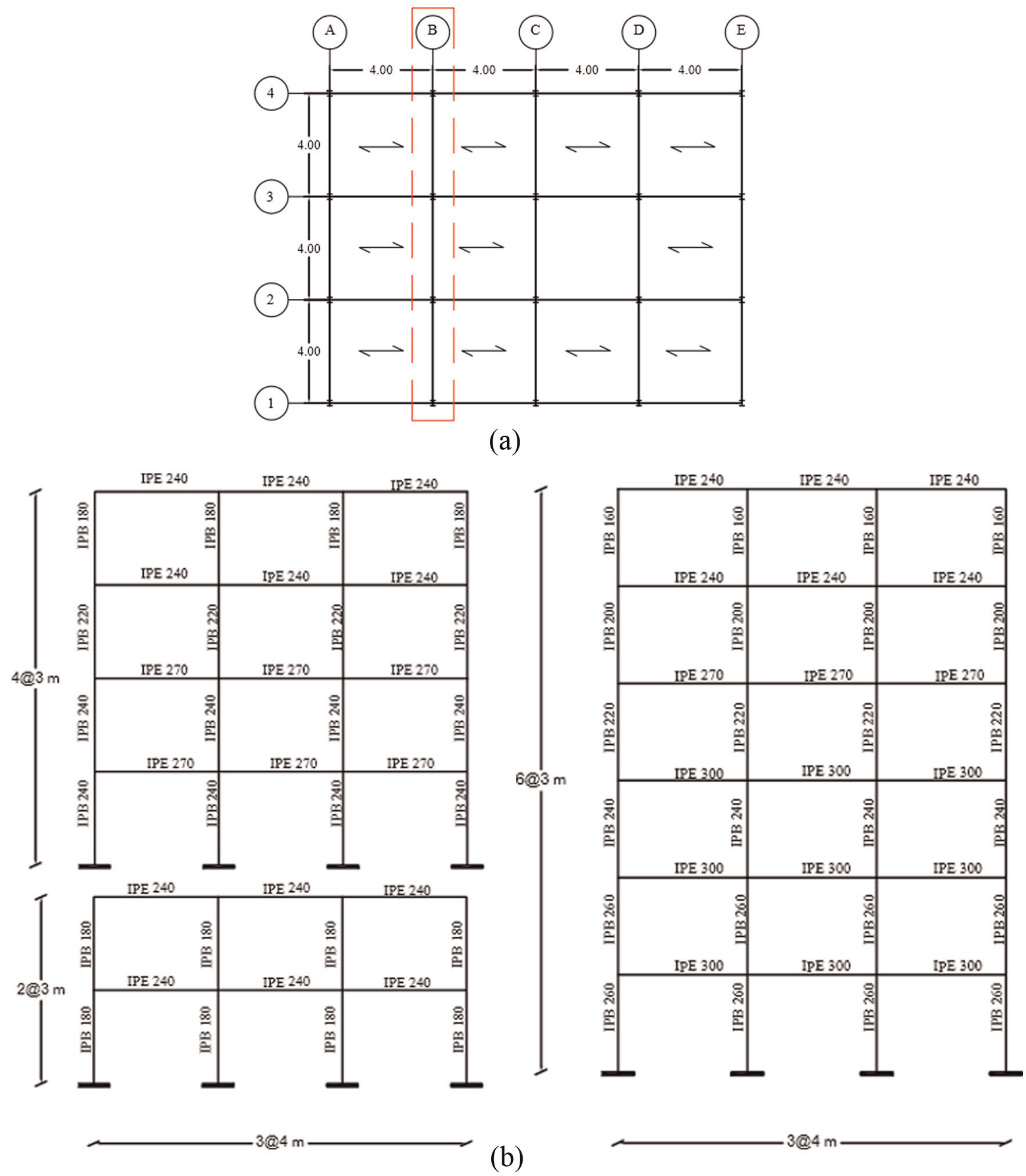

Figure 2. (a) Plan of two-, four- and six-storey MRFs and (b) geometry of extracted two-dimensional frames.

as time-consuming nature of nonlinear dynamic analysis.

2. Reducing the volume of the structure to ensure more accurate assessment and comparison.

The frame located in B-axis was derived from each tri-dimensional building and modelled in the ABAQUS software. In order to accelerate the analysis time and simplify the model, the members were modelled in the form of wire with beam element for beam and column, and truss element for cable. The material of the beam and column was considered in the software as nonlinear (elastoplastic) and that of cable as linear (elastic). In order to better illustrate the behaviour of cable–cylinder bracing, the existing two-, four- and six-storey MRFs were strengthened once with cable cross-bracing and then with cable–cylinder bracing.

The mentioned frames were subjected to the records of Bam, Cobe, Loma Prieta, Morgan Hill, Northridge

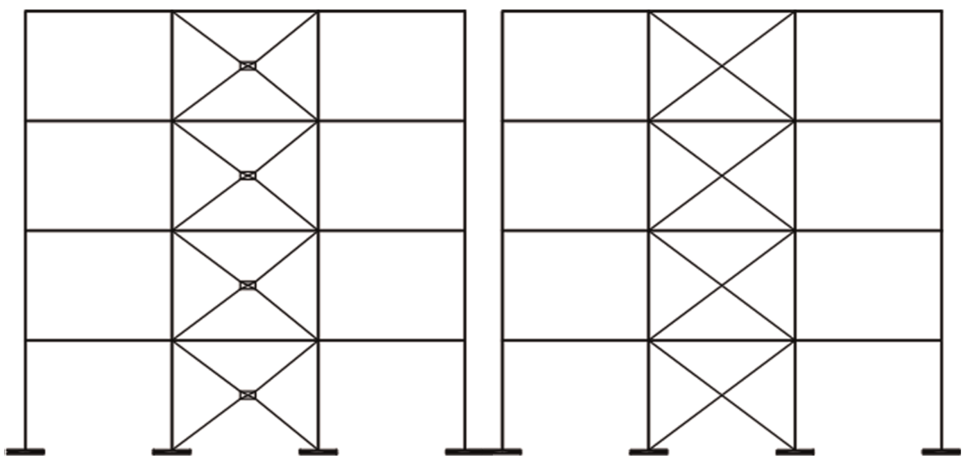

Figure 3. Studied structural strengthening systems: (a) cable–cylinder bracing and (b) cable cross bracing.

Table 1. Cross-sectional areas of bracing cables.

Storey numbers	Two	Four	Six
Cable cross-sectional area (cm^2)	5.9	6.5	7

and Parkfield earthquakes. The obtained results were compared to each other. It should be mentioned that the accelerograms were scaled at one time with peak ground acceleration (PGA) = 0.35g and then with PGA = 0.50g. Figure 3 presents the four-storey models. The accelerograms used in analyses are presented in Figure 4.

The cross-sectional areas of cables were calculated in the frames with cable cross-bracing in such a way for them to remain elastic under accelerograms with PGA = 0.50g. The cross-sectional areas of cables in the frames with cable–cylinder bracings were considered equal to those of cable cross-bracing. Table 1 presents the cross-sectional areas of the bracing cables.

It is of crucial importance in the modelling to determine appropriately the dimensions of the cylinder. When one of the cables is straightened, the frame lateral displacement is called δ_s. For frame lateral displacement greater than δ_s, one cable does not work anymore. If the displacement is towards the right, the force will be 0 in the left cable at the displacement δ_s where the right cable is straightened. The cylinder dimensions should be selected in such a way that first, δ_s is equal to or slightly higher than the displacement of the frame's damage limit in order to ensure that both cables are under tension. Second, the cable reaches its final strength at the frame's damage limit displacement for optimal use of cable strength and frame ductility. According to Figure 7, δ_s is where that strain of left cable becomes 0. Its value is about 73 mm for the theoretical relations.

In this research, bilinear stress–strain envelope is considered to have a yielding stress of 240 MPa, regarding the building steel of ST-37, and post yielding branch slope of 2% of elastic modulus (0.02 E) in order to consider the strain hardening of steel. The density of steel was taken as 7800 kg/m^3. Rayleigh damping was used in the dynamic analyses. On this basis, there will be

$$C = \alpha M + \beta K \tag{1}$$

where C is the damping of the system; K and M are the matrices of stiffness and mass, respectively. The coefficients α and β are obtained by equations (2) and (3), respectively

$$\alpha = \xi \frac{2\omega_1\omega_2}{\omega_1 + \omega_2} \tag{2}$$

$$\beta = \xi \frac{2}{\omega_1 + \omega_2} \tag{3}$$

where ω_1 and ω_2 are the natural frequencies of the first and second modes, respectively, and ξ is the damping ratio, considered as 0.05 in this modelling. The values of α and β of the models have been calculated and presented in Table 2.

Verification of modelling in ABAQUS software

Ensuring the validity of the numerical modelling is the first step prior to nonlinear FE analysis. Therefore, it is necessary to assess the behaviour of MRF

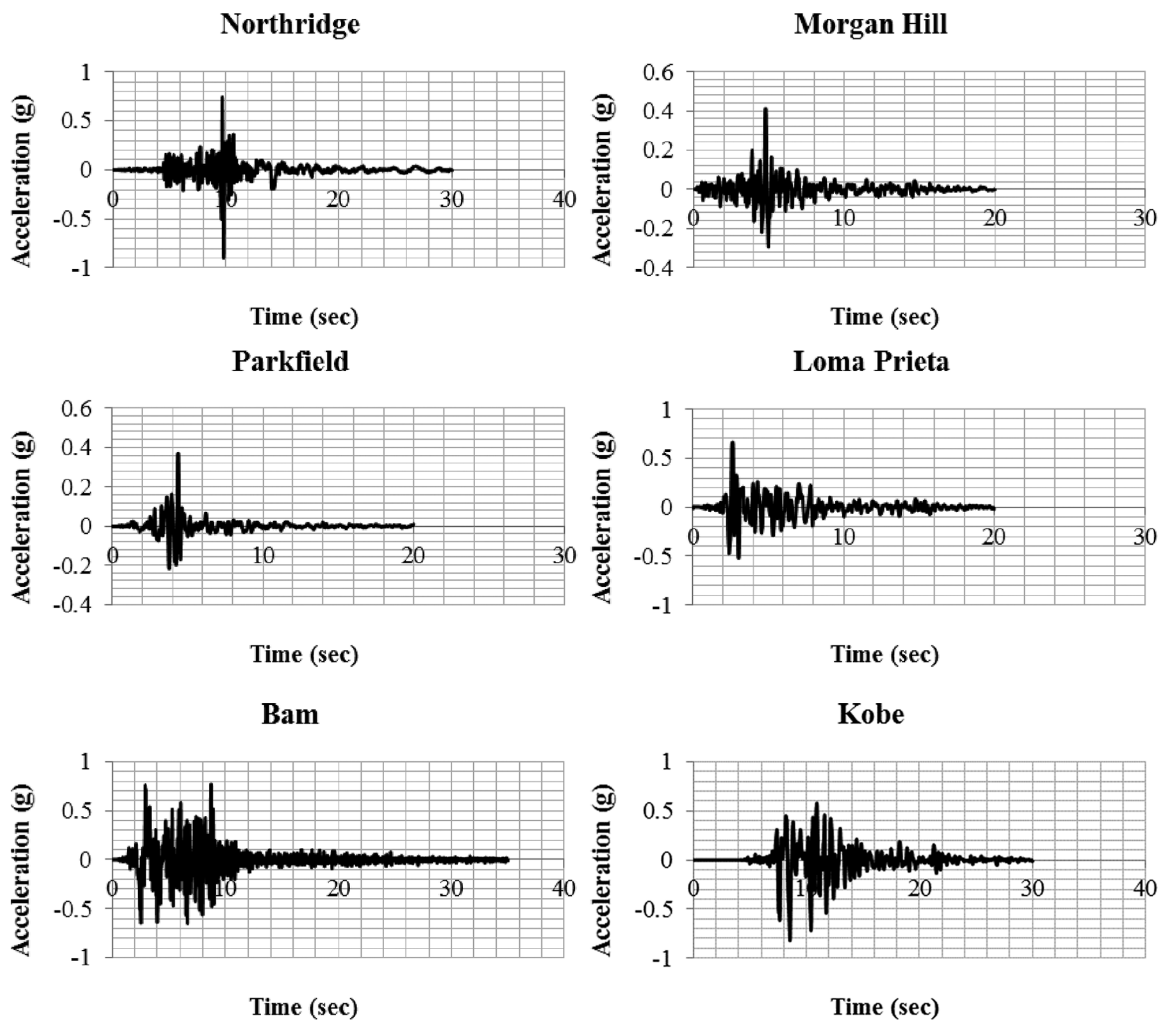

Figure 4. Accelerograms used in the seismic analyses.

Table 2. Damping parameters of studied frames.

Structural system	Number of storeys	ω_1 (rad/s)	ω_2 (rad/s)	α	β
MRF	Two	7.81	25.73	0.599	0.00298
	Four	4.99	15.12	0.375	0.00497
	Six	3.69	9.96	0.269	0.00732
MRF with cable cross-bracing	Two	18.93	51.38	1.383	0.00142
	Four	10.88	32.1	0.812	0.00232
	Six	7.38	21.99	0.552	0.0034
MRF with cable–cylinder bracing	Two	7.81	25.73	0.599	0.00298
	Four	4.99	15.12	0.375	0.00497
	Six	3.69	9.96	0.269	0.00732

MRF: moment-resisting frame.

strengthened by cable–cylinder bracing and derive P–δ and ε–δ curves (where P, δ and ε are the applied lateral force to the frame, lateral displacement of the frame and strain of the right cable, respectively) before conducting dynamic analysis. For this purpose, these curves are superposed with the curves plotted by the

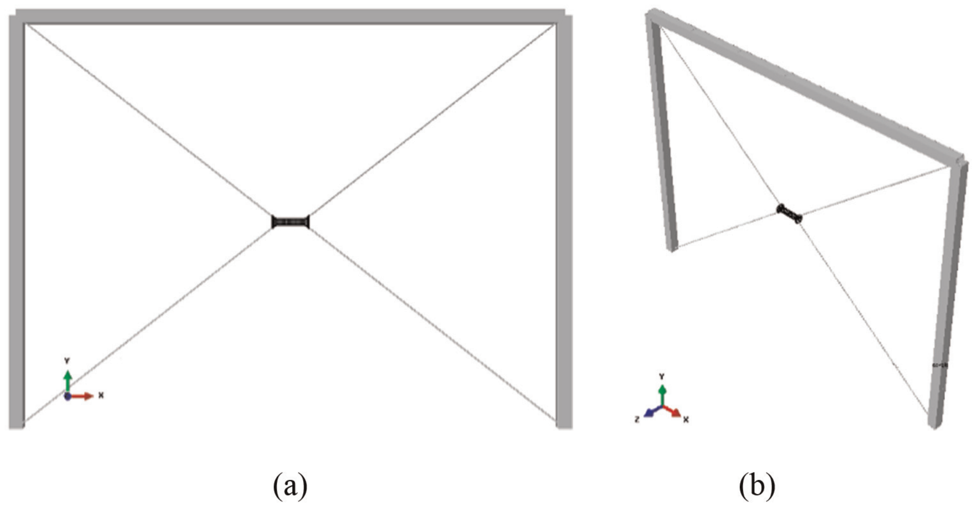

Figure 5. FE models of frame with cable–cylinder bracing: (a) front view of 3D model and (b) side view of 3D model.

theoretical relations presented by the same researchers in a previous study (Fanaie et al., 2016). In this way, the validity of modelling is confirmed and the results of analysis are more credited.

When an MRF is stiffened by cable–cylinder bracing, it is supposed to have an MRF which is combined with a simple frame braced using cable–cylinder bracing. In this stiffened MRF, MRF and cable bracing system act as parallel systems because they have the same lateral displacements; moreover, the lateral force is distributed between them. The stiffness of parallel systems such as this stiffened MRF equals the summation of the stiffness of each system. The stiffness of an MRF can be easily developed in terms of Young's modulus of material and geometrical characteristics of beam and columns. Therefore, total stiffness of stiffened MRF can be calculated by adding these two stiffnesses if there is an explicit equation for stiffness of cable–cylinder bracing. The theoretical curve can be plotted for lateral force versus lateral displacement (P–δ). Regarding the previous research of the authors (Fanaie et al., 2016), it is not possible to develop an explicit equation for the stiffness of simple frame braced by cable–cylinder bracing. Therefore, it was decided that an FE model for simple frames braced with cable–cylinder bracing be created and their analytical results verified (P–δ and ε–δ curves) by comparing them with those obtained from the theoretical equations developed recently by the authors (Fanaie et al., 2016).

On this basis, the portal frame with hinge connections and cable–cylinder bracing is modelled in ABAQUS software in 2D and three-dimensional (3D) forms. In this model, as shown in Figure 5, the beam length is 4 m, column height 3 m, cylinder length 22 cm, internal diameter of cylinder minus cable diameter 5 cm, the section of columns of box section 100 × 100 × 8 mm and cable cross-sectional area 1 cm^2. The cylinder is considered rigid.

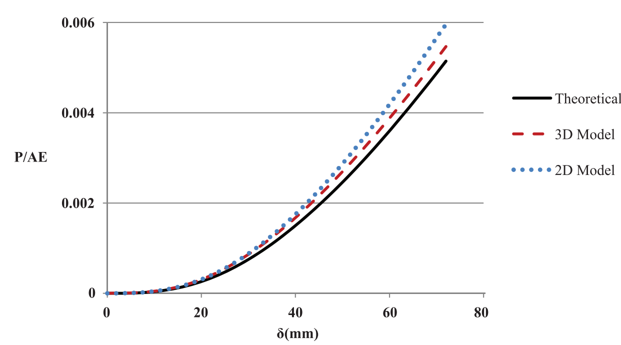

Figure 6. The P–δ curves of theoretical relations and numerical modelling.

The P–δ and ε–δ curves corresponding to the 2D and 3D models are compared with the results of the theoretical relations and presented in Figures 6 (for the right cable) and 7, respectively. In these figures, 'R' and 'L' refer to right (member 'a' in Figure 1) and left (member 'b' in Figure 1) cables, respectively.

According to Figures 6 and 7, the results obtained from 2D and 3D models are slightly different from those of the theoretical equations. The difference between the curves increases with increasing lateral displacement up to its maximum value at δ_s, where the shape of the right cable is totally straight like a solid line and the force of the left cable is 0 due to the equilibrium of moments in the cylinder. In the δ_s curves, the maximum difference between 2D models and the theoretical results is 15% while that of 3D model is 7%.

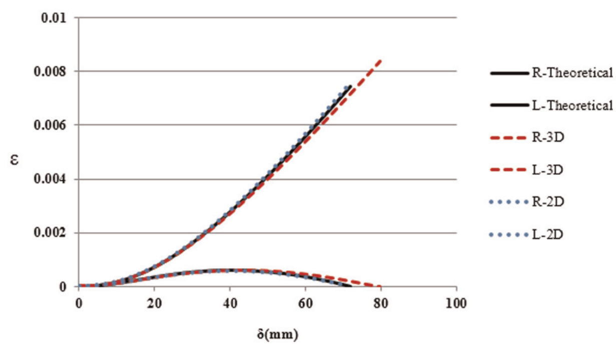

Figure 7. The ε–δ curves of theoretical relations and numerical modelling.

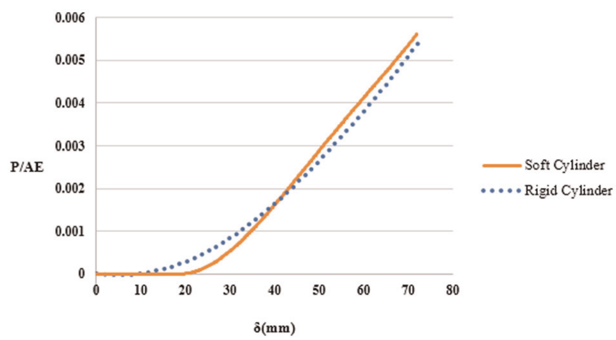

Figure 8. P–δ curves for rigid cylinder and the cylinder with the modulus of elasticity equal to 0.001 times of steel.

The differences between the curves result from the axial deformation of the beams and columns which was ignored in the curves obtained from the theoretical relations. Besides, the contact between the cylinder and the cable was modelled more realistically in the 3D model and the cable can slide on the cylinder under lateral displacement of the frame. However, in the 2D model, the cables inside and outside the cylinder are considered as separate elements adjoined to each other by a hinge.

In order to study the effect of rigidity of the cylinder on the behaviour of cable–cylinder bracing, several nonlinear pushover analyses were conducted on the frame with the mentioned dimensions using 3D model for different rigidity values. The cylinder thickness was taken as 5 mm. According to the results of the analyses, the P–δ and ε–δ curves which correspond to the rigid and steel cylinders coincide. The P–δ and ε–δ curves as shown in Figures 8 and 9, respectively, are related to the rigid cylinder and the cylinder with the modulus of elasticity equal to 0.001 times of steel. In these figures, E, A and P are the modulus of elasticity of cable, each cable cross-sectional area and horizontal components resultant of cables' force, respectively.

According to the results of the analyses, the steel cylinder will be the indicator of rigid cylinder if it remains elastic, due to its very slight deformation. The relations governing the behaviour of steel cable–cylinder bracing are marginally different from that of the rigid one. Fortunately, because cylinder dimension variation is infinitesimal in the elastic status, the relations of the rigid cylinder can be used with excellent accuracy. 3D model can be used for general status, different rigidity values, cylinder thickness and different loadings.

In this research, the cylinder material was assumed to be the same as the steel material. Therefore, 2D model with the rigid cylinder was used for seismic analysis due to its higher speed of analysis compared to that of 3D.

Results of nonlinear analyses

In this section, the results of nonlinear time history analyses are presented including fundamental period,

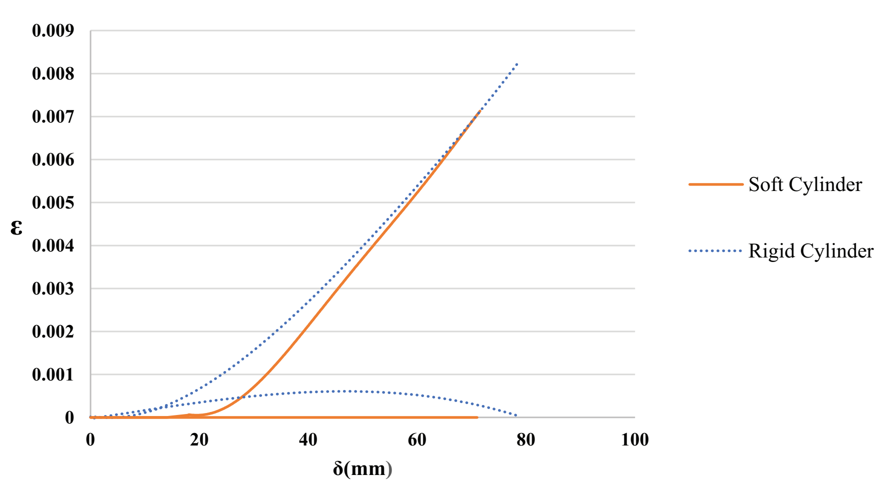

Figure 9. ε–δ curves for rigid cylinder and the cylinder with the modulus of elasticity equal to 0.001 times of steel.

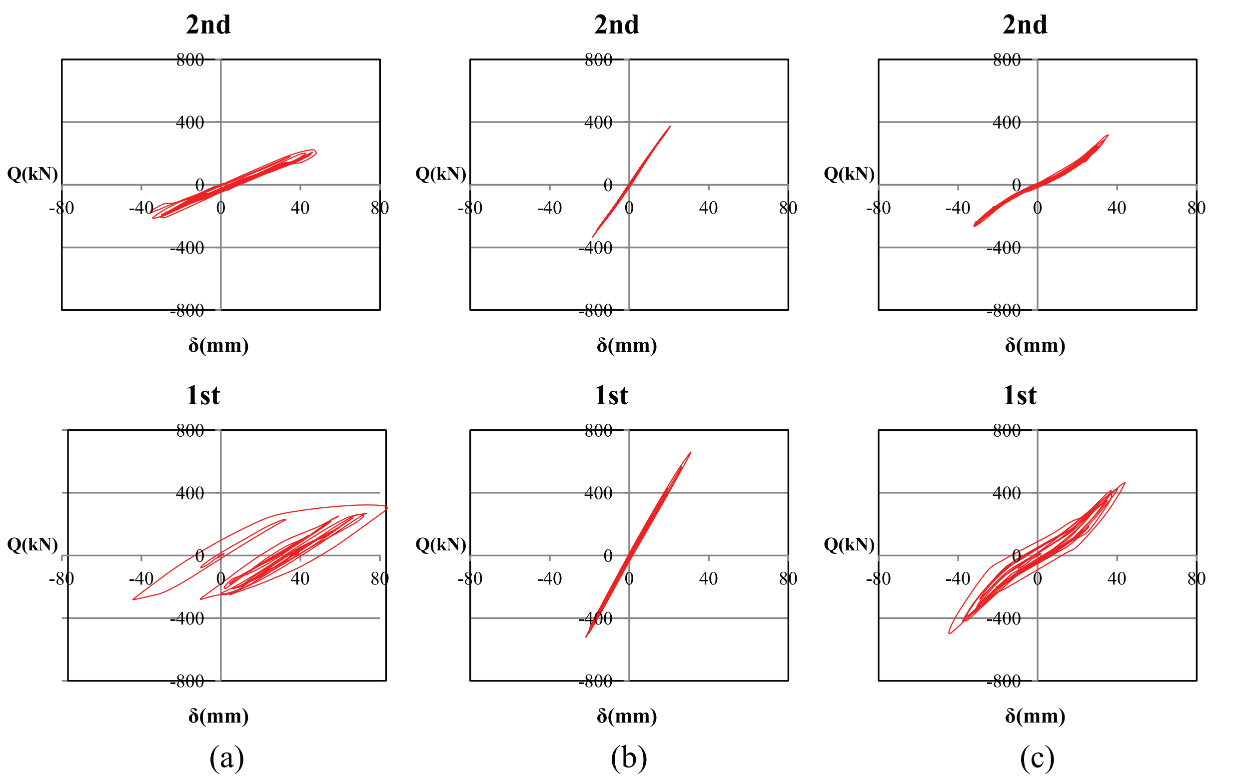

Figure 10. Hysteresis curves of two-storey frames subjected to Cobe earthquake record with PGA = 0.35g: (a) MRF, (b) MRF with cable cross-bracing and (c) MRF with cable–cylinder bracing.

Table 3. Fundamental periods of studied frames (s).

Number of storeys	MRF	MRF with cable cross-bracing	MRF with cable–cylinder bracing
Two	0.8	0.33	0.8
Four	1.26	0.58	1.26
Six	1.7	0.85	1.7

MRF: moment-resisting frame.

hysteresis curves, relative drift distribution, compressive force of the braced frame's columns and stress in the bracing cables. The results are compared for each item in terms of MRF, MRF with cylinder–cable bracings and MRF with cable cross-bracings.

Fundamental period of frames

The fundamental period was calculated for the models based on the eigen value analyses conducted on the studied models and presented in Table 3.

According to Table 3, the fundamental period of MRF with cable cross-bracing is lower in comparison to that of MRF. However, the fundamental period of MRFs with cable–cylinder bracing is equal to those of MRFs due to the ineffectiveness of cable–cylinder bracing in the initial lateral displacement.

Hysteresis curves of the frames

Figures 10 to 15 present the hysteresis curves of the two-, four- and six-storey frames, respectively, subjected to Cobe earthquake record, with PGA = 0.35g and PGA = 0.50g.

According to Figures 10 to 15, the MRFs are under large lateral displacements. Particularly, large residual displacement is observed in the first storey of the two-storey MRF under Cobe earthquake record with PGA = 0.5g. However, the displacement values of the storeys were reduced in the MRFs with cable cross- and cable–cylinder bracings. Despite the mentioned fact, the storey shear significantly increased in the MRF with cable cross-bracing compared to that with cable–cylinder bracing. In other words, higher forces were applied to the cable bracings. Therefore, the vertical component of the forces transferred to the adjacent columns may damage the columns. Based on these figures, it can be concluded that the energy dissipation of the frames with cable–cylinder bracings is relatively higher compared to those with cable

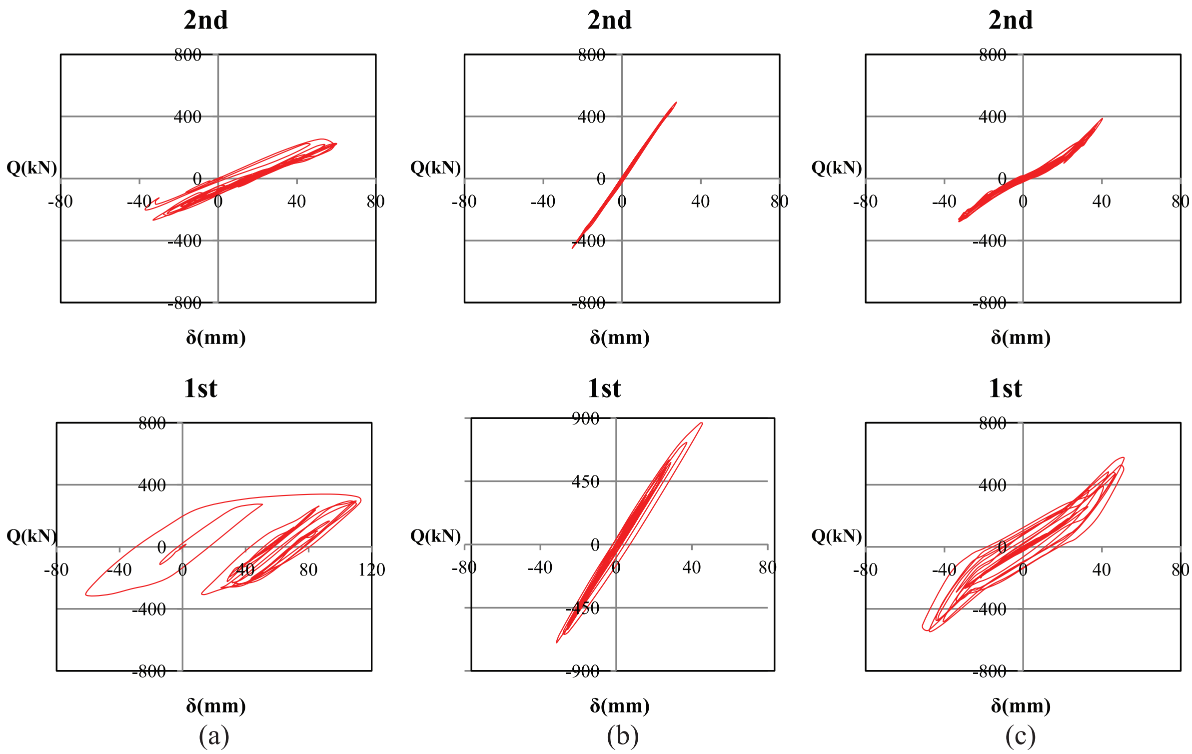

Figure 11. Hysteresis curves of two-storey frames subjected to Cobe earthquake record with PGA = 0.50g: (a) MRF, (b) MRF with cable cross-bracing and (c) MRF with cable–cylinder bracing.

cross-bracings. This fact confirms the appropriate seismic performance of the frames with cable–cylinder bracing in comparison to those of cable cross-bracing.

Relative drift distribution of storeys in the height of frames

Figures 16 to 21 present the relative drift of storeys for studied frames under applied records. In these figures, X-bracing and C-bracing correspond to the moment frame with cross-cable bracing and flexural frame with cable–cylinder bracing, respectively.

According to Figures 16 to 21, both cable bracings prevent the formation of large drift in the storeys. Usually, the drift is lower in frames with cable cross-bracings compared to others. Still concerning the figures, the lateral displacements of the frames with cable–cylinder bracings are higher than the drift of MRFs, yet acceptable in some cases; for example, in the four-storey frame under Cobe earthquake record. In other words, cable–cylinder bracing has the capability of distributing the drift in the frame height and preventing the concentration of damage in a certain storey. This fact is apparently observed in the figure related to the six-storey frame under Cobe earthquake record. Therefore, it can be said that the mentioned bracing makes the MRF use better its energy absorption capacity because of proper distribution of the drift in the frame height.

Compressive force of the braced frame columns

The bracings used in the seismic strengthening tolerate a part of earthquake lateral force. The vertical component force of the added bracings is transferred to its adjacent columns. This force increases significantly with loosening, impacting on cables in the cross-cable bracing. Therefore, more forces are applied to the under pressure column which may cause the rupture of the cable or early buckling of the column, and finally instability of the structure. In such cases, the strengthening of columns should be considered and the strength of the foundation should be evaluated. Figures 22 to 27 present the ratios of the maximum compressive force of the first storey braced frame columns of the systems with cable cross- and cable–cylinder bracings to the maximum compressive force of the flexural frame columns.

According to Figures 22 to 27, the increase in compressive force due to the addition of cable–cylinder bracing is lower compared to that of cable cross-bracing. This is because of the elimination of the impact due to cable loosening as well as high period of the structure with cable–cylinder bracing. Table 4 presents

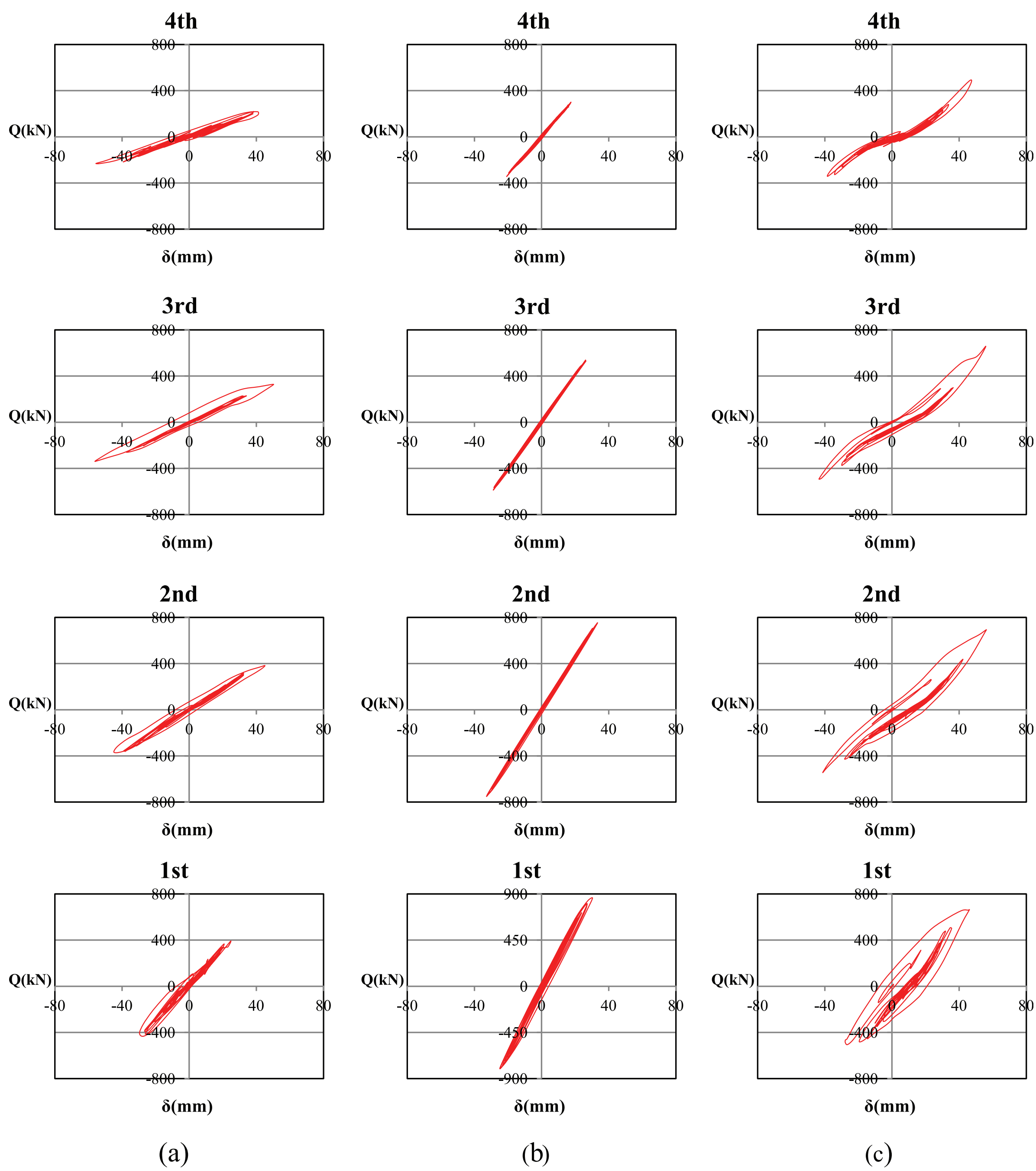

Figure 12. Hysteresis curves of four-storey frames subjected to Cobe earthquake record with PGA = 0.35g: (a) MRF, (b) MRF with cable cross-bracing and (c) MRF with cable–cylinder bracing.

Table 4. Ratio of compressive forces of braced frame columns.

Number of storeys	$P_{x\text{-}bracing}/P_{MRF}$	$P_{c\text{-}bracing}/P_{MRF}$
Two	2.65	1.52
Four	2.32	1.7
Six	2.17	1.44

the average maximum increase in columns' compressive forces caused by adding the cable cross- and cable–cylinder bracings under applied records.

Stress in the bracing cables

Figures 28 to 33 present the maximum stresses of bracing cables in the systems with cable cross- and cable–cylinder bracings.

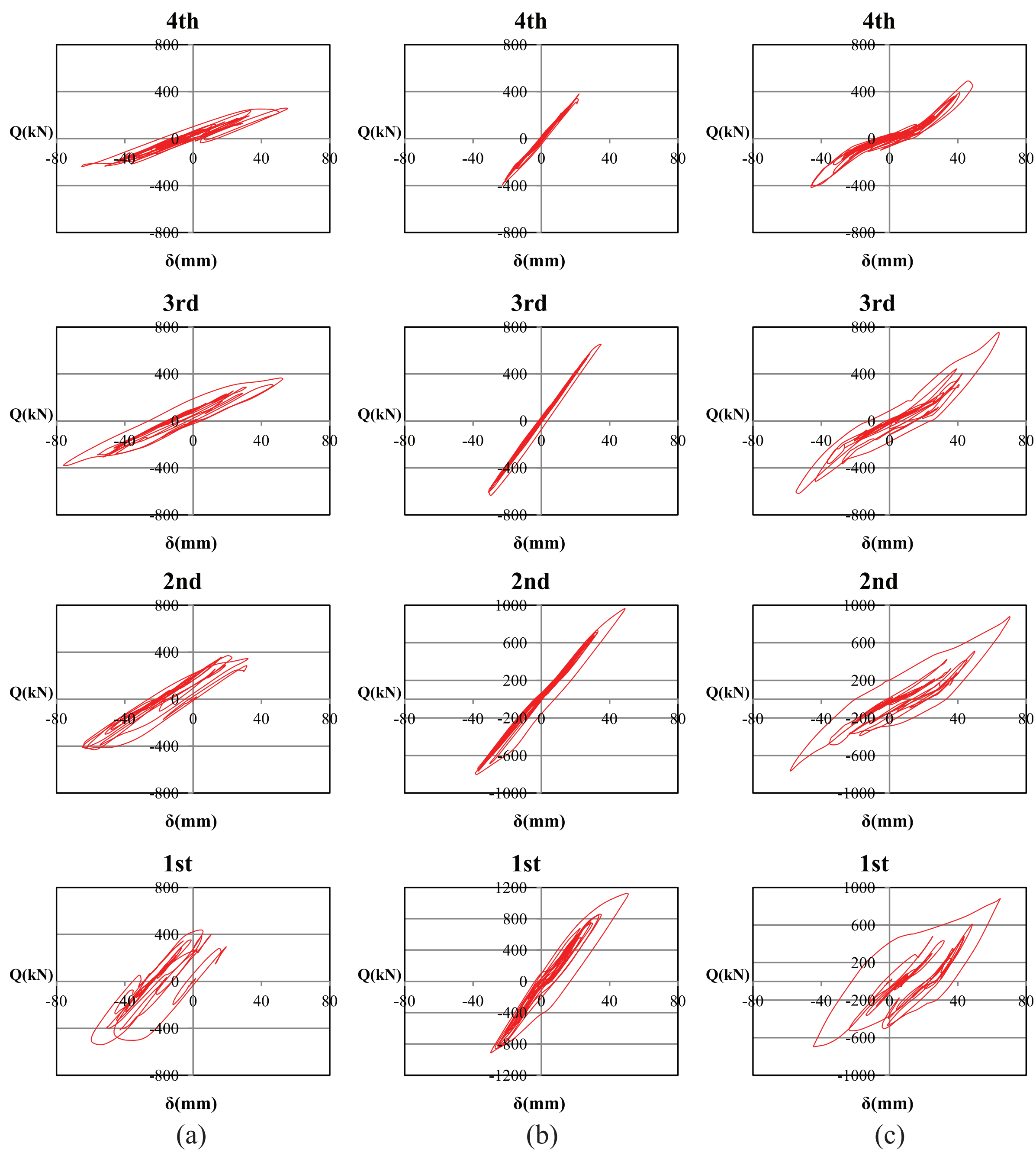

Figure 13. Hysteresis curves of four-storey frames subjected to Cobe earthquake record with PGA = 0.50g: (a) MRF, (b) MRF with cable cross-bracing and (c) MRF with cable–cylinder bracing.

According to Figures 28 to 33, stress is lower in the cables of cable–cylinder bracing compared to those of cable cross-bracing. In this research, the cross-sectional areas of cables were considered to be the same for the purpose of comparing the systems. Therefore, in order to have equal maximum stress in both systems, the cross-sectional area needed for the cables is lower in the system with cable–cylinder bracing in comparison to those of cable cross-bracing system. Table 5 illustrates the average stress of cables as well as the ratio of cable stress of cable–cylinder bracing system to that of cable cross-bracing system under applied record as per megapascal.

Conclusion

Cables are appropriate options for bracing of simple frames or strengthening the existing MRFs due to the

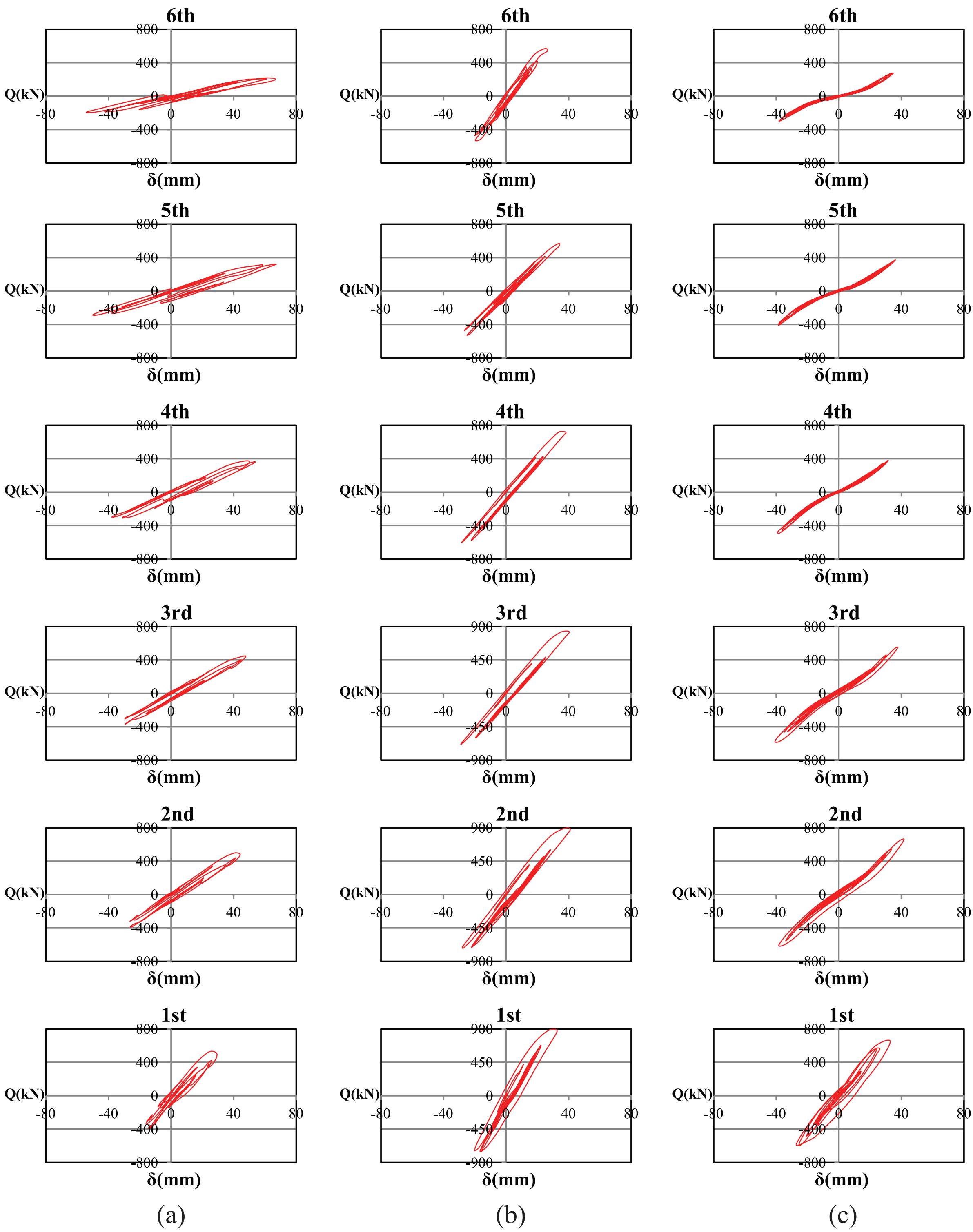

Figure 14. Hysteresis curves of six-storey frames subjected to Cobe earthquake record with PGA = 0.35g: (a) MRF, (b) MRF with cable cross-bracing and (c) MRF with cable–cylinder bracing.

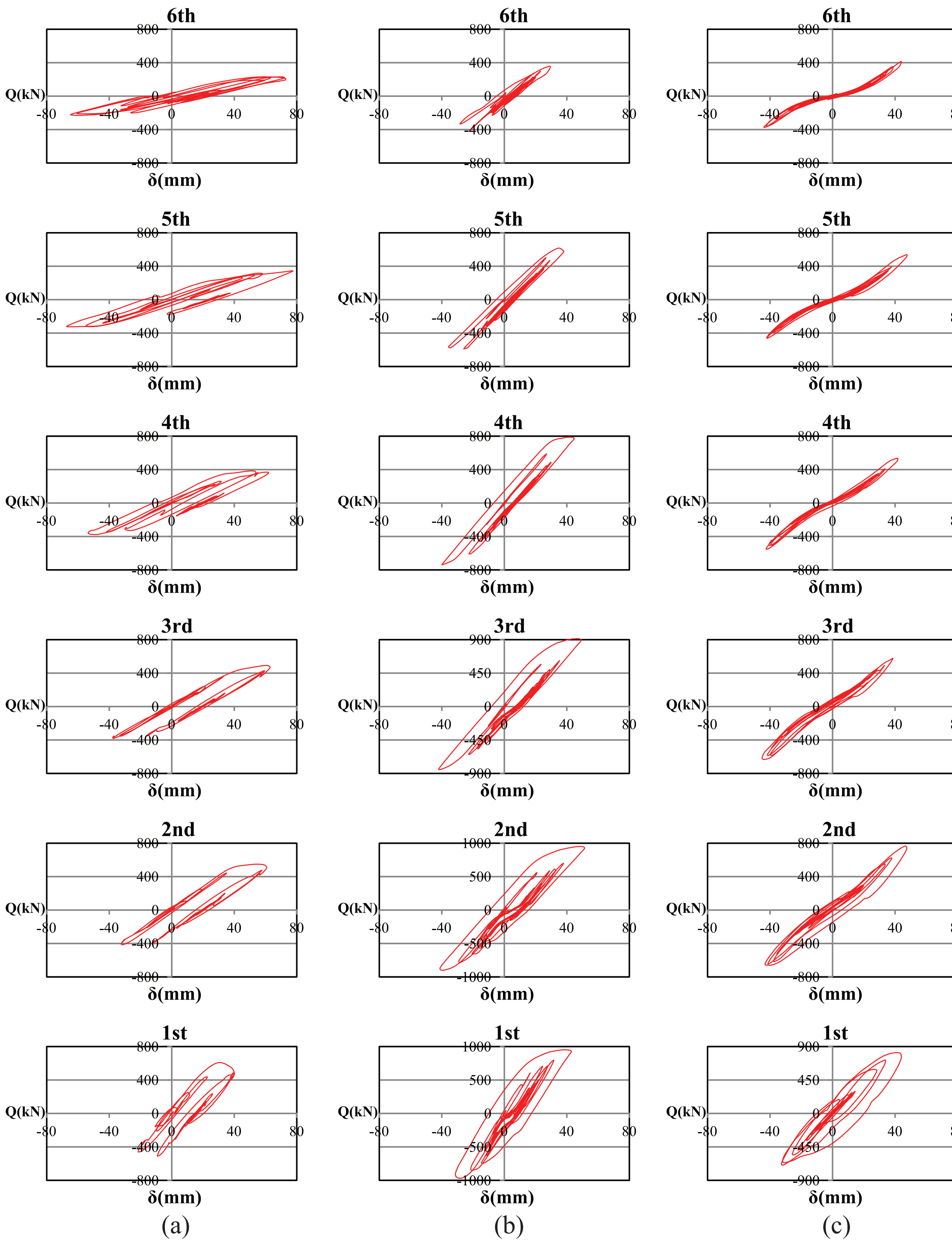

Figure 15. Hysteresis curves of six-storey frames subjected to Cobe earthquake record with PGA = 0.50g: (a) MRF, (b) MRF with cable cross-bracing and (c) MRF with cable–cylinder bracing.

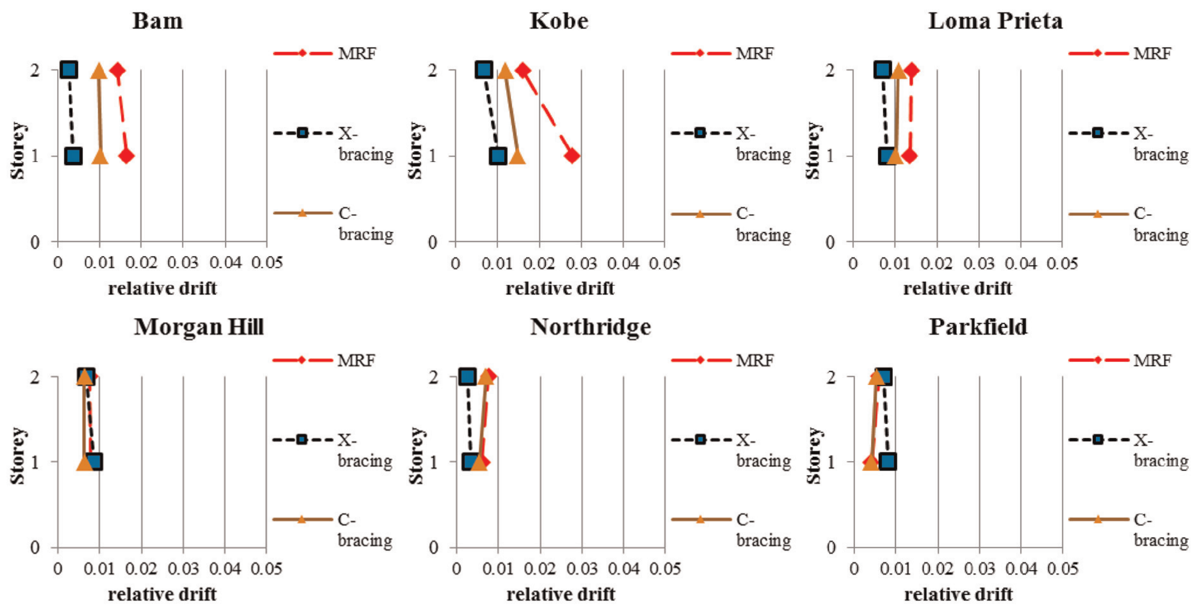

Figure 16. Relative drift of storeys of two-storey frames for PGA = 0.35g.

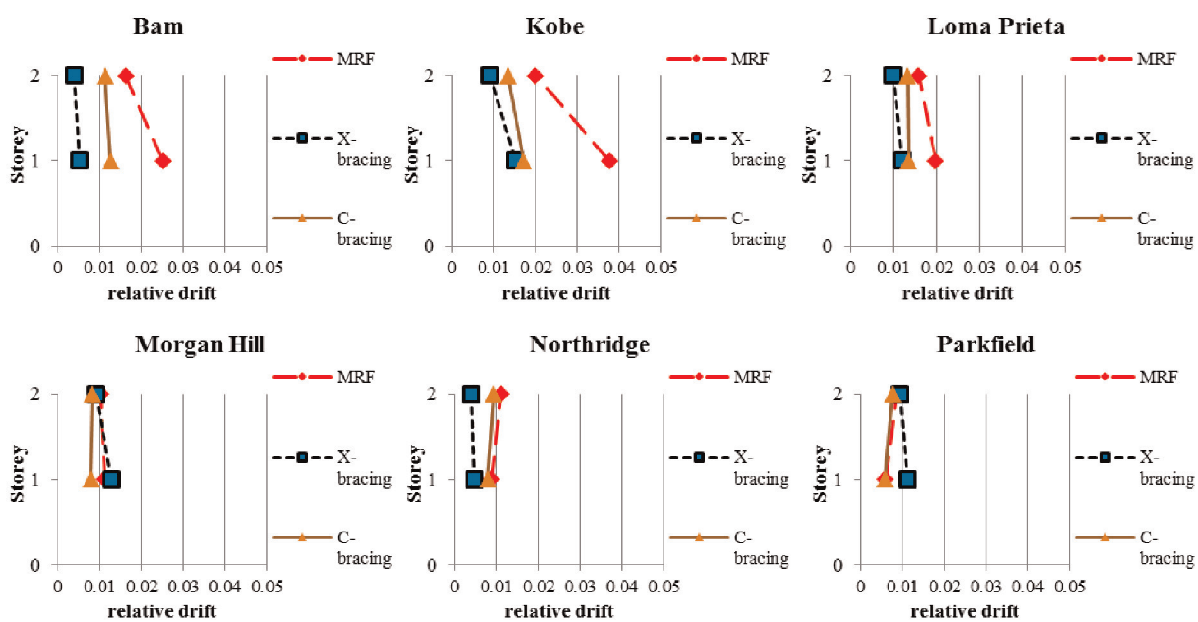

Figure 17. Relative drift of storeys of two-storey frames for PGA=0.50g.

Table 5. Average stress in the bracing cables (as per MPa).

Number of storeys	$\sigma_{x\text{-}bracing}$	$\sigma_{c\text{-}bracing}$	$\sigma_{c\text{-}bracing}/\sigma_{x\text{-}bracing}$
Two	798	313	39%
Four	631	423	67%
Six	673	321	47%

high strength of their material as well as their extraordinary flexibilities. Cables can be used for strengthening the MRFs which do not meet the necessary strength or stiffness. In the cable–cylinder bracing systems, which are included in the relatively modern systems, one cylinder is used for passing the right and left cables. The cylinder prevents the cables from loosening

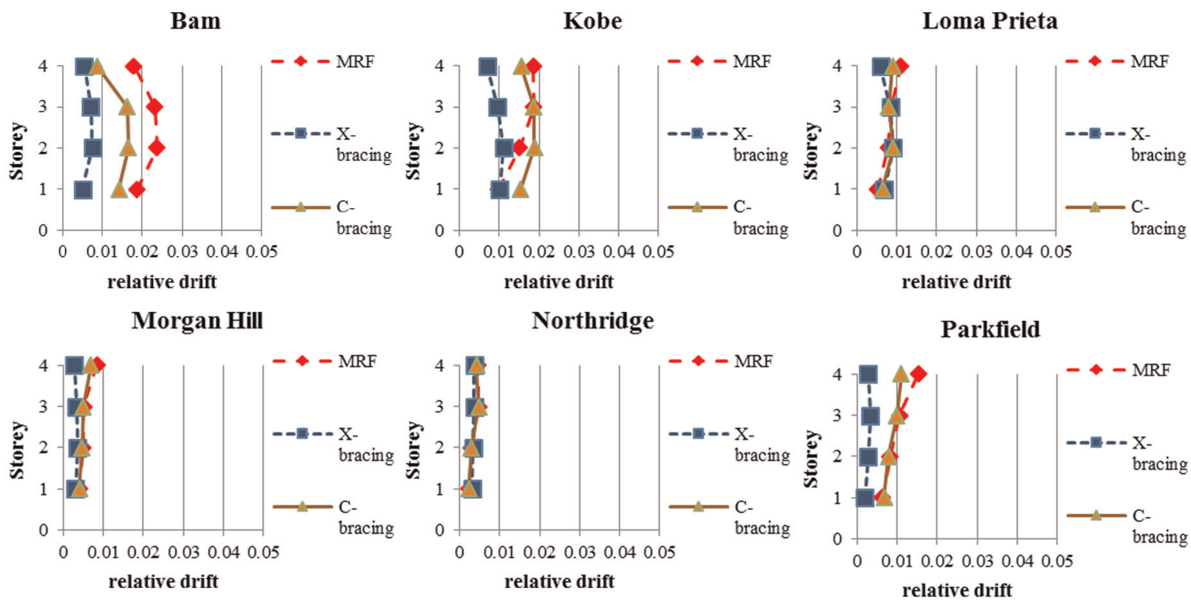

Figure 18. Relative drift of storeys of four-storey frames for PGA = 0.35g.

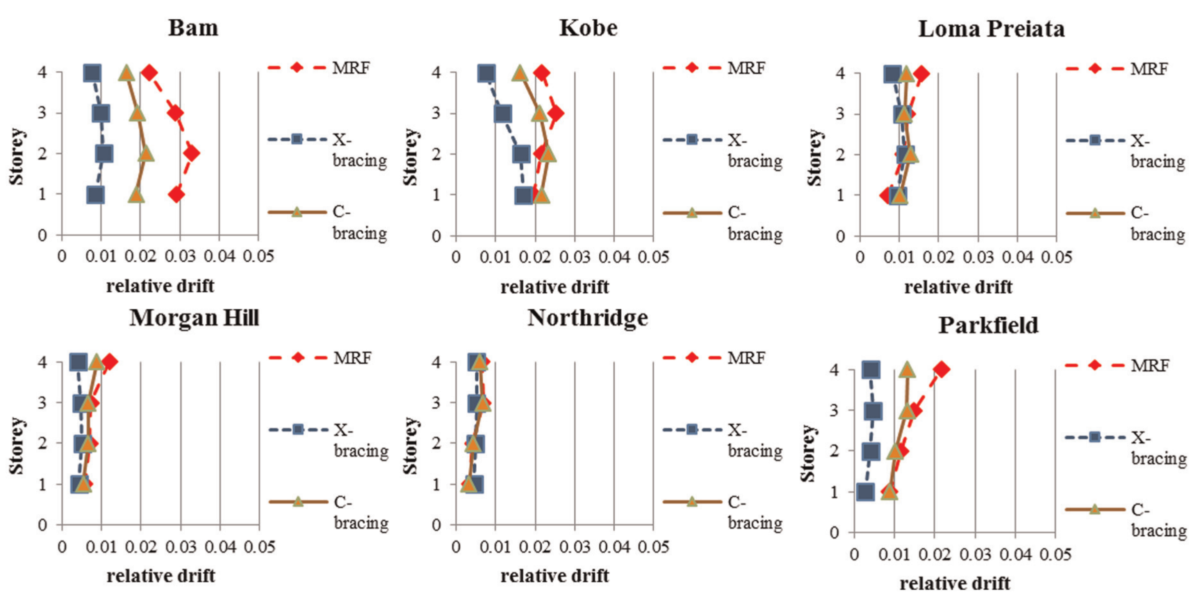

Figure 19. Relative drift of storeys of four-storey frames for PGA = 0.50g.

during lateral load application. Consequently, the impact caused by cables' loosening is avoided at their intersection, leading to a more effective performance.

In this research, two-, four- and six-storey MRFs were strengthened by cable cross- and cable–cylinder bracings. Accordingly, the seismic performance of the initial MRFs was compared to those of the strengthened ones, showing the proper performance of cable–cylinder bracing system. The obtained results are briefly summarized as follows:

1. In the low drifts, the stiffness of cable–cylinder bracing system is nearly 0, having no effect on the structural behaviour. Consequently, the MRFs and those strengthened by cable–cylinder bracing have equal fundamental periods. Cable–cylinder bracing system shows its positive effect with increasing lateral displacement.
2. Based on the hysteresis curves, energy dissipation is relatively higher when cable–cylinder

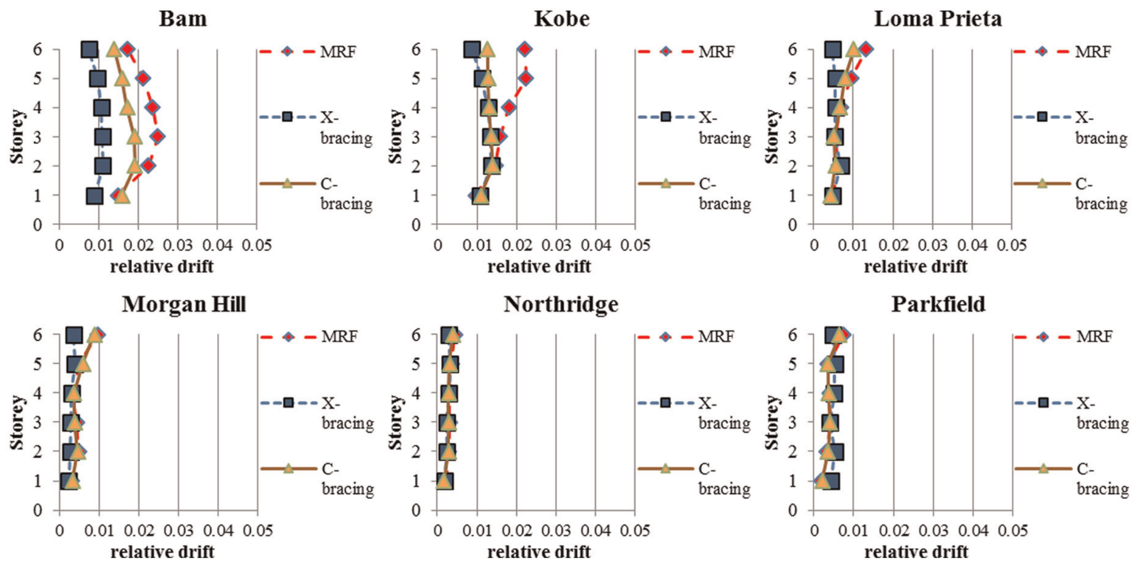

Figure 20. Relative drift of storeys of six-storey frames for PGA = 0.35g.

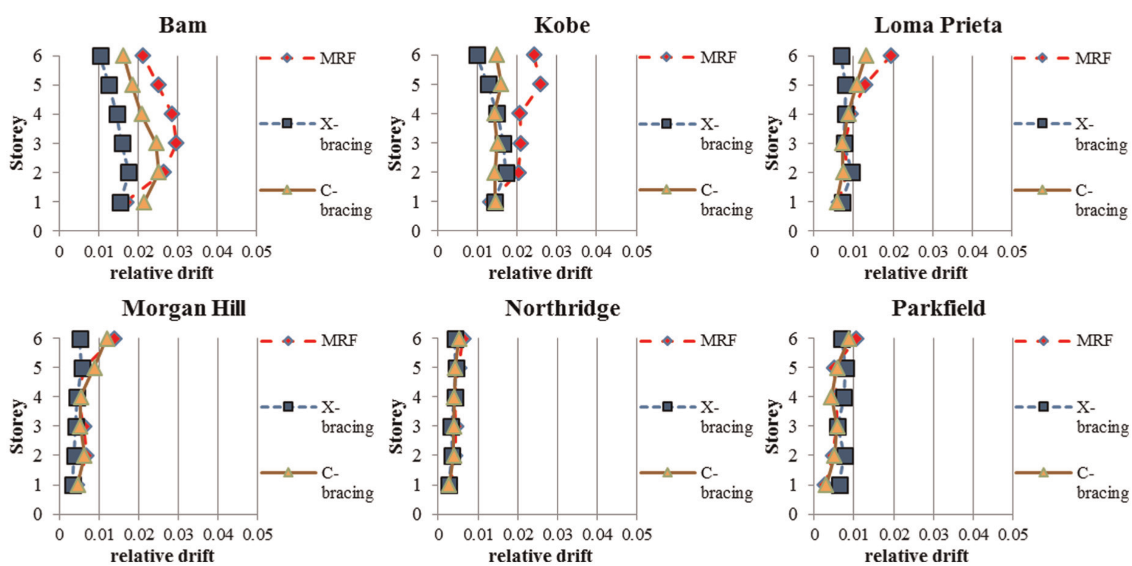

Figure 21. Relative drift of storeys of six-storey frames for PGA = 0.50g.

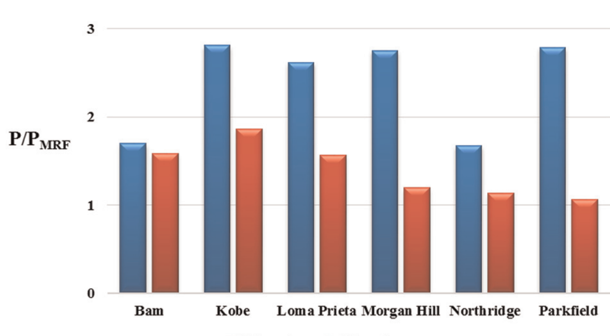

Figure 22. Ratio of braced frame column force of strengthened frames to the column force of MRFs in two-storey frames for PGA = 0.35g.

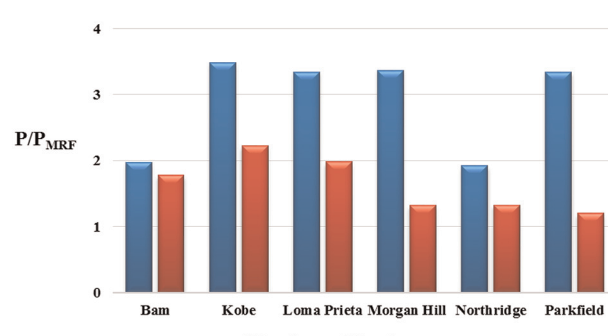

Figure 23. Ratio of braced frame column force of strengthened frames to the column force of MRFs in two-storey frames for PGA = 0.50g.

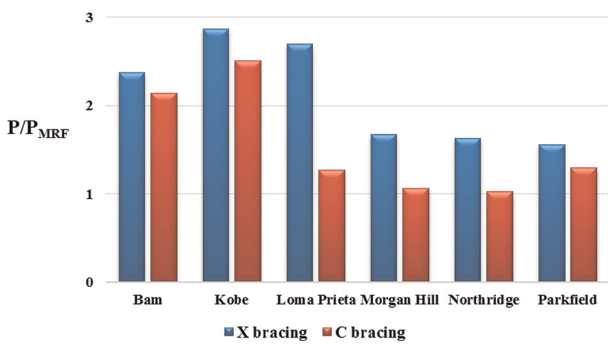

Figure 24. Ratio of braced frame column force of strengthened frames to the column force of MRFs in four-storey frames for PGA = 0.35g.

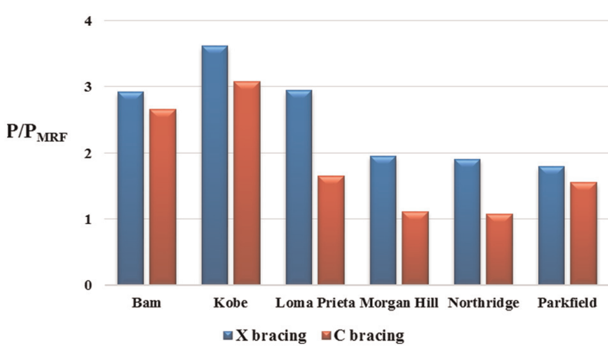

Figure 25. Ratio of braced frame column force of strengthened frames to the column force of MRFs in four-storey frames for PGA = 0.50g.

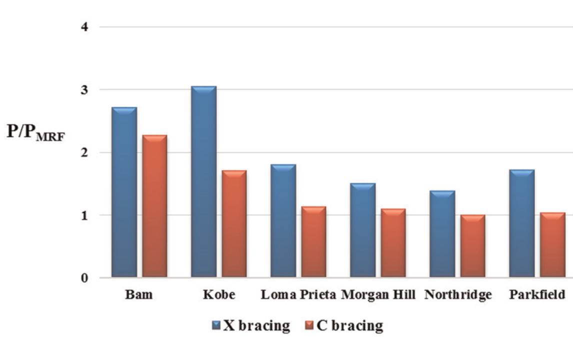

Figure 26. Ratio of braced frame column force of strengthened frames to the column force of MRFs in six-storey frames for PGA = 0.35g

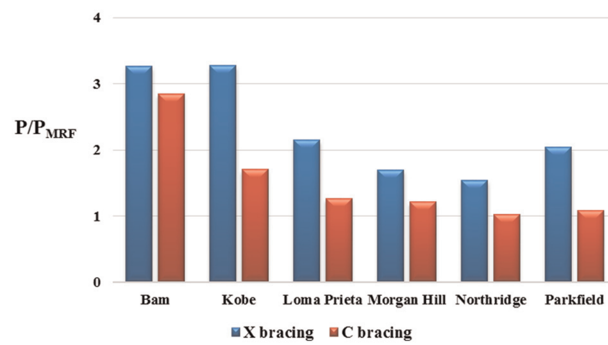

Figure 27. Ratio of braced frame column force of strengthened frames to the column force of MRFs in six-storey frames for PGA = 0.50g.

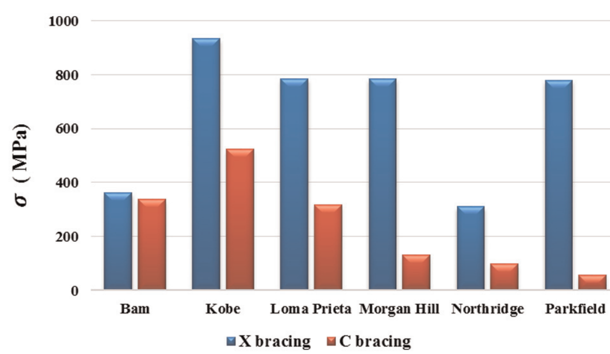

Figure 28. Maximum stress of bracing cables of two-storey frames for PGA = 0.35g.

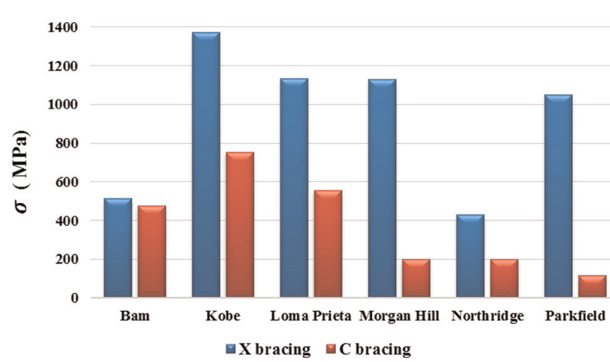

Figure 29. Maximum stress of bracing cables of two-storey frames for PGA = 0.50g.

bracing is used in comparison to cable cross--bracing. The former can increase the lateral strength of the frame without reducing ductility.

3. Cable and cylinder of cable–cylinder bracing remain elastic under earthquake records and have no energy dissipation. They prevent the concentration of damages in a particular storey of a building as well as soft storey formation due to the distribution of relative displacement of storeys in the frame's height.
4. The increase in compressive axial force of the columns due to the addition of bracing to the MRF is considerably lower with cable–cylinder

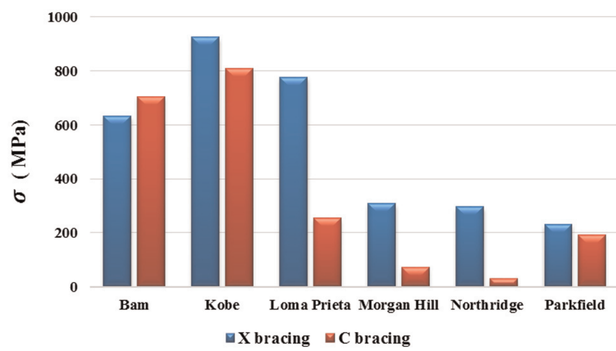

Figure 30. Maximum stress of bracing cables of four-storey frames for PGA = 0.35g.

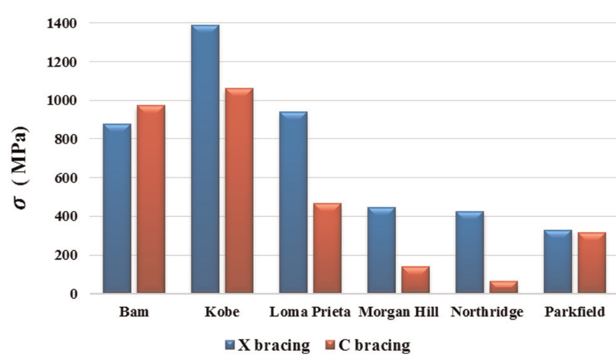

Figure 31. Maximum stress of bracing cables of four-storey frames for PGA = 0.50g.

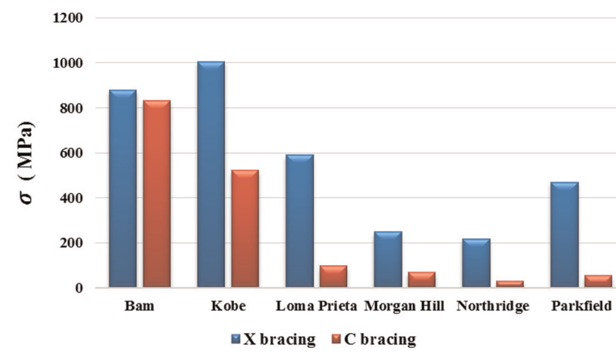

Figure 32. Maximum stress of bracing cables of six-storey frames for PGA = 0.35g.

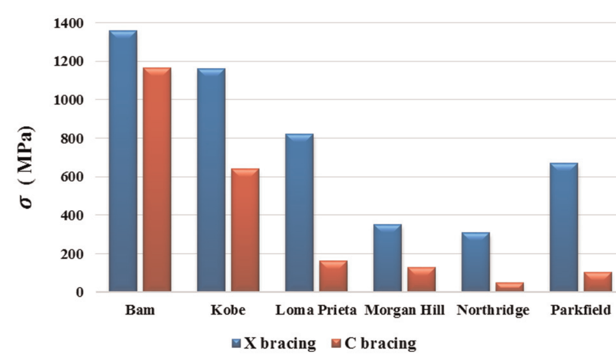

Figure 33. Maximum stress of bracing cables of six-storey frames for PGA = 0.50g.

bracing compared to that of cable cross-bracing. Therefore, the probability of column damage is reduced in the strengthened spans.

5. The stresses were studied and analysed in the cables used in the cable cross- and cable–cylinder bracings. The results showed that the cross-sectional area needed for cable–cylinder bracing is lower in comparison to that of cable cross-bracing. This fact is considered as an appropriate advantage of cable–cylinder bracing system.

Declaration of Conflicting Interests

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References

Aiken ID, Nims DK, Whittaker AS, et al. (1993) Testing of passive energy dissipation systems. *Earthquake Spectra* 9(3): 335–370.

American Institute of Steel Construction (AISC) (2005) *ANSI/AISC360–05: Specification for Structural Steel Buildings*. Chicago, IL: AISC.

American Society of Civil Engineers (ASCE) (2010) *Minimum design loads for buildings and other structures (ASCE7-10)*. Reston, VA: ASCE.

Bartera F and Giacchetti R (2004) Steel dissipating braces for upgrading existing building frames. *Journal of Constructional Steel Research* 60(3–5): 751–769.

Bruneau M and Bhagwagar T (2002) Seismic retrofit of flexible steel frames using thin infill panels. *Engineering Structures* 24(4): 443–453.

Fanaie N, Aghajani S and Afsar Dizaj E (2016) Theoretical assessment of the behaviour of wire rope bracing system with central steel cylinder. *Advances in Structural Engineering* 19(3): 463–472.

Fanaie N, Aghajani S and Shamloo S (2012) Theoretical assessment of wire rope bracing system with soft central cylinder. In: *15th world conference on earthquake engineering*, Lisbon, 24–28 September 2012.

Hanson RH (1993) Supplemental damping for improved seismic performance. *Earthquake Spectra* 9(3): 319–334.

Hou X and Tagawa H (2009) Displacement-restraint bracing for seismic retrofit of steel moment frames. *Journal of Constructional Steel Research* 65(5): 1069–1104.

International Building code Council (2006) IBC 2006. Virginia, USA.

Keun-Hyeok Y, Gwang-Hee K and Hong-Suk Y (2011) Shear behaviour of continuous reinforced concrete T-beams using wire rope as internal shear reinforcement. *Construction and Building Materials* 25(2): 911–918.

Kurata M, Leon R and DesRoches R (2012) Rapid seismic rehabilitation strategy: concept and testing of cable bracing with couples resisting damper. *Journal of Structural Engineering* 138(3): 354–362.

Nordin H (2005) *Strengthening Structures with Externally Prestressed Tendons* (technical report). Luleå: Division of Structural Engineering, Department of Civil and Environmental Engineering, Luleå University of Technology.

Saleem MA and Saleem MM (2010) Cable bracing system to resist wind forces on tall building in Miami. In: *3rd fib international congress*, Washington, DC, 29 May–2 June 2010.

Sarno LD (2006) Bracing systems for seismic retrofitting of steel frames. In: *Proceedings of the fifth international conference on behaviour of steel structures in seismic areas*, 14–17 August 2006, pp. 821–826.

Soong TT and Dargush GF (1997) *Passive Energy Dissipation Systems in Structural Engineering*. Chichester: John Wiley & Sons.

Sorace S and Terenzi G (2012) The damped cable system for seismic protection of frame structures – part II: design and application. *Earthquake Engineering and Structural Dynamics* 41: 929–947.