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Sensitivity Analysis on Response Modification Factor of New Cable-Cylinder Bracing Systems

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ABSTRACT

Cable bracing systems have been increasingly investigated in recent years. The new cable-cylinder bracing system is made of bracings with two cables and one cylinder. In this system, the cables pass through the cylinder at their crossing region. For the first time in the present research, the overstrength factor, ductility factor, and response modification factor of this bracing system are evaluated using a two-dimensional model. For this purpose, incremental dynamic analyses are conducted on the system using 10 earthquake records. Based on the allowable stress design method, the values 2.33, 1.47, and 4.94 are obtained for the overstrength, ductility, and response modification factors, respectively. The response modification factor of the moment frame with cross-cable bracing is calculated and compared with that of the cable-cylinder bracing. Sensitivity analysis has been conducted on the dimensions of the cylinder, including its length and internal diameter, and pre-stressing stress of cables. According to the obtained results, under low pre-stressing stress, the response modification factor increasesby increasing the length and decreasing the diameter of the cylinder, in other words with increase in δ_{sr}. Moreover, the response modification factor decreases with increase in pre-stressing stress of the cables. According to the results obtained from sensitivity analysis, the highest change in the response modification factor with different cylinder lengths, inner diameters of the cylinder, and pre-stressing stresses of the cables is 0.34, 0.377 and 0.612 respectively; i.e. the sensitivity of the response modification factor to the pre-stressing of cables is greater, compared to its sensitivity to the dimensions of the cylinder. Finally, an equation has been presented for calculating the values of response modification factor as per the dimensions of the cylinder and pre-stressing stress of cables.

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Cable-Cylinder Bracing; Incremental Dynamic Analysis; Overstrength Factor; Response Modification Factor; Sensitivity Analysis

1. Introduction

Tagawa and Hou [2007] presented a new bracing method for seismic strengthening of moment steel frames using cables and a hollow cylinder through which the cables pass at their intersections, Fig. 1. Pipes with high or low stiffness, steel or PVC, respectively, can be used for the cylinder. The cylinder causes an increase in the lengths of cables in comparison to those with cross-cable bracing and consequently an increase in the ductility of the bracing system. [Tagawa and Hou, 2007].

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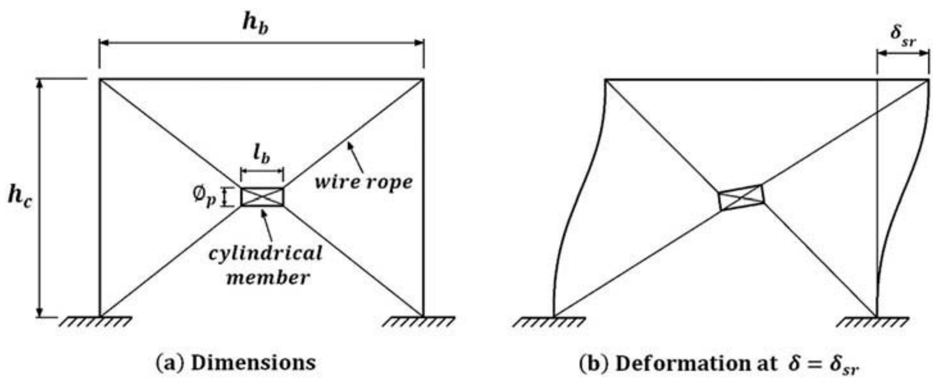

Figure 1. Cable-cylinder bracing system: (a) dimensions; and (b) deformed frame [Tagawa and Hou, 2007].

The advantages of this bracing system are briefly summarized as follows:

(a) The drifts of stories are limited without increasing their base shears and reducing the increase in compression force of the columns compared to the cross-cable bracing system [Fanaie and Aghajani, 2012];
(b) The stiffness of the cable-cylinder bracing system is almost zero in the low drifts. Therefore, the period of moment frame with cable-cylinder bracing is the same as period of moment frame in low drifts [Fanaie *et al.*, 2016a].
(c) Energy dissipation is higher in the cable-cylinder bracing system compared to that of a cross-cable bracing system;
(d) The cable-cylinder bracing system prevents the damage from being concentrated in a certain story (soft story) [Fanaie *et al.*, 2016a].

Under lateral loading Q, for very soft cylinder in the range $\delta \leq \delta_{s,}$ considering the very low stiffness of the cylinder and its high ductility, the cylinder may be deformed in such a way that the cables experience no length increase and their internal forces will remain zero until one of the cables becomes straight (the active cable under lateral load). Under lateral force (Q), the cables are inactive in the cable_soft cylinder bracing $\delta < \delta_s$ where, δ is lateral displacement of the story, and δ_s is the specified story drift at which the bracing members become linear. Therefore, the braced frame can present ductile behavior like the moment frame for low and medium drifts. In the range of larger displacements $\delta > \delta_s$), the bracing members are activated and tensile force (T_a) increases as shown in Fig. 2 [Tagawa and Hou, 2007].

The relative displacement of story (δ_s) for which the bracing members start to work can be controlled according to the following equation:

$$\delta_s = \sqrt{\left(2l_B + d_p\right)^2 - h_c^2} - l_b \tag{1}$$

where, h_c and l_b are the lengths of the column and beam, respectively; lp is the length of the cylinder; ϕ_p is the internal diameter of the cylinder; and ϕ_B is the diameter of cable.

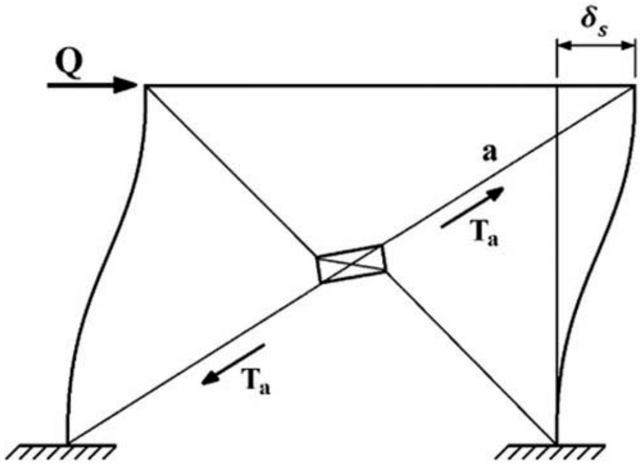

Figure 2. Bracing system with soft cylinder [Tagawa and Hou, 2007].

The length of the cable inside the cylinder (d_p) and length of each cable outside the cylinder (l_B) are calculated as follows [Tagawa and Hou, 2007]:

$$d_p = \sqrt{l_p^2 + \left(\varphi_p - \varphi_B\right)^2} \tag{2}$$

$$l_B = \sqrt{\left(\frac{h_b - l_p}{2}\right)^2 + \left(\frac{h_c - \varphi_p}{2}\right)^2} \tag{3}$$

In the cable bracing system with soft cylinder, the horizontal cylinder will be effective if the following equation is satisfied [Fanaie *et al.*, 2012]:

$$\frac{l_p}{\varphi_p - \varphi_B} > \frac{l_b}{h_c} \tag{4}$$

If the cylinder is placed vertically, its condition for being effective is given by Eq. (5); and the cylinder remains ineffective if $\frac{l_p}{\varphi_p - \varphi_B} \leq \frac{h_c}{l_b}$ [Fanaie *et al.*, 2012]

$$\frac{l_p}{\varphi_p - \varphi_B} > \frac{h_c}{l_b} \tag{5}$$

When the cylinder is rigid, it is not deformed; therefore, the lengths of cables cannot remain constant with the lateral displacement of the frame; the cables are always under tension for each lateral displacement of frame. However, the behavior of the brace should not be considered as that of ordinary cross-cable bracing. In such cases under the static lateral displacement (δ) of the frame toward the right, the center of the cylinder moves horizontally toward the right by $\frac{\delta}{2}$. The horizontal cylinder rotates counterclockwise by θ. The cylinder should rotate in order that the moment applied by the cables be zero [Aghajani, 2011].

In the cable bracing with stiff cylinder, both bracing members are under tension due to the rotation of the cylinder before the displacement reaches δ_{sr}. According to Fig. 3, tensile force (T_b) is created in member b as well [Tagawa and Hou, 2009].

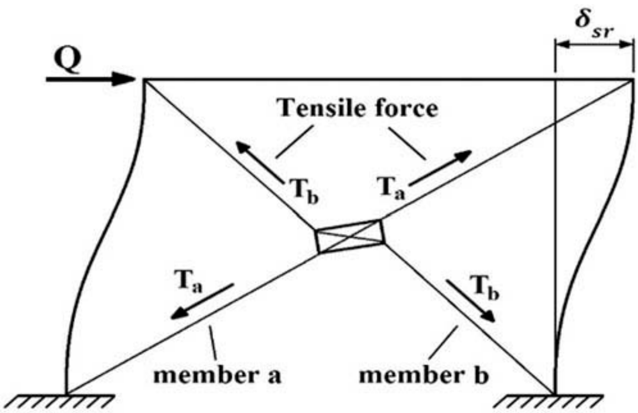

Figure 3. Bracing system with stiff cylinder [Tagawa and Hou, 2009].

Moreover, the main period of the flexural frame is equal to that of a flexural frame with stiff cylinder-cable bracing due to ineffectiveness of bracing in the initial lateral displacements [Aghajani, 2011].

The moment frame, moment frame with cross-cable bracing, and moment frame with cable-cylinder bracing were subjected to cyclic loadings in the laboratory investigation of Tagawa and Hou [2009]. The relevant hysteresis curves of these structures are presented in Fig. 4.

According to this figure, the ultimate displacement is lower in the braced frames in comparison to that of the frame without bracing. Moreover, story shear is lower in the frame with cable-cylinder bracing compared to that of the one with cross-cable bracing. Cable-cylinder bracing has a higher capability to absorb energy in comparison to that of cross-cable bracing [Tagawa and Hou, 2009]. Two advantages of the cable-bracing system with stiff cylinder can be pointed out, considering the conducted investigations. Firstly, the cable in the cable-cylinder bracing reaches its ultimate strength in higher story drift. Consequently, the frame's ductility increases, and therefore the cable's ductility weakness is covered. Secondly, both cables are under tension in a considerable range of loading; none of the cables are loosened under lateral displacement; hence, the impact caused by cable loosening is removed.

According to Fanaie *et al.* (2016a) the cross-section area needed for cable-cylinder bracing is lower in comparison to that of cross-cable bracing. This is considered as an advantage of the cable-cylinder bracing system [Fanaie *et al.*, 2016a]. In another research, Fanaie *et al.* (2016b) have presented the equations governing the behavior of stiff cable-cylinder bracing (like steel cylinder). In this research the effects of cylinder dimensions and pre-stressing of cables have been assessed on the behavior of cable-cylinder bracing. Then, the $P - \delta$ and $\varepsilon - \delta$ curves, obtained from the resulting constitutive formulas and numerical modeling, have been compared with each other [Fanaie *et al.*, 2016b]. Based on Aghajani's numerical investigations [2011], the value of δ_{sr} increases with increase in the length and decrease in the internal diameter of the cylinder. Moreover, the value of δ_{sr} increases with increase in pre-stressing stress of cables. Therefore, the cables reach their yield stress at a lower story drift [Aghajani, 2011].

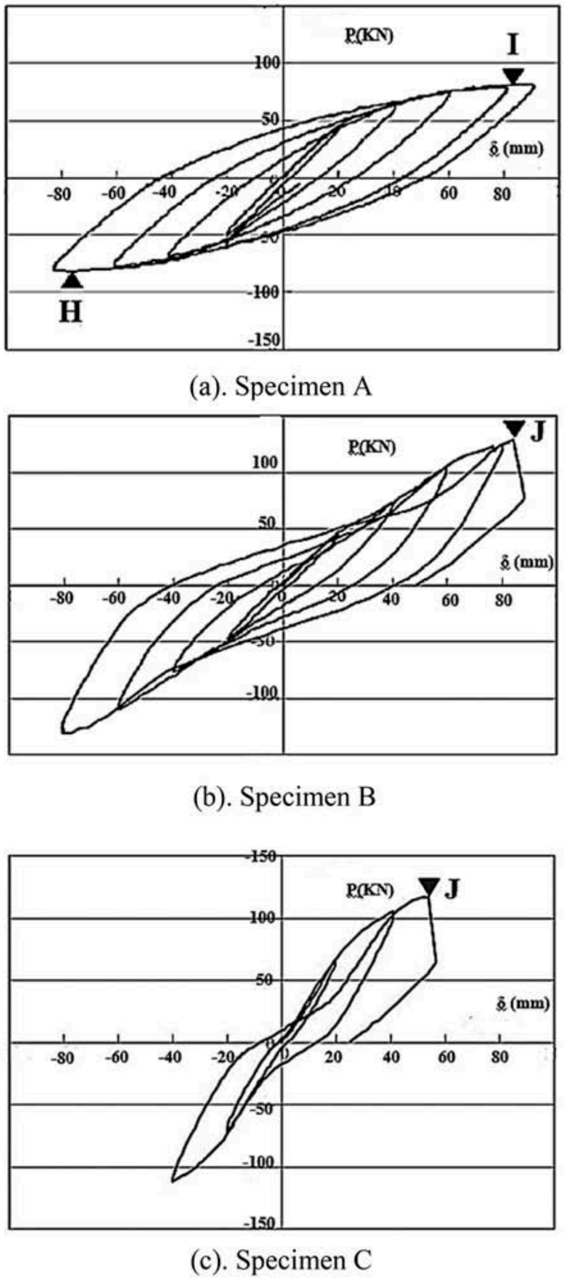

Figure 4. Hysteresis curves for laboratory samples [Tagawa and Hou, 2009]. (a) Specimen A, (b) Specimen B, and (c) Specimen C.

Assuming the displacement of the frame in one direction when one of the cables becomes straight: (a) the cables, inside and outside the cylinder, are placed in the same directions; (b) the strain becomes zero in the opposite cable. Accordingly, δ_{sr} is calculated in the stiff cylinder by solving the following equations [Aghajani, 2011]:

$$\begin{cases} \theta = \tan^{-1}\left(\frac{h_c}{l_b+\delta_{sr}}\right) - \tan^{-1}\left(\frac{y}{x}\right) \\ \sqrt{[(-l_b+\delta_{sr}) + x\cos\theta + y\sin\theta]^2 + [h_c + x\sin\theta - y\cos\theta]^2} = \sqrt{(l_b-x)^2 + (h_c-y)^2} \\ -\frac{F_{ps}}{AE}\left(\sqrt{(l_b-x)^2 + (h_c-y)^2} + \sqrt{(x^2+y^2)}\right) \end{cases} \tag{6}$$

where, θ is the rotation angle of the cylinder; F_{ps} is the pre-stressing force of cables; x is equal to lp (the length of the cylinder); and y = $\phi_P - \phi_B$ (ϕ_P is inner diameter of the cylinder); and ϕ_B is the cable diameter.

2. Incremental Dynamic Analysis (IDA)

The intrinsic randomness of earthquakes is one of the main uncertainties that should be considered in assessing the seismic behavior of structures. For quantifying such uncertainties, the seismic response of a structure should be determined by performing different dynamic analyses in the course of different earthquake ground motions. In this study, earthquake uncertainty has been considered using Incremental Dynamic Analysis (IDA). In this regard, sufficient numbers of records are used to consider the uncertainties in the frequency content and earthquake records' spectra shapes [Vamvatsikos and Cornell, 2002]. Then, each earthquake record is scaled in such a way to cover appropriate ranges of seismic intensities and also structural responses, from elastic limit to collapse. For IDA, the intensity measure (IM) (eg: PGA or S_a (T_1)) is scaled with a proper algorithm, starting from a very low amount to a certain level, in order to motivate the elastic response in the considered structural model and target collapse state, respectively. Time history analysis is conducted in IDA, using different records generated by various scale factors. DM (Damage Measure) values, corresponding to the IM levels, used in the dynamic analysis, are determined at the end of each analysis.

3. Applied Models

Three frame models, applied in this research, have the same specifications, excluding the sections of beam and column. The first and second models are considered for verification in OpenSees software. In these models, 3- and 1-story frames are used, respectively, with the assumptions of rigid beam and box section for columns. The third model is applied for pushover and incremental dynamic analyses, using one-story frame with the beam of IPE section, equivalent to the box section. The plastic section modulus of box section with the dimensions of 200 × 200 × 8 is 442.6 cm^3. The nearest plastic section modulus to this value is related to IPE270. IPB200 section has been used for the columns, as box sections are not ordinarily applied in one-story buildings.

Steel with a yielding stress of 300 MPa and elasticity modulus of 205 MPa is used for beams and columns. The slope of the inelastic region is considered as 1% of elastic one.

The story height and span length are 3.5 and 5 m, respectively, in the studied frames. The bracing complex, including cables and cylinder, are modeled in the form of truss in which the axial stiffness of the cylinder and its inner cables is 1500 times that of outside cables (α and β = 1500) [Tagawa and Hou, 2009], Fig. 5. Table 1 presents the specifications of a cable-cylinder bracing system [Nolan. Domenico, 1995; Tagawa and Hou, 2009].

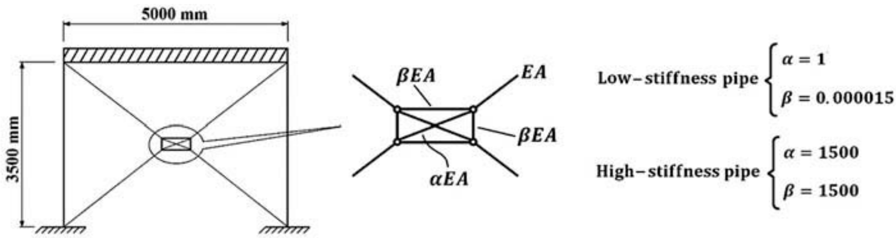

Figure 5. Modeling cable and cylinder [Tagawa and Hou, 2009].

Table 1. Specifications of a cable-cylinder bracing system.

Modulus of elasticity of cable (MPa)	Cable's section area) mm^2)	Ultimate tensile strain of cable	Diameter of cable (mm)	Internal diameter of cylinder)mm)	Length of cylinder)mm)
137000	374	0.015	28	200	703

3.1. *Modeling in OpenSees Software*

In this research, OpenSees software ver.2.4.5 has been used for modeling and performing nonlinear static and incremental dynamic analyses [Mazzoni *et al.*, 2007]. Nonlinear beam-column elements and fiber sections are used for modeling the beam and column. The nonlinear behavior of these elements has been modeled by applying Steel02 bi-linear material with 1% hardening. In the performed modeling, the cylinder is defined in the two-dimensional form, using four cable elements. Co-rotational truss element, two-end hinged element, has been used for modeling the cable. The cables have no compressive strengths and work only under tension. Therefore, an elastic-perfectly plastic material is used for expressing this specification and InitStressMaterial with initial stress for applying pre-stressing in the cables. The masses of stories are concentrated in the nodes.

Along with the global system, each element has a local coordinate system. Different geometric parameters of each element such as stiffness and ductility should be transmitted to the global system through appropriate transformation. In this research, the effects of P-delta have been considered using Transformation $P - \Delta$. In this method, the transition is performed linearly from a local coordinate system to the global coordinate system by considering the secondary effects of $P - \Delta$.

3.2. *Model Verification in OpenSees Software*

A two-dimensional 3-story frame has been analyzed with the specifications of one-story frame (the first model) in OpenSees software to verify the accuracy of modeling and proper selection of material and elements for the beam, column, cable, and cylinder. The calculated fundamental period is 0.69 s, exactly equal to that of ANSIS in the Tagawa model. Besides, nonlinear static analysis has been conducted on the one-story frame, presenting its pushover curve in Fig. 6.

According to this figure, the pushover curve, obtained from the OpenSees model, coincides with that of the Tagawa model in the nonlinear region with very slight difference. This fact verifies the geometric modeling, the selection of parameters in

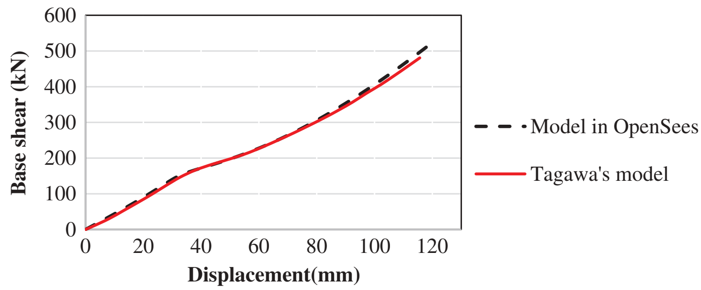

Figure 6. Pushover curves of the frame modeled in OpenSees and Tagawa's model.

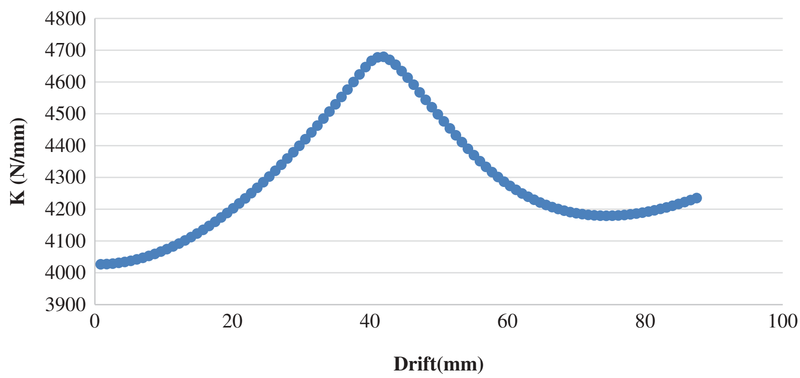

Figure 7. Stiffness-drift curve of cable-cylinder braced frame.

material modeling, the conditions for modeling the connections of structural elements and most particularly bracing elements in OpenSees software.

Fig. 7 presents the drift-stiffness curve of the frame. The stiffness is not constant in the steel cable-cylinder braces; and it increases with increase in the lateral displacement of the stories.

4. The Analysis Results

4.1. *Nonlinear Static Analysis*

Pushover curves plotted for a moment frame with cable-cylinder bracing system and a moment frame with cross-cable bracing are presented in Fig. 8. The value of 0.02 h has been used for calculating the target displacement in these braced frames [ASCE, 2007]. Table 2 presents the values of base shear corresponding to the first yielding.

4.2. *Selected Records for IDA*

Records of 10 well-known earthquakes have been selected for conducting incremental dynamic analysis on the considered frames. The specifications of these records have been presented in Table 3. Fig. 9 presents IDA curves related to a cable-cylinder bracing system [FEMA P695].

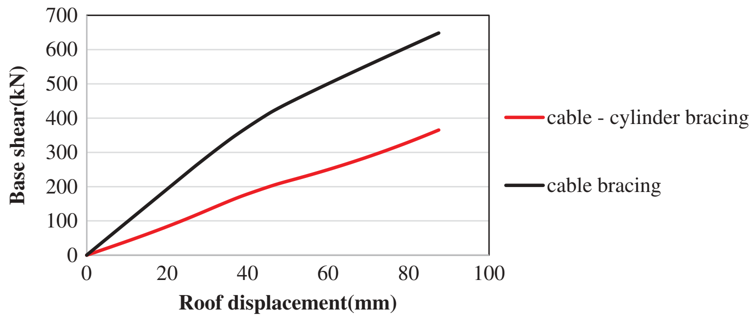

Figure 8. Pushover curves.

Table 2. Shear base corresponding to the first yielding.

System type	Base shear corresponding to the first yield (kN)
MRF+ Cross-cable bracing	361.64
MRF+ Cylinder-cable bracing	155.89

Table 3. Specifications of the records used in IDA.

Record No.	Record	Station name	Date of occurrence	PGA (g)
1	chi chi – Taiwan	CHY101	09/20/1999	0.398
2	Hectormine	Hector	10/16/1999	0.328
3	Imperial Valley	Delta	10/15/1979	0.35
4	Kobe	Nishi-Akashi	01/16/1995	0.483
5	Landers	Cool Water	06/28/1992	0.417
6	Kocaeli	Duzce	08/17/1999	0.364
7	Loma Prieta	Capitola	10/18/1989	0.511
8	Manjil	Abbar	06/20/1990	0.515
9	Northridge	Canyon Country	01/17/1994	0.472
10	Superstition Hills	Poe Road	11/24/1987	0.475

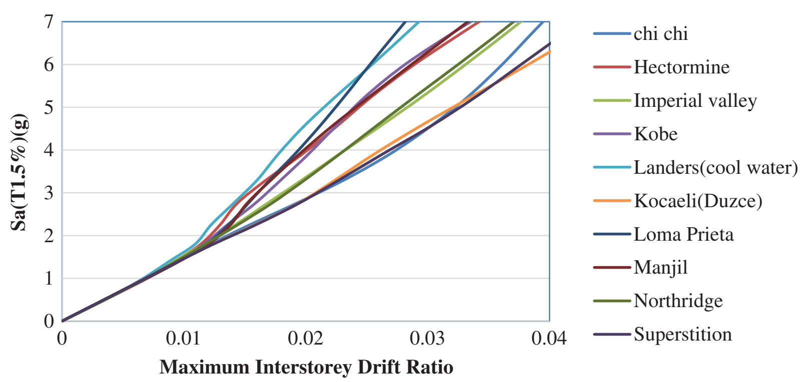

Figure 9. IDA curves for the moment frame with cable-cylinder bracing system.

4.3. *Calculating Response Modification Factor*

Nonlinear static and linear and nonlinear dynamic analyses are conducted on the moment frame with a cross-cable bracing system and moment frame with a cable-cylinder bracing system. Accordingly, their ductility, overstrength, and response modification factors are calculated for 10 records considered in the design methods of ultimate limit and allowable stress. The obtained results are presented in Tables 4–5. Moreover, by averaging the results, these factors are calculated for two kinds of considered frames and presented in Table 6. According to the tables, the frame with cable-cylinder bracing system has a higher ductility factor due to the presence of the cylinder, compared to that of a cross-cable bracing system. The bracing cables are deviated from their diameter direction by the cylinder, resulting in the increase in their lengths. Consequently, they reach their ultimate strengths in the higher drifts, causing an increase in ductility.

According to Tables 4 and 5, the response modification factor values obtained from the allowable stress design method are 4.17 and 4.94 in the cross-cable and cable-cylinder braces, respectively. It can be concluded that the response modification factor is higher in the cable-cylinder bracing system, compared to that of a cross-cable bracing system.

Table 4. Overstrength, ductility, and response modification factors of moment frame with cross-cable bracing system.

records	DM Max Drift	IM $S_a(T_1,5\%)$	$V_{b(Dyn,u)}$ (kN)	$V_{b(zt,y)}$ (kN)	$V_{b(Dyn,c)}$ (kN)	R_S	R_μ	R_{LRFD}	R_{ASD}
chi chi	0.02	0.62	804.28	361.64	1026.90	2.22	1.28	2.84	4.09
Hectormine	0.02	0.59	801.45	361.64	906.91	2.22	1.13	2.51	3.61
Imperial valley	0.02	0.92	805.24	361.64	1106.06	2.23	1.37	3.06	4.40
Kobe	0.02	0.79	806.43	361.64	1106.43	2.23	1.37	3.06	4.41
Landers(Cool Water)	0.02	0.52	800.97	361.64	960.29	2.21	1.20	2.66	3.82
Kocaeli(Duzce)	0.02	0.59	802.37	361.64	987.95	2.22	1.23	2.73	3.93
Loma Prieta	0.02	0.99	806.96	361.64	1264.75	2.23	1.57	3.50	5.04
Manjil	0.02	2.08	803.35	361.64	1048.47	2.22	1.31	2.90	4.17
Northridge	0.02	1.13	802.05	361.64	937.66	2.22	1.17	2.59	3.73
Superstition	0.02	0.71	806.58	361.64	1118.99	2.23	1.39	3.09	4.46
average						2.22	1.30	2.89	4.17
sigma						0.12	0.40	0.28	0.30
C.V						0.06	0.31	0.10	0.07

Table 5. Overstrength, ductility, and response modification factors of moment frame with cable-cylinder bracing system.

records	DM Max Drift	IM $S_a(T_1,5\%)$	$V_{b(Dyn,u)}$ (kN)	$V_{b(zt,y)}$ (kN)	$V_{b(Dyn,c)}$ (kN)	R_S	R_μ	R_{LRFD}	R_{ASD}
chi chi	0.02	0.83	373.50	155.89	444.72	2.39	1.19	2.85	4.11
Hectormine	0.02	0.98	353.87	155.89	482.18	2.27	1.36	3.09	4.45
Imperial valley	0.02	0.73	355.03	155.89	469.13	2.28	1.32	3.01	4.33
Kobe	0.02	1.34	360.59	155.89	574.23	2.31	1.59	3.68	5.30
Landers(Cool Water)	0.02	1.25	359.37	155.89	462.35	2.31	1.29	2.97	4.27
Kocaeli(Duzce)	0.02	1.11	359.37	155.89	538.13	2.31	1.50	3.45	4.97
Loma Prieta	0.02	1.81	363.86	155.89	762.98	2.33	2.10	4.89	7.05
Manjil	0.02	1.15	367.38	155.89	654.11	2.36	1.78	4.20	6.04
Northridge	0.02	1.25	368.66	155.89	460.66	2.36	1.25	2.96	4.26
Superstition	0.02	0.73	368.41	155.89	494.89	2.36	1.34	3.17	4.57
average						2.33	1.47	3.43	4.94
sigma						0.04	0.27	0.63	0.90
C.V						0.02	0.18	0.18	0.18

Table 6. Overstrength, ductility, and response modification factors of different structures.

System type	R_S	R_μ	R_{LRFD}	R_{ASD}
MRF+ Cross-cable bracing	2.22	1.3	2.89	4.17
MRF+ Cylinder-cable bracing	2.33	1.47	3.43	4.94

4.4. Variation of Response Modification Factor on Changing the Sections of Beam and Column

The values of response modification factor have been obtained for the moment frame with cross-cable bracing and cable-cylinder bracing systems, considering different sections of beam and column. Incremental dynamic analysis has been used for this purpose. The obtained results are briefly presented in Table 7.

According to the tables, the weaker the beam section is, the higher the response modification factor will be. The reason is that as the beam section becomes weaker, the first plastic hinge is formed in lower base shear, resulting in the increase in overstrength factor and response modification factor. Moreover, as the section of column becomes weaker, the frame becomes weaker as well. Consequently, lower base shears are observed in the frame, causing the decrease in response modification factor. In the moment frame with cable-cylinder bracing system, the base shear corresponding to the formation of first plastic hinge is almost constant due to their fixed beams.

5. Sensitivity Analysis

Sensitivity analysis is used to assess the effects of different parameters related to a model on the obtained response. In this research, the parameters are: length of cylinder, inner diameter of cylinder, and pre-stressing stress of cables. The response of the model is the response modification factor of a cable-cylinder bracing system in a one-story frame, calculated by IDA. A total of 27 statuses have been considered for performing sensitivity analysis and are presented in Table 8 (f_{ps} is pre-stressing stress of cables).

It should be mentioned that IDA has been performed for all 27 statuses. However, considering the limitation in presenting the curves, IDA curves are plotted only for the 7th and 27th statuses, corresponding to the highest and lowest values of response modification factor, respectively, Figs. 10 and 11.

The results of response modification factor are obtained for 27 mentioned statuses. For brevity, only the results corresponding to the 7th and 27th statuses are presented in Tables 9 and 10.

The average results obtained for response modification factor of the mentioned 27 statuses are briefly presented in Table 11.

Table 7. Variation of response modification factor by changing the sections of beam and column.

	Beam	Column	V_s (kN)	V_u (kN)	V_e (kN)	R_s	R_μ	R_{LRFD}
MRF+ Cross-cable bracing	IPE270	IPB200	361.64	803.97	1046.44	2.22	1.3	2.89
	IPE240		282.34	777.10	893.25	2.75	1.15	3.16
	IPE220		218.96	761.92	874.89	3.48	1.15	4.00
	IPE220	IPB200	218.96	761.92	874.89	3.48	1.15	4.00
		IPB180	247.87	735.41	865.86	2.97	1.18	3.49
		IPB160	307.94	711.90	848.08	2.31	1.19	2.75
MRF+ Cylinder-cable bracing	IPE270	IPB200	155.89	368.66	460.66	2.36	1.25	2.95
	IPE240		106.89	348.57	469.14	3.26	1.35	4.39
	IPE220		73.04	335.63	467.51	4.60	1.39	6.40
	IPE220	IPB200	73.04	335.63	467.51	4.60	1.39	6.40
		IPB180	73.46	306.18	393.07	4.17	1.28	5.35
		IPB160	81.86	282.44	341.92	3.45	1.21	4.18

Table 8. Different statuses for performing sensitivity analysis.

Run	l_p (mm)	φ_p (mm)	f_{ps} (MPa)	Run	l_p (mm)	φ_p (mm)	f_{ps} (MPa)	Run	l_p (mm)	φ_p (mm)	f_{ps} (MPa)
1	580	80	100	10	640	80	100	19	700	80	100
2	580	80	300	11	640	80	300	20	700	80	300
3	580	80	500	12	640	80	500	21	700	80	500
4	580	140	100	13	640	140	100	22	700	140	100
5	580	140	300	14	640	140	300	23	700	140	300
6	580	140	500	15	640	140	500	24	700	140	500
7	580	200	100	16	640	200	100	25	700	200	100
8	580	200	300	17	640	200	300	26	700	200	300
9	580	200	500	18	640	200	500	27	700	200	500

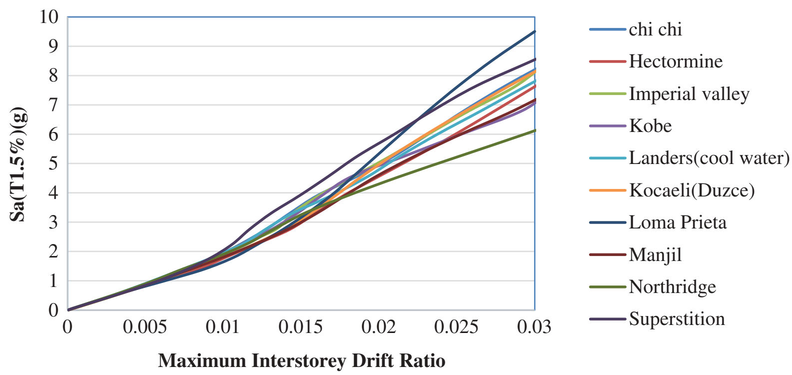

Figure 10. IDA curves for the frame with cable-cylinder bracing system in the 7th status.

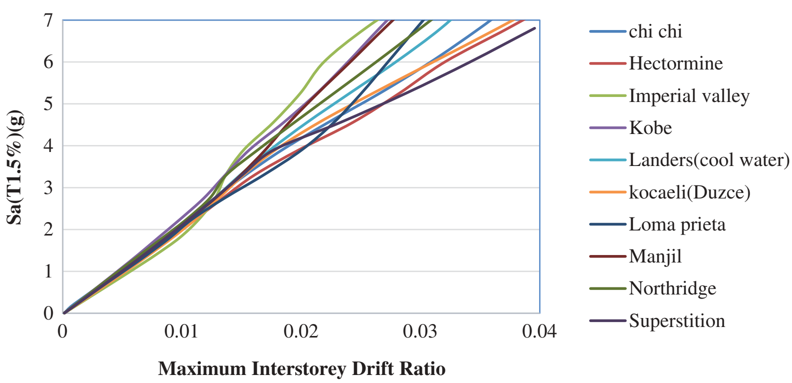

Figure 11. IDA curves for the frame with cable-cylinder bracing system in the 27th status.

In all statuses, the response modification factor of the system decreases with increase in pre-stressing stress of cables. On the one hand, base shear of the first hinge formation in the beam increases with increase in pre-stressing stress. On the other hand, the period of braced frame is reduced with increase in pre-stressing stress, resulting in a stiffer structure. In most statuses, increasing the cylinder length and decreasing the inner diameter of the cylinder, or in the other words, the increase

Table 9. Overstrength, ductility, and response modification factors of model in the 7th status.

records	DM Max Drift	IM $S_a(T_1,5\%)$	$V_{b(Dyn,u)}$ (kN)	$V_{b(zt,y)}$ (kN)	$V_{b(Dyn,c)}$ (kN)	R_S	R_μ	R_{LRFD}	R_{ASD}
chi chi	0.02	0.81	596.52	213.92	694.44	2.79	1.16	3.25	4.67
Hectormine	0.02	0.83	535.53	213.92	625.01	2.50	1.17	2.92	4.21
Imperial valley	0.02	0.68	596.52	213.92	756.28	2.79	1.27	3.54	5.09
Kobe	0.02	1.29	596.52	213.92	796.91	2.79	1.34	3.73	5.36
Landers(Cool Water)	0.02	0.92	516.74	213.92	596.52	2.42	1.15	2.79	4.02
Kocaeli(Duzce)	0.02	1.34	516.74	213.92	619.78	2.42	1.20	2.90	4.17
Loma Prieta	0.02	2.00	516.74	213.92	769.24	2.42	1.49	3.60	5.18
Manjil	0.02	1.14	516.74	213.92	867.08	2.42	1.68	4.05	5.84
Northridge	0.02	1.02	539.47	213.92	815.79	2.52	1.51	3.81	5.49
Superstition	0.02	0.84	534.07	213.92	596.52	2.50	1.12	2.79	4.02
average						2.55	1.31	3.34	4.80
sigma						0.16	0.18	0.44	0.64
C.V						0.06	0.14	0.13	0.13

Table 10. Overstrength, ductility, and response modification factors of model in the 27th status.

records	DM Max Drift	IM $S_a(T_1,5\%)$	$V_{b(Dyn,u)}$ (kN)	$V_{b(zt,y)}$ (kN)	$V_{b(Dyn,c)}$ (kN)	R_S	R_μ	R_{LRFD}	R_{ASD}
chi chi	0.02	0.65	475.15	239.49	546.74	1.98	1.15	2.28	3.29
Hectormine	0.02	0.63	475.07	239.49	529.61	1.98	1.11	2.21	3.18
Imperial valley	0.02	0.68	447.94	239.49	730.96	1.87	1.63	3.05	4.40
Kobe	0.02	1.48	459.13	239.49	785.02	1.92	1.71	3.28	4.72
Landers(Cool Water)	0.02	0.82	467.98	239.49	578.66	1.95	1.24	2.42	3.48
Kocaeli(Duzce)	0.02	0.99	452.53	239.49	515.37	1.89	1.14	2.15	3.10
Loma Prieta	0.02	1.52	449.86	239.49	589.09	1.88	1.31	2.46	3.54
Manjil	0.02	1.23	451.59	239.49	713.58	1.89	1.58	2.98	4.29
Northridge	0.02	1.21	476.64	239.49	706.54	1.99	1.48	2.95	4.25
Superstition	0.02	0.58	470.38	239.49	495.83	1.96	1.05	2.07	2.98
average						1.93	1.34	2.59	3.72
sigma						0.05	0.23	0.41	0.60
C.V						0.02	0.17	0.16	0.16

in δ_{sr}, causes the most deviation of the cable from its initial direction or from the frame's diameter. This results in the increase in cable's length from the frame's diameter. Consequently, the cable reaches its ultimate strength in the higher drift causing an increase in ductility in the frame braced with cable and cylinder, and subsequently an increase in ductility factor. Moreover, overstrength factor is reduced with the increase in δ_{sr}. As the effects of overstrength are higher in the cable-cylinder bracing system, compared to that of ductility, the response modification factor (ductility factor times overstrength factor) is reduced with the increase in δ_{sr}. It should be mentioned that the reduction of the response modification factor cannot be strictly claimed in the high pre-stressing stress. According to Table 11, the highest change in the response modification factor with change in the length of the cylinder, inner diameter of the cylinder, and pre-stressing stress of cables is 0.34, 0.377, and 0.612, respectively, considering the response modification factor values of different statuses. Accordingly, the response modification factor is more sensitive to pre-stressing stress of cables, compared to the dimensions of the cylinder. The curves are plotted for the sensitivity of the response modification factor against each parameter of the cable-cylinder bracing system and are presented below.

Table 11. Overstrength, ductility, and response modification factors for 27 statuses.

Run	l_p (mm)	φ_p (mm)	f_{ps} (MPa)	R_s	R_μ	R_{LRFD}
1	580	80	100	1.83	1.68	3.05
2	580	80	300	1.79	1.58	2.83
3	580	80	500	1.77	1.50	2.64
4	580	140	100	2.18	1.46	3.18
5	580	140	300	2.05	1.43	2.92
6	580	140	500	1.92	1.34	2.56
7	580	200	100	2.56	1.31	3.34
8	580	200	300	2.23	1.43	3.20
9	580	200	500	2.04	1.37	2.80
10	640	80	100	1.72	1.72	2.95
11	640	80	300	1.70	1.64	2.78
12	640	80	500	1.70	1.54	2.61
13	640	140	100	2.01	1.56	3.12
14	640	140	300	1.94	1.46	2.83
15	640	140	500	1.84	1.43	2.63
16	640	200	100	2.37	1.41	3.33
17	640	200	300	2.12	1.35	2.85
18	640	200	500	2.02	1.41	2.86
19	700	80	100	1.68	1.73	2.90
20	700	80	300	1.64	1.70	2.77
21	700	80	500	1.64	1.63	2.68
22	700	140	100	1.87	1.65	3.07
23	700	140	300	1.83	1.53	2.81
24	700	140	500	1.80	1.48	2.66
25	700	200	100	2.20	1.45	3.19
26	700	200	300	2.07	1.42	2.92
27	700	200	500	1.93	1.34	2.59

The variation of the response modification factor versus length and internal diameter of the cylinder and pre-stressing stress of cables are presented in Tables 12–14. These variations are graphically depicted in Figs. 12–14 as well.

Based on Table 12, Fig. 12, and the discussion presented at the beginning of this section, the response modification factor increases with increase in cylinder diameter and decrease in cylinder length.

Assuming the length and internal diameter of the cylinder are constant, the response modification factor decreases with increase in pre-stressing stress. In the case of constant

Table 12. The variation of response modification factor versus length and internal diameter of the cylinder with assumed 100 MPa pre-stressing stress.

f_{ps} = 100 MPa		
L_p (mm)	φ_p (mm)	R_{LRFD}
580	80	3.05
580	140	3.18
580	200	3.34
640	80	2.95
640	140	3.11
640	200	3.33
700	80	2.90
700	140	3.07
700	200	3.19

Table 13. The variation of response modification factor versus the internal diameter of the cylinder and pre-stressing stress with assumed 580 mm cable length.

L_p = 580 mm		
φ_p (mm)	f_{ps} (MPa)	R_{LRFD}
80	100	3.05
80	300	2.83
80	500	2.64
140	100	3.18
140	300	2.92
140	500	2.56
200	100	3.34
200	300	3.20
200	500	2.80

Table 14. The variation of response modification factor versus cylinder length and pre-stressing stress with assumed 80 mm internal diameter.

φ_p = 80 mm		
L_p (mm)	f_{ps} (MPa)	R_{LRFD}
580	100	3.05
580	300	2.83
580	500	2.64
640	100	2.95
640	300	2.78
640	500	2.61
700	100	2.90
700	300	2.77
700	500	2.68

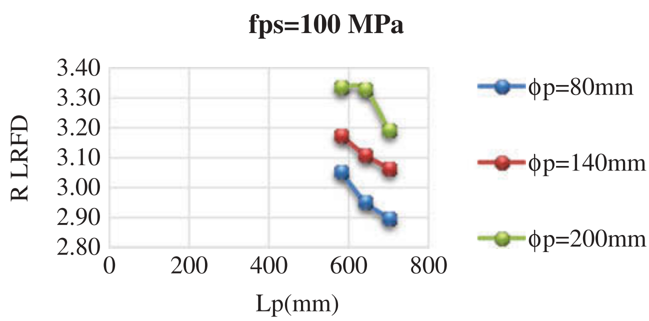

Figure 12. The variation of response modification factor versus the length and internal diameter of the cylinder with assumed 100 MPa pre-stressing stress.

length and pre-stressing, the response modification factor increases with increase in internal diameter of the cylinder.

According to Table 14 and Fig. 14, the response modification factor is reduced with the increase in cylinder length of the cylinder with constant diameter and pre-stressing stress.

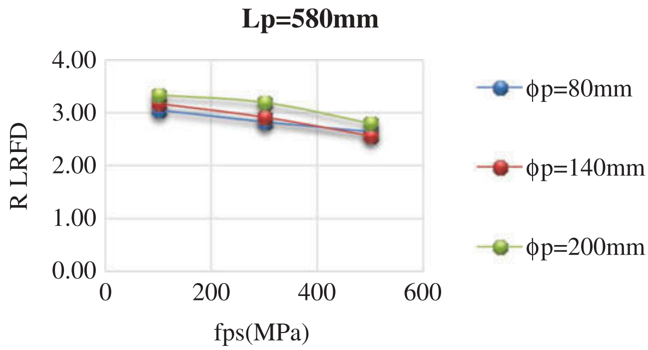

Figure 13. The variation of response modification factor versus the internal diameter of the cylinder and pre-stressing stress with assumed 580 mm cable length.

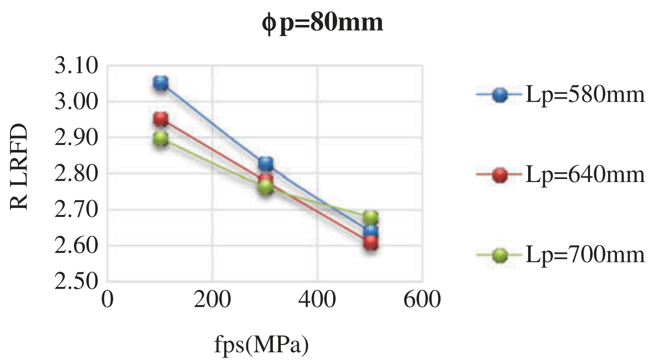

Figure 14. The variation of response modification factor versus cylinder length and pre-stressing stress with assumed 80 mm internal diameter.

6. A Relation for Response Modification Factor of Cable-Cylinder Bracing System

In this section, a relation is presented for calculating the response modification factor of the cable-cylinder bracing system as per cylinder length, cylinder internal diameter, and pre-stressing stress of cables, using the results of sensitivity analysis and performing response surface method.

The response surface method explains the relation between one dependent variable and several independent variables. This method is a combination of statistical and mathematical techniques, used for developing a proper relation between the considered response surface (y) and input variables (x_1, x_2, …, x_k). The central composite method is the most applicable response surface method. In this method, three surfaces of high, medium, and low are considered for each factor that can be used in all possible experiments (3^k experiments) or subset of 3^k experiments (k is the number of independent variables of the problem). In the present research, the central composite method has been used for developing an equation, considering all of experiments [Khuri and Mukhopadhyay, 2010].

Based on the central composite method, three values are considered for each variable: cylinder lengths of 580, 640, and 700 mm; cylinder diameters of 80, 140, and 200 mm; and cable pre-stressing stresses of 100, 300, and 500 MPa. It should be mentioned that Minitab software has been used to develop the equation.

A relation is suggested for calculating the response modification factor as per the mentioned variables and presented as follows:

$$\begin{aligned} R_{LRFD} &= 7.03 - 0.01297L_p + 0.00892\varphi_p - 0.001881F_{ps} \\ &+ 0.000010L_p \times L_p - 0.000003\varphi_p \times \varphi_p + 0.000001F_{ps} \times F_{ps} \\ &- 0.000008L_p \times \varphi_p + 0.000001L_p \times F_{ps} - 0.000005\varphi_p \times F_{ps} \end{aligned} \tag{7}$$

where, L_p is the cylinder length; φ_p is the cylinder internal diameter, and F_{ps} is the pre-stressing stress of cables.

The results obtained from sensitivity analysis along with the values predicted by Eq. (7) have been presented in Table 15 and are used for verifying the equation.

The values of response modification factor are obtained through sensitivity analysis through the Uang method and also by Eq. (7).

Regarding the results presented in Table 15 and Fig. 15, the suggested formula has proper accuracy in presenting the response modification factor as per length and internal diameter of the cylinder and pre-stressing stress of cables.

Table 15. The values of response modification factor obtained from Uang method and Minitab software.

Run	L_p (mm)	φ_p (mm)	f_{ps} (MPa)	R_{LRFD} (Calculated)	R_{LRFD} (Minitab)	Error (%)
1	580	80	100	3.05	3.03	0.64
2	580	80	300	2.83	2.77	1.90
3	580	80	500	2.64	2.59	1.74
4	580	140	100	3.18	3.22	1.47
5	580	140	300	2.92	2.90	0.46
6	580	140	500	2.56	2.66	3.84
7	580	200	100	3.34	3.39	1.51
8	580	200	300	3.20	3.01	5.88
9	580	200	500	2.80	2.71	3.32
10	640	80	100	2.95	2.96	0.10
11	640	80	300	2.78	2.71	2.60
12	640	80	500	2.61	2.54	2.70
13	640	140	100	3.11	3.11	0.14
14	640	140	300	2.83	2.81	0.77
15	640	140	500	2.63	2.58	1.94
16	640	200	100	3.33	3.25	2.37
17	640	200	300	2.85	2.88	1.15
18	640	200	500	2.86	2.75	3.74
19	700	80	100	2.90	2.95	1.77
20	700	80	300	2.77	2.71	1.88
21	700	80	500	2.68	2.56	4.59
22	700	140	100	3.07	3.08	0.45
23	700	140	300	2.81	2.78	0.83
24	700	140	500	2.66	2.57	3.52
25	700	200	100	3.19	3.19	0.22
26	700	200	300	2.92	2.83	3.03
27	700	200	500	2.59	2.55	1.18

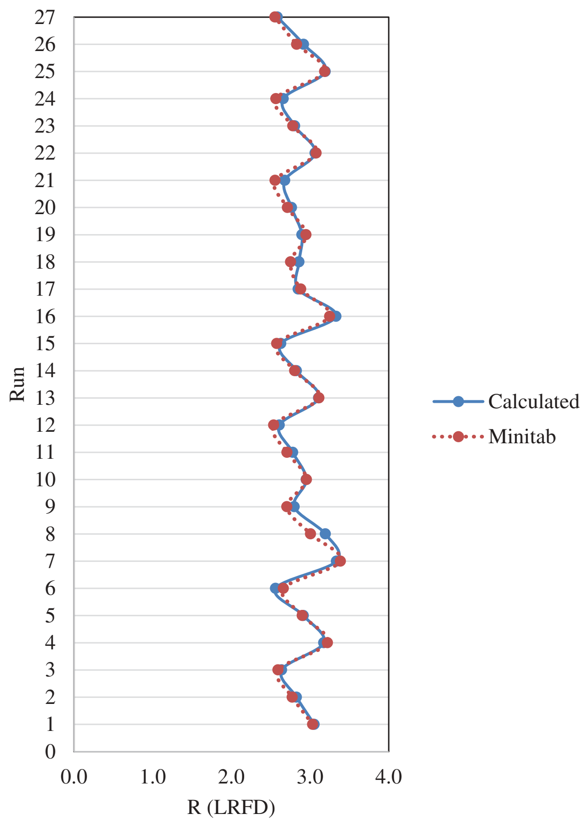

Figure 15. The response modification factors, calculated by OpenSees and Minitab for different sensitivity analyses.

7. Effect of Pre-Stressing on the Fundamental Period

In this section, fundamental period is assessed in the cable-cylinder bracing system against pre-stressing stress of cables in the 0–500 MPa range with a step of 10 MPa. The specifications of the studied braced frame are the same as the third model, presented in Sec. 3 (Applied models). The obtained results are presented in Table 16 and Fig. 16. (T_0 in the table is the fundamental period under zero pre-stressing stress).

As it is expected, with increase in pre-stressing stress and subsequently pre-stressing strain, the fundamental period is reduced because the structure becomes stiffer. A relation is obtained for the fundamental period as per pre-stressing strain, using regression analysis and is presented as follows:

$$\frac{T}{T_0} = 1 - 83.31\varepsilon + 7940.6\varepsilon^2 \tag{8}$$

Table 16. The change of fundamental period with change in pre-stressing strain of cables in cable-cylinder bracing.

Prestressing Strain	T/T0	Prestressing Strain	T/T0	Prestressing Strain	T/T0
0.000000	1.000	0.001241	0.906	0.002482	0.842
0.000073	0.995	0.001314	0.902	0.002555	0.839
0.000146	0.989	0.001387	0.898	0.002628	0.836
0.000219	0.982	0.001460	0.893	0.002701	0.833
0.000292	0.975	0.001533	0.889	0.002774	0.830
0.000365	0.969	0.001606	0.885	0.002847	0.827
0.000438	0.963	0.001679	0.881	0.002920	0.824
0.000511	0.958	0.001752	0.877	0.002993	0.821
0.000584	0.952	0.001825	0.873	0.003066	0.818
0.000657	0.946	0.001898	0.869	0.003139	0.816
0.000730	0.941	0.001971	0.866	0.003212	0.813
0.000803	0.935	0.002044	0.862	0.003285	0.810
0.000876	0.930	0.002117	0.859	0.003358	0.808
0.000949	0.925	0.002190	0.855	0.003431	0.805
0.001022	0.920	0.002263	0.852	0.003504	0.803
0.001095	0.915	0.002336	0.848	0.003577	0.800
0.001168	0.911	0.002409	0.845	0.003650	0.798

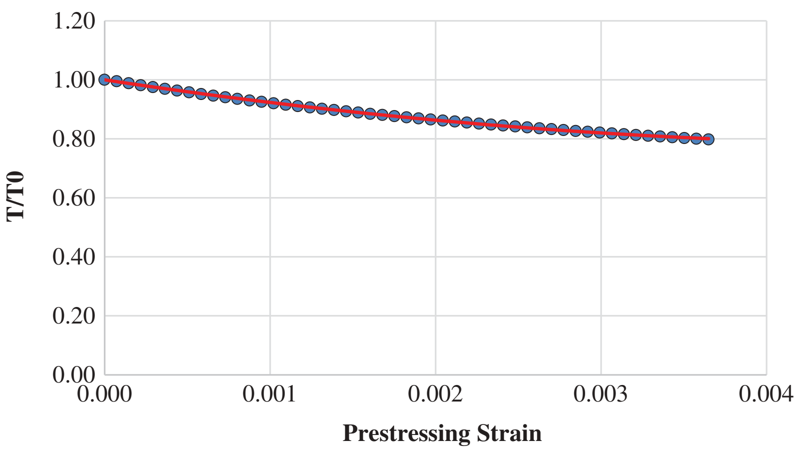

Figure 16. The curve of variation of fundamental period with changing pre-stressing strain.

8. Conclusion

One modern bracing systems uses a cable with a cylinder in which a couple of cables pass through the cylinder at their intersections. In such a bracing system, the cables are used in such a way as to remove the weakness of cables' ductility. So far, few theoretical and experimental researches have been conducted on the mentioned bracing systems. Little knowledge is available about the behavior of these braces due to insufficient literature.

In this research, the response modification factor is obtained for a one-story two-dimensional Tagawa frame and compared with that of a cross-cable bracing frame. Then, sensitivity analysis is conducted on this frame. All analyses have been performed using IDA and 10 earthquake records.

The results obtained from assessing the cable-cylinder system are briefly summarized as follows:

(a) Response modification factor is obtained as 4.94 for the one-story frame with cable-cylinder bracing (Tagawa model) in the allowable stress design method.
(b) The values of overstrength factors are 2.22 and 2.33 for the moment frame with cross-cable bracing and moment frame with cable-cylinder bracing, respectively.
(c) The values of ductility factors are 1.30 and 1.47 for the moment frame with cross-cable bracing and moment frame with cable-cylinder bracing, respectively.
(d) The ductility of cable-cylinder bracing system is higher compared to that of cross-cable bracing system.
(e) The weaker the beam section and the stronger the column section are, the higher the response modification factor is.
(f) Sensitivity analysis is performed on the one-story frame with cable-cylinder bracing system. Accordingly, in most statuses, overstrength factor decreases and ductility factor increases with increase in cylinder length and decrease in internal diameter of the cylinder (in the other words with the increase of δ_{sr}).
(g) In low pre-stressing, response modification factor decreases with increase in cylinder length and decrease in internal diameter of the cylinder (in the other words with the increase of δ_{sr}).
(h) Response modification factor decreases with increase in pre-stressing, due to the increase of base shear corresponding to the first plastic hinge formation and decrease of fundamental period. Subsequently, the structure is stiffened.
(i) The highest values of response modification factor obtained by changing the length and internal diameter of the cylinder and pre-stressing stress of cables are 0.34, 0.377 and 0.612, respectively. The sensitivity of response modification factor is higher to changes in pre-stressing stress, compared to that of the cylinder dimensions.
(j) A relation is presented for obtaining response modification factor as a function of cylinder length, the internal diameter of cylinder, and pre-stressing stress of cables, using the response surface method and Minitab software. Besides, a relation is also suggested for calculating the fundamental period of a cable-cylinder bracing system versus pre-stressing strain of cables.

References

Aghajani, S. [2011] "Assessment of behaviour of steel frames with cable bracing," Master thesis, Under supervision of Dr. Nader Fanaie, K.N. Toosi University of Technology.

ASCE/SEI 41-06. [2007] *Seismic Rehabilitation of Existing Buildings.*

Fanaie, N., Aghajani, S., and Afsar Dizaj, E. [2016a] "Strengthening of moment-resisting frame using cable-cylinder bracing," *Advances in Structural Engineering*, 1–19.

Fanaie, N., Aghajani, S., and Afsar Dizaj, E. [2016b] "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," *15th World Conference on Earthquake Engineering*, LISBON.

Fanaie, N. and Aghajani, S. [2012] "Wire-rope bracing system with central cylinder," *Finite Element Based Application. 15th World Conference on Earthquake Engineering*, LISBON.
FEMA P695. [2009] *Quantification of Building Seismic Performance Factors*.
Khuri, A. and Mukhopadhyay, S. [2010] "Response surface methodology," *Wiley Interdisciplinary Reviews: Computational Statistics* **2**(2), 128–149.
Mazzoni, S., McKenna, F., Scott, M. H., Fenves, G. L., and Jeremic, B. [2007] *Opensees Command Language Manual*.
Nolan, G. D. [1995] "Bond Properties of CFCC Prestressing strand in pretensioned concrete beams," Master of Science in Civil Engineering, Department of Civil and Geological Engineering, University of Manitoba.
Tagawa, H. and Hou, X. [2009] "Diplacement-rastraint bracing for seismic retrofit of steel moment frames," *Journal of Constructional Steel Research* **65**, 1096–1104.
Tagawa, H. and Hou, X. [2007] "Seismic retrofit of ductile moment resisting frames using wire-rope bracing," *Proceedings of the Eighth Pacific Conference on Earthquake Engineering*.
Vamvatsikos, D. and Cornell, C. A. [2002] "The incremental dynamic analysis and its application to performance-based earthquake engineering," *12th European Conference on Earthquake Engineering*, Paper Reference 479.