# Wire-rope Bracing System with Central Cylinder, Finite Element Based Application

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**15 WCEE**
LISBOA 2012

SUMMARY:

Wire-rope bracing system with a central cylinder is a modern bracing system, which can be used in strengthening steel and concrete Moment Resistant Frame (MRF). This paper is focused on several multi- story steel MRFs with cable-cylinder bracing subjected to seismic loads. In this regard multi-story steel MRFs are analyzed with and without cable bracing systems. The effectiveness of cable-cylinder bracing system is then discussed by the obtained results. A model of MRF with cable-cylinder bracing has been implemented in the finite element program (ABAQUS) in order to predict the frames' behaviors for cylinders with different rigidities. The cylinders of both high and low stiff have been used in finite element modeling. According to the conducted analyses, both cables are in tension under lateral loads in the high stiff cylinder and therefore rotation of central cylinder causes no slack in the cables. However, in low stiff modeling, only one cable experiences the tension force. Regarding seismic responses, the bracing systems prevent any increasing in column compression force, resulted by brace actions. In cable-cylinder bracing system, the story drifts are limited to a specified range; however, no significant increase occur in the story shear force.

*Key words: cable-cylinder bracing; story drift; story shear; soft cylinder; rigid cylinder*

## 1. INTRODUCTION

Seismic rehabilitation of existing buildings is a difficult task. Several factors involved in rehabilitation are: architectural constraints, cost of possibly closing the building (or part of it) and the necessity of heavy equipments. Concentric bracings are worth considering as they are simple and effective rehabilitation system, especially where story drifts should be limited. Bracing systems should be strong enough to resist against the seismic forces and yet light enough to guarantee the existing structural elements for further reinforcement. Additionally, these systems would be still more desirable if they are installed quickly without needing the evacuation of structures (eg: seismic rehabilitation of hospitals) (Berman, Celik & Bruneau, 2005). The bracing system with tension–only elements such as cables can be installed easily. This system is effective in seismic rehabilitation due to its minimum requirement to the site construction, no need to heavy equipments and resulting in minimal environmental impact and noise (Kurata, DesRoches, & Leon, 2012).

Cables are defined as flexible tension members with negligible resistance against bending. Cables with high strength-to-weight ratio have a variety of applications in civil engineering (Jeong-In & Sung Pil, 2000). They are frequently used in bridges and large span spatial structures; however, their application in the buildings has been limited (Azhar Saleem & Mazhar Saleem, 2010; Osamu, Kouhei, & Taro, 1999). Some researchers have examined the application of cables in buildings (Tan & Astaneh-Asl, 2003; Chuang, Zhuge & McBean, 2004; Kurata et al., 2012). Wire rope bracing system with a central cylinder is a modern bracing system, shown in Fig. 1.1. The bracing members do not act for small and medium

vibration amplitudes, while in the large ones they prevent unacceptable large story drift, Fig. 1.1. (Tagawa & Hou, 2009).
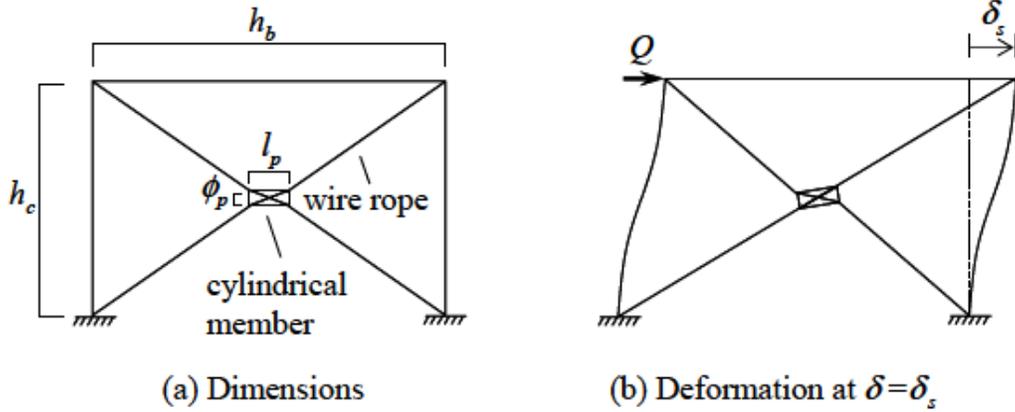


(a) Dimensions        (b) Deformation at $\delta=\delta_s$

**Figure 1.1.** Wire rope bracing system with central cylinder (Tagawa and Hou 2007)

The story drift $\delta_s$ at which the bracing member starts acting is controlled by cylindrical member size and, expressed as follows:

$$\delta_s = \sqrt{\left(2l_b + d_p\right)^2 - h_c^{\,2}} - h_b \tag{1.1}$$

Where, $h_c$ is column length; $h_b$ is beam length; $d_p$ and $l_b$ are defined as follows:

$$d_p = \sqrt{l_p^{\,2} + \left(\varphi_p - \varphi_b\right)^2} \tag{1.2}$$

$$l_b = \sqrt{\left(\frac{h_b - l_p}{2}\right)^2 + \left(\frac{h_c - \varphi_p}{2}\right)^2} \tag{1.3}$$

Where, $l_p$ is length of cylindrical member; $\varphi_p$ is inner diameter of cylindrical member; $\varphi_b$ is wire rope diameter (Tagawa & Hou, 2009)

## 2. ANALYTICAL MODELS

### 2.1. Specifications of Models

Pushover and time history analysis is conducted for two-story frames and shown in Fig. 2.1. The models are A (MRF), B (MRF with typical cable bracing), and C (MRF with cable-cylinder bracing). The model A is designed using AISC360-05. Equivalent static analysis is used for seismic design of structures and base shear coefficient is calculated based on Iranian seismic code. The yield strength and modulus of elasticity are presumed as 240MPa and 210 GPa, respectively. Bilinear stress_strain relationship with 2 percent strain hardening is used in the analyses. European wide flange sections (IPB and IPE) are selected for column and beam members. The live loads are assumed as 2 kN/m$^2$ and 1.5 kN/m$^2$ for the roof and

first story floor, respectively; the dead load of 6 kN/m$^2$ is considered for the whole structures. The sections used in two-story MRF model are presented in Table 2.1.

**Table 2.1.** The beams and columns used in all frames

| Story | Columns | Beams |
|---|---|---|
| 1 | IPE240 | IPB180 |
| 2 | IPE240 | IPB180 |

To determine the bracing system of model B, some preliminary seismic analyses are conducted using ABAQUS software and finally same steel cable bracings with section area of 5.9cm$^2$ are assigned in all stories. Cables have sufficient tensile strength to remain elastic during the selected earthquakes. The cable bracings are the same in the models C and B. The length and inner diameter of rigid cylindrical member (steel pipe) are 220 mm and 50 mm, respectively.
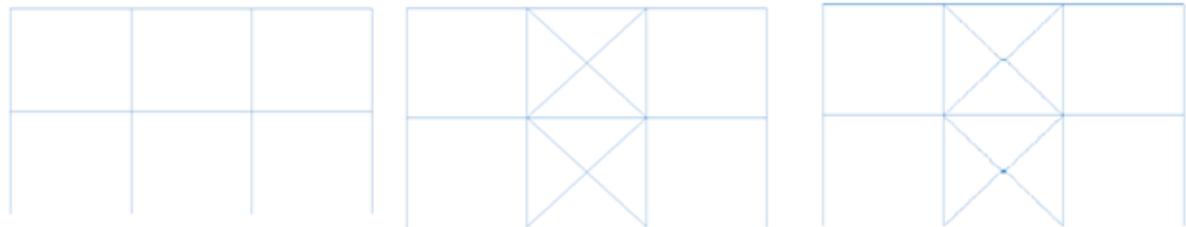


(a) Model A(bare frame).     (b) Model B(typical braced frame).   (c) Model C(cable-cylinder braced frame).

**Figure 2.1.** Modeled frames

## 2.2. Pushover Analysis

Static pushover analysis is conducted on one-story simple frame with cable-cylinder bracing in order to determine the hysteresis characteristics. The column and beam members are modeled as beam elements. The wire ropes, located inside and outside the cylinder, are modeled using truss elements with axial rigidity of AE and αEA, respectively, and the cylindrical member with that of βEA. The low and high stiff pipes are simulated using two coefficients α and β. The low and high stiff pipes are modeled with extremely low (0.001 times the cable axial rigidity) and extremely high (1000 times the cable axial rigidity) stiff elements, respectively. The geometrical nonlinearity should be considered in the analysis. The relationships between lateral force and displacement (P-δ curves) are obtained from static pushover analysis and shown in Fig. 2.2. In the braced frame with low- stiff pipe, the brace starts acting when the story drift reaches $\delta_s$ (25 mm); this fact confirms the validity of Eq (1-1). Regarding the braced frame with high-stiff pipe, the bracing members start acting earlier than $\delta_s$; thereby two P-δ curves are separated before $\delta_s$. However, the initial stiffness is zero in both cases. For $\delta > \delta_s$ the difference between two curves decreases as δ increases and finally they intersect each other.

The strain of cables is depicted versus the displacement of frame (ε-δ curves), Fig. 2.3. According to the figure, both cables are always in tension in the high stiff pipe (steel pipe); therefore, their slacks and hittings are disappeared.
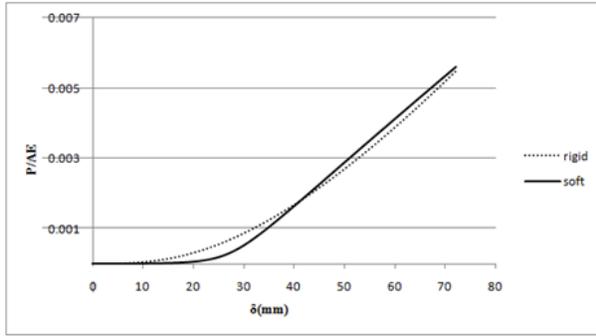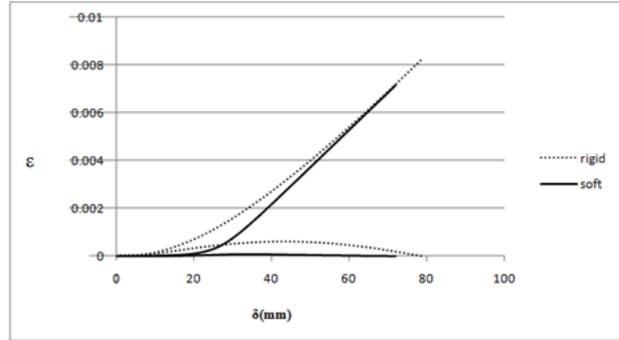
**Figure 2.2.** P-δ curves for soft and rigid cylinders



**Figure 2.3.** ε-δ curves for soft and rigid cylinders

## 3. TIME HISTORY ANALYSIS

Six earthquake records are used for time history analysis. Each acceleration record is scaled in such a way that the maximum accelerations reach 5oo cm/s², shown in Fig. 3.1.
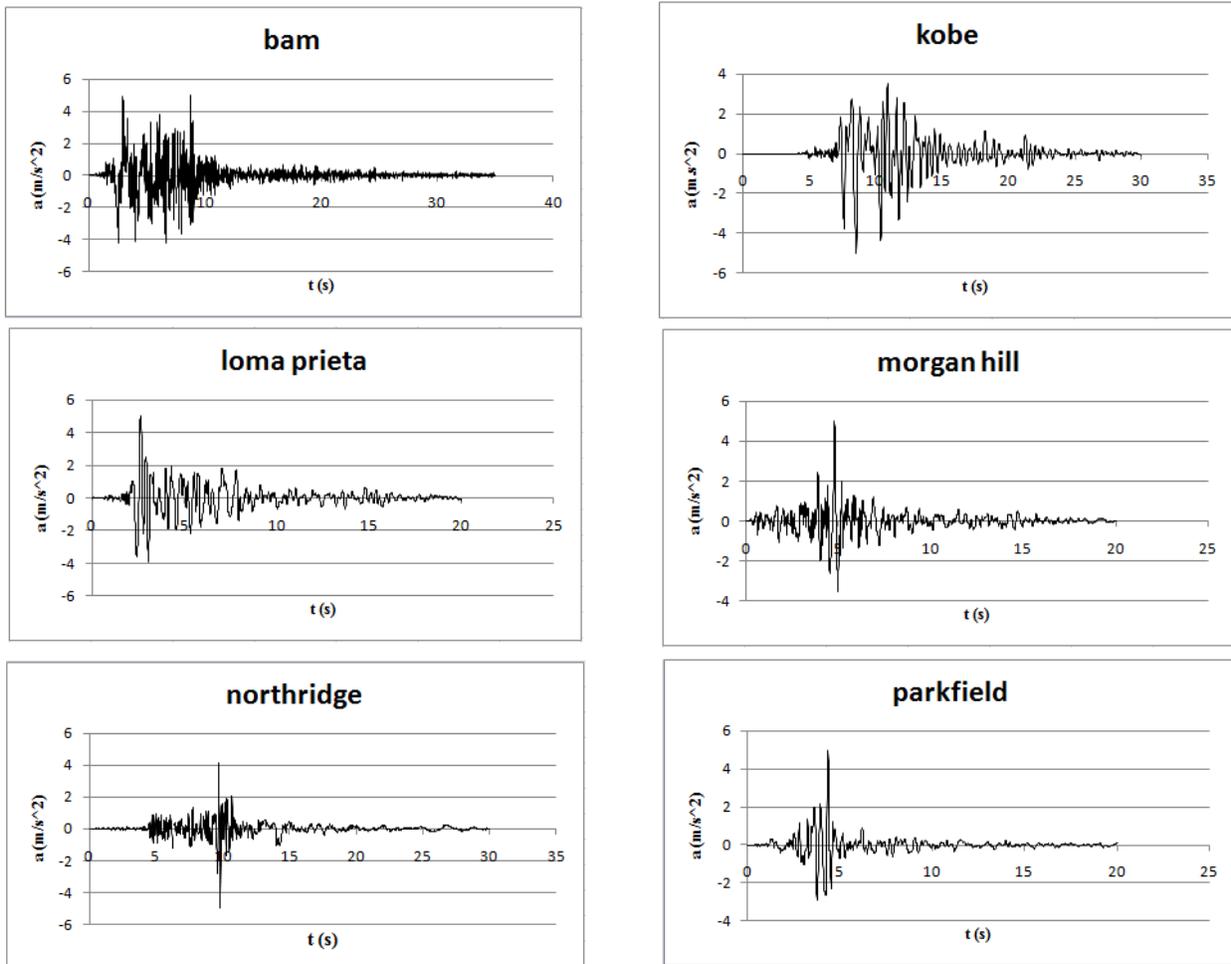


**Figure 3.1.** Ground motion accelerations used in time history analysis (PGA =500 cm/s²)

Shear is plotted versus drift under Kobe record for the first and second stories in different frames and shown in Fig. 3.2. The MRF model (model A) exhibits the largest story drifts; large residual deformation is observed in its first story. In contrast, the story drift is limited in the braced frames (models B and C). The bracing members remain elastic under Kobe record. Maximum story shear is smaller in model C comparing with model B, especially in the first story.
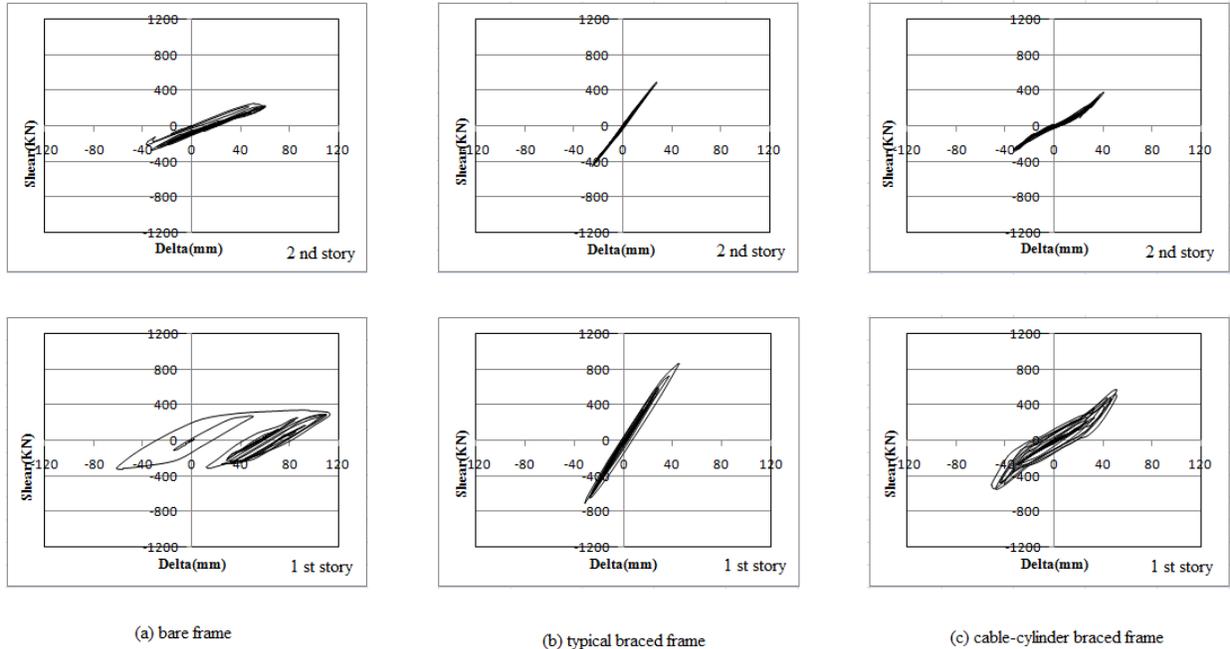


**Figure 3.2.** Story shear versus story drift in different models

When cable brace is used for seismic rehabilitation, it absorbs seismic lateral force and the vertical component of cable force is transferred to the adjacent columns. The column force is increased severely when the cable is stiffened and hit the beam and column connection. This phenomenon may cause cable failure or column buckling and finally structural instability. Therefore, the columns should be strengthened and the foundation capacity controlled in seismic rehabilitation using cable bracing. In Fig. 3.3. maximum compressive force in the cable bracing systems (models B and C) is plotted versus those of columns in the MRF (model A). The average increases of compressive forces are 190% and 64% for MRF with typical cable bracing and cable-cylinder bracing, respectively. Fig. 3.4. depicts the distribution of maximum story drift ratios (story drift to story height) for 3 models under different earthquake records. The first story of MRF model exhibits the largest story drift. The story drifts are reduced in the braced frames. Regarding the cable-cylinder braced frame (model C), the story drift ratio is limited to about 0.015 rad.
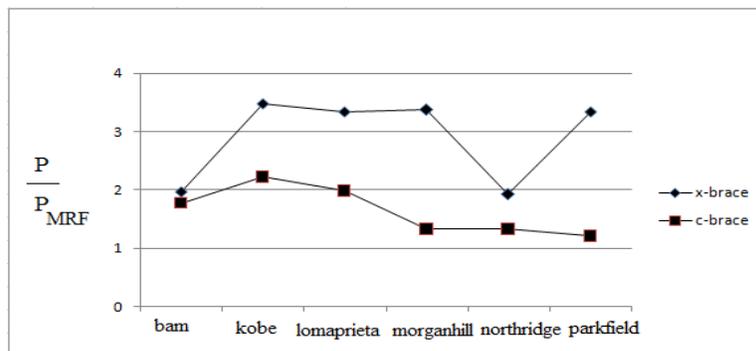


**Figure 3.3.** The maximum compressive force ratios of models B and C to model A in different earthquakes
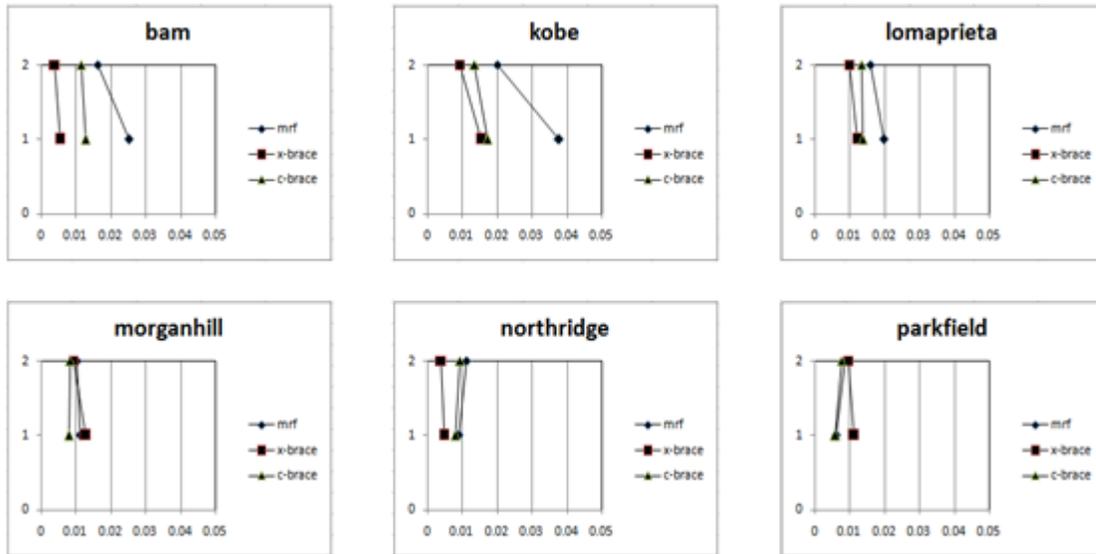
**Figure 3.4.** The distribution of maximum story drift ratios of 3 models

## 4. CONCLUSION

In this study, seismic response analysis is conducted on two-story MRFs with and without cable bracing systems. In cable-cylinder bracing, the cables meet their ultimate strength in higher drifts. Regarding high stiff pipes, both cables are always in tension and therefore they have no slack or hit. The results show that the cable-cylinder bracing system can limit story drifts to a certain range without any significant increase in the story shear force. Furthermore, adding cable-cylinder bracing to MRF increases the compressive forces of column much less than those of typical cable bracing. Concerning all these advantages, cable-cylinder bracing is highly recommended in seismic strengthening and rehabilitation.

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