Full Scale Shaking Table Tests of A Steel Structure with Multi-Curved Buckling Restrained Braces

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ABSTRACT:

Since the buckling restrained brace had been presented in the 1970s, many countries have gradually adopted this device for seismic mitigation. However, several shortcomings of the traditional BRB need to be improved such as complex procedures, bad precision, too many fabricating interfaces of different materials and time consuming during the manufacturing processes. The processes in the manufacture of the traditional BRB can not assure whether the debonding material has been stuck or pasted well on the steel core and the concrete used to prevent steel core from buckling need time to develop its strength. Therefore, the fabricating quality of the traditional BRB is not easy to control and time consuming. In addition, there is no support for the steel tube in the traditional BRB to preventing sliding down during earthquakes. Furthermore, the glue material between the steel core and the debonding material will damage at high temperature and will cause sliding of the steel tube and lose its function. In this study, a multi-curved buckling restrained brace, MC-BRB, is proposed to correct abovementioned disadvantages of the traditional BRB. The component test and shaking table test of a full-scale steel structure with multi-curved buckling restrained braces were carried out to investigate its behavior and the capability for seismic mitigation. The experimental results illustrate that the MC-BRB possesses the stable mechanical behavior under cyclic loadings and provides good protection for structures from earthquake damage.

KEYWORDS: Earthquake Engineering, Buckling Restrained Brace, Passive Control, Structural Control, Damper

1. INTRODUCTION

Previously, braces within structures were used to resist the energy transmitted from earthquake, but force redistribution resulted in energy concentrating on certain locations due to buckling phenomenon occurrence in braces. This disadvantage had been improved until the unbonded braces or buckling restrained braces were presented in the 1970's. More investigations had not been published to examine the behaviors of buckling restrained braces under cyclic loadings [1-3]. The final target of buckling restrained braces within structures is expected to update the capability of structures in seismic mitigation. However, few related shaking table test results especially for a full scale structure equipped with BRBs. were found in previous publications. In this study, the component test and shaking table test of a full-scale steel structure with multi-curved buckling restrained braces, as shown in Figure 1 [4-6], were carried out in Feng Chia University and the Center for Research on Earthquake Engineering, Taiwan respectively to investigate its behavior and the capability for seismic mitigation. Experimental results illustrated that MC-RBRB not only possesses stable behavior but also effectively provided large stiffness and favorable damping effects to reduce the roof displacements, column shear forces and accelerations.

2. MECHANICAL BEHAVIOR OF ADVANCED BUCKLING RESTRAINED BRACES

As shown in Figure 2, the axial deformation of the multi-curved reinforced BRB can be obtained by integrating all segments of the entire length of the steel core. The deformation in segments 1-1, 2-2, 3-3, 4-4 and 5-5 can respectively be expressed as [4-6]:

$$\Delta_1 = \int_{L_2+L_3}^{L_1+L_2+L_3} \varepsilon_1 dx = \frac{PL_1}{EA_1} \tag{1}$$

$$\Delta_2 = \int_{L_3}^{L_2+L_3} \varepsilon_2 dx = \frac{PL_2}{E(A_1 - A_3)}(\ln A_1 - \ln A_3) \tag{2}$$

$$\Delta_3 = \int_0^{L_3} \varepsilon_3 dx = \int_0^{L_3} \frac{P}{EA_3} dx = \frac{PL_3}{EA_3} \tag{3}$$

$$\Delta_4 = \int_{L_3+L_2+L_1+L_5}^{L_3+L_2+L_1+L_5+L_4} \varepsilon_4 dx = \frac{PL_4}{EA_4} \tag{4}$$

$$\Delta_5 = \int_{L_3+L_2+L_1}^{L_3+L_2+L_1+L_5} \varepsilon_5 dx = \frac{PL_5}{E(A_m - A_1)}(\ln A_m - \ln A_1) \tag{5}$$

where L_1, L_2, L_3, L_4 and L_5 are the lengths of segments 1-1, 2-2, 3-3, 4-4 and 5-5, respectively. A_1, A_3 and A_4 are the areas of segments 1-1, 3-3 and 4-4, respectively and A_m is the largest area of the segment 5-5. P is axial force of the member, and E is the modulus of elasticity.

Because of connection in series for segments in steel core, the stiffness of the multi-curved reinforced BRB could be obtained as:

$$k_b = \frac{k_1 k_2 k_3 k_4 k_5}{\left(2k_2k_3k_4k_5 + 2k_1k_3k_4k_5 + 2k_1k_2k_4k_5 + 2k_1k_2k_3k_4 + k_1k_2k_3k_5\right)} \tag{6}$$

where

$$k_1 = \frac{EA_1}{L_1},\quad k_2 = \frac{E(A_1 - A_3)}{L_2(\ln A_1 - \ln A_3)},\quad k_3 = \frac{EA_3}{L_3},\quad k_4 = \frac{EA_4}{L_4},\quad k_5 = \frac{E(A_m - A_1)}{L_5(\ln A_m - \ln A_1)}$$

When the stress of the MC-RBRB is in inelastic range, the total displacement increment can be given by:

$$d\Delta = \frac{2dpL_1}{E_t A_1} + \frac{2dpL_2\left(\ln A_3 - \ln A_1\right)}{E\left(A_3 - A_1\right)} + \frac{2dpL_3}{E_t A_3} + \frac{dpL_4}{EA_4} + \frac{2dpL_5\left(\ln A_m - \ln A_1\right)}{E\left(A_m - A_1\right)} \tag{7}$$

where the E_t is the tangential modulus

Rearranging equation (6) lead to the effective tangential stiffness

$$k_p^{eff} = \frac{1}{\left[\frac{2L_1}{E_t A_1} + \frac{2L_2\left(\ln A_3 - \ln A_1\right)}{E\left(A_3 - A_1\right)} + \frac{2L_3}{EA_3} + \frac{L_4}{EA_4} + \frac{2L_5\left(\ln A_m - \ln A_1\right)}{E\left(A_m - A_1\right)}\right]} \tag{8}$$

3. COMPONENT TESTS AND SEISMIC SIMULATOR TESTS OF STRUCTURE WITH MULTI-CURVED REINFORCED BUCKLING RESTRAINED BRACES

In order to investigate the behaviors of the multi-curved reinforced BRB, the component tests of the multi-curved reinforced BRB were carried out in the Department of Civil Engineering, Feng Chia University, Taichung, Taiwan. Figure 3 shows the set-up for the multi-curved reinforced BRB on the MTS machine. Furthermore, the yield forces are 4 tons and 6 tons for the multi-curved reinforced BRBs. According to the draft Recommend Provisions for Buckling Restrained Braces (SEAOC-AISC 2001), the designed braces should be tested in accordance with the procedures and acceptance criteria of its appendix, therefore, the procedures of component tests, which accepted displacement control is given in Figure 4. The experimental results shown in Figure 5 and Figure 6, the hysteresis loops of multi-curved reinforced BRB were very stable and the distinctions between the tension and compression forces were much smaller than 30% which is required for the test provisions.

Seismic simulator tests for a structure equipped with multi-curved reinforced buckling restrained braces, MC-RBRBs, were carried out to assess the feasibility and efficiency of MC-RBRBs to promote earthquake resistance capability of structures. The tested structure is a three-story full scaled steel structure. The beam-column frame, for each floor, has a length of 4.5 m, a width of 3.0 m, and a height of 3.0 m, and the cross-sections of the beams and columns are H200×150×6×9 mm and H200×204×12×12 mm, respectively. The dimension of the floor slab at each floor is 4m×2.5m×11.5cm consisting of concrete and supplement with a 6930 kg mass block, as shown in Figure 7.

According to the SR value that the ratio between brace and frame stiffness and the B/D value that the ratio of the brace to the MC-RBRB latter stiffness, the optimum size of MC-RBRB had been designed and installed on tested structure. Each floor was equipped with four MC-RBRBs, as shown in Figure 8. The ground motions included the 1940 El Centro earthquake (California), 1995 Kobe earthquake (Japan) and 1999 Chi-Chi earthquake (TCU084, Taiwan). Furthermore, Figures 9 to 11 show the comparisons of the maximum column shear force at first floor between of structure with and without MC-RBRBs under three-directional different earthquakes. It can be found that the column shear force responses of the structure with MC-RBRBs are smaller than that without MC-RBRBs. Similarly, the acceleration responses of the structure with MC-RBRBs have also been reduced during three-directional earthquakes, as shown in Figures 12 to 14. Tables 1 to 3 express the efficiency of the structure with MC-RBRBs under different earthquakes with various PGAs. From the results above mentioned, MC-RBRBs installed in the tested structure can provide the stiffness and damping to reduce the roof displacements, column shear forces and absolute accelerations of the structure during earthquakes.

4. CONCLUSIONS

MC-BRB possesses the stable mechanical behavior under cyclic loadings and the shaking table tests of the three-story full scale steel structure with MC-RBRBs in this study show that the most parts of responses in the tested structure including the roof displacements, column shear forces have been significantly reduced. Therefore, MC-RBRB can be recognized as a good device in seismic mitigation.

ACKNOWLEDGEMENT

Financial support for this study has been provided by the Taiwan Science Council. (Project No. NSC 94-2211-E-035-015). Special thanks are given for the financial support to complete this project.

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Table 1 Comparisons of relative roof displacement between structure with and without MC-RBRBs under three-directional excitations

Max. Response	Relative Roof Displacement (mm)			
Earthquake		El Centro	Kobe	Chi-Chi
Traditional Structure	0.1g	27.99	38.55	72.21
	0.3g	86.39	112.45	263.11
Structure with MC-RBRB	0.1g	4.23	6.68	6.40
	0.3g	14.82	20.14	14.61
Efficiency	0.1g	84.89%	82.67%	91.14%
	0.3g	82.84%	82.09%	94.45%

Table 2 Comparisons of column shear force between structure with and without MC-RBRBs under three-directional excitations

Max. Response	Column Shear Force (KN)			
Earthquake		El Centro	Kobe	Chi-Chi
Traditional Structure	0.1g	10.79	10.90	23.50
	0.3g	33.31	31.80	85.62
Structure with MC-RBRB	0.1g	1.57	1.93	1.14
	0.3g	5.72	12.04	4.12
Efficiency	0.1g	85.45%	82.29%	95.15%
	0.3g	82.83%	62.14%	95.19%

Table 3 Comparisons of absolute acceleration between structure with and without MC-RBRBs under three-directional excitations

Max. Response	Roof Absolute Acceleration			
Earthquake		El Centro	Kobe	Chi-Chi
Traditional Structure	0.1g	0.180	0.190	0.359
	0.3g	0.555	0.556	1.309
Structure with MC-RBRB	0.1g	0.140	0.189	0.116
	0.3g	0.528	0.584	0.443
Efficiency	0.1g	22.17%	0.53%	67.72%
	0.3g	4.90%	-5.04%	66.17%

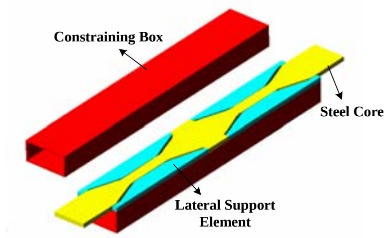

Figure 1 Sketch of multi-curved reinforced buckling restrained brace

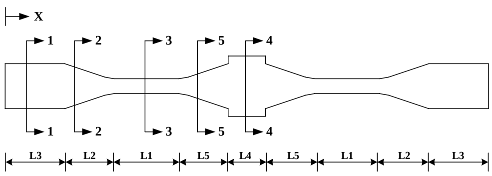

Figure 2 Sketch of the steel core of the multi-curved reinforced BRB


Figure 3 Test setup for the multi-curved reinforced BRB

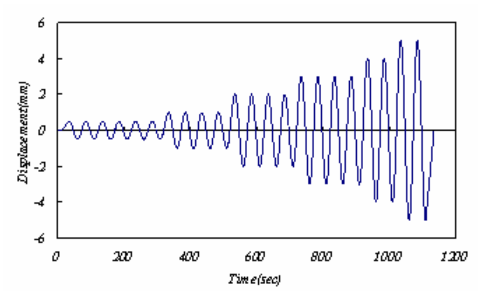

Figure 4 Procedural time history of multi-curved reinforced BRB

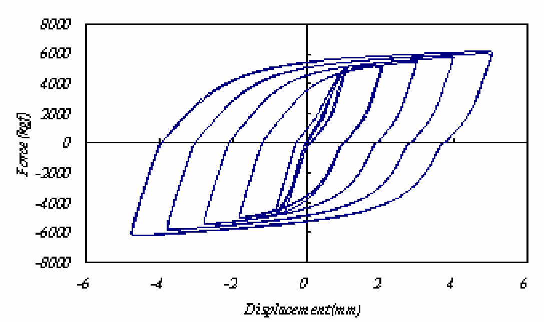

Figure 5 The hysteresis loops of the multi-curved reinforced BRB with a yield force of 4 tons

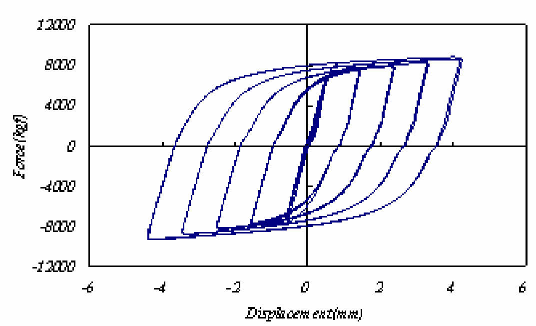

Figure 6 The hysteresis loops of the multi-curved reinforced BRB with a yield force of 6 tons

Figure 7 A three-story full scaled steel structure

Figure 8 Three-story full scaled steel structure with MC-RBRBs

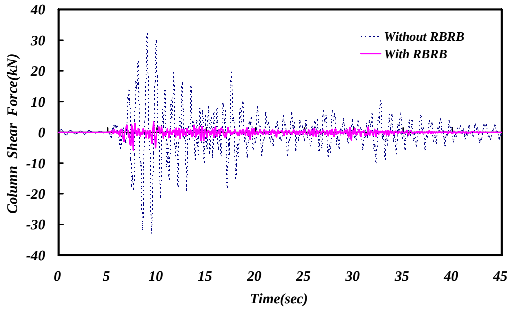

Figure 9 Column shear forces of structure with and without MC-RBRBs under three-directional El Centro earthquake (X=0.3g, Y=0.184g, Z=0.207g)

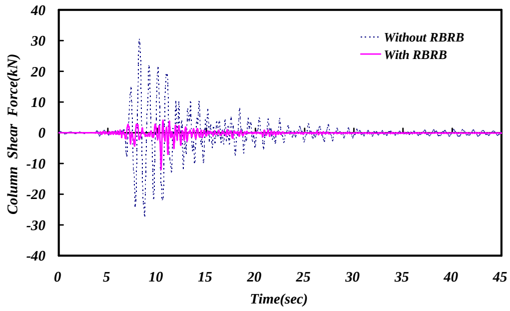

Figure 10 Column shear forces of structure with and without MC-RBRBs under three-directional Kobe earthquake (X=0.3g, Y=0.266g, Z=0.122g)

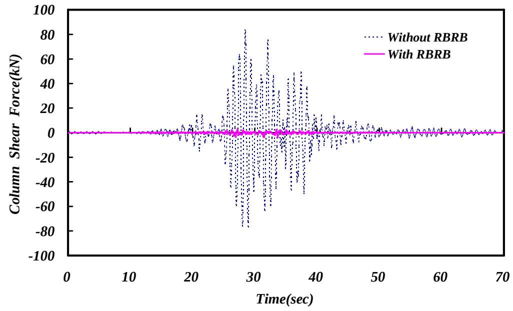

Figure 11 Column shear forces of structure with and without MC-RBRBs under three-directional Chi-Chi earthquake (X=0.3g, Y=0.128g, Z=0.095g)

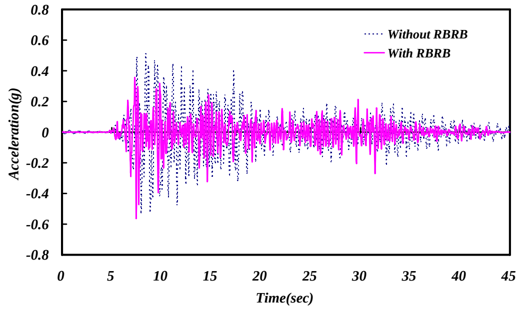

Figure 12 Absolute accelerations of structure with and without MC-RBRBs under three-directional El Centro earthquake (X=0.3g, Y=0.184g, Z=0.207g)

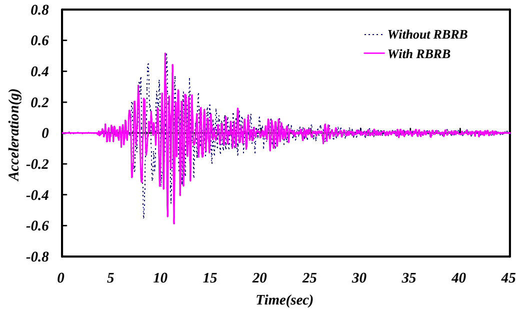

Figure 13 Absolute accelerations of structure with and without MC-RBRBs under three-directional Kobe earthquake (X=0.3g, Y=0.266g, Z=0.122g)

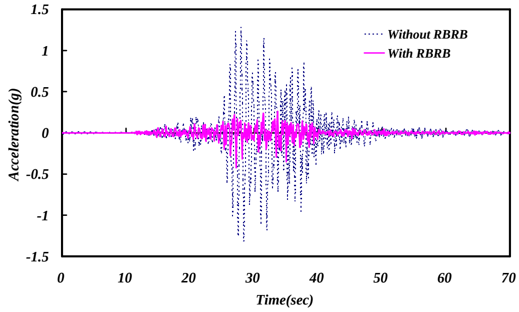

Figure 14 Absolute accelerations of structure with and without MC-RBRBs under three-directional Chi-Chi earthquake (X=0.3g, Y=0.128g, Z=0.095g)