Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct



Component tests of buckling-restrained braces with unconstrained length

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ARTICLE INFO

Article history: Received 6 August 2007 Received in revised form 8 September 2008 Accepted 9 September 2008 Available online 12 November 2008

Keywords: Buckling-restrained braces Component test Unconstrained length Energy dissipation

ABSTRACT

The load-resisting capacity of buckling-restrained braces (BRB) composed of an H-shaped core element and an external tube was investigated in this study by component testing. A study was carried out on the effect of the design parameters such as the thickness of the constraining tube and the length of the unconstrained length of the core ends on the maximum strength and the energy dissipation capability. The performance of the BRB was evaluated by comparing the test results with the recommended provisions for BRB. It was found that the thickness of the external tube and the unconstrained part of the core had a significant effect on the strength and hysteretic behavior of the BRB; with the correct thickness of external tube and unconstrained length, the BRB behaved stably throughout the cyclic loading history until the cumulative plastic deformation reached 330, which far exceeded the value of 200 required by the recommended provisions.

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1. Introduction

A buckling-restrained brace (BRB) generally comprises a steel core element that carries the entire axial load and a restraining exterior element that prevents the core from buckling in compression. Due to the confining effect of the exterior element, a BRB yields in both tension and compression and dissipates a significant amount of hysteretic energy during earthquakes.

The BRB has been applied in many building structures throughout the world as an economic method for seismic loadresisting systems. The seismic load-resisting capacity of BRB has been proven by numerous component and subassembly tests: Watanabe et al. [1] showed the effectiveness of bucklingrestrained braces and investigated the effect of the outer tube configuration on the overall load capacity of the brace. Tremblay et al. [2] conducted a quasi-static loading test on BRB and showed that the strain hardening behavior is most likely the result of the Poisson effect on the steel plate undergoing large inelastic deformation. Huang et al. [3] carried out static and dynamic loading tests on structures with BRB and showed that the energy dissipation capacity of a frame increased with the installation of BRB, and that the main frame remained elastic even when it was subjected to large earthquake load. Black et al. [4] carried out a stability analysis against flexural and torsional buckling of BRB, and presented test results of five buckling-restrained braces with various configurations. Their study concluded that BRB is a reliable and practical alternative to conventional lateral load resisting systems.

In this study, component tests of seven buckling-restrained braces were performed to examine their behavior under simulated seismic loading. H-shaped steel sections with a constant crosssectional area were used as core members, which were confined by an external rectangular tube that was not filled with concrete. A total of seven specimens were prepared with design variables such as the thickness of the external tube, the end reinforcement of the core, and the length of the unrestrained part of the core. The specimens were tested with loading protocol recommended by the AISC [5] to investigate the seismic capacity. Based on the test results, an investigation was carried out on the effect of the thickness of the external tube and the unrestrained length of the core on the hysteretic behavior, the failure mode, and the energy dissipation capacity.

2. Test schedule

The buckling-restrained braces investigated in this study comprise an H-shaped core element and an external tube, as shown in Fig. 1. To reduce the cost of manufacturing, the tube is not filled with any filler material (such as mortar), and the crosssectional area of the core is kept constant. The dimensions and

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^{0141-0296/\$ -} see front matter © 2008 Elsevier Ltd. All rights reserved. doi:10.1016/j.engstruct.2008.09.014

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Size of test speciment

No	Specimens	Core	External tube	Unconstrained length (mm)
1	B1-O-O		_	_
2	B2-R3A-L2		$\Box - 108 \times 108 \times 3t$	200 (No end reinforcement)
3	B3-R4A-L2		$\Box - 110 \times 110 \times 4t$	200 (No end reinforcement)
4	B4-R4B-L2	$H-100 \times 100 \times 6 \times 8(SS400)$	$\Box - 110 \times 110 \times 4t$	200 (End reinforcement)
5	B5-R5B-L2		$\Box - 112 \times 112 \times 5t$	200 (End reinforcement)
6	B6-R4B-L3		$\Box - 110 \times 110 \times 4t$	300 (End reinforcement)
7	B7-R5B-L3		$\Box - 112 \times 112 \times 5t$	300 (End reinforcement)

B1: Brace specimen number 1; R3: With tube of t = 3 mm, O: W/O tube; A: W/O core-end reinforcement, B: With core-end reinforcement; L2: Unconstrained length = 200 mm, L3: Unconstrained length = 300 mm.



Fig. 1. The buckling-restrained brace used in the experiment.

detailed descriptions of the test specimens are presented in Table 1 and Fig. 2. All specimens are fabricated of SS400 steel with yield strength of 240 MPa. H-100 \times 100 \times 6 \times 8 sections of 2.5 m length are used for core members in all specimens. The end condition of the braces is considered as a hinge. Specimen B1 is a normal steel brace not restrained by the external tube. The external tubes have three different thicknesses of 3 mm, 4 mm, and 5 mm. The core element is divided into two parts: the part constrained by the external tube and the unconstrained part which is required to make connections. The unconstrained length of specimens B2 to B5 is 200 mm and that of specimens B6 and B7 is 300 mm. The unconstrained parts of specimens B4 to B7 are reinforced with welded steel plates. 40 mm-thick plates were welded at both ends of the specimens to uniformly distribute the axial load.

The test specimens were manufactured in the order of: reinforcement of the unconstrained part of the core by welding steel plates, attachment of strain gages, placement of the core inside the external tube, and reinforcement of the ends of the external tube. To prevent excessive slip between the core and the tube, stoppers were welded at the flange of the core. Figs. 3 and 4 show the process of manufacturing the specimens and the locations of the strain gages, respectively. Fig. 5 shows the test setup for the component test of BRB. The experiments were carried

ladie 2		
Results of coupon	tests	(MPa)

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	Yield stress	Ultimate strength	Yielding ratio
Tube PL-3T	3.36	4.51	0.75
Tube PL-4T	3.53	5.01	0.70
Tube PL-5T	3.35	4.65	0.72
Core Web-6T	3.60	4.94	0.73
Core Flange-8T	3.35	4.77	0.70

out using a universal testing machine with a maximum capacity of 3000 kN. To evenly distribute the axial load along the crosssection, a 40 mm-thick steel plate and a pin-zig were tightly connected by high-tension bolts at the ends of the brace. The axial deformation of the test specimens was measured by a load-cell and two LVDT's. The applied loading histories (the Loading Protocol 2 of the Recommended Provision [5] shown in Fig. 6), included a quasi-static cyclic test with stepwise incremental displacement amplitudes at a constant rate of 0.01 mm/s [6,7]. To assess the maximum cumulative plastic deformation and energy-dissipation capacity, the load was increased until the maximum displacement of 2.0D_{bm} (the maximum displacement regulated by the loading protocol), was exceeded and failure occurred [8].

To evaluate the mechanical properties of the structural steel of the BRBs, a coupon test was carried out in accordance with the Korean Standard KSB 0801. 3 mm, 4 mm, and 5 mm thick coupons were taken out of the flange and the web of the core member and of the external tube. The test specimens were fabricated of mild steel SS400 with nominal yield stress of 240 MPa. The tensile test results are summarized in Table 2, where it can be seen that all the specimens satisfied the requirements of the Korean Standard.

3. Results and analysis

3.1. Failure modes

From the experiments, it was observed that the specimens failed either by flexural buckling at the end of the core or by

Table 3
Ultimate strength and failure mode of test specimens.

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Specimens	Point of buckling	$P_{\rm max}$ (kN)	Failure mode	Observation
B1-0-0	1-1	30.20	Global buckling in the middle of the specimen	Buckling at the computed critical load (31.6 kN)
B2-R3A-L2	2-1	49.79	Flexural yielding of tube before compressive yielding of core	Lack of bending strength of external tube
B3-R4A-L2	2-1	58.36	Flexural yielding of core-end before yielding of core	Lack of bending strength of core-end
B4-R4B-L2	2-1	66.64	Flexural yielding of tube before compressive yielding of core	Lack of bending strength of external tube
B5-R5B-L2	4-1	76.80	Flexural yielding of tube followed by compressive yielding of core	Inelastic deformation, slight lack of bending strength of tube
B6-R4B-L3	3-1	71.40	Flexural yielding of tube followed by compressive yielding of core	Inelastic deformation, slight lack of bending strength of tube
B7-R5B-L3	7-1	86.80	Compressive yielding of core followed by flexural yielding of tube	Inelastic deformation, satisfaction of AISC requirements





flexural yield in the middle of the external tube. The ultimate strength and the failure mode of test specimens are summarized in Table 3. The load-displacement relationship and the failure modes are also depicted in Figs. 7 and 8, respectively. It can be observed that the specimen not restrained by an external tube (B0-0-0) failed by buckling at the first compressive loading cycle. However, specimen B7, which had the thickest external tube and a 300 mm unconstrained length with reinforcement, showed superior performance to the other specimens, while displaying stable hysteretic curves until the ductility ratio reached 15. The test results showed that the maximum strength increases as the unconstrained length of the core increases to 300 mm and as the thickness of the external tube increases. Furthermore, the addition of the stiffener which shortens the core length also plays a role.

3.2. Effect of the design parameters

Fig. 9 shows a comparison of the load-displacement relationship of the specimens at their maximum compressive loading cycle. It can be observed that the specimens with a 5 mm-thick external tube (B5 and B7) showed superior performance in maximum displacement as well as strength. In particular, the maximum deformation of specimen B7, with 300 mm unconstrained length, is more than twice that of specimen B5 with 200 mm unconstrained length.

Fig. 10 shows the load-displacement relationship of specimens with various thicknesses of external tube. When the unconstrained length is 200 mm, the maximum compressive strengths of specimens with tube thickness of 4 mm and 5 mm are 34% to 54% larger, respectively, than that of the specimen with 3 mm tube thickness. This can be expected because the increase in thickness causes an increase in the bending stiffness and strength of the external tube, which results in an increase in the axial-load resisting capacity of the core elements. For economy, however, the thickness of the external tube needs to be optimized.

To find the effect of the constrained length at the end of the core, the B4-R4B-L2 specimen was tested under the same loading condition as that of the B3-R4A-L2 specimen. The inelastic deformation is planned to start at the second cyclic loading stage, which is $0.5D_{bm}$ (=7.15 mm). The strains of the B4-R4B-L2 specimen, measured in the longitudinal direction at the first cyclic load at the second loading stage are shown in Fig. 11, where the



(d) End details.



measuring locations are at the center of the core and tube, and at the end of the core.

In the case of specimen B3-R4A-L2 with an unconstrained length at both ends, the flexural deformation in the weak axis was found at the end of the core accompanying the degradation of the strength. The flexural deformation of the core at the end is determined by the combination of the axial force of the core and the bending moment due to out-of-plane deformation. For the BRB that had an unconstrained length of over 200 mm at the end of the core, the increased section is recommended at the end of the core in order to obtain the required compressive strength.

The effect of unconstrained length is plotted in Fig. 12, where a comparison is shown of the load–displacement curves of four specimens at maximum compression. It can be observed that the maximum strengths of the specimens with an unconstrained length of 300 mm (B6 and B7) are 8%–13% larger than those of



(a) Welding of the core-end with end plate.



(b) Welding of cover plate for reinforcement.



(c) Attachment of strain gages.



(d) Reinforcement of tube end.





Fig. 4. Location of LVDT's and strain gages.



Fig. 5. Test setup for the buckling-restrained brace.

the specimens with an unconstrained length of 200 mm (B4 and B5) and that the specimens with 300 mm unconstrained length showed more stable hysteretic behavior. This is because, as the unconstrained length increases, the length of the external tube decreases, resulting in an increase in bending rigidity.

Fig. 13 shows a plot of the accumulated hysteretic energy and axial plastic deformation at each loading cycle, where it can be observed that the accumulated plastic deformation (η) of specimen B7 with 300 mm unconstrained length and 5 mm tube thickness reached 330, which exceeded the value of 200 required by the seismic provision. AISC/SEAOC Recommended Provisions [10] were also plotted in Fig. 13.

3.3. Ultimate strength of BRB

Watanabe et al. [1] proposed the following equation for the ultimate strength of a BRB based on Euler's buckling formula:

$$P_b \cong \frac{\pi^2 EI}{(KL)^2} \tag{1}$$

where P_b is the ultimate strength of BRB, E is the elastic modulus, L is the length of the brace, and I is the second moment of inertia of the external tube. Chen et al. [9] proposed the following formulas (2) and (3), respectively, considering the effect of strain hardening:

$$\frac{\phi P_e}{1.3P_y} \ge 1.0 \quad \text{or} \quad \frac{P_e}{P_y} \ge 1.5 \tag{2}$$

$$P_b = \frac{P_e}{1 + \frac{P_e \delta_0}{M_v}}; \qquad P_e = \frac{\pi^2 E I}{L^2}$$
(3)

where P_e is the buckling strength of the constrained element, P_y is the yield strength of core elements, δ_0 is the initial deflection,

Comparison of the ratio of the maximum stress and the yield stress.

Specimens	P _{max} (kN)	$P_{\rm max}/P_{y,\rm exp}$	$P_{u,\text{pred}}$ (kN)	
			Watanabe	Powell and Chen
B1-0-0	30.20	0.53	31.69	31.69
B2-R3A-L2	49.79	0.89	54.81	46.51
B3-R4A-L2	58.36	1.04	75.24	62.37
B4-R4B-L2	66.64	1.19	75.24	62.37
B5-R5B-L2	76.80	1.37	96.80	74.64
B6-R4B-L3	71.40	1.27	75.24	62.37
B7-R5B-L3	86.8	1.55	96.80	74.64



Fig. 6. Loading protocol.

and M_y is the nominal strength of the external tube. The strength reduction factor ϕ of 0.85 was used in both equations.

Table 4 summarizes the results of the experiments, including the maximum compressive strengths. It was found that the maximum strengths were 13%–26% smaller than those computed by Eq. (1), which included the bending stiffness of the external tube, and were similar to those obtained by Eq. (3), which considers the effect of the initial displacement and the yield moment. However, these equations cannot be applied when the strength is determined by the buckling of the unconstrained part of the core element. Therefore, in order to obtain a more precise estimation of the strength of the BRB, the effect of the unconfined length also needs to be considered. Since the test results concur with the proposed equation by Chen [9], then Eq. (2) proposed by Powell and Chen is considered to be appropriate for the BRBs investigated in this paper.

3.4. The strain hardening and the compression strength adjustment factors

The tensile strength of a steel member is generally higher than the nominal yield strength due to the strain hardening effect. Also, as can be noticed in Fig. 16, the maximum compressive strength of BRB is larger than the maximum tensile strength due to the confining effect of the external tube. The AISC Seismic Provision [5] specifies that the bracing connections and adjoining members shall be designed to resist forces calculated based on the adjusted brace strength of $\omega R_v P_v$ in tension and $\beta \omega R_v P_v$ in compression, where



Fig. 7. Load-displacement relationship of test specimens.

the strain hardening adjustment factor ω and the compression strength adjustment factor β are obtained as follows:

$$\omega = \frac{\omega F_y A}{F_y A} = \frac{T_{\text{max}}}{F_y A}$$
(4)

$$\beta = \frac{\beta \omega F_{y} A}{\omega F_{y} A} = \frac{P_{\text{max}}}{T_{\text{max}}}$$
(5)

where F_y is the nominal yield stress, A is the cross-sectional area of the core, and T_{max} and P_{max} are the maximum tensile and compressive strengths, respectively, obtained from the experiment. Using these factors, the load-displacement relationship of the BRB is idealized, as shown in Fig. 14.

Based on the hysteretic load-displacement curve of specimen B7, which showed the most stable performance, the prediction equation of the strain hardening adjustment factor ω is proposed



(a) Specimens B1, B2 and B3.



(b) Specimens B5, B6 and B7.

Fig. 8. Failure mode of test specimens.



Fig. 9. Load-displacement relationship at the maximum compressive loading cycle.

with two linear equations as follows:

$$\omega = 0.033 \left(\frac{\Delta}{D_{by}}\right) + 1.248, \quad \Delta < 5D_{by} \tag{6}$$

$$\omega = 0.023 \left(\frac{\Delta}{D_{by}}\right) + 1.297, \quad \Delta \ge 5D_{by}.$$
(7)

In Fig. 16 it can be observed that the compression strength adjustment factor (β) ranged from 1.0–1.06, satisfying the upper limit of 1.3 specified in the Seismic Provision. The strength adjustment factor is used to compute the unbalanced force imposed on a girder in chevron-braced frames when they are subjected to a large seismic load. Based on the hysteretic curve of specimen B7, the following linear equation was proposed in order to predict the compression strength adjustment factor at various states of axial deformation Δ :

$$\beta = m\left(\frac{\Delta}{D_{by}}\right) + b = 0.012\left(\frac{\Delta}{D_{by}}\right) + 0.974.$$
(8)

Figs. 15 and 16 show the strain hardening and the compression strength adjustment factors obtained from experiments and the above prediction formulas. It can be observed that the prediction formulas match well with the test results. It also can be noticed that the adjustment factors increase as the axial deformation increases.

4. Conclusions

From the component tests of BRB, comprising an H-shaped steel core placed inside a steel tube, it was found that buckling could be effectively prevented and the stable hysteretic behavior could be induced if the thickness of the external tube was sufficient and if



(a) Specimens with unconstrained length of 200 mm.



Fig. 10. Load-displacement relationships of the specimens with different unconstrained lengths at the loading cycle with maximum compression.



Displacement (mm)

Fig. 11. Displacement-strain relationship in the core and the tube of the specimen B4-R4B-L2.

the unconstrained part of the core was properly reinforced. Based on the test results, the following observations were made:

(1) The buckling-restrained braces fabricated of an H-shaped core member and external tube were effective in resisting compressive as well as tensile forces; the maximum strength



Fig. 13. Accumulated hysteretic energy and the inelastic deformation.

increased as high as 290% of that of the regular brace with the same core cross-sectional area. In particular, specimen B7 with the thickest external tube and 300 mm unconstrained length behaved stably until the ductility ratio reached 15, showing symmetric hysteretic curves and a high energy-dissipating capacity.

(2) The BRBs with 4 mm and 5 mm-thick external tubes showed a 34%-54% higher compressive strength than those with a 3 mmthick tube.



Fig. 12. The load-displacement curves of four specimens with different unconstrained length at the loading cycle of maximum compression.



Fig. 14. Idealized force-deformation relationship of a buckling restrained brace.



Fig. 15. The strain hardening adjustment factors obtained from experiments (ω).

(3) Based on the specimens tested, the unconstrained part of the core (the part not enclosed by the tube), must be reinforced when the length exceeds 200 mm. It was observed that as the length of the unconstrained part increased to 300 mm (i.e. as the length of the external tube decreased) the compressive strength increased as a result of the increase in bending stiffness of the external tube.

(4) The cumulative ductility ratio of specimen B7 was 330, which is significantly larger than the value of 200 required by the AISC Seismic Provisions, and the compression strength adjustment factor β was 1.0–1.06 smaller than 1.3, which is the upper limit of the AISC Seismic Provision.



Fig. 16. The compression strength adjustment factors obtained from experiments (β) .

Acknowledgments

This research was supported by the Ministry of Construction & Transportation of Korea (03R&D C103A1040001-03A0204-00110), and Basic Research Program of the Korea Science & Engineering Foundation (Grant No. R0A-2006-000-10234-0). It was also supported by a Korea University Grant (K0718321).

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