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STRUCTURAL BEHAVIOR OF H-SHAPED BRACE REINFORCED WITH NON-WELDED COLD-FORMED ELEMENT

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ABSTRACT

Braces controlling tension have been used to resist lateral force in most of medium and row-rise steel structures. Providing high stiffness and strength, these steel brace frames are effective to resist lateral force and control story drift. However, the steel braces are subject to compressive load, they experience the deterioration in load capacity due to bending buckling before yield stress and ideal energy dissipation is unfeasible, which causes unstable behavior of the structure. Therefore, this study has to do with a reinforcing method of the compression brace proposed as friction bolt connection. In order to verify the compressive behavior of the reinforced braces, structural performance test was conducted with variables of slenderness ratio and the amount of reinforcement.

Keywords: H-Shape Brace, Non-Welded, Cold-formed, Reinforced Brace

1. BACKGROUND & PURPOSE

Large-scale earthquakes have occurred more frequently worldwide and the loss of life and property caused by them has also increased tremendously. An earthquake sometimes causes national infrastructure to malfunction and results in black out in the area. When a braced frame structure is subject to lateral force, axial stiffness and strength resist it. Requiring the minimum amount of steel to resist horizontal load and secure structural safety, the braced frame is considered to be an efficient structural system. Most of power plants, one of national infrastructure, are steel structures where columns and beams are pin-connected and various types of braces shown in figure 1 resist lateral force.

| (a) Inverted V-Brace | (b) X-Brace | (c) /-Brace |

Figure 1: Various Types of Brace

According to a report made in 2012, 43% of the power plants in Korea were seismically designed, 23% of them were not and 34% were not identified. It is because the requirement for seismic design has been strengthened since it was established in 1988. Since existing braced frames were designed to resist wind load on the assumption of elastic behavior, seismic load accompanying

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inelastic behavior can cause building collapse due to plastic deformation. In non-seismically designed power plants, slenderness ratio is large because most of the braces were designed to work in tension only. This study suggests reinforcing the H-shaped braces in power plants with non-welded cold-formed element to restrain lateral buckling and maximize compressive strength and evaluates structural behavior of the reinforced braces.

2. METHOD TO RESTRAIN BUCKLING

2.1. Previously conducted studies

Previously conducted studies on buckling restrained braces (BRB) focus on those which are covered with reinforcement material having greater stiffness than the core resisting axial force to restrain buckling of the core and those in which load capacity is decided by the axial deformation of the core, not by the external deformation of the reinforced section. Table 1 summarizes the studies.

Table 1 : Previous Researches of BRB

Year	Researcher	Proposal Equation	Stiffener	Filler	Note
1988	Watanabe	$P_e/P_y \geq 1.5$	Steel Tube	Concrete	-
2002	Tsai	$P_{max} = \Omega\Omega_h\beta P_y$	Steel Tube	Concrete	Double core Tube
2002	Chen	$P_{max} = P_e/(1 + (P_e\delta_0/M_y))$	Steel Plate	Square Tube	Welded Steel Plate
2008	Jin-koo, Kim	$P_e/P_y \geq 3.5$	Steel Plate	Square Bars	Un-Bonded

In addition, Inoue et al. (2002) suggested the non-dimensionalized strength-stiffness equations for the estimation of reinforcement length to secure the safety of existing braces through reinforcement. This study suggests a method to reinforce the braces employed in existing power plants based on the equations.
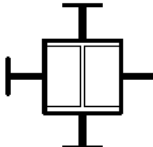
2.2. Shape of reinforcement element

The reinforcement material suggested in this study is intended to restrain the buckling of the core to achieve the followings.

• The core resists axial force only and does not buckle.
• The reinforcement material restrains the buckling of the core and resists the moment caused by the flexural deformation of the core.
• Ultimate strength is reached in the core's whole section.

In table 2, ALT1 is currently used reinforcement method using plate girders and ALT2~4 show the reinforcement of the core of H-shaped brace. They differ in the shape of the reinforcement material.

Table 2 : Performance Comparison of Section Shape

Division	ALT1	ALT2	ALT3	ALT4
Shape				
Reinforcement method	Adhesion Plate	Square Steel Tube	Reinforced Weak axis	Extrude 4-axis
Moment of inertia Ratio	0.1	0.8	0.85	1.0
Contact method	Welded	Welded	Bolt	Bolt

The following problems are inherent in the maintenance and reinforcement of a power plant since its operation should not be interrupted.

• Wet construction can't be employed.
• Welding should be avoided due to the possible risk of a fire.
• Working area is small because of medium/large scale equipment.

ALT1 and ALT2 were excluded because they involve welding process. ALT4 which provides the largest second moment of area was selected.

3. TEST

3.1. Strength-stiffness relationship of reinforced brace

The non-dimensionalized bending strength-stiffness equations suggested by Inoue et al. (2001) for the estimation of reinforcement length can be summarized as follows.
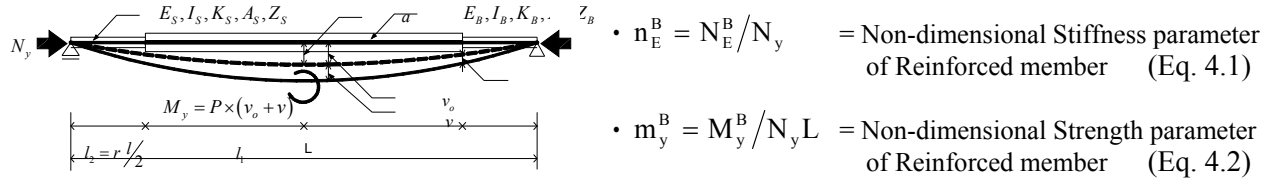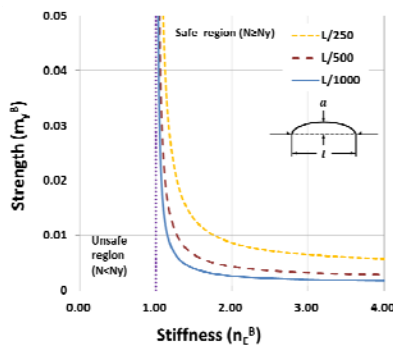

- $n_E^B = N_E^B / N_y$ = Non-dimensional Stiffness parameter of Reinforced member (Eq. 4.1)

- $m_y^B = M_y^B / N_y L$ = Non-dimensional Strength parameter of Reinforced member (Eq. 4.2)

Figure 2 : Concept of Unreinforced Length

- $M_C^B = \dfrac{N_y a}{1 - N_y / N_E^B}$ = Maximum bending moment at the center of the Reinforced member (Eq. 4.3)

- $N_E^B = \dfrac{\pi^2 E_B I}{l^2}$ = Euler load of the reinforced member (Eq. 4.4)

- $M_C^B < M_y^B$ =   (Eq. 4.5)

- $N < N_y$ =   (Eq. 4.6)

Figure 3 : Strength-Stiffeness Graph

In order for the core to reach yield strength without buckling, the ultimate moment at the central part of the reinforcement material should be smaller than yield moment as shown in equation 4.5. Equation 4.5 and equation 4.3 can be summarized as equation 4.2. Based on the equations, the graph for evaluating the buckling stability associated with initial deformation can be created.   The axes of the graph are the non-dimensionalized expression of the core's stiffness and strength and stability evaluation is made based on the reinforcement material without the involvement of the core's load capacity. Axial load which is greater than yield load means instability.

3.2. Test Plan

Main test was conducted with W-shaped built-up member based on the result of the preliminary test and the strength-stiffness equations suggested by Inoue et al. Figure 6 is the strength-stiffness relationship of the specimens. The equations were applied to the specimens conservatively.
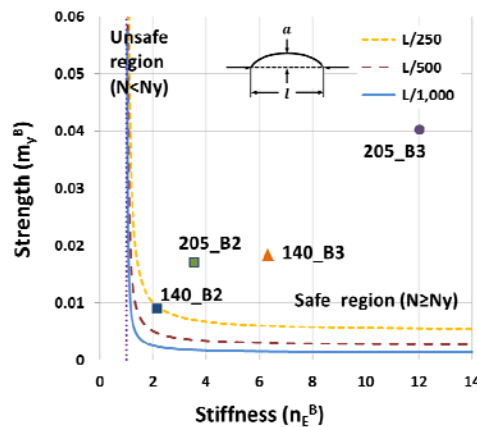

Figure 4 : Strength-Stiffness Evaluation of Test member

In this test to find how to reinforce H-shaped slender braces in steel structure to enhance compressive strength and cost-efficiency of the structure, slenderness ratio and reinforcement amount were selected as parameters.   Slenderness ratios were 140 and 205 and reinforcement length was set to be 85% of the core based on the result of the preliminary test.

Table 5 and figure 7 show the specification and dimensions of the specimens.   Bolts were placed at an interval of 200mm.   The test was conducted at the Research Institute of Industrial Science & Technology in Song-do, Korea using a 3,000kN UTM.   Monotonic compressive load was applied at the speed of 0.001mm per second and 2 wire LVDTs installed at the load cell of the UTM and the end of the specimen measured axial strain.

Table 3: Main Test List

No.	Member	Reinforcement I_{sy} (㎜⁴)	I_{sy}/I_{by}	Reinforced length (㎜)	Prediction Force (kN)
140_B1	H-75×75×4.5/4.5 (Iby = 316,907) (L=2,100 ㎜)	-	-	-	145
140_B2		1,047,476	3.4	1,750 mm	279
140_B3		3,153,183	10.1	1,750 mm	
205_B1	H-75×75×4.5/4.5 (Iby = 316,907) (L=3,700 ㎜)	-	-	-	47
205_B2		4,339,061	13.7	2,590 mm	279
205_B3		14,761,436	46.6	2,590 mm	

(a) Unreinforced Brace (140-B1)   (a) Unreinforced Brace (205-B1)

(b) Reinforced Brace (140-B2, 140-B3)   (b) Reinforced Brace (205-B2, 205-B3)

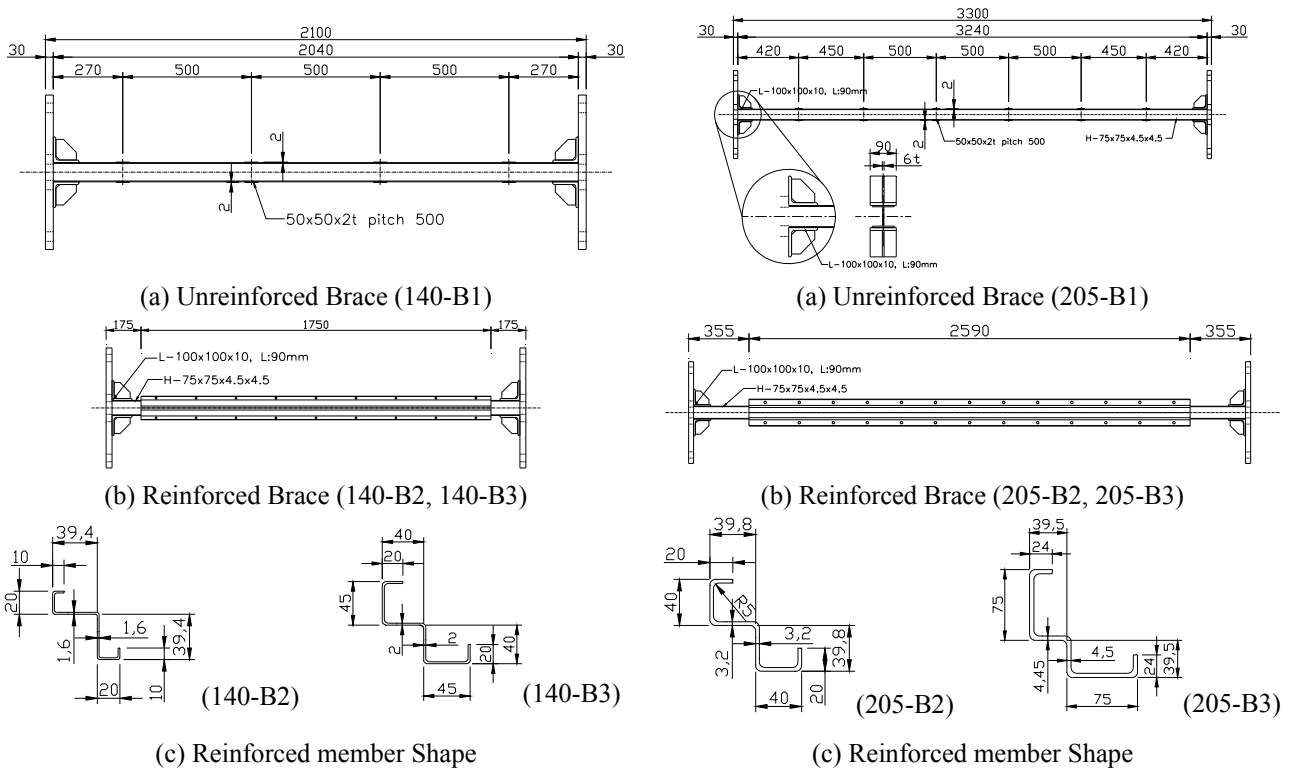(c) Reinforced member Shape   (c) Reinforced member Shape

Figure 5: Main Test Shape

3.3. Result and analysis

In the compressive strength test, unreinforced specimens showed the result similar to the estimation. They presented rapid deterioration in load capacity after buckling and failed.   As shown in table 6, strength was higher and the deterioration in load capacity was more gradual in reinforced specimens than in unreinforced ones.   Among the specimens having the slenderness ratio of 205, B3 specimen showed the greatest load capacity of 307kN. Load capacity of 338kN observed at 140B2 specimen was the highest among those with the slenderness ratio of 140.

Table 4: Main Test Result

No.	I_{sy}/I_{by}	Prediction Force (kN)	P_{max} (kN)	δ_{max} (㎜)	Failure Mode
140_B1	-	145	170	2.3	Global Buckling of Core member
140_B2	3.4	279	338	9.54	Occure Deformation of Reinforced member and Global Buckling of Whole member
140_B3	10.1		324	9.15	Local buckling of the core at the unreinforced end point
205_B1	-	47	69	1.5	Global Buckling of Core member
205_B2	13.7	279	293	10.4	Local buckling of the core at the unreinforced end point
205_B3	46.6		307	12.6	Local buckling of the core at the unreinforced end point

140B1 specimen experienced buckling at 170kN, which was followed by rapid deterioration in load capacity and failure. Buckling of the core first occurred at 150kN and load capacity rose up to 337kN in 140B2 specimen as shown in figure 8. Deformation at the lower end of the core under reinforcement material was followed by the buckling of the whole section. In 140B3 specimen, the buckling of the core was observed at 180kN and load capacity rose up to 324kN. The local buckling of the core flange was deepened at 260kN.
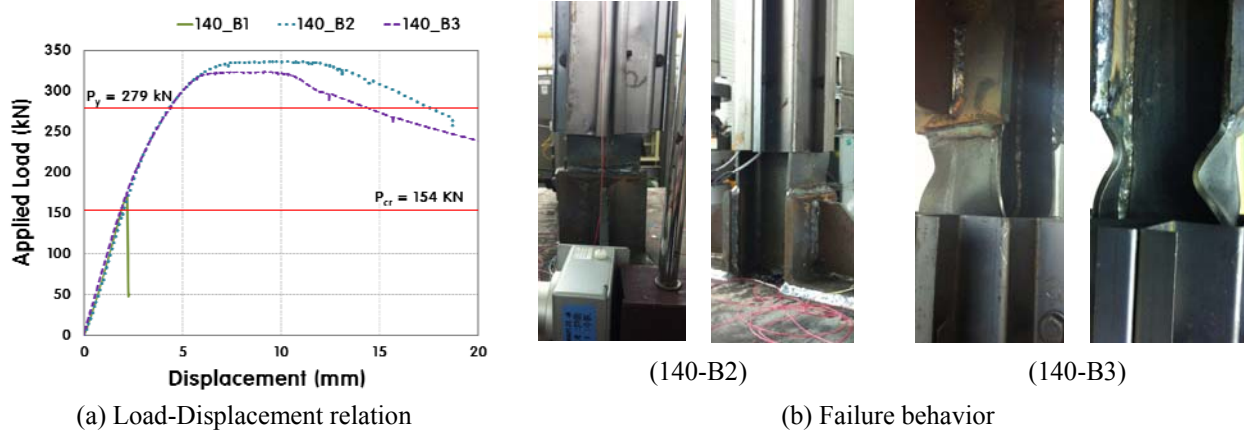

(a) Load-Displacement relation

(b) Failure behavior

Figure 6: Load-Displacement relation and Failure behavior (140 Member)

Unreinforced 205B1 specimen experienced buckling at 69kN and failed after rapid deterioration in load capacity. As shown in figure 9, 205B2 and B3 specimens exhibited similar behaviors. In 205B2 specimen, the flexural buckling of the core was observed at 140kN and it caused additional moment. And, local buckling occurred at the lower end of the core under reinforcement material. Due to stress concentration in this part, load capacity increased up to 293kN, local buckling was accelerated and the core ruptured at 224kN. As a result, plastic hinge occurred and load capacity decreased rapidly.
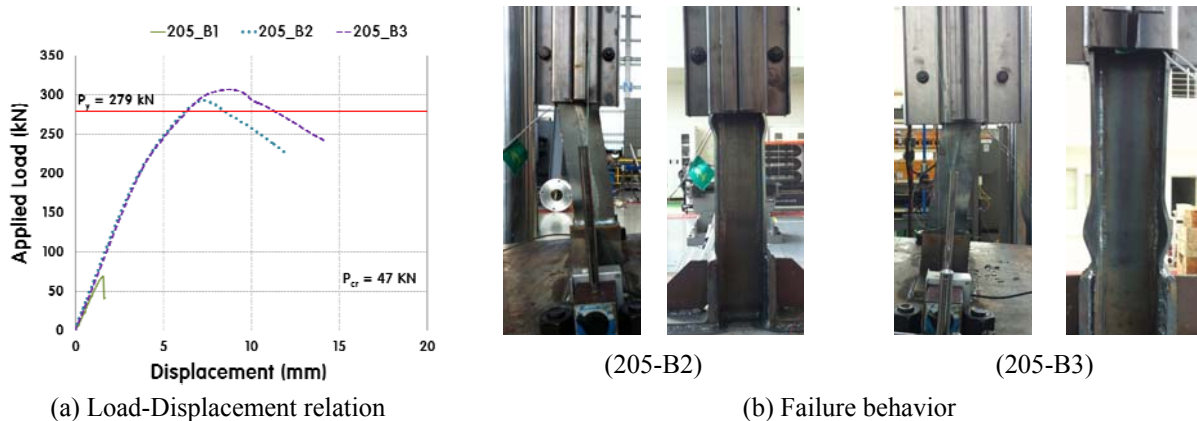

(a) Load-Displacement relation

(b) Failure behavior

Figure 7: Load-Displacement relation and Failure behavior (205 Member)

4. CONCLUSION

In this study, the reinforcement of the slender braces in non-seismically designed steel structure resisting tensile force only with non-welded cold-formed element was suggested and the maximum load, deformation and structural behavior associated with the reinforcement were analyzed. The findings in the study are as follows.

(1) Covering the 4 sides of the H-shaped brace with bolt-connected W-shaped cold-formed built-up member restrains the flexural buckling of the brace and enhances compressive strength.

(2) In the specimens having the slenderness ratio of 140, maximum load of reinforced 140B2 and B3 specimens improved to 330kN, which was 1.95 times when compared with 170kN of unreinforced 140B1 specimen. The deformation capacity of the reinforced specimens also improved as much as 4 times from 2.3mm to 9.5mm. The increase in compressive strength was approximately 1.2 times.

(3) In the specimens having the slenderness ratio of 205, maximum load of reinforced 205B2 and B3 specimens improved to 300kN, which was 4.3 times when compared with 69kN of unreinforced 205B1 specimen. The deformation capacity of the reinforced specimens also improved as much as 16 times from 1.5mm to 11mm. The increase in compressive strength was approximately 1.1 times.

(4) Reinforcement material was selected based on the strength-stiffness relationship. Test result shows that 140B2 specimen exhibits greater load capacity than over-reinforced 140B3 specimen. It is deduced that the excessive confinement resulting from over-reinforcement causes the local buckling of the core. Appropriate amount of reinforcement and the equation for stability evaluation of the members with different slenderness ratios should be found by follow-up studies.

While the reinforcement of slender H-shaped braces suggested in this study to improve the resistance to lateral force restrained the buckling of the brace and enhanced the maximum strength over yield strength, final rupture occurred at the lower end of the core under reinforcement material. The studies on how to restrain the local buckling and enhance ductility need to be carried out.

5. ACKNOWLEDGMENTS

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