Abstract: In this study, innovative enhancements of rectangular tube-type buckling-restrained braces are proposed to prevent bulging failure on the surface of the outer restrainer and validated experimentally. First, an inner restrainer composed of a bent plate, which increases the stiffness and strength to resist outward force exerted by the steel core subjected to higher-mode buckling, is installed inside the outer restrainer. Second, the unbonding material surrounding the steel core is partially thickened to create additional space to prevent the outward force from being transferred directly along the centerline of the cross-section. Buckling-restrained braces with and without the enhancements are tested via cycling loading to validate the efficiency of the proposed enhancements. Improvements in strength and deformation capacity are evaluated quantitatively. The proposed enhancements increased the compressive strength and cumulative inelastic deformation capacity of the buckling-restrained braces. However, the increased outward force owing to the compression-hardening phenomenon led to bulging failure, where the added inner restrainer terminated. An analytical formula is proposed to estimate the outward-force-resisting capacity of the inner restrainer, which predicted bulging failure adequately.

Keywords: buckling-restrained brace; rectangular tube; bulging failure; bent plate; unbonding material; cyclic loading test

1. Introduction

Steel-braced frames can efficiently achieve a higher stiffness and strength compared to steel moment-resisting frames. However, the buckling of braces limits the ductility of steel-braced frames. To improve the ductility of braced frames, special concentrically braced frames, in which the brace members have lower slenderness and width-to-thickness ratios, or eccentrically braced frames, in which inelastic deformation is concentrated on the links, are used [1]. As an efficient alternative, innovative details of braced frames have been developed to achieve a more robust behavior, such as the utilization of a specially detailed mid-height gusset plate as an energy-dissipating fuse [2,3]. Furthermore, a buckling-restrained brace (BRB) is used to obtain a more robust and ductile behavior of the concentrically braced frames.

The BRB is a type of brace designed to ensure compressive strength and deformation capacity comparable to tensile strength and deformation capacity, thereby preventing premature buckling failure. Seismic-force-resisting systems that incorporate BRBs can behave in a ductile manner and dissipate energy stably by preventing a sudden decrease in the lateral resistance owing to buckling [4]. In a typical BRB, a restrainer is installed around the perimeter of the steel core to prevent buckling. Researchers have developed
different types of restrainers and steel cores to prevent premature buckling efficiently [5,6].

One of the simplest BRBs constitutes the combination of a plate-shaped steel core and a restrainer composed of a rectangular steel tube filled with mortar. In such a BRB, the thickness of the restrainer can be reduced to save the steel material that does not resist external loads directly, as long as sufficient flexural stiffness of the restrainer is retained. However, the reduced thickness makes the restrainer vulnerable to bulging because the steel core, which has undergone flexural deformation inside the restrainer, exerts an outward force on the mortar filler as the compressive force increases. Bulging is a typical failure mode of the BRB [7,8].

Lin et al. (2016) and Lin et al. (2018) derived a formula for the capacity of a restrainer with a rectangular tube section resisting outward forces by applying the yield line theory based on the results of finite element analysis [9,10]. Takeuchi et al. (2010), Takeuchi et al. (2012), and Xu and Pantelides (2017) idealized the perimeter wall of a restrainer with a rectangular or circular tube section resisting outward forces as an effective beam [11–13]. They proposed a resistance capacity based on a plastic mechanism and compared the calculation results with cyclic loading test results. Yang et al. (2019) proposed local bulging criteria for BRBs with a steel core of a triangular cross-section and compared the calculation results with experimental results [14]. Takeuchi et al. (2022) observed numerous bulging failure modes in a timber restrainer and derived the capacity of the timber restrainer [15]. Gu et al. (2021, 2023) theoretically presented the bulging resistance of a circular restrainer based on an experiment and a finite element analysis of BRBs with a corrugated core bar [16,17]. According to these studies, bulging can be prevented by increasing the thickness of the restrainer because most of the outward force resistance is proportional to the square of the restrainer thickness. However, in this process, more steel than that required to prevent only flexural buckling may be consumed.

In this study, two types of enhancements are proposed for BRBs with a rectangular tube section restrainer to prevent bulging failure in the restrainer. First, bent steel plates, serving as inner restrainers, were inserted to increase the outward-force-resisting capacity against steel core deformation. Second, a gap was formed where the steel core contacted the mortar filler for the outward force to bypass the longitudinal center plane of the restrainer. The outward-force-resisting capacity of the inserted bent steel plate was determined using yield line theory with respect to the inner restrainer design. To validate the proposed enhancements, BRBs with different outer and inner restrainer thicknesses and selective gaps in the load path of the outward force were produced along with unreinforced BRBs. Cyclic loading tests were conducted to compare the strength and deformation capacities of different BRBs. The proposed outward-force-resisting capacity was applied to predict the occurrence of bulging, and the results were compared with the experimental results. Several specimens were cut at the bulging location, and the inner damage was investigated to confirm the efficiency of the proposed enhancements.

2. Proposed Enhancements to Prevent Local Bulging Failure

2.1. Local Bulging Failure Mechanism of the Buckling-Restrained Braces

BRBs with a restrainer filled with mortar typically have an unabonding material layer around the steel core designed to prevent bonding between the mortar filler and the steel core. The unabonding material layer is highly flexible, forming a space in which the steel core can deform freely before being restrained by the hardened mortar filler. When the compressive axial force acting on the steel core exceeds the primary mode buckling load of the steel core, higher-mode buckling occurs in the aforementioned space, as shown in Figure 1a, after which a local outward force acts at the contact point between the steel core and the mortar filler. As the axial compressive force increases, the outward force causes the mortar filler to break, and the restrainer undergoes local out-of-plane deformation; that is, bulging failure occurs. Lin et al. (2016) derived expressions for the outward force
demand induced by the steel core and the outward-force-resisting capacity of the restrainer, as described by Equations (1)–(3) [9].

The outward force demand caused by the higher-mode buckling of the steel core can be determined using the following equation based on the moment equilibrium between the transverse and longitudinal forces formed between the two contact points, as shown in Figure 1b:

\[
P_{d,w} = \frac{4N_{cu}(2s_{rw} + \nu_p t_c \epsilon)}{L_{p,w}}
\]

where \( P_{d,w} \) is the outward force due to the higher-mode buckling of the steel core, \( N_{cu} \) is the compressive axial force acting on the brace, \( t_c \) is the thickness of the steel core, \( s_{rw} \) is the gap between the core and the filler, and \( \nu_p \) is the Poisson’s ratio. In addition, \( L_{p,w} \) is the wavelength of higher-mode buckling, which can be calculated by considering the deformation shape, as shown in Figure 1b, using Euler’s buckling equation as follows:

\[
L_{p,w} = \sqrt{\frac{4\pi^2(El)_{eff}}{P_y}}
\]

where \( P_y \) is the yield axial force of the steel core and \( (El)_{eff} \) is the effective flexural stiffness after yielding, for which 5.5% of the elastic flexural stiffness, as recommended by Lin et al. (2016), is applied [9]. The outward-force-resisting capacity of the restrainer can be calculated based on yield line theory, as follows:

\[
P_{c,w1} = \frac{2 - B_c/B_r}{1 - B_c/B_r} t_r^2 F_{yr}
\]

where \( P_{c,w1} \) is the outward-force-resisting capacity of the restrainer; \( B_c \), \( B_r \), and \( t_r \) are the width of the core and the width and thickness of the restrainer, respectively; and \( F_{yr} \) is the yield strength of the restrainer.

The restrainer thickness needs to be increased to enhance the outward-force-resisting capacity based on Equation (3). However, a large amount of steel material is allocated to the restrainer, which does not directly contribute to the axial force resistance of the brace and is uneconomical. In this study, instead of increasing the overall thickness of the restrainer, enhancements that can resist bulging failure more efficiently are proposed.
Figure 1. Higher-order buckling of the steel core in BRB: (a) Higher-order buckling of steel core about weak axis; (b) Illustration of higher-order buckling of steel core about weak axis in detail.

2.2. Inner Restrainer Resisting Outward Force

In this study, an efficient inner restrainer that can resist the outward forces applied by steel core bending in higher-mode buckling is proposed. The steel tube enclosing the mortar filler is designated as the outer restrainer to distinguish it from the inner restrainer. As shown in the cross-sectional view in Figure 2a, the inner restrainer is a bent plate that wraps around the steel core on both sides and efficiently resists outward forces owing to the out-of-plane deformation of the steel core; additional webs are formed in both the upward and downward directions. These webs effectively resist the outward forces by increasing the moment of inertia of the inner restrainer. In addition, as shown in Figure 2a, a considerable amount of the outward force is anticipated to be transmitted to the upper-left and upper-right corners rather than the middle of the outer restrainer, where bulging failure typically occurs, through the compressive struts formed between the corners of the inner and outer restrainers.

Figure 2. Enhancements to prevent local bulging failure: (a) Inner restrainer; (b) Thickened unbonding material.

2.3. Partially Increased Thickness of Unbonding Material

Upon partially increasing the thickness of the unbonding material between the two inner restrainers, as shown in Figure 2b, the steel core does not come into contact with the mortar but only transfers the bearing force through the inner restrainers on both the left and right sides, even if the steel core buckles in a higher mode. This condition helps reduce the amount of outward force transferred to the center of the outer restrainer. Therefore,
the partially increased thickness of the unbonding material is expected to mitigate the possibility of bulging failure.

2.4. Outward-Force-Resisting Capacity of Added Inner Restrainer

A mathematical expression for the outward-force-resisting capacity is a prerequisite for designing an inner restrainer. In this study, the outward-force-resisting capacity of the inner restrainer is derived using yield line theory [18]. The three-dimensional shape and deformation after the application of the outward force on the right inner restrainer illustrated in Figure 2a are shown in Figure 3a,b. It is assumed that plastic bending deformations occur at line segments EG, EH, DG, GH, and HF of the flange. The ABED and BCFE segments in the upper vertical web are assumed to undergo only in-plane deformation owing to the constraints provided by the mortar filler. In addition, shear governs the deformation of those segments because the lengths of the deformed segments are not long compared to their depth, as discussed in Section 4.2. Based on these assumptions, the internal and external work owing to plastic deformation can be calculated as follows, respectively:

\[ W_{I2} = 2 \left[ 2(0.6F_{ys}A_{ws})d_s + 8d_s \left( \frac{t_s^2}{4} \right) F_{ys} \right] \] (4)

\[ W_{E2} = 2 \left( \frac{P_c}{2} \right) d_s \] (5)

where \( W_{I2} \) and \( W_{E2} \) are the internal and external work, respectively; \( P_{c,w2} \) is the outward-force-resisting capacity of the inner restrainer; \( F_{ys} \) is the yield strength of the inner restrainer; and \( B_c, B_r, \) and \( t_r \) are the widths of the steel core and outer restrainer and thickness of the outer restrainer, respectively. Additionally, \( A_{ws} \) is the cross-sectional area of the upper or lower web of the inner restrainer and \( t_s \) is the thickness of the inner restrainer. By equating the internal and external work expressed by Equations (4) and (5), respectively, \( P_{c,w2} \) can be calculated as follows:

\[ P_{c,w2} = 4(0.6F_{ys}A_{ws}) + 4t_s^2F_{ys} \] (6)

---

**Figure 3.** Deformation of the inner restrainer due to outward force: (a) Before deformation; (b) After deformation; (c) In-plane shear yielding of vertical plate element; (d) Flexural plastic deformation of horizontal plate element.
Experimental Method

3.1. Test Program

In this study, cyclic loading tests were conducted on BRBs with and without the proposed enhancements to verify their effectiveness in avoiding bulging failure. The outer restrainer of the BRBs was composed of a rectangular steel tube filled with non-shrinkage mortar. The test specimens are listed in Table 1. The thickness of the steel tube was varied between 6 mm and 9 mm to investigate the effective range of the proposed enhancements. The inner restrainer thickness was varied from 2 mm to 4 mm to investigate the extent to which steel materials could be saved to avoid bulging failure. Partially thickened unbonding material at the middle of the steel core cross-section was applied to only those specimens with designations ending with ‘-G’ to check the effectiveness of the improvement. The inner restrainer was distinguished by its thickness (2 mm or 4 mm), enabling examination of the effectiveness of the thinner inner restrainer.

Table 1. List of specimens.

<table>
<thead>
<tr>
<th>Designation</th>
<th>Outer Restrainer (mm × mm × mm)</th>
<th>Steel Core (mm × mm)</th>
<th>Bent Steel Plate (mm)</th>
<th>Partial Increase in the Unbonding Material Thickness (mm)</th>
<th>Number of Specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>NR-T9</td>
<td>250 × 150 × 9</td>
<td>NA (1)</td>
<td>0</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>R-T9S4</td>
<td></td>
<td>4</td>
<td>0</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>R-T9S2</td>
<td></td>
<td>2</td>
<td>0</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>R-T9S4-G</td>
<td></td>
<td>4</td>
<td>+2</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>R-T9S2-G</td>
<td></td>
<td>2</td>
<td>+2</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>NR-T6</td>
<td>250 × 150 × 6</td>
<td>NA (1)</td>
<td>0</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>R-T6S4</td>
<td></td>
<td>4</td>
<td>0</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>R-T6S4-G</td>
<td></td>
<td>4</td>
<td>+2</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

(1) Not available.

3.2. Details of Specimens

The cross-sections of the eight specimens are illustrated in Figure 4. All specimens have a steel core located in the center, an unbonding material surrounding the steel core, and a non-shrinkage mortar filler inside the rectangular outer restrainer. The inner restrainer is installed surrounding the unbonding material such that the steel core can deform slightly in the space formed by the unbonding material, which wraps around the steel core with a thickness of 2 mm. Specimens R-T9S4-G, R-T9S2-G, and R-T6S4-G have an additional unbonding material with a thickness of 2 mm in the middle of the steel core cross-section, which results in a total thickness of 4 mm. The inner restrainer is a type of bent plate with a three-dimensional shape, as shown in Figure 5, in which small pieces of perforated steel plates are welded to connect two opposing bent plates using threaded bolts.

Figures 6 and 7 show the longitudinal shapes of specimens NR-T9 and R-T9S4-G, respectively. The proposed enhancements were applied only to R-T9S4-G. The steel core was reinforced by welding steel plates on each side of both ends while gradually expanding at both ends to concentrate the tensile yielding and higher-mode buckling deformations in the middle part. In addition, a stopper was welded to the center of the steel core to prevent the outer restrainer from sliding down in the setup for vertical loading. A 9 mm thick end plate was welded at each end of the outer restrainer to contain the mortar filler. Considering the axial deformation of the steel core, a 50 mm clearance was formed with the unbonding material at the initial position of the expanded part. Similarly, the same clearance was left between the end of the inner restrainer and the extended part of the steel core using the unbonding material.
Figure 4. Cross-sections of the specimens: (a) NR-T9; (b) R-T9S4; (c) R-T9S2; (d) R-T9S4-G; (e) R-T9S2-G; (f) NR-T6; (g) R-T6S4; (h) R-T6S4-G.
Figure 5. Three-dimensional diagram of the inner restrainer.

Figure 6. Specimen NR-T9: (a) Steel core; (b) Side view of steel core; (c) Section E-E' of steel core; (d) Plan.
Figure 7. Specimen R-T9S4-G: (a) Steel core; (b) Side view of steel core; (c) Section E-E’ of steel core; (d) Plan.

3.3. Material Strength

The nominal and material strength test results for the steel and mortar are summarized in Table 2. The strength of each specimen was calculated by dividing the force measured using the load cell by the nominal cross-sectional area of the specimen. The strength exhibited by the steel was the average of three test specimens, and that of the non-shrinkage mortar was the average of eight cubic specimens. The outer restrainer exhibited a strength that was significantly higher than the specified yield strength of 275 MPa.

Table 2. Material test results.\(^1\)

<table>
<thead>
<tr>
<th>Component</th>
<th>Designation or Nominal Strength</th>
<th>Thickness (mm)</th>
<th>Number of Specimens</th>
<th>Compressive Strength (MPa)</th>
<th>Average Yield Strength (MPa)</th>
<th>Average Tensile Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel core</td>
<td>SM355</td>
<td>16</td>
<td>3</td>
<td>-</td>
<td>358.7 (0.022)</td>
<td>527.8 (0.005)</td>
</tr>
<tr>
<td>Outer restrainer</td>
<td>SRT275</td>
<td>9</td>
<td>3</td>
<td>-</td>
<td>434.2 (0.044)</td>
<td>492.1 (0.026)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
<td>3</td>
<td>-</td>
<td>399.8 (0.010)</td>
<td>485.7 (0.004)</td>
</tr>
<tr>
<td>Inner restrainer</td>
<td>SS275</td>
<td>4</td>
<td>3</td>
<td>-</td>
<td>263.6 (0.020)</td>
<td>388.4 (0.012)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>3</td>
<td>-</td>
<td>242.8 (0.009)</td>
<td>365.6 (0.002)</td>
</tr>
<tr>
<td>Mortar filler</td>
<td>61.4 MPa</td>
<td>-</td>
<td>8</td>
<td>51.4 (0.157)</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

\(^1\) Numbers in parentheses are coefficients of variation.

3.4. Test Setup

Cyclic loading tests were performed using a 10,000 kN universal testing machine (UTM). The test specimens were installed by clamping the grip at each end of a hydraulic tensile test chuck. The experimental setup is illustrated in Figure 8. The axial force was measured using a 10,000 kN load cell and the displacement was measured by the internal sensor of the universal testing machine. A sufficient grip length was secured at the end of the specimen such that no slippage occurred. To check for the occurrence of bulging, strain gauges were attached to the front and back faces of the outer restrainer, with 14 gauges per face at 150 mm intervals. The locations of the strain gauge attachments are shown in Figure 9. The longitudinal deformation of the specimens was measured directly using the UTM.
3.5. Loading Protocol

The loading protocol for the cyclic loading test is depicted in Figure 10. The loading protocol is determined by referring to the cyclic load requirements presented in the Seismic Design Criteria for Steel Structures (KDS 14 31 60) and the similar “Cyclic Tests for Qualification of Buckling-Restrained Braces” in ANSI/AISC 341-16 [1,19], where the displacement amplitude is defined as the multiple of the deformation $\Delta_{bm}$, corresponding to the design story drift. $\Delta_{bm}$ was assumed to be 25 mm. However, after the termination of the cycle corresponding to $2\Delta_{bm}$, the additional cycles of $1.5\Delta_{bm}$ in the reference standard [1,19] were enhanced to two cycles of $2.5\Delta_{bm}$ and four cycles of $3\Delta_{bm}$. The displacement-controlled loading was terminated and returned to zero displacement when the axial load measured during the experiment fell below 80% of the peak load under compression or...
tension. If the entire loading protocol was completed and no strength degradation occurred, monotonic compression loading was applied until strength degradation occurred.

Figure 10. Loading protocol.

4. Test Results

4.1. Observations

The force–displacement relationship for each specimen is plotted in Figure 11. The compressive strengths of all the specimens are greater than the tensile strengths, and the difference increases when the inner restrainer is installed. No flexural buckling of the entire brace occurs in any of the specimens.
Figure 11. Force–displacement relationship: (a) NR-T6; (b) R-T6S4; (c) R-T6S4-G; (d) NR-T9; (e) R-T9S4; (f) R-T9S4-G; (g) R-T9S2; (h) R-T9S2-G.

4.1.1. Specimens with Outer Restrainer of 6 mm Thickness

Specimen NR-T6, which did not have an inner restrainer installed, exhibited no significant changes until the completion of the 11th cycle, and out-of-plane deformation occurred 600 mm from the upper end of the outer restrainer while increasing the compressive displacement in the 12th cycle (Figure 12a). In addition, a distinct decrease in the strength was observed, and the loading was terminated. Specimen R-T6S4 specimens with inner restrainers and specimen R-T6S4-G with partially thickened unbonding material in addition to inner restrainers showed no significant degradation until the 12th cycle, and out-of-plane deformation of the rear face of the outer restrainer occurred approximately 350 mm from the upper end of the outer restrainer with a significant decrease in the strength, while increasing the compression displacement in the 13th cycle (Figure 12b).
4.1.2. Specimens with Outer Restrainer of 9 mm Thickness

Specimen NR-T9 did not exhibit any buckling, fracture or bulging phenomena until all of the prescribed cycles were completed. After the loading was terminated, monotonic compression loading was applied, and the load degraded when bulging failure occurred at a compressive deformation of 100 mm. Specimen R-T9S2 exhibited slight out-of-plane deformation while increasing the compressive displacement in the 15th cycle, and fracture occurred during the subsequent tensile loading process in the 16th cycle.

4.2. Location of Bulging Failure

The location of the out-of-plane deformation (that is, the bulging failure of the outer restrainer) was 300–600 mm from the outer restrainer end, as shown in Figure 12. For specimen NR-T6, in which the inner restrainer was not installed, the out-of-plane deformation was located 625 mm from the end of the outer restrainer. In the steel core, this location corresponds to the segment where inelastic deformation is intended on account of a reduced cross-section. However, the other specimens experienced bulging failure within 300–375 mm from the end of the outer restrainer. Regardless of the thickness of the outer restrainer, the out-of-plane deformation had an extremum primarily located 350 mm from the end of the outer restrainer. Mostly, the out-of-plane deformation was distributed within a radius of approximately 50 mm. At this location, the inner restrainer does not extend and cannot effectively resist the outward force. Therefore, an insufficient length of the inner restrainer also limits the improvement in strength and deformability, as is examined later. Hence, certain enhancements are necessary to ensure that the inner restrainer works effectively for a more extended range.

4.3. Strength

The measured strengths of the specimens are listed in Table 3. In this table, the completed stage refers to the completion of two cycles with the same displacement amplitude and without strength degradation. All of the specimens strengthened with an inner restrainer showed an obviously higher compressive strength than the tensile strength. The specimens with an outer restrainer thickness of 9 mm exhibited a higher strength than those with an outer restrainer thickness of 6 mm. The hardening phenomenon observed in the compression zone of Figure 11 was caused by the friction between the steel core bent in the higher buckling mode and the mortar filler enclosing the steel core; furthermore, the constraint on the Poisson expansion of the steel core by the mortar filler is another reason [20,21]. The specimens with the inner restrainers exhibited a more prominent hardening in compression than those without because the inner restrainers constrained the steel core more strongly than the mortar filler alone. The specimens with a partially increased unbonding material thickness did not exhibit a distinct additional strengthening effect. However, although the difference in the compressive strength was significant, the difference in the tensile strength was negligible.

The Korean Seismic Design Standard for Steel Structures (KDS 14 31 60) stipulates cyclic tests for the qualification of BRBs [19]. The acceptance criteria presented in the standard require that the compression strength adjustment factor (= maximum compressive force divided by maximum tensile force), abbreviated as the CSA factor, shall not exceed 1.3. The ANSI/AISC 314-16 Seismic Provisions for Structural Steel Buildings stipulate 1.5 as the upper limit of the CSA factor [1]. The CSA factors based on the completed stages are listed in Table 3. Both NR-T6 and NR-T9, to which no enhancements are applied, satisfy the acceptance criteria of KDS 14 31 60, with a compression strength adjustment factor of 1.15–1.19. In contrast, the CSA factor of the specimens strengthened with inner restrainers range from 1.26 to 1.50, which are relatively high values compared to those of specimens with no inner strainers. R-T6S4, R-T6S4-G, and R-T9S2 have CSA factors that
are less than or almost equal to 1.3, conforming to KDS 14 31 60, whereas the other enhanced specimens only satisfy the requirements of ANSI/AISC 314-16. Notably, the CSA requires further improvement.

Table 3. Maximum strength of specimens. (1)

<table>
<thead>
<tr>
<th>Specimen</th>
<th>For Completed Cycles</th>
<th>For Entire Test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Compression (kN)</td>
<td>Tension (kN)</td>
</tr>
<tr>
<td>NR-T6</td>
<td>1070</td>
<td>927.9</td>
</tr>
<tr>
<td>R-T6S4</td>
<td>1271</td>
<td>962.0</td>
</tr>
<tr>
<td>R-T6S4-G</td>
<td>1248</td>
<td>951.8</td>
</tr>
<tr>
<td>NR-T9</td>
<td>1178</td>
<td>987.1</td>
</tr>
<tr>
<td>R-T9S4</td>
<td>1484</td>
<td>989.7</td>
</tr>
<tr>
<td>R-T9S4-G</td>
<td>1439</td>
<td>992.6</td>
</tr>
<tr>
<td>R-T9S2</td>
<td>1298</td>
<td>1029</td>
</tr>
<tr>
<td>R-T9S2-G</td>
<td>1351</td>
<td>984.7</td>
</tr>
</tbody>
</table>

(1) The precision of forces is 10 kN. (2) Additional monotonic compression loading.

4.4. Demand and Capacity for Outward Force

The outward-force-resisting capacity, considering both the outer and inner restraints, was calculated and compared with the seismic demand of the restrainers, as presented in Table 4. The outward-force-resisting capacity was calculated by summing the resistances calculated using Equations (3) and (6). The outward force demand caused by the steel core was calculated using Equation (1), where the maximum compressive force measured for each test specimen was applied to $N_{cm}$. The material strength was determined based on the results of the material tests. The ratio of the demand to the resisting capacity for the outward force is denoted as DCR (demand–capacity ratio) in Table 4.

Because bulging failure occurred in all of the specimens, the DCR should be close to 1. For NR-T6, the DCR was 2.75, which was significantly greater than 1 because the inner restrainer was not installed in the specimen. For NR-T9, the DCR was 1.26, which was also greater than 1 but considerably lower than that of NR-T6 owing to the increased thickness of the outer restrainer. The DCR was overestimated because of the following reasons. First, the outward force demand was overestimated upon neglecting the resistance of the bending moment against a couple caused by the higher-mode buckling of the steel core, as shown in Figure 1b. Second, the outward-force-resisting capacity was underestimated upon neglecting the contribution of the mortar filler. Most of the enhanced specimens exhibited a DCR greater than or close to 1; however, the DCRs of R-T9S4 and R-T9S4-G were significantly lower than 1. In these cases, the outward-force-resisting capacity might have been somewhat overestimated because bulging occurred at the end of the inner restrainer where the resistance to the outward force could not be fully achieved, as discussed in Section 4.2. The DCR would have been higher than or close to 1.0 if the bulging failure had occurred sufficiently far from the end of the inner restrainer. Therefore, Equation (6) proposed in this study to estimate the outward-force-resisting capacity added by the shear and bending deformation of the inner restrainer, combined with Equation (3), which indicates the outward-force-resisting capacity of the outer restrainer and was proposed by Lin et al. (2016, 2018), can be successfully used to check whether the designed inner and outer restrainers are adequate for preventing bulging failure.

Comparing NR-T9 and R-T6S, the outward force demand ($P_{d,w}$) values of the specimens are similar to one another, as shown in Table 4; however, the total outward-force-resisting capacity ($P_{r,w}$) increases from 103 kN for NR-T9 to 125 kN for R-T6S. Consequently, the DCR values decreased from 1.35 for NR-T9 to 1.08 for R-T6S. As a result, the
steel material volume of the restrainer, which does not directly resist the axial force, can be reduced by 27% from 0.0179 m$^3$ for NR-T9 to 0.0131 m$^3$ for R-T6S4, of which the latter includes the volume of the inner restrainer. Therefore, the proposed enhancement combined with Equation (6) enables a more efficient resistance against bulging failure than using only the outer restrainer designed by Equation (3) proposed by Lin et al. (2016, 2018).

However, the hardening in compression increased the outward force demand such that it was higher than the outward-force-resisting capacity enhanced by the inner restrainer and led to bulging failure in the final stage. Therefore, efforts to reduce the hardening effect are required in future research.

Table 4. Outward force demand and resisting capacity of restrainers.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Demand $P_{d,w}$ (kN)</th>
<th>Outer Restrainer $P_{cw1}$ (kN)</th>
<th>Inner Restrainer $P_{cw2}$ (kN)</th>
<th>Sum $P_{cw}$ (kN)</th>
<th>Increase Rate (%)</th>
<th>DCR $P_{d,w}/P_{cw}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NR-T6</td>
<td>94</td>
<td>42.1</td>
<td>NA (1)</td>
<td>42.1</td>
<td>NA</td>
<td>2.23</td>
</tr>
<tr>
<td>R-T6S4</td>
<td>137</td>
<td>42.1</td>
<td>82.7</td>
<td>125</td>
<td>196</td>
<td>1.08</td>
</tr>
<tr>
<td>R-T6S4-G</td>
<td>136</td>
<td>42.1</td>
<td>82.7</td>
<td>125</td>
<td>196</td>
<td>1.09</td>
</tr>
<tr>
<td>NR-T9</td>
<td>139</td>
<td>103</td>
<td>NA (1)</td>
<td>103</td>
<td>NA</td>
<td>1.35</td>
</tr>
<tr>
<td>R-T9S4</td>
<td>136</td>
<td>103</td>
<td>82.7</td>
<td>185</td>
<td>80</td>
<td>0.732</td>
</tr>
<tr>
<td>R-T9S2</td>
<td>150</td>
<td>103</td>
<td>30.7</td>
<td>133</td>
<td>30</td>
<td>1.13</td>
</tr>
<tr>
<td>R-T9S4-G</td>
<td>103</td>
<td>103</td>
<td>82.7</td>
<td>185</td>
<td>80</td>
<td>0.558</td>
</tr>
<tr>
<td>R-T9S2-G</td>
<td>133</td>
<td>103</td>
<td>30.7</td>
<td>133</td>
<td>30</td>
<td>0.994</td>
</tr>
</tbody>
</table>

(1) Not available.

4.5. Deformation Capacity

The maximum deformations of the specimens are listed in Table 5. Overall, the specimens with an outer restrainer of 9 mm thickness exhibit higher strengths and better deformation capacities than those with an outer restrainer of 6 mm thickness. Considering only the completed cycles, no improvement was observed on account of the application of the inner restrainer. However, in the case of the maximum deformation for the entire cycle, an increase was confirmed in specimens R-T6S4 and R-T6S4-G specimens with an outer restrainer of 6 mm thickness, and R-T6S4-G with a partially thickened unbonding material showed additional deformation capacity under compression.

Table 5. Maximum deformation of specimens. (1)

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Compression (mm)</th>
<th>Tension (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Completed Cycles</td>
<td>Entire Cycles (2)</td>
</tr>
<tr>
<td>NR-T6</td>
<td>62.6</td>
<td>62.6</td>
</tr>
<tr>
<td>R-T6S4</td>
<td>62.7</td>
<td>67.7</td>
</tr>
<tr>
<td>R-T6S4-G</td>
<td>62.7</td>
<td>75.2</td>
</tr>
<tr>
<td>NR-T9</td>
<td>75.3</td>
<td>109.5 (3)</td>
</tr>
<tr>
<td>R-T9S4</td>
<td>75.2</td>
<td>75.2</td>
</tr>
<tr>
<td>R-T9S4-G</td>
<td>75.2</td>
<td>75.2</td>
</tr>
<tr>
<td>R-T9S2</td>
<td>75.2</td>
<td>75.2</td>
</tr>
<tr>
<td>R-T9S2-G</td>
<td>75.2</td>
<td>75.2</td>
</tr>
</tbody>
</table>

(1) The precision of deformation is 0.1 mm. (2) Displacement at the strength decrease by more than 80%. (3) Additional monotonic compression loading.

Two design standards, KDS 143160 and ANSI/AISC 341-16, stipulate cyclic tests to qualify BRBs [1,19]. Both standards require that the cumulative inelastic deformation of a
BRB achieve a minimum of 200 times the yield deformation, during which fracture, instability, and joint failure do not occur. The yield deformation, cumulative deformation, and their ratios for each specimen are listed in Table 6; all specimens met the cumulative inelastic deformation requirement. In particular, the specimens using an outer restrainer of 6 mm thickness show an improvement of approximately 24% in the cumulative inelastic deformation capacity upon application of the inner restrainer.

Table 6. Cumulative deformation of specimens.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Yield Deformation (A) (mm)</th>
<th>Cumulative Inelastic Deformation (B) (mm)</th>
<th>B/A</th>
</tr>
</thead>
<tbody>
<tr>
<td>NR-T6</td>
<td>4.12</td>
<td>1247</td>
<td>303</td>
</tr>
<tr>
<td>R-T6S4</td>
<td>4.10</td>
<td>1541</td>
<td>376</td>
</tr>
<tr>
<td>R-T6S4-G</td>
<td>4.11</td>
<td>1548</td>
<td>377</td>
</tr>
<tr>
<td>NR-T9</td>
<td>4.12</td>
<td>2304</td>
<td>559</td>
</tr>
<tr>
<td>R-T9S4</td>
<td>4.09</td>
<td>2108</td>
<td>516</td>
</tr>
<tr>
<td>R-T9S4-G</td>
<td>4.11</td>
<td>1990</td>
<td>485</td>
</tr>
<tr>
<td>R-T9S2-G</td>
<td>4.13</td>
<td>1827</td>
<td>443</td>
</tr>
</tbody>
</table>

5. Section Cut after Test

Several specimens were cut at two locations after completion of the test. As shown in Figure 13, the first cut was made at the section where the rise of the bulging surface in the outer restrainer was most prominent, and the second cut was made sufficiently away from the bulging area. Specimens NR-T9 and R-T9S2 were cut and compared. The cut sections of each specimen are shown in Figures 14 and 15.

In the case of NR-T9 without enhancements, cracks in the mortar filler developed diagonally from the left and right ends of the steel core to the corner of the outer restrainer at section A-A', where bulging occurred prominently (Figure 14). Similar cracks were also observed in section C-C', which was located sufficiently away from the bulging deformation. In the case of R-T9S2 strengthened with inner restrainers, section A-A' showed cracks similar to those in NR-T9, but with a slower slope connecting the end of the inner restrainer and the corner of the outer restrainer. In particular, cracks were not observed in section C-C' of R-T9S2, which was the most distinct difference from that of NR-T9.

Sections A-A' and B-B' are magnified in Figure 16a,b, respectively. Section A-A', where the bulging failure is the most prominent, demonstrates that the circular corner of the inner restrainer, initially with a radius of curvature of 2 mm, deforms into a nearly right-angled shape (marked with an elliptical dotted line) owing to the outward bearing force exerted by the steel core subjected to higher-mode buckling about the weak axis. In contrast, in section B-B', where bulging deformation does not occur, the deformation of the inner restrainer is not observed, as shown in Figure 16b. From this observation, it is inferred that the higher-mode buckling of the steel core is concentrated locally, the enhanced resisting capacity provided by the inner restrainer increases the outward forces, and the compressive axial force of the steel core in moment equilibrium with the outward forces increases correspondingly, resulting in a higher CSA factor, as described in Section 4.3.

The shape of the deformed steel core in higher-mode buckling can be observed by separating the steel core from the cut portion of R-T9S2. The distances between a peak and its adjacent valley are measured and shown in Figure 17. The effective buckling wavelength can be considered twice the marked number and falls within the range of 70–80 mm. However, the effective buckling wavelength calculated using Equation (2) is 165 mm, and the measured value is significantly smaller than the theoretical value by a factor of
1/2. This indicates that improvement is required for the current approach to determine the effective buckling wavelength.

Figure 13. Location of cutting test specimen.

Figure 14. Section of NR-T9 cut after test: (a) A-A'; (b) C-C'.

Figure 15. Section of R-T9S2 cut after test: (a) A-A'; (b) C-C'.
6. Conclusions

In this study, two types of innovative enhancements are proposed to protect buckling-restrained braces from bulging failure of the restrainer, and they are validated experimentally. The first approach involves adding inner restrainers composed of a bent steel plate, and the other approach is the use of a partially thickened unbonding material for the outward force to bypass the centerline of the cross-section. Cyclic loading tests were performed to investigate the behavioral characteristics of the buckling-restrained braces with one or both types of enhancements, and the effects of the enhancements were evaluated in terms of the strength and deformation capacity. The experimental results and findings are summarized as follows:

(1) The inner restrainer is more efficient for BRBs with relatively thin outer restrainers. For an outer restrainer of 6 mm thickness, the compressive strength increases by 20%, the maximum deformation increases by 8–20%, and the cumulative deformation increases by 25% upon inserting the inner restrainer. However, for an outer restrainer of 9 mm thickness, the compressive strength increases by only 10%, and there is no significant improvement in the maximum and cumulative deformations. The effect on the tensile strength is minimal.

(2) The outward force from the steel core increases in correspondence with the resistance enhanced by the inner restrainer, accompanied by an increase in the compressive force in the steel core. Thus, the compression strength adjustment factor increases to the range of 1.26–1.5 and exceeds the acceptable threshold depending on the applicable standard. Therefore, efforts are required to improve the proposed inner restrainer to alleviate the compression-hardening effect.

(3) Even when the inner restrainer is installed, bulging failure eventually occurs. Bulging failure most often occurs at the location where the inner restrainer is terminated, and accordingly, a strengthening effect is hard to achieve.

(4) An analytical formula for estimating the outward-force-resisting capacity of the inner restrainer was proposed based on the yield-line theory for the flange element and the inelastic shear deformation of the web element. The proposed theoretical outward-force-resisting capacity conservatively predicts the demand-to-capacity ratio for most of the strengthened specimens. An unconservative prediction for the two specimens with thicker outer and inner restrainers is inferred to be caused by the location of the bulging failure close to the end of the inner restrainer.

(5) Upon observing the cross-section of a strengthened specimen, it is found that cracks do not appear in the mortar filler where bulging failure does not occur, implying the effectiveness of the proposed inner restrainer. However, it is necessary to improve the details such that the inner restrainer is sufficiently extended or the steel core is stiffened at the vulnerable location.

(6) The effective buckling wavelength of the steel core cut from the specimen is lower than the value predicted in previous studies by approximately 50. Shorter
wavelengths result in a higher outward force from the steel core. Therefore, in-depth research in this respect is necessary in the future.

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