Timber Buckling Restrained Brace

The timber buckling-restrained brace (TBRB) experiment at California Polytechnic State University, San Luis Obispo (Cal Poly), began in 2018 with the goal of finding whether timber may provide proper restraint against buckling of a steel brace. The TBRB was motivated by the limited lateral force resisting systems (LFRS) available for low-to-mid-rise, type V construction; this system would provide strength and ductility at a scale and level of cost appropriate to timber construction.

Early research consisted of uniaxial component testing, where researchers played with the balance between the core brace design and utilization of timber casings for buckling restraint, with minimal material use at the forefront. While iterating on the design, uniaxial component testing graduated to lateral braced-frame testing in Spring of 2021, eventually leading to the proof-of-concept design detailed in the following paper.

Authors’ Note:

The TBRB research at Cal Poly culminated in June 2022 with the last braced-frame test resulting in a compression-to-tension capacity ratio of 1.06, with an average of 0.96 among the latest five tests. This research was presented at the Structural Engineers Association of California (SEAOC) Convention in 2022, accompanied with the publication of the following paper.

A special thanks to Professor Kevin Dong for leading the way on the TBRB experiment, to previous student researchers at Cal Poly who helped shape the TBRB into what it is today, and to supporters who are determined to help push the TBRB further.
Abstract

Buckling-restrained braced frames (BRBFs) were first popularized by Nippon Steel in the 1980’s as the unbonded brace (Watanabe et. al., 1988) and have since become a prominent lateral-force resisting system (LFRS) in the industry, known for their stable energy dissipation as well as affordable installation in existing and new construction (Bruneau, Uang, Sabelli, 2011). The buckling-restrained braces (BRBs) have cyclically symmetric behavior due to the presence of a mortar-filled casing that inhibits the buckling response of the steel core when in compression. While BRBFs are an efficient and affordable solution for mid-to-high-rise buildings, there are concerns for the appropriate economical use of this system in low-rise construction. In such applications, a timber-buckling-restrained brace (TBRB) is proposed. The TBRB solution allows for the use of non-proprietary connections and assemblies; the TBRB consists of a slender steel brace inhibited by steel plates on either side, encased by timber. This paper discusses the full matrix of TBRBs conducted at Cal Poly, with an emphasis on more recent scaled-frame tests. Experimental results indicate that this timber solution would provide a level of cost, constructability, and simplicity suitable for the type of construction that is most common throughout the modern construction industry.

Results indicate that the latest TBRB design presented in this paper meet minimum drift requirements per standard BRB cyclic testing protocol as defined in AISC 341-16. The proposed gusset-to-brace connection (protected zone) produces a significant ductile response in the steel core (yield zone) while using timber as a primary buckling-inhibiting element. This research study shows that timber is a viable material to be implemented into a buckling-restrained brace frame system, provided the correct detailing and an appropriate building scale. One shortcoming of the current design, slated for future investigation, is related to the higher buckling modes where there are outward pressures that could not be mitigated by the proposed connections.

Introduction

Due to the lack of variety in timber lateral force resisting systems (LFRS), and therefore absence in building codes in the United States, as timber construction begins to increase in height and complexity, designers tend to implement steel or concrete systems (Blomgren, et. al., 2016). One system being the codified buckling restrained brace (BRB) which inhibits the buckling of a slender steel core brace using a hollow steel section (HSS) filled with mortar, such that the steel develops its full elastic and ductile capacity in compression (Uang, Nakashima, Tsai, 2004). An analogous approach was taken in the design of TBRB using a slender steel brace inhibited by steel plates on either side, encased by solid sawn lumber sections. BRBs are advantageous for mid to high-rise construction in meeting seismic performance goals, but inefficient in low to mid-rise light frame construction. The
TBRB would inherently address this shortcoming by providing adequate capacity with cost reductions in labor and materials.

This paper discusses the development of the timber buckling-restrained braced (TBRB) frame at the California Polytechnic State University, San Luis Obispo (Cal Poly) since 2018, with a focus on experimental testing conducted in 2022. The goal of efforts in 2022 was to fabricate, test, and refine the TBRB design to produce reliable and consistent response for a sample of tests per the AISC 341-16 Section K3 loading protocol, and specifically to verify the system achieved stable and symmetric hysteretic behavior beyond yield as well as the minimum required story drift of 2%.

**Timeline of TBRB Development**

The first three rounds of experiments were brace-only testing which explored steel core geometry and wood shell composition to limit compression buckling of the core plate.

The TBRB development began at Cal Poly in 2018 with Fernandez and Derakhshani (2018) determining the minimum required sizes for the brace component. This resulted in the fabrication and axial cyclic testing of four specimens. Each consisted of two 4-in. by 8-in planed sawn lumber segments sandwiching a dog-bone core brace; two specimens with, and two without, sheet metal. Sheet metal was implemented at each face of the brace to evenly distribute outward pressure, as it was found that the sawn lumber was not stiff enough to mitigate concentrated buckling loads on its own. It was found that sheet metal was not sufficient.

The following experiment, conducted by Pit and Liu, aimed to find an appropriate thickness for these additional buckling restraining plates (BRPs) (2019). These brace specimens would match the BRP thickness; larger strains were attained but buckling would occur outside of the timber case.

A similar investigation was performed in 2019 by Resta, with improved fabrication techniques for the BRPs (2019). These prototypes reached higher strains than previous tests, but not equivalent to strains associated with 2 times brace deformation at design story drift, $\Delta_{\text{nom}}$. The failure mechanism was undesirable due to insufficient stiffness outside of the timber casing where out-of-plane brace deflections were two or more inches as shown in Figure 1, rendering the connection inoperable. This design is improved by providing stiff connections at the ends of the core-brace plate to enforce inelastic straining in this zone; thus, the addition of stiffener plates at the ends of the core brace plate.

Stiffener plates at brace ends were implemented in the first round of scaled-frame testing conducted by Ayers (2021). This series of tests focused on simplifying the configuration while implementing it into a conventional timber frame. One stiffener plate was welded at each brace end and on one face, oriented perpendicular to the brace to increase moment of inertia out-of-plane; the stiffener plates started inside of the timber casing and terminated within an inch from the first bolt. This was intended to force buckling in the designated yielding area within the timber casing. While there were light signs of yielding of the brace within the timber casing, failure was identical to previous iterations. Buckling occurred outside of the restrained brace, between the end of the stiffener plate and first bolt, shown in Figure 2.
**TBRB Assembly**

The latest TBRB design uses two stiffener plates at each end and on one face of the brace, oriented perpendicular to the brace. The fins protrude eight inches into the timber case and terminate after the last bolt at the brace-to-gusset plate connection. Two stiffener plates were required to achieve this connection and ensure load transfer across all bolts.

**Components**

The brace encasement includes two 4x DF-L sawn lumber sections, with two 3-in. by 3/8-in. grade A36 steel flat-bars screwed to the wood sections at third points. The 3/8-in. plates will be referred to as buckling restraining plates (BRPs), as they assist the wood encasement in restraining the brace. The brace itself was a 3-in. by 1/8-in. grade A36 steel flat-bar; stiffener plates, or fins, welded to the face of the brace were 1/4-in. A36 bars. Note that the brace is sandwiched between the timber casing and BRPs, but not bonded or connected to them. However, the timber casing bears on the brace via a pin at midspan as well as the stiffener plates, such that the timber sleeve stays in place during erection.

**Figure 3. Frame Elevation and Brace Configuration**

**Figure 4. TBRB Components**

The frame consists of 6x6 posts and a 6x8 beam. Connections consisted of Simpson Strong-Tie connectors (holdowns, post caps) and gusset plates composed of 1/4-in. thick plates.

For test set-up, to transfer load from the actuator to the frame, a steel channel was modified with a cleat welded to the end and connected at the top of the beam via lag screws, effectively acting as a collector.
Fabrication

All fabrication took place at the Cal Poly CAED Support Shop by the authors, with the assistance of shop staff and colleagues. Components that were either fabricated in previous years, recycled, or bought as-is include: gusset plates, collector channel, and Simpson Strong-Tie hardware.

- **Timber Case**: All timber sections were pre-drilled where screws were required. Each half of the timber case were dado-cut in equal depths, with 1/8-in. tolerance, to create slots for the BRPs and brace. One half of the timber case was dado-cut to receive the stiffener plates.

- **BRPs**: Countersunk holes were drilled out of the BRPs for third-point connections to the timber cases, and slots were cut out to of one BRP to receive the stiffener plates where they protrude into the timber case.

- **Brace**: Stiffener plates were cut down to length, mitered, and sanded down for welding. The brace was drilled oversized holes by 1/8-in. for bolted connections to the gusset plate, and stiffener plates were stitch welded on either side of the bolt holes, on one face of the brace.

- **Channel**: Resourced from the CAED Support Shop and recycled, the collector channel was drilled holes for lag screws. The cleat for attachment to the actuator was field welded to the end of the channel to ensure the line of action was not skewed.

- **Erection**: Frame assembly was done manually by the authors. First, the columns then beam were erected. Gusset plates were put in place, as well as columns caps. Then, with four people, the brace was lifted and bolted into place within ten minutes.

Cost Breakdown

The following cost breakdown represents the cost of one TBRB frame assembly, at the scale used in 2022 TBRB experiments. Note that material costs fluctuate frequently; the information provided is for scale of the cost benefits of a TBRB.

A characteristic of BRBs is limited damage to connections, such that only the brace need be replaced (Bruneau, Uang, Sabelli, 2011). In this experiment, it was found that the BRPs and wood screws had limited damage and could therefore be recycled for each brace, replacing screws when necessary. Similarly, frames and frame connections saw little to no damage.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Cost</th>
<th>Qty</th>
<th>Total A</th>
<th>Total B</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Steel</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[Core Brace]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PL. 1/8&quot; x 3&quot; x 10'</td>
<td>$20</td>
<td>1</td>
<td>$20</td>
<td>$20</td>
</tr>
<tr>
<td>[Gusset Plates]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PL. 1/4&quot; x 2' x 4'</td>
<td>$110</td>
<td>2</td>
<td>$220</td>
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</tr>
<tr>
<td>[Stiffener Plates]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PL. 1/4&quot; x 4&quot; x 16&quot;</td>
<td>$3.93</td>
<td>4</td>
<td>$16</td>
<td>$16</td>
</tr>
<tr>
<td>[BRPs]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PL. 3/8&quot; x 3&quot; x 10'</td>
<td>$52</td>
<td>2</td>
<td>$104</td>
<td></td>
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<tr>
<td><strong>Wood</strong></td>
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<tr>
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</tr>
<tr>
<td>6x8 x 8'-0&quot;</td>
<td>$59</td>
<td>2</td>
<td>$117</td>
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</tr>
<tr>
<td>6x6 x 8'-0&quot;</td>
<td>$45</td>
<td>4</td>
<td>$181</td>
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<td>[Wood Casing]</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>4x6 x 8'-0&quot;</td>
<td>$15</td>
<td>2</td>
<td>$30</td>
<td>$30</td>
</tr>
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<td><strong>Connections</strong></td>
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<td></td>
</tr>
<tr>
<td>[Post Caps &amp; Base]</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>EPCZ</td>
<td>$38</td>
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<td>$77</td>
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</tr>
<tr>
<td>CB³</td>
<td>$43</td>
<td>1</td>
<td>$43</td>
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<td>HDU14</td>
<td>$36</td>
<td>2</td>
<td>$71</td>
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<td>[Wood Screws]</td>
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<td>SDWS22500</td>
<td>$80</td>
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<td>$80</td>
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<td>(100pk)</td>
<td></td>
<td></td>
<td></td>
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<td>[Lag Screws]</td>
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</tr>
<tr>
<td>5/8&quot;Ø x 5&quot; Hex</td>
<td>$2.58</td>
<td>50</td>
<td>$129</td>
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<tr>
<td>[Bolts]</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>5/8&quot;Ø-18 Hex</td>
<td>$1.52</td>
<td>10</td>
<td>$15</td>
<td></td>
</tr>
<tr>
<td>[Nuts]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5/8&quot;Ø-18 Hex</td>
<td>$0.54</td>
<td>10</td>
<td>$5</td>
<td></td>
</tr>
<tr>
<td>[Washers]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11/16&quot;Ø ID</td>
<td>$0.33</td>
<td>50</td>
<td>$17</td>
<td>$17</td>
</tr>
<tr>
<td>[TOTAL]</td>
<td>$1,237</td>
<td></td>
<td>$90</td>
<td></td>
</tr>
</tbody>
</table>

Note:
1. Total A represents the up-front cost of one TBRB frame using new material.
2. Total B represents the cost to replace a TBRB. Components omitted from this list will see little damage and can therefore be reused.
3. For this project, a post base was made from scratch out of recycled materials in the CAED Support Shop (Ayers, 2021).
Iterations

A total of seven braces were fabricated and tested. The first brace was intended to confirm that the single-fin connection was not sufficient. The second brace was intended to be a proof-of-concept; fabricated such that only the steel brace changed, without modifying the BRPs. Two fins were welded on either side of the bolts for continuous bracing as well as to engage all the bolts in the load path; this would be considered the intermediate double-fin. This connection was successful at preventing buckling outside of the brace. With improved performance, this proof-of-concept confirmed the transition from a single-fin to double-fin connection. The remainder of tests, braces #3 through #7, use a double-fin connection.

Figure 5. Stiffener Plate Configurations. (a) single-fin, (b) intermediate double-fin, (c) double-fin

Screws tying the timber case together will be referred to as confining screws. Screws perpendicular to confining screws will be referred to as transverse screws. See Figure 6 for reference. Transverse screws were utilized within the first two feet at each end of the brace for additional resistance against buckling near the fins.

Figure 6. Wood Screws

The following table summarizes the variations between tests regarding fin configuration and implementation of transverse screws.

Table 2: Variations in Brace Iterations

<table>
<thead>
<tr>
<th>Brace #</th>
<th>Fin Type</th>
<th>Transverse Screws</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>a</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>b</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>c</td>
<td>X</td>
</tr>
<tr>
<td>4</td>
<td>c</td>
<td>X</td>
</tr>
<tr>
<td>5</td>
<td>c</td>
<td>X</td>
</tr>
<tr>
<td>6</td>
<td>c</td>
<td>X^2</td>
</tr>
<tr>
<td>7</td>
<td>c</td>
<td>X^2</td>
</tr>
</tbody>
</table>

^1Refer to Figure 5

^2Transverse screws along full length of timber case.

Testing

Tensile tests were performed on samples of the brace material with specimen fabrication consistent with ASTM E8. Below is a stress-strain plot representative of these samples.

Figure 8. Stress Strain Behavior of Brace Material
Average material properties were as follows:
Modulus of Elasticity, E: 26300 ksi
Plastic Modulus: 0.01 E
Yield Strength, Fy: 55 ksi
Ultimate Strength, Fu: 74 ksi

These measured material properties were used in the following test protocol.

### Test Protocol

Due to capacity limitations of the available reaction frame in the testing facility, the authors opted to design and test a scaled-down version of what they consider a realistic typical bay. The dimensions of the full-scale bay would be 20-ft wide by 12-ft tall. The dimensions of the scaled-down frame would be approximately 7-ft wide by 7-ft tall. The scaled-down frame is related to the theoretical full-scale frame via strain demands, which is reflected in the cyclic testing protocol, based on AISC 341 section K3.

A design story drift of 1.25% the story height is used. Thus:

\[
\Delta_d = \text{design story drift} = 0.0125H \\
\Delta_{bm} = \text{brace deformation at design story drift} = \Delta_d \cos \Theta \\
\Delta_{by} = \text{yield brace deformation} = \varepsilon_y \text{L}_{BR,eff}
\]

Where: \text{L}_{BR,eff} is the effective brace length equal to the distance between the first bolt at each gusset plate. Assuming all diagonal deformation occurs within the effective brace length.

### Figure 9. Frame Elevation with Symbols

Tables 3 through 5 detail the test protocol for a hypothetical 20-ft by 12-ft frame; note the strains associated with 2% story drift. The aforementioned strains are the basis of the test protocol for the scaled down, 7-ft by 7-ft frame.
Table 7: Cyclic Loading and Story Drift: 7’ x 7’ Frame

<table>
<thead>
<tr>
<th>Step</th>
<th>Demand</th>
<th>( P_{\text{Horiz}} ) [k]</th>
<th>( \Delta_{\text{Horiz}} ) [in]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( \Delta_y )</td>
<td>14.6</td>
<td>0.48</td>
</tr>
<tr>
<td>2</td>
<td>0.5( \Delta_{\text{bm}} )</td>
<td>14.6</td>
<td>0.56</td>
</tr>
<tr>
<td>3</td>
<td>( \Delta_{\text{bm}} )</td>
<td>14.8</td>
<td>0.89</td>
</tr>
<tr>
<td>4</td>
<td>1.5( \Delta_{\text{bm}} )</td>
<td>15.0</td>
<td>1.16</td>
</tr>
<tr>
<td>5</td>
<td>2( \Delta_{\text{bm}} )</td>
<td>15.2</td>
<td>1.49</td>
</tr>
<tr>
<td>6</td>
<td>1.5( \Delta_{\text{bm}} )</td>
<td>15.0</td>
<td>1.16</td>
</tr>
</tbody>
</table>

Above is the test protocol used in this research. Note that expected displacements for the experimental 7-ft by 7-ft frame are inclusive of bolt slip as well as holdown deformations.

Data Acquisition

Measurements taken during tests include displacement along the length of the brace, horizontal frame displacement, strains of the brace, and applied load. These measurements were simultaneously recorded on a data acquisition script developed by Cal Poly professors.

Test Results

Table 8 indicates the last step in loading protocol which was reached for each test. Note that due to inherent imperfections in hand-pumped actuating, it is common for cycles to go beyond the planned load and displacement.

Table 8: Summary of Cyclic Loading Extent for Each Test

<table>
<thead>
<tr>
<th>Brace #</th>
<th>Step</th>
<th>Cycle</th>
<th>Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>1</td>
<td>( \Delta_{\text{bm}} )</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>1</td>
<td>2( \Delta_{\text{bm}} )</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>1</td>
<td>( \Delta_{\text{bm}} )</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>1</td>
<td>1.5( \Delta_{\text{bm}} )</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>2</td>
<td>2( \Delta_{\text{bm}} )</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td>1</td>
<td>2( \Delta_{\text{bm}} )</td>
</tr>
<tr>
<td>7</td>
<td>4</td>
<td>1</td>
<td>1.5( \Delta_{\text{bm}} )</td>
</tr>
</tbody>
</table>

Test protocol for braces 01 and 02 assumed a modulus of elasticity of 27,000 ksi, as initial tensile testing of the brace material was unsuccessful. Upon testing, it was found that the lateral load vs displacement relationship was not as calculated, warranting further investigation. After a successful sample of additional tensile tests, test protocol was adjusted for measured strength of the brace material. This is reflected in the following cyclic pushover plots, where positive load indicates pull (tension) and negative indicates push (compression).
Testing Continued

Figure 13: Lateral Load vs. Horizontal Displacement
Figure 13. Lateral Load vs. Horizontal Displacement (Continued)

Figure 14. Lateral Load vs. Horizontal Displacement: Final Cycle in Test Protocol for Double-Fin Design
Figure 15. Brace Stress-Strain Plots
Testing Continued

Figure 15. Brace Stress-Strain Plots (Continued)

Figure 16. Strain vs. Stress: Final Cycles for Double-Fin Design
Discussion

Observations

Frame members and connectors experienced negligible damage. Observations of damage to frame elements include 1/16-in. embedment of gusset plate to column at the base, deformation of washers, and wear on gusset plates around bolt holes. Three frame assemblies were used throughout all tests presented in this research; the improvement in overall assembly performance as research progressed is a testament to the preservation of frame integrity.

Natural cracks in wood members are inevitable. These cracks are easily widened by timber connections; thus, cracks are best mitigated by visually inspecting each member and orienting such that the least amount of cracks will be exploited. This is especially useful for the frame assembly. For timber braces, these cracks would be mitigated by using DF-L No.1, planed down by 1/4-in.

Test 01

Test 01 was performed to reaffirm previous testing. Under an identical environment and testing protocol, the cyclic performance as well as failure mechanism matched that of testing performed by Ayers (2021). Figure 17 shows some of the damages that occurred in the brace.

Damage to the brace include:

- Minor-axis buckling in the unrestrained zone resulting in premature failure as shown in Figure 17
- Yielding striations appearing at approximately 45-degree angle concentrated at fin ends and midspan of brace as shown in Figure 17
- Stress concentration at the inner most bolt hole; negligible signs of stress at outer bolt holes
- Significant elongation of inner-most bolt hole; negligible elongation of outer bolt holes

Cyclic behavior of Test 01 provided under Test Results indicate similar performance to that of a typical steel brace in compression, where buckling occurs within the elastic range of capacity.

Test 02

Test 02 was performed as a proof-of-concept to confirm the transition from single-fin to double-fin design. The continuity of stiffener plates outside of the timber casing, past all bolts, proved to eliminate undesirable buckling outside of the buckling-inhibiting assembly.

Damage to the brace from Test 02 include:

- Early signs of inelastic higher-order minor-axis buckling in the restrained, designated yielding area
- Sudden timber case burst/cracking
- Yielding striations appearing at approximately 45-degree angle evenly distributed throughout the yielding area
- Distributed elongation of bolt holes with similar slipping striations across all bolt holes.

Note that the bright silver spots on the brace shown in Figure 17 indicate areas sanded down for strain gage application; yielding striations appear light grey with scaling at 45 degrees.
While the intermediate double-fin connection was successful in forcing failure to occur within the timber brace, it also allowed for a previously unachieved (to the authors) failure mode to occur. The timber case abruptly cracked in cross-grain bending on the side opposite the stiffening plates. At this point, testing ended. Elastic higher-order buckling was observed. An unexpected benefit of the authors’ unbonding solution — measurable imprints of the buckling pattern from the steel brace shown the BRP’s indicating the buckling wavelength. Although there is slight variation, the distance between peaks measured to be approximately between 6in-8in.

Test 03

Test 03 was the first to implement the double fin solution as well as transverse screws.

Damage to the brace from Test 03 include:

- Inelastic higher-order minor-axis buckling in the restrained, designated yielding area
- Inelastic folding of steel core
- Abrupt cracking of the timber case
- Yielding striations appearing at approximately 45-degree angle evenly distributed throughout the yielding area
- Distributed elongation of bolt holes with similar slipping striations across all bolt holes.

Initially, the hysteretic curve for Test 03 mimicked that of Test 02, using the double-fin connection rather than the intermediate double-fin. Similar abrupt behavior to Test 02 was developing, indicated by loud popping due to timber case cracking. The test was stopped in early cycles upon indication of similar failure to Test 02, transverse screws were drilled in-place through the cracked face, and the test proceeded. It was postulated that transverse screws would confine the wood casing and combat the abrupt failure observed in Test 02, analogous to tension steel reinforcement in a concrete beam, demonstrated in Figure 20. This effort proved to be successful at controlling cracking of the timber case; cracking was prolonged. Ultimately, cracking persisted, allowing space for the brace to locally buckle and fold on itself. Transverse screws were used in the initial fabrication of TBRB assemblies from this point on, experimenting with the quantity and spacing.

Bolt slippage at the brace-to-gusset plate connection became apparent within the brace yield deformation, $\Delta_{y}$, time frame of each cycle.
Test 04

Test 04 sought to address the cracking of the timber case. As part of fabrication, transverse screws were placed around the ends of the timber case but avoiding interaction with the stiffening plates.

Damages to brace 04 included:

- Inelastic higher-order minor-axis buckling in the restrained, designated yield zone
- Prolonged timber case cracking
- Yielding striations appearing at approximately 45-degree angle evenly distributed throughout the length of the yield zone
- Distributed elongation of bolt holes with similar slipping striations across all bolt holes.

The timber case was subjected to cross-grain bending at the bottom brace-gusset plate connection, causing cracking at the stiffener plates as shown in Figure 23. This could be explained as exploitation of the compromised section of wood casing due to the void for the stiffener plates.

Test 04 achieved 1.5 times the yield deformation at the design story drift, an improvement from Test 03. Additionally, less cracking of the timber case occurred, which can be visually described by the decrease in drop-offs of capacity on the hysteresis plot under Test Results. Benefits of confinement from transverse screws is increasingly apparent in this iteration.

Test 05

The same design was used in Test 04, modified with more transverse screws extending further into the middle of the brace.

Damages to brace 05 included:

- Inelastic higher-order minor-axis buckling in the restrained, designated yielding zone
- Prolonged timber case cracking
• Yielding striations appearing at approximately 45-degree angle, evenly distributed throughout the length of the yield zone

• Distributed elongation of bolt holes with similar slipping striations across all bolt holes.

The timber case was subjected to cross-grain bending at the top brace-gusset plate connection, causing severe cracking at the stiffener plates as shown in Figure 24. This could be explained as exploitation of the compromised section of wood casing due to the void for the stiffener plates, like Test 04. Blomgren, et al, (2016) and Murphy, et al, (2021), and similar in concept to a study by Inoue, et al, (2001).

Of all tests, the test protocol was executed furthest for test 05, accomplishing two cycles for 2% drift. However, the hysteresis plots show room for improvement with narrow loops. As demonstrated in Figure 24, buckling wavelengths were shorter where transverse screws occurred and longer toward the middle of the casing where there was an absence of transverse screws. It was determined that using transverse screws across the full length of the timber case would be beneficial; this would be the primary modification for tests 06 and 07.

**Test 06**

The double-fin design was implemented in test 06 with the addition of transverse screws throughout the full length of the brace. Additionally, transverse screws were placed on the face of the casing where the stiffener plates occurred; in past tests these areas were left untouched.

Damages to brace 06 include:

• Inelastic higher-order minor-axis buckling in the restrained, designated yield zone; highest buckling peaks near stiffener plates similar to test 04

• Prolonged timber case cracking

• Yielding striations appearing at approximately 45-degree angle, evenly distributed throughout the length of the yield zone

• Distributed elongation of bolt holes with similar slipping striations across all bolt holes.

The main concern had become cracking occurring where the timber case was dato-cut to accommodate the double fin connection. Strengthening this area posed a multifaceted issue. The double fin connection was a fixture of the brace assembly, and the concern then was that the spacing between the edge of the dato-cut surface and the exterior of the timber case was not enough to engage the screws across the tension plane of the cross-grain bending. The desired effect of having transverse screws across the whole length of the timber case was to develop the outward pressure caused by higher-order buckling away from the end condition where there is a weakened cross-section in the timber case due to the dato-cut. Although the additional screws did prolong the bursting event, the case eventually cracked, allowing the steel core to inelastically buckle as shown in Figure 25.

**Figure 24. Test 5: Inelastic Higher Order buckling following the Pattern of Transverse Screw Spacing (Above); Timber Case Cracking (Below)**

**Figure 25: Test 6: Inelastic Folding of Steel Core**
Test 06 was successful at attaining 2% story drift while exceeding energy dissipation demonstrated by tests 01 through 05, based on the widened hysteresis loop shown under Test Results. This would indicate that the additional transverse screws are beneficial and likely necessary for improved ductility of the TBRB.

Test 07

Identical fabrication to test 06, test 07 performed equally as well as test 06 in terms of energy dissipation and drift, despite test 06 being pushed further cycles. Test 07 being the last, and in spirit of experimentation, the base gusset plate was welded to the grade beam to eliminate additional frame displacement due to gusset plate rotation and elongation of holdowns. Thus, lower horizontal displacement would be expected; given that test 07 was based on protocol including elongation of holdowns, the deformations attained exceeded expectations.

Timber case cracking was prolonged but ultimately served to be the failure mechanism. As opposed to test 06, cracking began between the stiffener plates as shown in Figure 27, rather than at the stiffener plates. This further supports the claim that transverse screws are indeed a vital component to the ductile design of the TBRB.

Another indication that more screws led to better confinement was the way each brace that cracked eventually buckled inelastically. While tests 03, 04, and 05 developed continuous sine wave buckling near the fins, these same sine waves are flattened at the peaks in tests 06 and 07 as shown in Figure 28. Each instance occurred approximately 1.5-in. away from the end of stiffening plate. This is indicative of adequate confinement by the timber buckling-inhibiting assembly.

By comparing test results of test 07 to test 06, it can be assumed that jumps in the hysteresis curves are likely due to imperfections in the test set-up; by eliminating gusset plate rotation and elongation of holdowns a stable, wide, and symmetric hysteresis curve is produced. Additionally, the frame recentered in test 07 where in tests 1 through 6, there were permanent frame deformations of 1-in. on average.
Global Observations

It should be reiterated that over the course of seven tests, three frames were used: two braces for the first frame, three for the second frame, and two for the last frame. The decision to cycle out frames was for quality of testing rather than out of necessity, as damage to framing was negligible. Brace performance was found to be dependent on the brace connection and presence of transverse screws – there was negligible influence by initial imperfections in framing. It was particularly evident of the second frame that a fourth test could reliably be performed relative to that frame. This speaks to the potential of the TBRB as a sustainable solution, where only the brace need be replaced post-seismic event with little to no damage to the surround frame and connections.

Recommendations

Further studies which the authors would recommend are as follows:

- Diminishing returns of transverse screws in mitigating buckling. What spacing, and frequency is the most efficient?

- Use of smaller diameter transverse screws to allow for reduced edge distances to the outside face of the casing, as well as decrease wood splitting. This would be recommended in the interest of sustaining the design for a 5.5” wide brace encasement.

- Use of nailed straps around the timber casing rather than screws. This would eliminate pre-mature splitting of the wood casing exacerbated by wood screws.

- Use of bolts instead of transverse screws which may require larger dimensions of lumber.

- Higher level: Calculation of a proper response modification coefficient for a TBRB (ASCE 7-16 §12.2).

- Use of engineered lumber as the brace encasement. Full-scale frames may demand engineered lumber due to increased brace length. Improved performance would be anticipated, as engineered lumber has greater stiffness properties than sawn lumber.

- Mitigation of permanent deformations in the frame assembly. In modern construction, fluid vicious dampers are commonly paired with BRBs; is there an analogous system which can be paired with the TBRB at an appropriate level of cost?

The authors recommend further testing be performed in a facility which has the capacity for full-scale testing. Ultimately, the goal would be to refine the design, measure performance at a testing facility verified to meet the International Code Council (ICC) standards and codify the TBRB as a new LFRS alternative for low to mid-rise type V construction.

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