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ARENA BLAST TESTING OF REINFORCED CROSS-LAMINATED TIMBER

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ABSTRACT: Previous studies involving blast, ballistic, and forced entry testing on Cross-Laminated Timber (CLT) showed that CLT provided greater protection than conventional wood construction, but typically needs reinforcement to comply with stringent antiterrorism requirements. Recent quasi-static testing has shown that embedding steel plates in CLT can increase both the flexural strength and ductility of the panel, which implies an improved blast response relative to an unreinforced panel. This paper describes a test program in which six CLT panels were reinforced with embedded steel plates and subjected to blast loading. Prior to explosive testing, three of the six panels were subjected to six months of outdoor weathering to investigate dimensional stability and the potential for delamination under temperature and moisture cycling that may occur if commonly recommended material storage practices are not followed during construction. The six panels were then subjected to arena blast testing to demonstrate the ability of reinforced CLT (RCLT) to exhibit a ductile post-peak response. The RCLT panels generally exhibited qualitative damage that was consistent with "Heavy Damage" or better for significant blast loads. This paper describes the selection and fabrication of the panels, documents the observed degradation during the weathering period, and provides results from the blast tests.

KEYWORDS: Cross-Laminated Timber, Reinforced CLT, RCLT, Protective Design, Blast

1 – INTRODUCTION

Natural weathering and blast testing of reinforced cross-laminated timber (RCLT) panels was performed. The purposes for this testing were twofold: (1) to determine whether RCLT panels maintain integrity or incur significant strength/stiffness reductions due to exposure to temperature cycling and moisture conditions associated with poor material storage practices and (2) to demonstrate the effectiveness of weathered RCLT panels to safely resist large blast loads.

2 – BACKGROUND

Buildings used by many U.S. federal agencies often must meet blast, ballistic, and forced entry (FE) design requirements to mitigate physical hazards associated with terrorism. Historically, these buildings have used concrete and steel construction to protect occupants from these threats. However, the emergence of mass timber construction, particularly cross-laminated timber (CLT), presents a sustainable, modular, and cost-effective alternative building material for high-security infrastructure. Previous studies involving blast, ballistic, and FE testing on CLT indicated that CLT provides much greater protection than conventional wood construction, but that it typically needs some form of reinforcement to comply with stringent antiterrorism requirements and broaden the use of wood structures in federal facilities [1-5].

Under a previous effort, full-scale CLT panels with steel reinforcement were constructed and tested under quasi-static four-point bending testing [6,7]. In this subsequent effort (discussed herein), two types of investigation were undertaken to further demonstrate the effectiveness of RCLT panels under adverse conditions: (1) weathering and (2) blast. The weathering testing investigated whether RCLT panels maintain their dimensional stability and if they are prone to delamination under exposure to

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temperature and moisture cycling that may occur if commonly recommended material storage practices are not followed during construction. The blast testing sought to demonstrate the ability of RCLT to resist a large blast load regardless of the material storage practices followed during construction. A primary focus of this effort was to ensure the developed RCLT panel designs were competitive with existing protection construction systems from both a cost and weight perspective.

3 – PROJECT DESCRIPTION

3.1 OVERVIEW

Six RCLT panels were fabricated by SmartLam North America (two specimens for each of three different layups = six total RCLT panels). Three of the panels were sent to Q-Lab in Homestead, Florida, and left outdoors for six months (from December 2022 until June 2023). The other three panels were sent to Tyndall Air Force Base (AFB) in Panama City, Florida, and left wrapped/covered for the same six-month period. The degradation of the three "weathered" (W) specimens at Q-Lab were documented through monthly photographs. In June 2023 the three weathered specimens were sent to Tyndall AFB and stored. In October 2023 two of the "unweathered" (U) RCLT specimens were subjected to arena blast testing. In December 2023 the remaining four RCLT specimens were subjected to arena blast testing. The October and December 2023 tests are herein referred to as Test 4 and Test 5, respectively, as these tests were part of a larger mass-timber test program.

3.2 TEST PANELS

SmartLam began fabricating the six RCLT panels in late October 2022. The panels were 3.63 m (11.92 ft) tall by 2.42 m (7.94 ft) wide. Each panel included two layers of steel plate. Since 3.66 m (12 ft) by 2.44 m (8 ft) steel plate was commercially unavailable at the time, each steel layer was composed of two steel plates butted up against one another (see Fig. 1). The steel butt joint was staggered between the two steel layers (i.e., the two butt joints do not align in plan). Other fabrication details and methods generally followed the approach used in the Phase I effort [6,7], except an adhesive with a smaller set time (20 minutes instead of 60 minutes) was used to expedite manufacturing. Like the Phase I fabrication approach, the steel plate layers included small strips of 82 mm (3.25 in) wide hardboard spacers around the perimeter of the panel, which are identified in Fig. 2.

As previously noted, two specimens were fabricated for each of three different layups. The three layups are referred to as Layup 2, 4, and 5. The three RCLT layups were selected based on the previous Phase I test program [6,7] and analyses of potential panel layups using a design methodology developed in Phase I (and subsequently improved during this second phase). The three layups are depicted in Fig. 3.

Layup 2 utilized seven wood layers and two steel layers. The strong axis (0 degree) wood layers utilized No. 2 Southern Pine (SP) while the weak axis (90 degree) layers utilized 2400F-2.0E machine stress rated (MSR) Southern Pine. This layup is identical to Layup 2 in the Phase I effort, which allowed for a direct comparison between the Phase I quasi-static test results and the Phase II dynamic test results.

Layup 4 utilized seven wood layers and two steel layers. The layup again utilized No. 2 Southern Pine and 2400f-2.0E MSR Southern Pine, but in an asymmetrical configuration. Two wood layers (layers 1 and 2) were located on the compression face of the panel to enable sufficient wood depth to allow hypothetical architectural attachments to the panel exterior (e.g., façade screws). Within the panel core (between the two steel layers), the two layers most susceptible to the highest shear stresses (layers 5 and 6) were oriented in the strong direction to reduce the likelihood of a rolling shear failure in the panel.

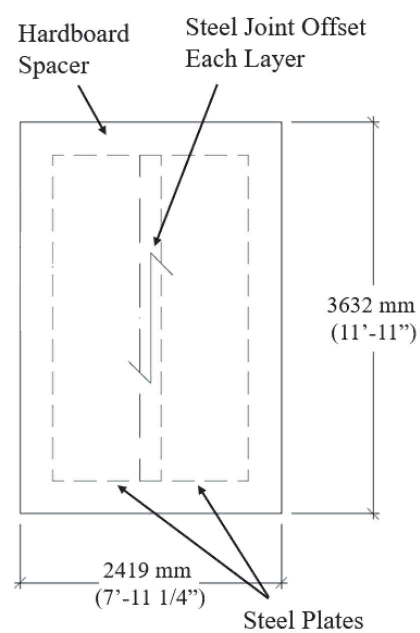

Figure 1. Panel Geometry (Plan View).

Figure 2. Layup 4 at the SmartLam Facility.

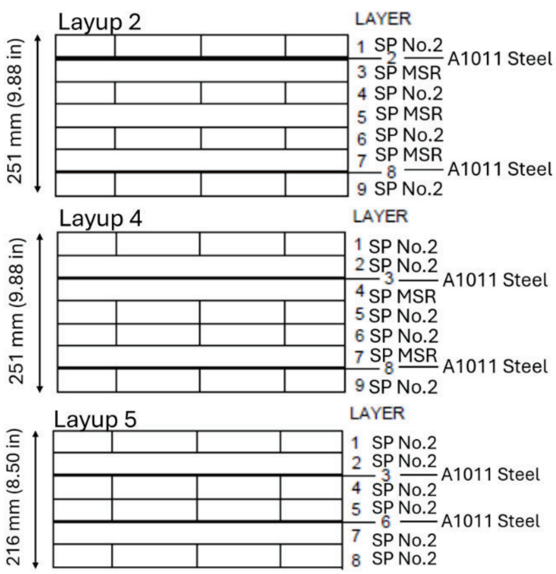

Figure 3. Cross-Sections for the Three RCLT Layups. All Wood Layers 35 mm (1.375 in) Thick. All Steel Layers 3.2 mm (0.1275 in) Thick.

Layup 5 utilized six wood layers and two steel layers in a symmetric layup. All layers utilized No. 2 Southern Pine to make the panel more cost-competitive. The panel core layers were oriented in the strong direction to reduce the likelihood of a rolling shear failure in the panel.

Dynamic material testing was performed by K&C to define stress-strain relationships for the A1011 steel at various strain rates. Yield strengths (true stress values) were deterimend as 280 MPa (40.6 ksi) and 330 MPa (47.9 ksi) at 0.01/sec and 1/sec strain rate, respectively. Ultimate strengths (true stress values) were determined as 450 MPa (65.3 ksi) and 500 MPa (72.5 ksi) at 0.01/sec and 1/sec strain rate, respectively. Tensile rupture strains (true strain values) exceeded 20%.

Using the stress-strain relationships for A1011 steel obtained from dynamic material testing, analytical resistance functions were developed for each RCLT panel to facilitate pre-test predictions of the panel response. The resistance functions were developed using a moment-curvature (MC) cross-section analysis methodology. The MC analysis imposes a curvature on a discretized user-defined RCLT cross section (assuming strain-compatibility across the layers), interpolates the material stress in the discretized element (based on a user-defined nonlinear material stress-strain curve), integrates the stress to determine the force resisted by the element, and integrates the forces to determine the cross-section moment associated with the applied curvature. The resulting MC relationship was then used to develop a resistance function assuming simple supports and a mid-span hinge. In Fig. 4, a detailed resistance curve is presented for Layup 5 where yielding and rupture of the various layers are identified (e.g., "Rupture 8" is tensile rupture of layer 8 in the cross-section). Fig. 4 also shows the simplified flexural resistance functions for the three fabricated layups used in subsequent Single-Degree-of-Freedom (SDOF) analyses.

4 – EXPERIMENTAL SETUP

4.1 OUTDOOR WEATHERING

Outdoor weathering of the three RCLT panels began on 21 December 2022 (see Fig. 5). The panels were oriented with layer 1 as the exposed layer while layer 8 or 9 faced the ground. The panels were placed on small supporting members (i.e., the panels were not sitting directly on the grass) to enable a forklift to place and eventually remove the panels. The outdoor weathering program lasted for six months with photos of the panels taken monthly to document degradation. Weather data was collected over the same period.

4.2 ARENA BLAST TESTING

The two arena blast tests utilized the Solutions Protecting Against Terrorism (SPAT) cubes at Tyndall AFB. The RCLT test articles were sized to fit the entire SPAT cube clear opening. Each test article consisted of two panels placed side-by-side though not physically connected, thus allowing the ability to test two layups simultaneously for the same blast loading. The three configurations are noted in Table 1. Fig. 6 identifies the unweathered and weathered panels for Layup 2 during Test 5. The blast load applied to the RCLT panels (in all tests) was characterized by a peak pressure of roughly 2.06 MPa (300 psi) and a peak positive phase impulse of roughly 2.76 MPa-ms (400 psi-ms).

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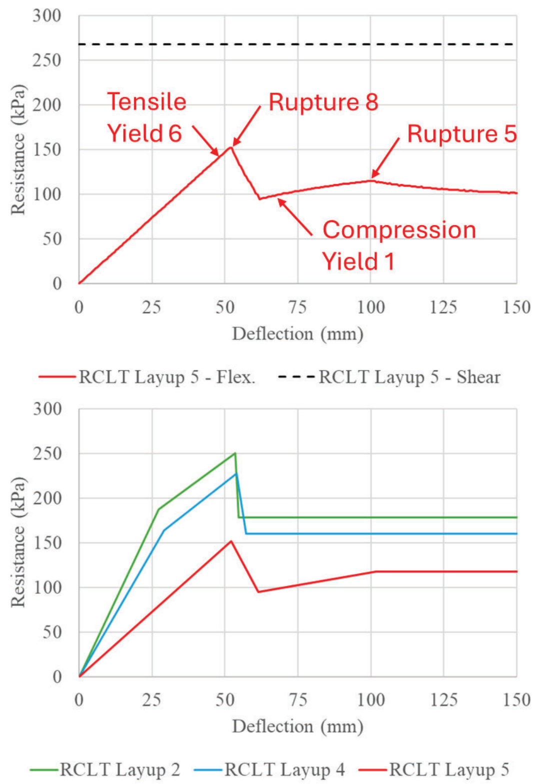

Figure 4. Top: Detailed Resistance Function for Layup 5. Bottom: Simplified Flexural Resistance Functions for All Three Layups.

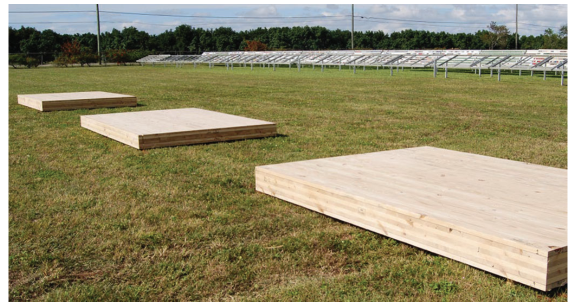

Figure 6. Panels at Outdoor Facility (Start of Weathering Program).

Table 1: Panel Placement

Test	**SPAT Cube**	**Test Article**	**Panel Layup**	
			Left	**Right**
4	2	12	No.4 (U)	No.5 (U)
5	1	13	No.2 (U)	No.2 (W)
	2	14	No.4 (W)	No.5 (W)

(U) – Unweathered; (W) - Weathered

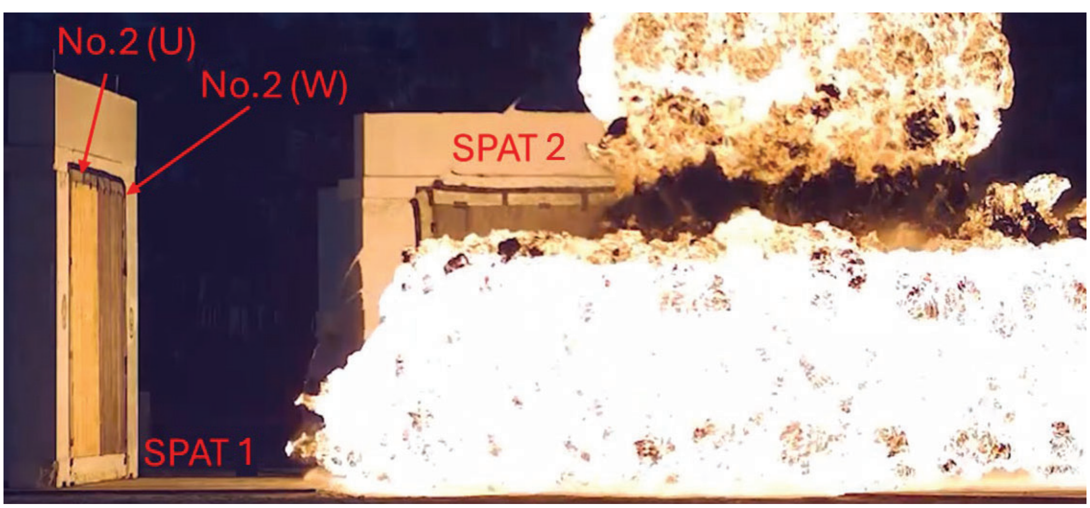

Figure 5. Exterior View of Unweathered and Weathered Panels During Blast Loading (SPAT Cubes Visible to the Left of and Behind the Fireball).

The RCLT panels were connected at top and bottom to the roof and floor slabs of the SPAT cubes, respectively (i.e., the panels provide one-way action). The connections were comprised of 150 x 100 x 8 mm (6 x 4 x 5/16 inch) steel angles, with wood screws and 19 mm (3/4 inch) post-installed concrete anchors as fasteners. The number (density) of fasteners varied for each panel, and was designed based on the expected strength of the restrained panel. The panel vertical edges (both at the SPAT cube centerline and those adjacent to the vertical cube walls) were not restrained.

Pressure transducers, displacement gages, accelerometers, and high-speed video were used to quantify the response of the panel test articles for each test.

5 – RESULTS

5.1 OBSERVATIONS FROM WEATHERING

Weather time history data (e.g., temperature, humidty, solar radiation, rainfall, and total wet hours) were recorded and are available, but are not presented here for brevity.

After one month of weathering the panels showed some discoloration, but no significant degradation.

After two months of weathering the panels showed further discoloration and signs of deterioration including sporadic hardboard separation around the panel perimeter and near the panel corners. Representative damage is shown in Fig. 7. The deterioration typically looked like delamination of the hardboard to one of the adjacent wood layers, or a through-thickness tearing of the hardboard. It is believed that moisture infiltrating the exposed edge of the hardboard caused non-uniform swelling around the perimeter of the panel causing this damage. It is noted that untreated hardboard is not intended for moisture resistance.

After three months of weathering there appeared to be more discoloration, but deterioration of the hardboard layers did not appear any worse. After four months of weathering the exposed layer of Layup 2 had several delaminated planks that pried upwards as a result of transverse swelling that overcame the adhesive bond strength (see Fig. 8). This behavior was only observed in Layup 2 and was not seen in Layups 4 or 5.

No significant changes were noted in the 5-month and 6-month weathering photos, which indicated that most of the visually observable weathering changes had taken place during the first four months.

Figure 7. Layup No.5, End of Month 2.

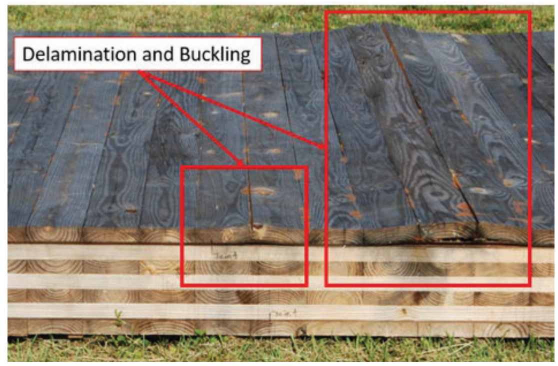

Figure 8. Layup No.2, End of Month 4.

It is interesting to note that only Layup 2 showed delamination and buckling of the exposed layer. For Layup 2, there was only one layer of wood (layer 1) between the exposed surface and first embedded steel plate (layer 2), while for Layups 4 and 5 there were two wood layers (layers 1 & 2) between the exposed surface and first embedded steel plate (layer 3); see Fig. 3. It is hypothesized that moisture/water was able to penetrate between the butted joints of the wood members (between the layer 1 wood planks) in Layup 2 and reach the adjacent steel plate. This moisture likely caused transverse swelling of wood layer 1 (leading to a prying force on the adhesive bond), oxidation of the steel plate and degraded the wood-to-steel bond, hence the delamination and buckling. For Layups 4 and 5, it is hypothesized that the additional wood layer (layer 2) and its orientation orthogonal to the exposed layer 1 resulted in less moisture/water reaching the embedded steel plate reducing/preventing steel oxidation and differential wood swelling, leaving the wood-to-steel bond more intact.

5.2 RESULTS FROM ARENA BLAST TESTING

Results are briefly described here, with additional descriptions and images available in the full project report [8].

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5.2.1 Test 4, SPAT Cube 2

Post-test photographs of the exterior and interior of Test Article 12 are shown in Fig. 9. From the exterior, several large blocks of concrete were seen in front of/below the Layup 5 panel. The failure of the SPAT cube concrete is attributed to the slab having previously undergone several blast tests (in which concrete cracking had accumulated) and a lack of tie reinforcement. Due to the failure of the lower connection (SPAT cube concrete), significant deformation of Layup 5 was visible. In the interior, there was no visible damage to the Layup 4 connections. Some wood rupture was visible on the protected face of Layup 4 (layer 9). Wood debris was seen inside the SPAT cube, which was all attributed to the Layup 5 panel. After the test, the panels were removed from the SPAT cube and inspected (Fig. 10). The inspection indicated extensive rolling shear cracking in Layup 4 and delamination between the steel plate and timber in Layup 5.

5.2.2 Test 5, SPAT Cube 1

Post-test photographs of the exterior and interior of Test Article 13 are shown in Fig. 11. While no damage was visible on the exterior surface of the unweathered panel, several boards completely delaminated from the exterior of the weathered panel exposing the underlying steel plate. As described previously (Fig. 8), several boards on the front surface of the panel had already delaminated during the weathering phase. Signs of corrosion were evident on the exposed portion of the steel plate (Layup 2, layer 2) following Test 5.

For the unweathered panel, the primary damage observed was the rupture and/or delamination of boards along the panel's vertical edges. It is notable that delamination occurred where at least a portion of the wood board (layer 9) was adhered to hardboard (layer 8). No other damage

Figure 9. Test 4, SPAT Cube 2 Post-Test Photographs. Left: Exterior. Right: Interior.

Figure 10. Test 4, SPAT Cube 2 Post-Test Photographs. Top: Layup 4 (U). Bottom: Layup 5 (U).

was visible on the interior surface of the unweathered panel. For the weathered panel, limited board delamination on the protected face was observed but a hairline flexural crack was observed near midspan along most of the panel's width. After the test, the panels were removed from the SPAT cube and inspected (Fig. 12). It was found that both the weathered and unweathered panels had rolling shear cracks through the thickness. Signs of localized hardboard delamination were also observed in the weathered panel.

5.2.3 Test 5, SPAT Cube 2

Post-test photographs of the exterior and interior of Test Article 14 is shown in Fig. 13. Apart from an edge board delaminating at the bottom left corner of the Layup 5 panel, no signs of visible blast damage were observed on the exterior surface of the panel. However, it was clear from the side that the top edge of the Layup 4 panel was pulling away due to damage through the thickness.

As with the unweathered panel in Test Article 13, edge board delamination occurred on the interior of both weathered Layup 4 and Layup 5 panels. Flexural cracking near midspan was extensive on the interior surface of the Layup 5 panel. Ruptures on the interior surface of the Layup 4 panel were also observed but they were concentrated in the upper third of the panel. Secondary debris was found on the floor of SPAT cube 2 following Test 5.

Typical photographs through the thickness of the Test Article 14 panels are shown in Fig 14. As with the unweathered panels in Test Article 12, the photographs indicate rolling shear cracking and steel-timber delamination.

5.2.4 Qualitative Damage Summary

Table 2 assigns a damage level (as defined in PDC-TR 06-08 [9]) to each panel based on the observed damage.

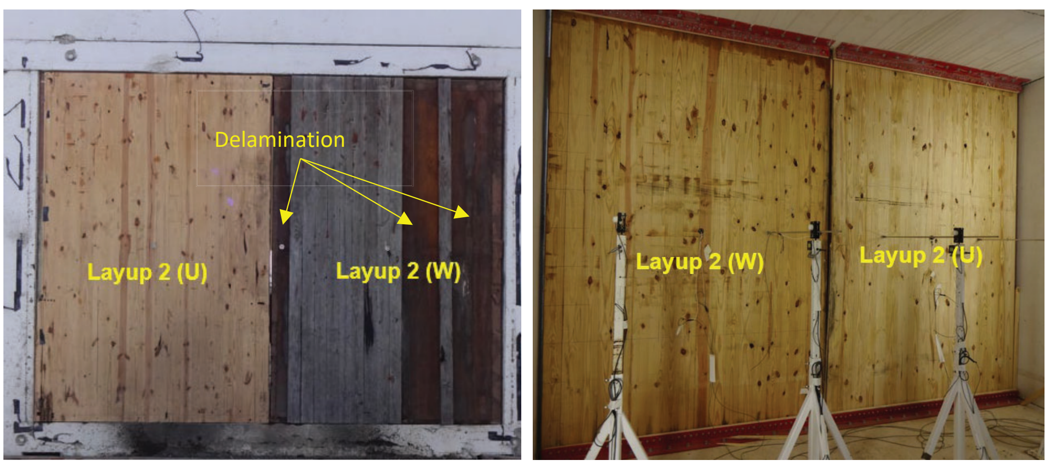

Figure 11. Test 5, SPAT Cube 1 Post-Test Photographs. Left: Exterior. Right: Interior.

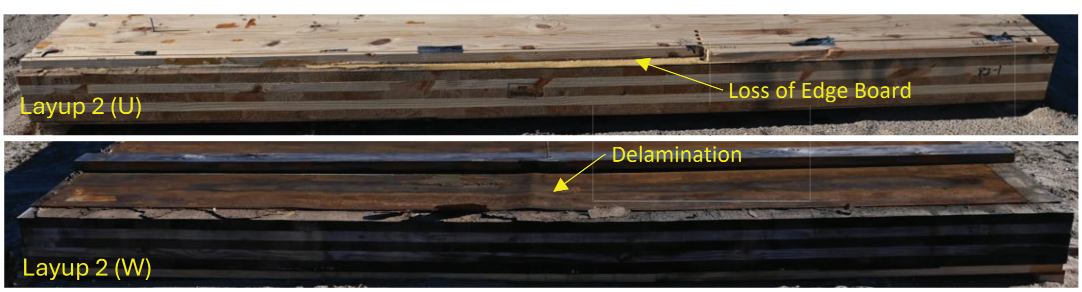

Figure 12. Test 5, SPAT Cube 1 Post-Test Photographs. Top: Layup 2 (U). Bottom: Layup 2 (W).

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5.3 TEST DATA EVALUATION

A series of SDOF dynamic analyses were performed using the average pressure history curves measured during Tests 4 and 5 and resistance functions generated from moment-curvature analyses (see Fig. 4). Table 3 summarizes the peak displacement results.

For Layups 2 and 4, which failed in rolling shear, it is interesting to note that the weathered panel peak displacement is between 30% and 40% greater than that of the unweathered panel. Conversely, for Layup 5, which failed in flexure, the weathered and unweathered panel peak displacements were essentially identical. These results seem to suggest that panel rolling shear strength is more susceptible to degradation when exposed to moisture and temperature cycling than its flexural strength.

6 – CONCLUSIONS

Six reinforced CLT (RCLT) panels were subjected to arena blast testing. Three of the panels had undergone outdoor weathering for a six month period prior to arena testing. During blast testing, the panels generally exhibited qualitative damage patterns that were consistent with "Heavy Damage" or better, as defined in PDC-TR 06-08 [9], for significant blast loads. The panels in which shear failures were observed showed notably different peak displacements between the weathered and unweathered panels while the panels in which flexural failures were observed showed almost no difference in peak displacement between the weathered an unweathered panels. These results indicate that RCLT panel rolling shear strength is more susceptible to degradation when exposed to moisture and temperature cycling than its flexural strength.

Future work, expected to be performed in 2025, includes small scale studies to determine superior spacer materials (i.e., materials to replace the hardboard spacer which showed degradation during weathering).

Figure 13. Test 5, SPAT Cube 2 Post-Test Photographs. Left: Exterior. Right: Interior.

Figure 14. Test 5, SPAT Cube 2 Post-Test Photographs. Top: Layup 4 (W). Bottom: Layup 5 (W).

Table 2: Qualitative Damage Summary

Layup	Observations	Observed Qualitative Damage Level
Layup 2 (U)	• Minor rolling shear cracking. • Delamination of edge board on interior surface of panel.	Moderate Damage(1)
Layup 2 (W)	• Rolling shear cracking. • Minor cracking on interior surface of panel.	Heavy Damage
Layup 4 (U)	• Extensive rolling shear cracking. • Minor cracking on interior surface of panel.	Heavy Damage
Layup 4 (W)	• Rolling shear cracking. • Rupture near third span on interior surface (appears to be associated with rolling shear cracking location).	Heavy Damage
Layup 5 (U)	• Rupture near midspan on interior surface (i.e., flexural failure). • Partial delamination of steel plate from adjacent timber ply. • Complete delamination of multiple boards on interior surface of panel.	Hazardous Failure
Layup 5 (W)	• Rupture near midspan on interior surface (i.e., flexural failure). • Partial delamination of steel plate from adjacent timber ply. • Delamination of edge board on interior surface of panel.	Heavy Damage(1)

(1) This damage assignment ignores the edge board debris that delaminates. This failure mechanism indicates that further attention needs to be given to the bond of wood lamella near the edges of RCLT panels

Table 3: Comparison of Blast Test and SDOF Calculation Results.

Layup	Peak Displacement			Panel Failure Mode	
	Test	Calculation	% Diff.	Test	Calculation
Layup 2 (U)	95 mm (3.73 in)	124 mm (4.89 in)	31.1%	V	V
Layup 2 (W)	132 mm (5.19 in)	124 mm (4.89 in)	-5.8%	V	V
Layup 4 (U)	102 mm (4.03 in)	130 mm (5.13 in)	27.3%	V	V
Layup 4 (W)	135 mm (5.33 in)	128 mm (5.04 in)	-5.4%	V	V
Layup 5 (U)	191 mm (7.51 in)	193 mm (7.58 in)	0.9%	F	F
Layup 5 (W)	199 mm (7.84 in)	200 mm (7.87 in)	0.4%	F	F

V=Shear, F=Flexure

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7 – ACKNOWLEDGEMENTS

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8 – REFERENCES

[1] E. Nagy, M. K. Weaver, "Quasi-Static Out-of-Plane Testing of CLT and NLT Panels," Karagozian & Case, Inc., Glendale, CA, K&C Report No. TR-16-42.1, 21 December 2016.

[2] M. K. Weaver, C. Newberry, C. O'Laughlin, L. Podesto, "Results from Blast Tests of Full-Scale Cross-Laminated Timber Structures," Karagozian & Case, Inc., Glendale, CA, K&C Report No. TR-17-17.1, 27 September 2017.

[3] M. K. Weaver, C. Newberry, C. O'Laughlin, L. Podesto, "Results from Phase 2 Blast Tests of Full-Scale Cross-Laminated Timber Structures," Karagozian & Case, Inc., Glendale, CA, K&C Report No. TR-18-06.2, 09 October 2020.

[4] M. K. Weaver, S. Lan, "High-Fidelity Physics-Based Modeling of Cross-Laminated Timber", Karagozian & Case, Inc., Glendale, CA, K&C Report No. TR-19-35.1, 09 October 2020.

[5] M. K. Weaver, M. Lo Ricco, A. Senalik, J. Cattelino, R. Tudhope. P. W. van der Meulen, "Development of a Cost-Effective CLT Panel Capable of Resisting DOS/DOD Design Basis Threats – Final Accomplishment Report," Karagozian & Case, Inc., Glendale, CA, K&C Report No. TR-19-41.2, 09 October 2020.

[6] E. Kjolsing, M. K. Weaver, A. Senalik, M. Lo Ricco, J. Cattelino, J. Henjum, R. Edgar and E. Nagy, "Demonstration of a Cost-Effective CLT Panel Capable of Resisting DOS/DOD Design Basis Threats - Phase I," Karagozian & Case, Inc., Glendale, CA, K&C Report No. TR-22-12, 30 July 2022.

[7] E. Kjolsing, M. Weaver, M. Lo Ricco, A. Senalik, J. Cattelino, J Henjum, R. Edgar, E. Nagy, "Quasi-Static Out-of-Plane Testing of Reinforced Cross-Laminated Timber," World Conference on Timber Engineering, 2023. Oslo, Norway.

[8] E. Kjolsing, M. K. Weaver, A. Senalik, M. Lo Ricco, J. Henjum, J. Johnson, "Demonstration of a Cost-Effective CLT Panel Capable of Resisting DOS/DOD Design Basis Threats – Phase II," Karagozian & Case, Inc., Glendale, CA, K&C Report No. TR-24-07, February 2024.

[9] PDC-TR 06-08, "Single Degree of Freedom Structural Response Limits for Antiterrorism Design, Revision 1," U.S. Army Corps of Engineers, 7 January 2008.