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INVESTIGATION OF CROSS-LAMINATED (CLT) DECKS FOR BRIDGE APPLICATIONS IN THE USA

Justin M. Dahlberg[1], Zhengyu Liu[2], James P. Wacker[3], Douglas R. Rammer[4]

ABSTRACT

Cross-Laminated Timber (CLT) panels have been primarily developed for the building industry. But there have been few instances where CLT panels have been used for bridge deck applications in North America. CLT is prefabricated, lightweight, dimensionally stable, and environmentally sustainable. The use of CLT in bridge structures has been limited and the adoption of CLT into governing bridge design codes has been slow-going in North America. The objective of this project was to investigate the feasibility of CLT as a primary structural material for highway bridge deck applications. To achieve the objective, two CLT interconnected deck panel configurations were investigated in the laboratory for their structural performance characteristics under simulated wheel loads. Configurations consisted of longitudinal deck panels that span the abutments and transverse deck panels supported by simply-supported longitudinal girders.

1 INTRODUCTION

Cross-laminated timber (CLT) has gained significant popularity over the past decade, driven by advances in research and construction projects, particularly in Europe. It has been widely adopted in vertical construction, where some of its key features—prefabrication, lightweight properties, dimensional stability, and environmental sustainability—make it a viable alternative to traditional materials like concrete and steel. Despite these successes, CLT's application in bridge structures remains limited, with few notable examples in North America, such as the Mistissini Bridge (2014) and Maicasagi Bridge (2011) in Quebec. Furthermore, its integration into governing bridge design codes has been entirely absent, limiting its widespread adoption.

In the United States, CLT is not yet recognized in the AASHTO *LRFD Bridge Design Specifications* (2020), hindering its broader implementation in bridge projects. By contrast, glue-laminated timber has been accepted for decades. While CLT shares many similarities with glulam, it has benefits of two way action and dimensional stability and additional research or proof-of-concept projects are needed to establish CLT's viability for bridge applications.

This paper summarizes the efforts to characterize the structural performance of CLT bridge decks under typical traffic loads. The material shows promise as a complementary or alternative construction material for bridge decks, offering benefits such as dimensional stability and the potential to incorporate underutilized timber species. With continued research and data supporting its durability and performance, CLT could become a viable option for inclusion in AASHTO bridge design codes, paving the way for its use in modern infrastructure.

To complete the study, a comprehensive literature review and manufacturer inquiries were conducted to evaluate current practices and manufacturing capabilities related to CLT in bridge construction. Laboratory tests assessed the strength and serviceability of CLT panels under typical highway loads in two

[1] Justin M. Dahlberg, Director, Bridge Engineering Center, Iowa State University, Co-Director, National Center for Wood Transportation Structures, Ames, USA, dahlberg@iastate.edu
[2] Zhengyu Liu, Adjunct Assistant Professor, Civil, Construction, and Environmental Engineering, Iowa State University, Ames, USA, zhengyu@iastate.edu
[3] James P.Wacker Research Engineer, USDA Forest Products Laboratory, Co-Director, National Center for Wood Transportation Structures, Madison, USA, james.p.wacker@usda.gov
[4] Douglas R. Rammer, Research Engineer, USDA Forest Products Laboratory, Madison, WI USA, douglas.r.rammer@usda.gov

configurations: spanning longitudinally as a complete superstructure and spanning transversely across longitudinal girders, functioning as the deck.

2 BACKGROUND

2.1 CLT Construction and Materials

CLT panels are composed of adjacent lumber boards in a flatwise orientation. Each layer is arranged crosswise, typically at 90-degree angles, and bonded together on their wide faces, with occasional bonding on the narrow faces. Modern CLT originated from industry-academia collaborations in Austria during the mid-1990s. Its use expanded significantly in Europe in the early 2000s, driven by the green building movement, improved efficiencies, product approvals, and enhanced marketing and distribution channels.

While CLT is well established in Europe but not yet fully adopted by the Eurocode, its implementation in the United States and Canada began more recently, in the 2010s. The U.S. edition of the *CLT Handbook* (2013) was published to support the U.S. design and construction industry, covering only glued CLT products and systems, and CLT was recognized in the NDS (2015) in 2015.

A typical CLT panel consists of at least three glued layers of boards placed flatwise and oriented orthogonally. Lumber thickness ranges from 16 mm to 51 mm, and widths range from 60 mm to 240 mm. Individual boards are finger-jointed with structural adhesives and kiln-dried. Panel sizes vary by manufacturer, with typical widths of 0.6 m, 1.2 m, 2.4 m, and 3.0 m, lengths up to 18 m, and thicknesses up to 500 mm.

CLT offers high in-plane and out-of-plane strength and stiffness, providing two-way action similar to the behavior of reinforced concrete slabs, except that flexural continuity across panel joints is difficult to establish. The cross-lamination increases splitting resistance in connection systems. For floor and roof systems, outer layers align parallel to the main span direction to optimize load capacity.

In North America, CLT design values adhere to the ANSI/APA PRG 320 standard (2018) and are certified through rigorous testing. While Annex A of PRG-320 outlines representative layups for validation, manufacturers can develop and certify custom configurations. For this project, the selected layup was not among those specified in PRG-320 and required independent certification to ensure it met the strength and stiffness requirements for bridge live-load conditions.

2.2 CLT Panel-to-Panel Connection Designs

Panel-to-panel connection designs for CLT have been successfully implemented in vertical construction, with potential adaptability for bridge applications. Common connection types, as outlined in the *CLT Handbook* (Gagnon, 2013), include:

1. **Single/Double Wooden Splines:** Internal splines joined with self-tapping screws and structural adhesive. Double splines provide greater resistance to out-of-plane loads but require precise profiling.
2. **Single/Double Surface Splines:** External splines attached with screws and optional adhesive, offering easier assembly but lower performance compared to internal splines.
3. **Half-Lapped Joint:** Overlapping panels secured with long screws. Quick to assemble and capable of handling normal and transverse loads but prone to splitting under uneven loading.
4. **Tube Connection:** Steel tubes with glued-in or screwed rods connect panels. This system requires minimal edge profiling and relies on pullout resistance for strength.

Panel-to-girder connections for bridge decks are less documented. Adaptable options include self-tapping screws and metal brackets. Screw connections are cost-effective but weaker when installed in the narrow side or end grain of panels. Angled installation improves strength. Metal brackets, such as “L” or “T” shapes, provide strong, efficient connections with simplified construction access.

A couple of case studies highlight the potential of CLT’s for bridge decks with different connection details. The Hundorp Bridge in Norway used timber screws, steel brackets, and lag bolts for adjacent panel and girder connections, ensuring simplicity and reliability (Abrahamsen and Nylokken, 2017). Similarly, the

Mistissini Bridge in Quebec featured a CLT walkway with integrated guardrail connections (Lefebvre and Richard, 2014).

2.3 Research on Adhesives and Treatments

Recent studies have focused on improving CLT performance for exterior applications. For example, Han et al. (2017) demonstrated that treating CLT panels with superheated steam reduced delamination failures by 50%. Tripathi and Lim (2018) and Lim et al. (2020) evaluated adhesive systems for treated CLT, finding that polyurethane adhesives performed better than others like melamine and resorcinol formaldehyde for bonding treated Southern Yellow Pine. Such findings highlight the need for appropriate pairing of lumber pre-treatment with adhesive selection to improve durability in wet environments.

2.4 Standards and Challenges for Exterior Use

CLT standards like PRG 320 primarily address indoor applications, limiting exterior use due to moisture and durability concerns. Adhesives used in CLT panels must meet standards such as ASTM D2559 for exterior exposure. While some adhesives already meet these criteria, further development of testing methods is needed to address the unique grain orientation in CLT and ensure durability under outdoor conditions.

2.5 Innovations in Lamination Type and Orientation

Adjusting lamination orientation has been shown to enhance performance. Buck et al. (2016) found that orienting transverse layers at 45° instead of 90° increased bending strength by 35% and reduced mid-span deflection, while Masoudnia et al. (2016) observed similar improvements in structural reinforcement. Composite laminated panels (CLP), using structural composite lumber for transverse layers, have also shown increased shear strength and stiffness compared to traditional CLT (Zhou et al., 2018).

2.6 Size Limits of CLT Panels in the United States

The project team surveyed CLT manufacturers and pressure treatment facilities across North America to determine the size limitations of CLT panels suitable for pressure treatment.

The ability to pressure-treat full panels after fabrication is constrained by current manufacturing capabilities. Feedback from several CLT manufacturers indicated that typical pressure treatment chambers in the United States limit panel widths to approximately 2.1 meters. This makes the process less economical than treating wider panels, such as those up to 3 meters. Protecting CLT panels for exterior use is critical to ensuring long-term structural integrity as with other timber bridge types.

Pressure-treating individual timber members before assembling them into CLT panels is cost-prohibitive. Treating before bonding requires plant quality control testing to ensure glue bonds meet quality standards, as the bonding process becomes more complex with treated boards. Typically, the lumber must be re-dried after treatment to achieve the necessary adhesive performance, further adding to the costs and complexity of the process.

2.7 Challenges and Future Research

CLT’s adoption in bridge construction faces several challenges, such as moisture resistance, adhesive testing, seismic resistance, and standardization. Effective pressure treatments and waterproof adhesives are critical for durability and affect timber's mechanical properties. New methods are required to evaluate adhesive performance in alternating grain orientations under exterior conditions. Enhancing CLT panel connections and diaphragm performance is vital for seismically active regions. Expanding standards like PRG 320 to include exterior durability tests is necessary for broader acceptance in bridge applications.

3 LABORATORY INVESTIGATIONS

At the Iowa State University Structures Laboratory, the project team conducted load tests on CLT panels in two configurations – spanning longitudinally (left photo) and transversely (right photo), in Figure 1.

The longitudinal deck panel system consisted of two single-span panels with a 9-lam layup measuring 314 mm deep × 2.48 m wide (see Figure 2). These panels spanned 7.62 m longitudinally between two concrete blocks serving as abutments.

The transverse deck panel system consisted of three panels with a 5-lam layup measuring 175 mm deep × 2.48 m wide (see Figure 2). These panels spanned transversely across longitudinal, simply-supported W-shape steel girders at two interval spacings.

All layers of the panels were constructed from visually-graded, untreated Douglas fir (Pseudotsuga menziesii) lumber. Select-structural grade lumber was used in the primary span direction, while #2 grade lumber was used for the transverse layers. Notably, the select-structural grade lumber in layers oriented with the primary span direction exceeds the typical quality of basic CLT grades. This addresses the higher structural demands imposed by highway service loads compared to those on standard panels of similar thickness.

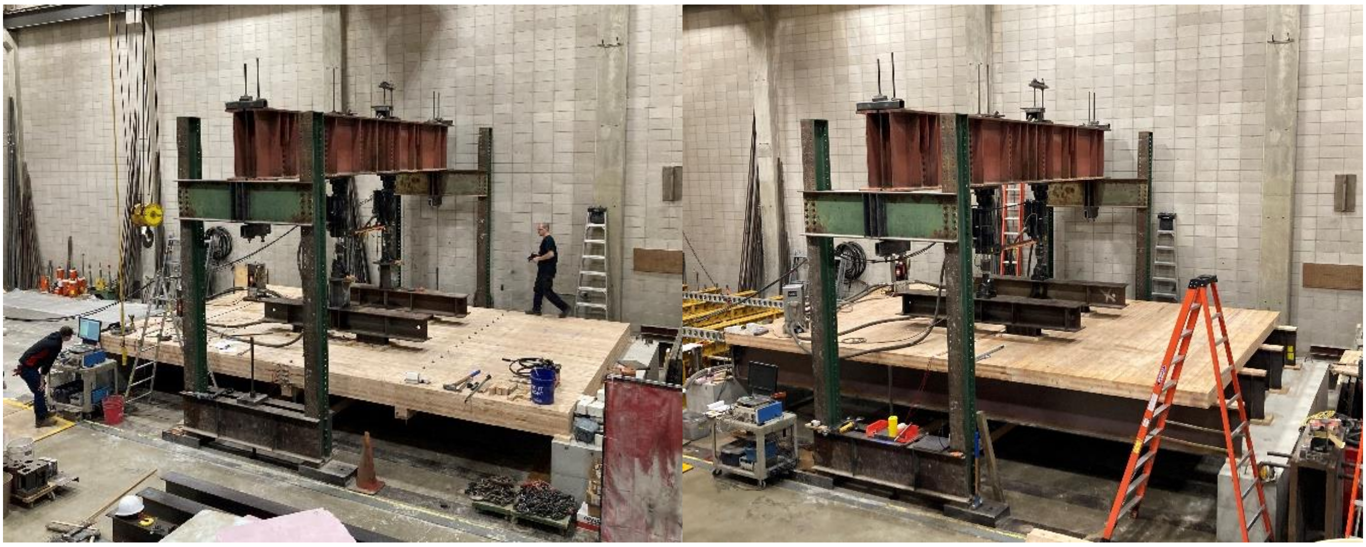


Figure 1. Load Tests of Longitudinal (left photo) and Transverse CLT Panels (right photo)

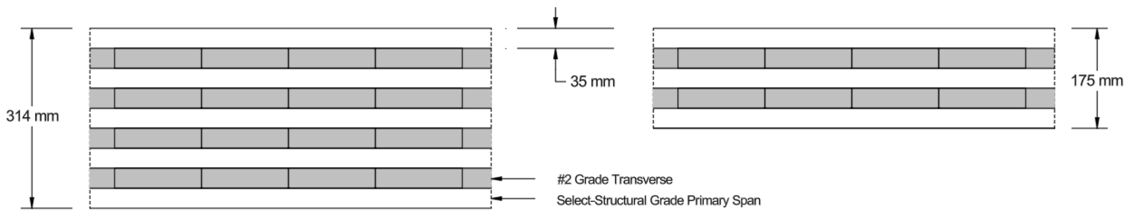


Figure 2. Layup of Longitudinal (left) and Transverse CLT Panels (right)

3.1 Laboratory Testing of Longitudinal Deck Panel System

The laboratory test setup featured two equal-width CLT panels placed side-by-side and spanning longitudinally, as illustrated in Figure 3 (left). The total deck width was 4.88 meters, constituting about half the width of an in-service bridge. To simulate bridge conditions, three built-up spreader beams (each made of four boards measuring 38 mm × 191 mm and connected with screws for a total cross-section of 152 mm × 191 mm) were attached to the underside of the deck. These beams were secured using 19 mm diameter threaded thru-rods spaced at 305 mm, consistent with AASHTO specifications.

These longitudinal panels were joined along their edges using a half-lap joint, a common connection detail employed with CLT in vertical construction panels and nail-laminated timber bridge deck panels. The overlap width was 76 mm, with screws securing the joint using an inclined configuration designed for higher stiffness and load capacity. Vertical screws (8 mm diameter × 302 mm length) and inclined screws (9.5 mm diameter × 400 mm length) were used to enhance joint performance.

Tests included both static and cyclic loading to simulate highway service loads. For the static tests, four load cases were applied to simulate the rear tandem axle of a dump truck, with loads positioned to maximize shear and bending reactions (see Figure 3). The cyclic tests were performed for only Load Case 2, applying a tandem axle load of 111.2 kN (55.6 kN per tire), consistent with HL-93 AASHTO design truck loading.

Instrumentation included strain and deflection gauges to monitor structural behavior. Vertical deflection gauges were placed transversely at the midspan and along the longitudinal joint to measure deflection and joint movement. Horizontal gauges along the joint captured relative motion or gapping. ST350 strain gauges (Bridge Diagnostics, Inc.) were installed at the top and bottom edges of the panels and at approximately 1.52 meters from the edges. Additional strain gauges were placed on individual laminations at one panel edge to assess the strain profile under loading. A horizontal displacement gauge was added to the lowest transverse lamination to monitor any gapping between members.

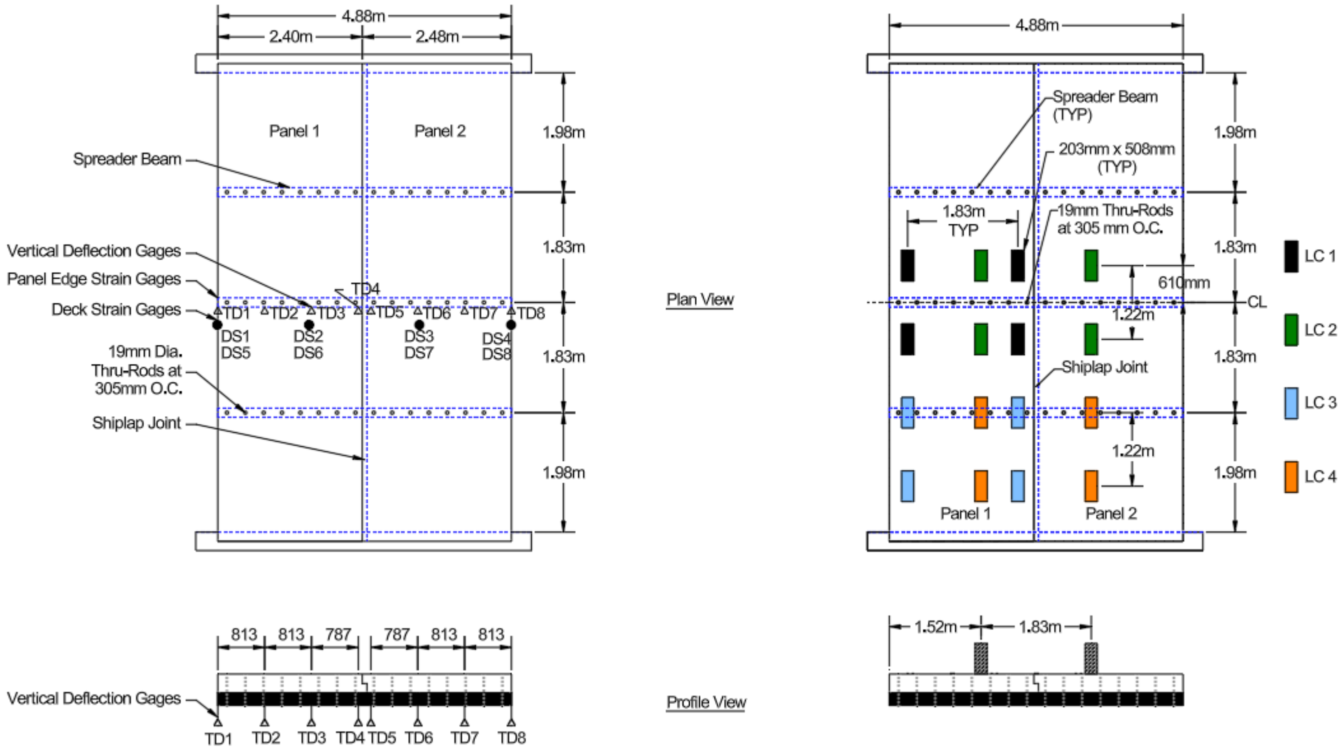


Figure 3. Longitudinal Panel Configuration, Instrumentation, and Load Case Position

3.2 Equivalent Strip Width

3.2.1 Equivalent Strip Width (ESW) Calculation for CLT Bridge Decks

The AASHTO LRFD Bridge Design Specifications (2020) prescribe an equivalent strip width (ESW) for longitudinal bridge deck strips to estimate the portion of the slab engaged in resisting live loads from vehicles. This method is commonly used for cast-in-place concrete slabs, stress-laminated wood decks, and glued/spiked wood panels with a spreader beam. While the AASHTO equations tend to be conservative, the actual ESW can be determined using strain and deflection measurements.

ESW is typically calculated by integrating the area under the moment distribution curve and dividing it by the maximum moment. Assuming uniform stiffness, deflection data can also be used for ESW determination (Equation 1):

$$ESW = \frac{\sum_{i=1}^{n}(deflection_i \times d_i)}{deflection_{max}} \qquad (1)$$

where, n is the total number of deflection sensors, $deflection_i$ is the deflection reading of the i-th sensor, $deflection_{max}$ is the maximum deflection measured by the sensors, and d_i is the spacing of adjacent deflection gauges. Using this approach, ESW values were calculated for longitudinal CLT deck panels under various load cases.

When the load was applied across both panels (Load Cases 2 & 4)**,** the ESW increased by approximately 70% compared to when the load was applied to a single panel (Load Cases 1 & 3)**.** This indicates greater engagement of the bridge width in load resistance. However, transverse load distribution was significantly reduced when the load was isolated to one panel. While the spreader beam rigidity (62 kN-m^2) was greater than the rigidity required by AASHTO design specifications (23 kN-m^2), a stiffer spreader beam could potentially improve load-sharing behavior.

3.3 Laboratory Testing of Transverse Deck Panel System

A full-scale bridge section using steel girders and transverse CLT panels was constructed and load-tested The test setup included two girder configurations to assess the performance of the same CLT deck under different girder spacings – a four girder (see Figure 4) and three girder (see Figure 5) configuration. The clear span of the girders was 7.62 m, and the bridge deck width was 4.88 m, equivalent to half of a full bridge width. Girder spacings ranged from 1.40 m to 2.10 m. Design calculations using glulam girders spaced at 2.10 m were completed and resulted in using a 24F-V3, 838 mm deep x 172 mm wide Spruce Pine glulam girders with a rigidity of 10,442 kN-m^2. Steel girders with near-equivalent rigidity were used in lieu of glulam girders due to lead time and availability. The W610x82 steel girders had a rigidity (E_{stl} x I_{xx}) of 11,235 kN-m^2, about 7.5% greater than the glulam.

The setup included three equal-width panels with the major strength direction in the transverse direction were connected to the top flange of the girders with flatwise 38 mm × 191 mm boards secured by 13 mm dome-head thru-bolts spaced 305 mm apart. The panels were joined using half-lap joints, a common technique in vertical construction. The joints featured a 76 mm overlap, secured with ASSY VG CYL 8 mm × 159 mm vertical screws and ASSY VG CSK 9.5 mm × 219 mm inclined screws. Inclined screws were chosen to provide higher stiffness and load capacity at inter-panel connections.

Two static test series were conducted. The first used the four-girder configuration with 1.40 m spacing, and the second used the three-girder configuration with 2.10 m spacing. Each test involved four load cases simulating the rear tandem axle of a dump truck, with a maximum load of 111.2 kN per axle (55.6 kN per tire), consistent with the AASHTO HL-93 design tandem loading (see Figure 4 and Figure 5).

The three-girder configuration was subjected to 500,000 cycles at the same load level and position as Load Case 2 to simulate several years of truck traffic. A static test followed to compare pre-and post-cyclic performance.

Strain and deflection gauges were used to monitor performance. Instrumentation included deflection gauges installed beneath each girder at midspan to measure vertical deflection and on the bottom side of the CLT panels at panel joints to monitor spacing changes. Strain gauges were placed at the bottom flange of the steel girders at midspan and on the top and bottom of the CLT panels in the strong direction, evenly spaced between girders.

The load cases were designed to maximize shear and bending reactions within the panels and to analyze force distribution across the bridge deck. Load Case 2 was specifically selected for cyclic testing due to its potential to stress the longitudinal joints and influence lateral load distribution. The 0 m transverse position in the results figures corresponds to the deck edge nearest Load Cases 1 and 3.

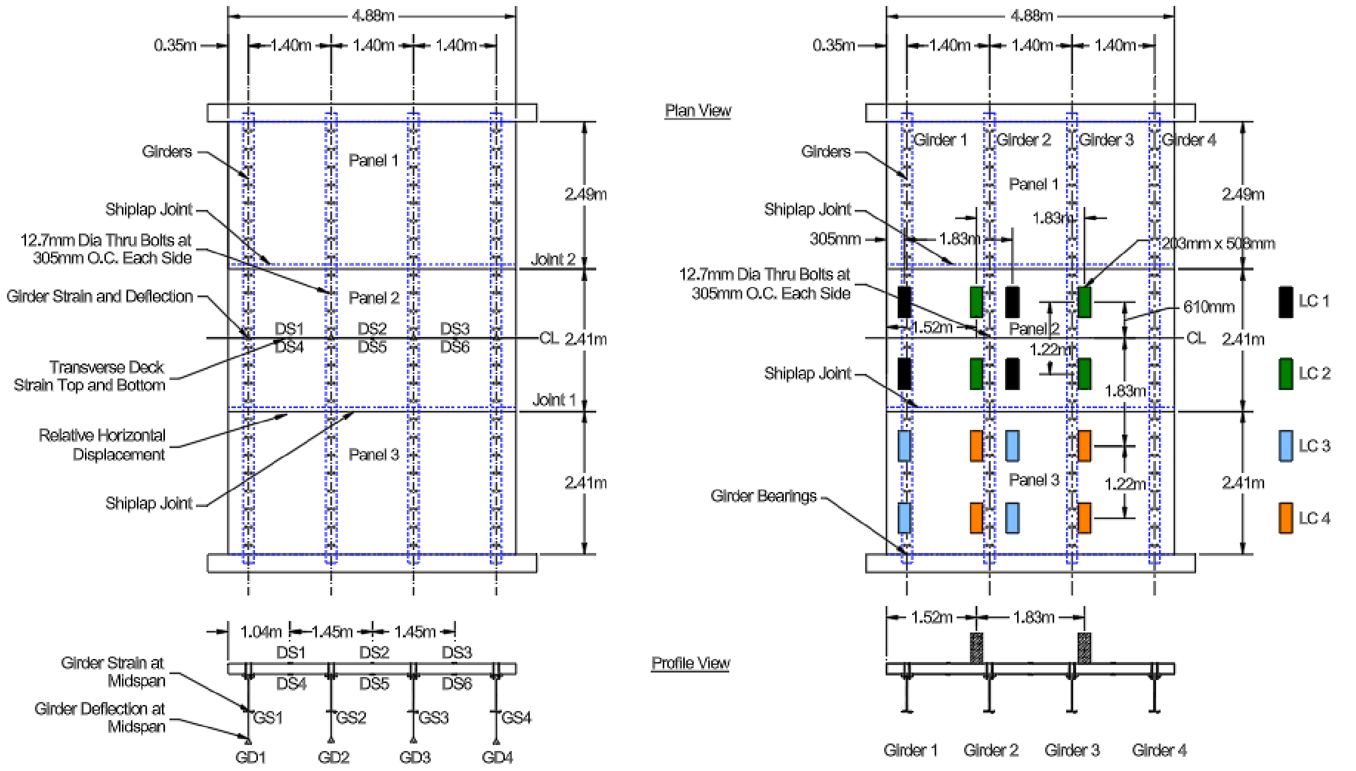


Figure 4. Four Girder Transverse Panel Configuration, Instrumentation, and Load Case Position

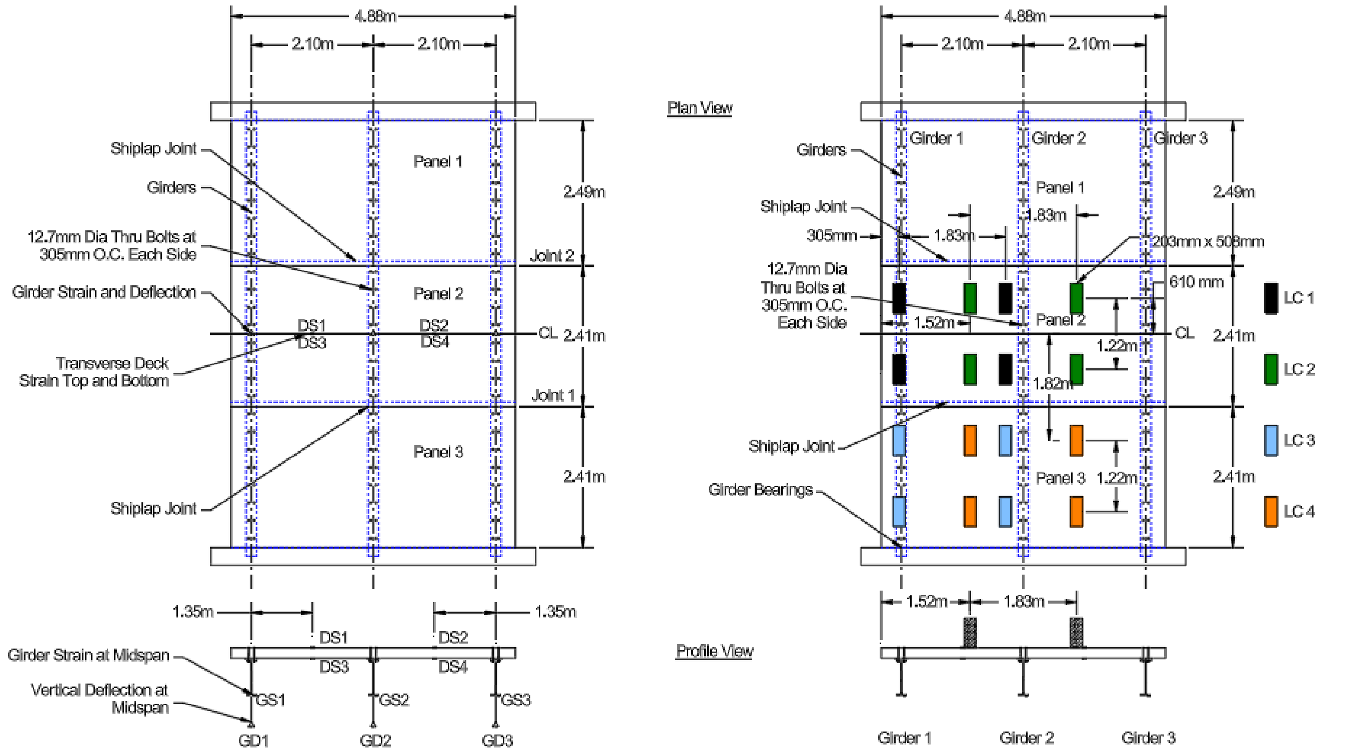


Figure 5. Three Girder Transverse Panel Configuration, Instrumentation, and Load Case Position

4 TEST RESULTS

For brevity, only the static and cyclic load test results for Load Case 2 of the longitudinal and transverse panel tests will be discussed in this paper.

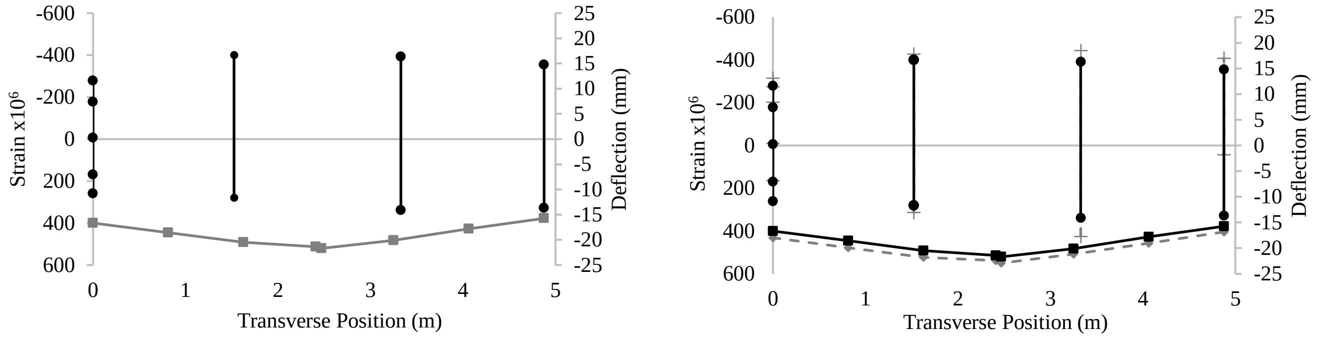
4.1 Longitudinal Panel Deck System Test Results

The static load test results for Load Case 2 are summarized below. Load Case 2 was conducted twice – once before and after the cyclic loading test – to assess any changes in structural performance after 500,000 load cycles.

The midspan strain (DS1 – DS8) and deflection plots (TS1 – TS8) at maximum load are provided in Figure 6 (left) For Load Case 2, the load was symmetrically applied to both panels—the maximum deflection was 21.6 mm at the longitudinal joint, corresponding to an L/D of 351. Deflection decreased uniformly from the joint to the panel edges, with minor reductions overall.

Strain values were relatively symmetric, ranging from 279 microstrain (compression) to 260 microstrain (tension) at the panel edge. The strain profile was linear through the panel depth, with a peak strain of 401 microstrain in compression at the top of the first interior position. Using a modulus of elasticity of 11,700 MPa for select structural Douglas Fir, the corresponding maximum stress was 4.8 MPa. Similar to the deflection behavior, strain values decreased slightly at the panel edges.

Figure 6 (right) also compares the static test results from before and after the completion of the cyclic loading. The comparison of strain and deflection values indicates that there is no appreciable change in the structure behavior as a result of the cyclic testing.

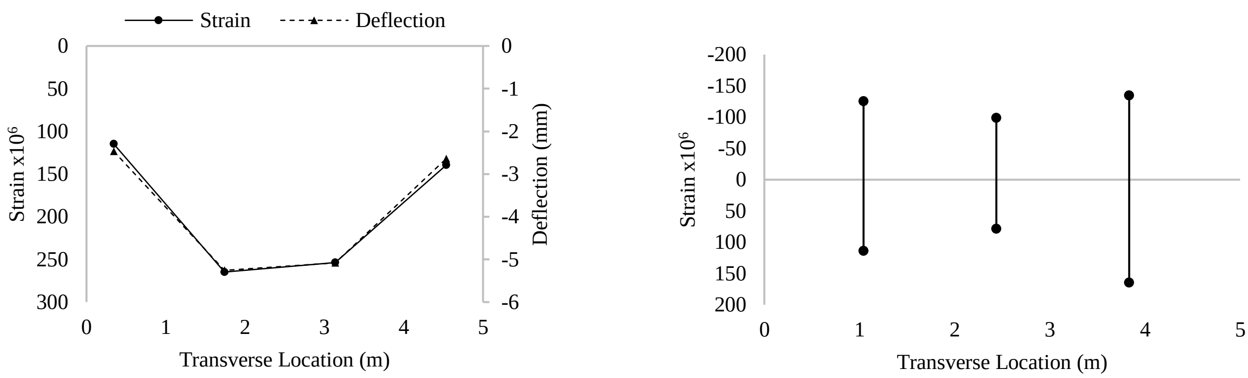


DS1-DS4 (Top, L-R) Compression, DS5-DS8 (Bottom, L-R) Tension   Pre-Cyclic = Black, Post-Cyclic = Grey

Figure 6. Load Case 2 Static Load Test Results Pre- (left) and Post-Cyclic Testing (right) for Longitudinal Panel Deck System

4.2 Transverse Panel Deck System Test Results – Four Girder Assembly

For Load Case 2, the midspan girder strain and deflection values at maximum load are shown in Figure 7. The highest deflection (5.3 mm) and bottom-flange tensile strain (265 microstrain) occurred near the transverse load location. These values correspond to a span-to-deflection ratio (L/D) of 1,371 and a live-load steel stress of 55.2 MPa, both within acceptable limits based on service deflection criteria and steel yield strength. CLT strain measurements (see Figure 7) across three transverse locations showed peak tensile and compression strains of 165 and 134 microstrain, respectively. Using a modulus of elasticity of 11,700 MPa for select structural Douglas Fir, these correspond to maximum stresses of 1.93 MPa (tension) and 1.59 MPa (compression).

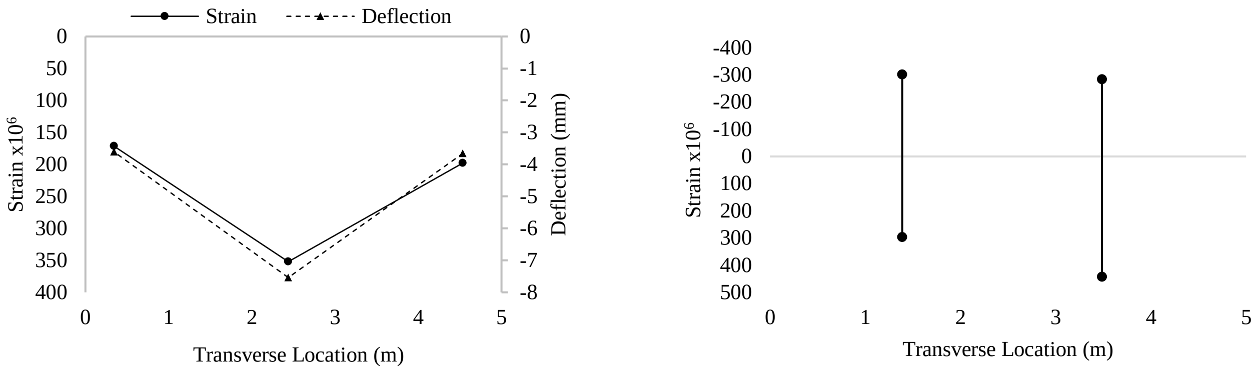


GS1-GS4 (L-R), GD1-GD4 (L-R)   DS1-DS3 (Top, L-R) Compression, DS4-DS6 (Bottom, L-R) Tension

Figure 7. Girder Strain and Deflection (left) and Transverse CLT Panel Strain (right) - Four Girder Assembly

4.3 Transverse Panel Deck System Test Results – Three Girder Assembly

For Load Case 2**,** the midspan girder strain, deflection, and CLT strain values at maximum load are shown in Figure 8. The highest deflection (7.6 mm) and bottom-flange tensile strain (197 microstrain) occurred near the transverse load location. These values correspond to a span-to-deflection ratio (L/D) of 960 and a live-load steel stress of 41.4 MPa, both within acceptable service deflection limits and steel yield strength. Strain measurements across two transverse locations showed peak tensile and compression strains of 443 and 301 microstrain, respectively. Using a modulus of elasticity of 11,700 MPa for select structural Douglas Fir, the corresponding maximum stresses were 5.17 MPa (tension) and 3.52 MPa (compression).



GS1-GS3 (L-R), GD1-GD3 (L-R)

DS1-DS2 (Top, L-R) Compression, DS3-DS4 (Bottom, L-R) Tension

Figure 8. Girder Strain and Deflection and Transverse CLT Panel Strain – Three Girder Assembly

After the cyclic test, an additional static test was conducted for Load Case 2 to assess any structural changes due to repeated loading. A comparison of midspan strain and deflection values before and after 500,000 load cycles is provided in Figure 9. The results show that post-cyclic structural performance remained nearly identical to pre-cyclic values. No significant changes in strain or deflection were observed. This indicates that cyclic loading had no appreciable effect on the CLT panels' strength or stiffness, confirming their durability and stability under prolonged load conditions.

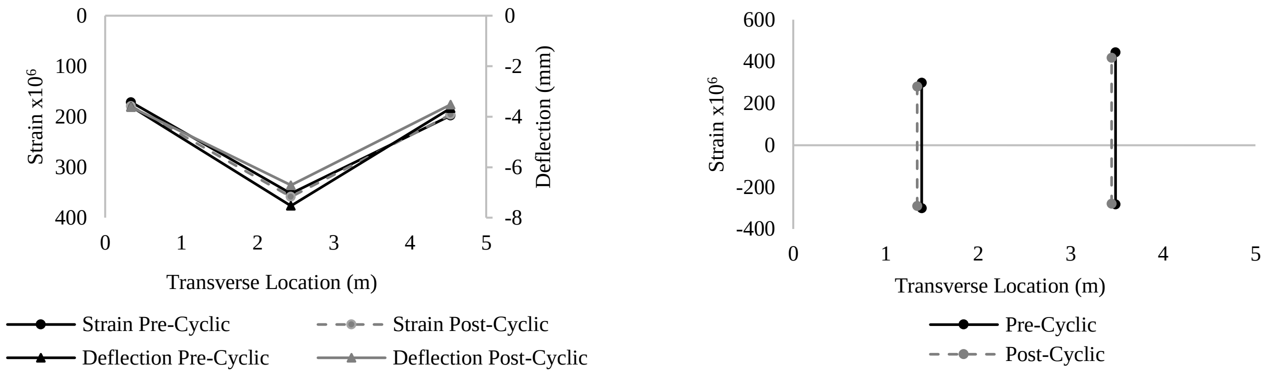


Figure 9. Load Case II Comparison of the Girder Strain, Deflection, and Transverse CLT Panel Results – Pre- and Post-Cyclic

5 CONCLUSIONS

CLT panels have been widely used in vertical construction but remain largely unexplored for bridge decks in North America. Challenges include limited pressure treatment capabilities and high costs associated with treating individual components before assembly. Further research is needed to develop cost-effective protection against environmental exposure.

CLT is prefabricated, lightweight, dimensionally stable, and environmentally sustainable. However, existing North American standards (PRG 320, CLT Handbook, NDS) currently restrict its use primarily to indoor applications. This study examined two CLT configurations under highway loads: longitudinal panels spanning between abutments and transverse panels supported by girders**.**

For longitudinal panels, static tests assessed equivalent strip width (ESW) and load distribution. When a single panel was loaded, ESW decreased by 40% compared to when both panels were loaded. Load distribution results aligned with previous slab-type timber bridge tests. Identifying methods to improve the transverse load distribution in CLT bridge decks would benefit future designs and ratings of these bridges. The panels performed consistently, though AASHTO LRFD guidelines for deflection limits (L/425) were exceeded in some cases. Increasing panel depth, improving transverse load distribution, or reducing span lengths could mitigate these serviceability concerns.

For transverse CLT decks, static and cyclic tests evaluated deflection, strain, and joint behavior across four-girder and three-girder configurations. The panels performed consistently within AASHTO LRFD deflection guidelines.

Cyclic tests subjected CLT panels to 500,000 load cycles simulating years of traffic. Post-cyclic static tests showed no significant change in strength or stiffness, confirming durability under sustained loads.

Code adoption challenges remain for bridge structures in North America. CLT lacks standardized exterior durability testing, and PRG 320 does not permit wet-use adhesives. Research on waterproof adhesives, pressure treatment, and performance under moisture exposure is essential for regulatory acceptance which will lead to broader CLT bridge construction in the future.

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The references should be in a numbered list in the order the references first appear in the paper. Reference numbers in the paper should be in square brackets, e.g. [1].

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