Evaluation of Stress-Laminated T-Beam Bridges Constructed of Laminated Veneer Lumber

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Abstract

Growing interest in wood bridges during the past decade has led to the use of new wood products and innovative designs for bridges. One new wood bridge system that is becoming increasingly popular involves solid, laminated veneer lumber T-beams that are stress laminated together. As part of the development of these bridges, an evaluation program to monitor field performance of six bridges was implemented. This paper describes results of field performance related to bar force, moisture content, and condition assessment, with presentation of load test and analytical evaluations for two of the six bridges.

Keywords: Bridges, Wood, Laminated veneer lumber, Field performance, Stress laminated.

Introduction

The objective of the Timber Bridge Initiative (TBI), passed by the U.S. Congress in 1988, was to further develop and extend the use of wood as a bridge material (USDA 1995). As part of this objective, emphasis has been placed on the use of new engineered wood products and innovative bridge designs. One engineered wood product that has recently been adapted for bridge applications is laminated veneer lumber (LVL). LVL, which is a subcategory of new wood products called structural composite lumber, is made from sheets of rotary-peeled wood veneer that are glued together with waterproof adhesive to form structural members (Figure 1). The thickness of the veneer laminations is commonly 2.5 to 6.4 mm (0.10 to 0.25 in.). In contrast to plywood, LVL laminations are oriented with the grain direction parallel, rather than having some laminations at right angles.

Several characteristics of LVL make it desirable for structural applications. Because it is a manufactured product, LVL can be produced in a variety of sizes and shapes. The laminating process disperses the natural strength-reducing characteristics of wood, which

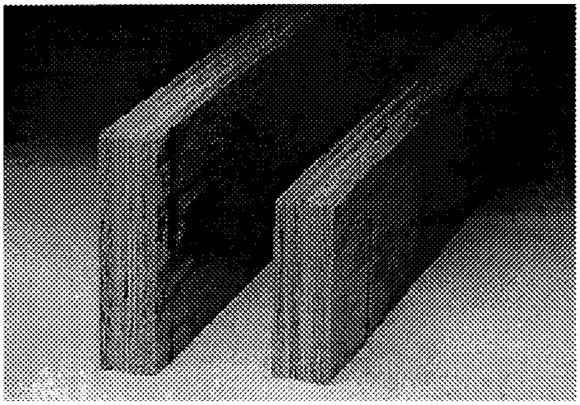


Figure 1 – Typical LVL beams.

reduces product variability and provides improved design strength and stiffness compared to sawn lumber. Because of this, design values of up to 20.2 MPa (2,900 lb/in^2) in bending and 13,800 MPa (2,000,000 lb/in^2) for modulus of elasticity (MOE) are possible. LVL also provides improved treatability with wood preservatives because of small lathe checks in the veneers that facilitate preservative penetration. The result is generally full preservative penetration of structural components (Tschernitz et al. 1974). Most LVL is produced from either Douglas-fir or Southern Pine veneers, but hemlock, yellow-poplar, oak, and spruce have also been used.

LVL is not a new material. It originated in the 1940s when research was being conducted for high strength aircraft structures (Forest Products Laboratory 1987) and has been produced commercially for more than 25 years. The primary use for LVL has historically been in residential and commercial building applications, such as beams and headers, chords of trusses, and the flange component of prefabricated wood I joists. The first known LVL bridge constructed in the United States was built in 1977 of "press-lam," a type of LVL developed at the USDA Forest Service, Forest Products Laboratory (FPL). This prototype structure, jointly sponsored by the Forest Service and the Virginia State Highway Department, consists of a 79-mm- (3.13-in.-) thick LVL deck supported on 114- by 508-mm (4.5- by 20-in.) LVL beams spaced 762 mm (30 in.) on-center (Youngquist et al. 1979). One of the next known uses of LVL in bridges was in 1988 when a 22.25-m (73-ft) span experimental stress-laminated T-beam bridge was constructed in West Virginia using LVL for the web components. For this structure, flanges constructed of nominal 38- by 229-mm (1.5- by 9-in.) oak lumber laminations were stress laminated between 152- by 1,145-mm (6- by 45-in.) LVL webs spaced 915 mm (36 in.) on-center (Dickson and GangaRao 1989).

The first effort to develop and market a bridge system constructed entirely of LVL was initiated by Trus Joist MacMillan in the late 1980s. These bridges consisted of a series of fully laminated T-beams that were stress laminated together through the flange to form the bridge width (Figure 2). By 1993, approximately 20 bridges of this type were constructed in the western United States, with clear spans of 7.3 to 15.2 m (24 to 50 ft) and widths of 3.0 to 11.0 m (10 to 36 ft). One obstacle to acceptance of the bridges was the lack of LVL design values in the *Standard Specifications for Highway Bridges* published by the American Association of State Highway and Transportation Officials (AASHTO). This was subsequently resolved, and design values for LVL bridges were included in the 1995 interim specifications (AASHTO 1992). As a result the system is becoming more popular as an alternative for new construction and bridge replacement. The bridges are also currently being constructed of another type of structural composite lumber known as parallel strand lumber (PSL) (Meyer 1995).

During the development process for stress-laminated LVL T-beam bridges, a field evaluation program was considered necessary to fully evaluate bridge performance and optimize design methodology. As a result, FPL was contacted to assist in field monitoring, load testing, and analytical evaluations, and a bridge monitoring program was initiated in 1991 for six bridges. The objective of the monitoring was to evaluate performance characteristics and improve design procedures for LVL T-beam bridges through field evaluation and analytical modeling. The scope of this

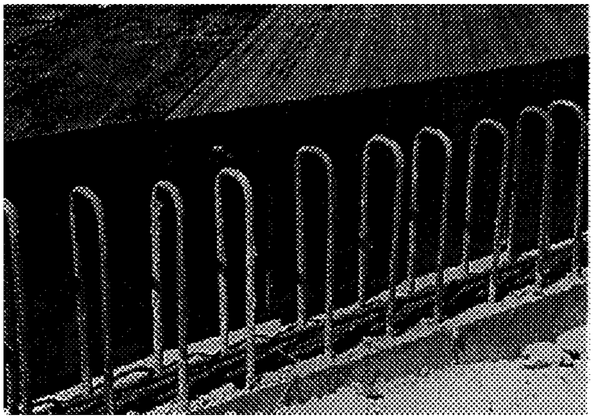


Figure 2 – Typical stress-laminated LVL T-beam showing (top) the end section of a solid LVL T-beam and (bottom) a completed bridge.

paper is limited to results of field performance related to bar force, moisture content, and condition assessment, with presentation of load test and analytical evaluations for two bridges.

Description of Bridges

Of the numerous LVL T-beam bridges constructed, six bridges located in the northwestern U.S. were selected as representative examples for field evaluation purposes. As shown in Figure 3, the bridges ranged in length from 7.92 to 13.41 m (26 to 44 ft) with widths of 4.88 to 11.43 m (16 to 37.5 ft). The size of the individual LVL T-beams varied for each bridge depending on specific design requirements and ranged from 610 to 635 mm (24 to 25 in.) wide and 356 to 711 mm (14 to 28 in.) deep, with a flange thickness of 152 mm (6 in.) and a web width of 203 mm (8 in.). Four bridges included LVL box beams along the edges of the bridge to improve dimensional stability.

All bridges were stress laminated with ASTM A 722 high strength steel bars spaced 762 mm (30 in.) on-center (ASTM 1988). The design bar force of 133 kN (30,000 lb) provided an interlaminar compression of approximately 1.15 MPa (167 lb/in^2) between the flanges. The LVL for all bridges was pressure treated with pentachlorophenol in heavy oil in accordance with American Wood Preservers' Association (AWPA) Standard C 14 (AWPA 1990). With the exception of the Kenally Creek bridge, which was provided with lumber running planks, all bridges were constructed with an asphalt wearing surface. A detailed description of the South Canal and Mill Creek bridges (discussed later in this paper) follows.

South Canal Bridge

The South Canal Bridge is located in Owyhee County, Idaho, and is a single-lane bridge with a span of 7.71 m (25.3 ft) center-to-center of bearings and an out-to-out width of 4.88 m (16 ft) (Figure 4). The bridge consists of 8 LVL T-beams, 610 mm (24 in.) wide and 356 mm (14 in.) deep.

Mill Creek Bridge

The Mill Creek Bridge is located in Stevens County, Washington. It is a two-lane bridge with a span of 8.93 m (29.3 ft) center-to-center of bearings and an out-to-out width of 7.32 m (24 ft) (Figure 5). The T-beams are 610 mm (24 in.) wide and 406 mm (16 in.) deep. The exterior box beams are 610 mm (24 in.) wide and 406 mm (16 in.) deep, with a top flange thickness of 152 mm (6 in.) and a bottom flange thickness and web width of 114 mm (4.5 in.).

Evaluation Methodology

Evaluation of the LVL T-beam bridges utilized procedures and equipment previously developed by FPL (Ritter et al. 1991). A description of the methodology for moisture content and bar force measurement, load test behavior, analytical evaluation, and condition assessment follows.

Moisture Content

Moisture content measurements were taken on the underside of the deck at web and flange locations using an electrical-resistance moisture meter with 76-mm (3-in.) probe pins in accordance with ASTM D4444-84 procedures (ASTM 1990). Measurements were obtained by driving the pins to depths of 25 to 51 mm (1 to 2 in.), recording the moisture content value, and adjusting the values for LVL temperature and species based on factors obtained from Trus Joist MacMillan. Moisture content measurements of the Petty Creek bridge were taken approximately monthly for 2.5 years. Moisture content measurements for the other bridges were taken prior to installation and at the time of load testing.

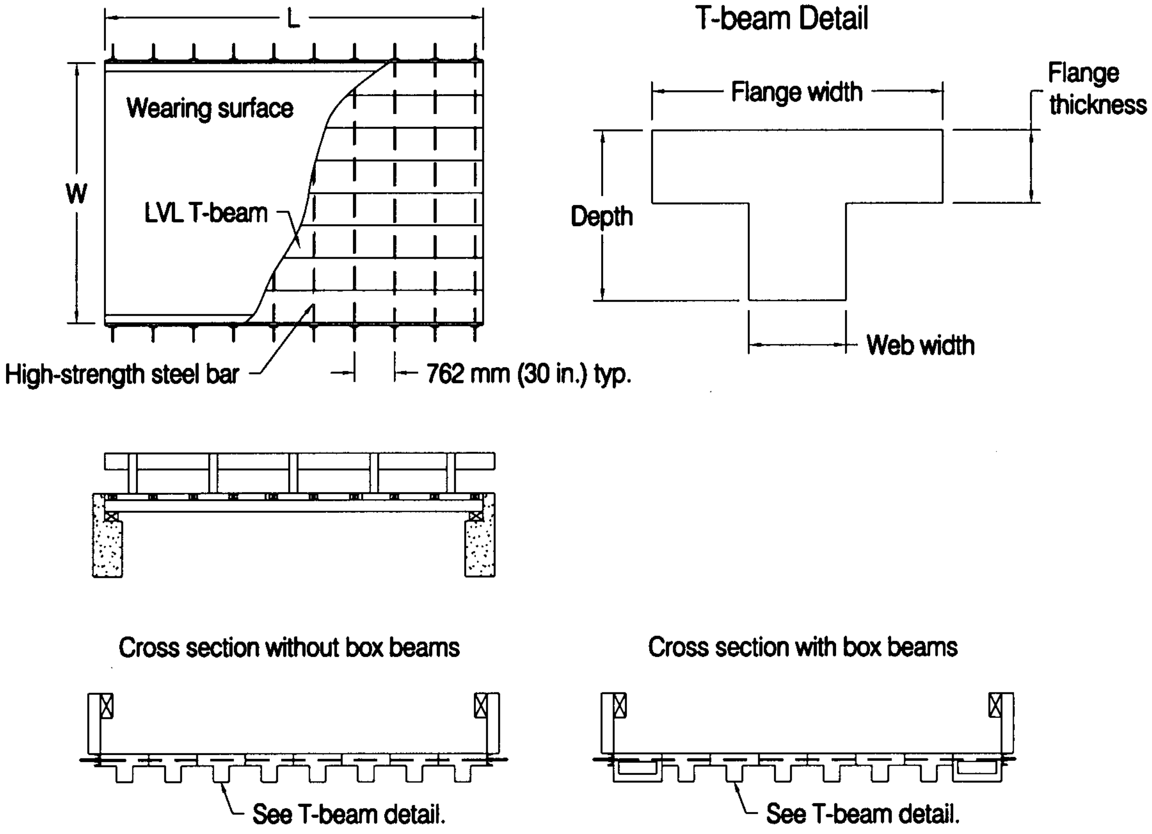
Bar Force

Bar force for the Petty Creek bridge was measured on a monthly basis using two load cells developed by FPL. Load cell strain measurements were obtained with a portable strain indicator and converted to units of bar tensile force by applying a laboratory conversion factor to the strain indicator reading. At the conclusion of the monitoring period, the load cells were removed, checked for zero balance shift, and recalibrated to determine time-related changes in the initial load cell calibration. Bar force for the other bridges was measured with a hydraulic jack at the time of construction and load testing.

Load Test Behavior

Static load testing consisted of positioning loaded test vehicles on the bridge deck and measuring the resulting deflections at a series of transverse locations at midspan. Measurement of bridge deflections were taken prior to testing (unloaded), for each load position (loaded), and at the conclusion of testing (unloaded). Deflection measurement from an unloaded to loaded condition was obtained by placing a calibrated rule at the bottom center of each web and reading values with a surveyor's level to the nearest 0.8 mm (0.03 in.).

The load test vehicles at both bridges were fully loaded three-axle dump trucks (Figure 6). At the South Canal bridge, a single truck with a gross vehicle weight (GVW) of 304 kN (68,500 lb) was used.



Bridge name	Length (L)	Width (W)	Depth	Skew (deg)	Edge box beams
Mill Creek	9.1 m (29.8 ft)	7.3 m (24 ft)	406 mm (16 in.)	0	Yes
Petty Creek	11.6 m (38.2 ft)	8.5 m (28 ft)	508 mm (20 in.)	32	Yes
Kenally Creek	9.9 m (32.4 ft)	5.2 m (17 ft)	457 mm (18 in.)	0	No
Franklin Road	13.4 m (44 ft)	11.0 m (36 ft)	711 mm (28 in.)	0	Yes
Wardwell	8.5 m (28 ft)	11.4 m (37.5 ft)	406 mm (16 in.)	0	Yes
South Canal	7.9 m (26 ft)	4.9 m (16 ft)	356 mm (14 in.)	0	No

Figure 3–Typical configuration details for the LVL T-beam bridges.

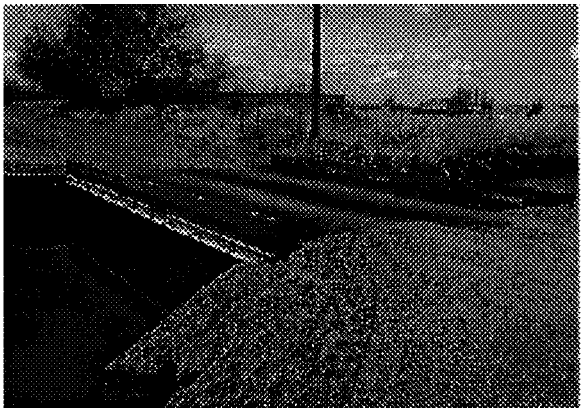


Figure 4–South Canal bridge, Owyhee County, Idaho.

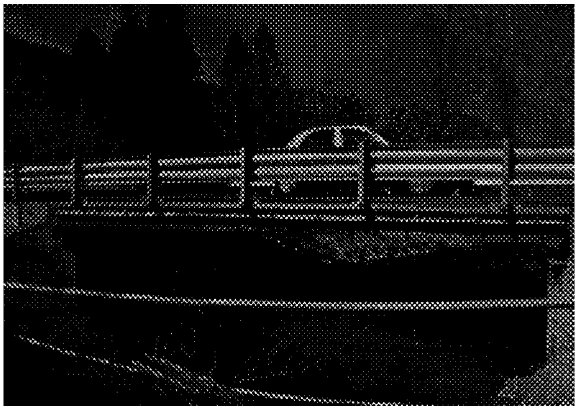


Figure 5-Mill Creek bridge, Stevens County, Washington.

At Mill Creek, two trucks were used: truck 20 with a GVW of 232 kN (52,200 lb) and truck 13 with a GVW of 227 kN (51,100 lb). The vehicles were positioned longitudinally on the bridges so that the two rear axles were centered at midspan and the front axles were off the bridge span. Transversely, different vehicles positions were used for single-lane and double-lane bridges. At South Canal, the three load positions included load position 1 with the vehicle centered on the bridge width and load positions 2 and 3 with the truck wheel line over the longitudinal bridge centerline (Figure 7). For the Mill Creek bridge, six load positions were used with the vehicles 0.61 m (2 ft) from centerline for load positions 1 through 3 and 1.22 m (4 ft) from centerline for load positions 4 through 6 (Figure 8).

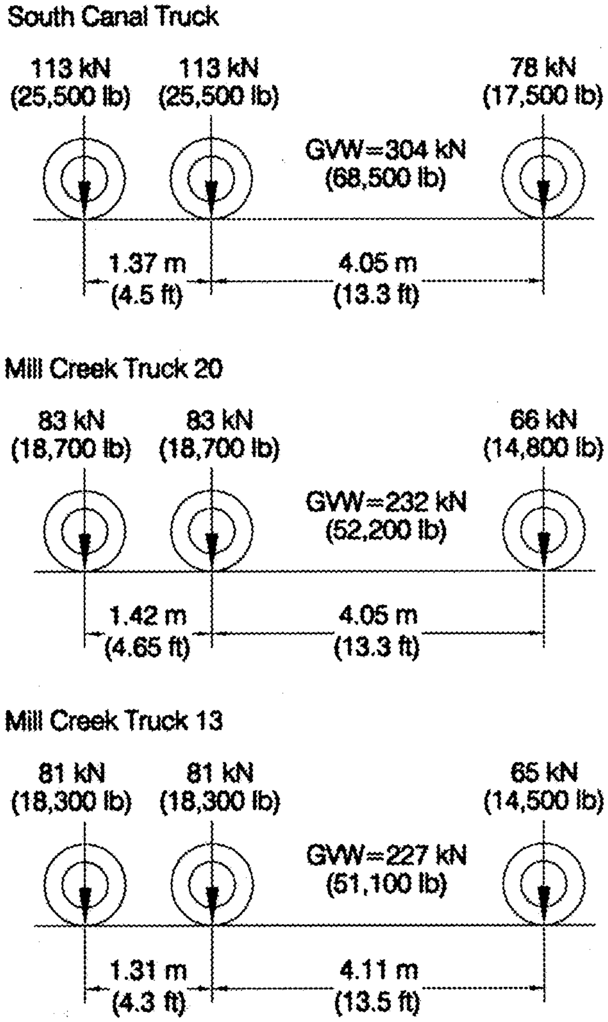


Figure 6 – Load test truck configurations and axle loads. The transverse vehicle track width, measured center-to-center of the rear wheel lines, was 1.82 m (6 ft).

Analytical Evaluation

The load test behavior of each bridge was evaluated analytically to further understand bridge behavior and form a basis for development of design load distribution criteria. Previous research showed that stress-laminated bridge decks could be accurately modeled as orthotropic plates (Oliva et al. 1990). Given the relatively compact section of the T-beams, an orthotropic plate analysis similar to that developed at FPL for stress-laminated decks was investigated. This was done so that the T-beam design criteria could parallel that for stress-laminated decks (currently under devdopment at FPL). To complete the orthotropic plate analysis, the plate thickness was taken as the T-beam flange thickness. To reflect the increase in longitudinal stiffness as a result of the T-beam webs, a transformed section analysis was

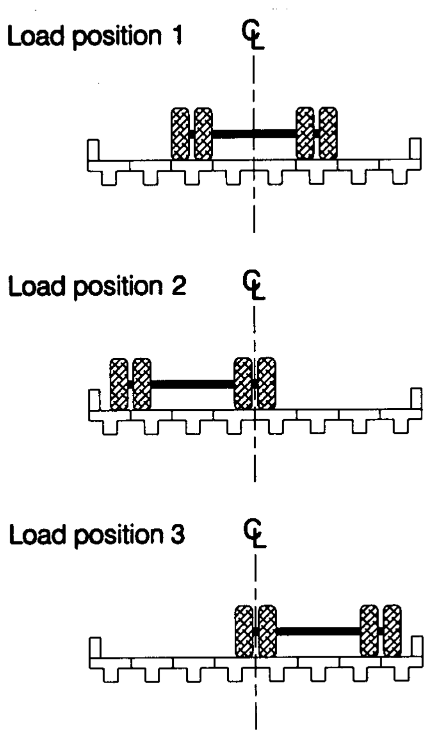


Figure 7 –Load test vehicle positions for the South Canal bridge (looking west). For all load positions, the two rear axles were centered over the bridge midspan with the front axle off the span.

completed to determine the equivalent longitudinal MOE of the plate. Properties in the transverse direction for MOE and shear modulus were based on the level of interlaminar compression in the bridge in accordance with the following equations.

$$E_{TS} = 168F_P + 108.6 \quad (E_{TS} = 168F_P + 15{,}749) \qquad (1)$$

$$G_{TS} = 234F_P + 261 \quad (G_{TS} = 234F_P + 37{,}897) \qquad (2)$$

where

E_{TS} = transverse MOE in MPa (lb/in^2)
G_{TS} = transverse shear modulus in MPa (lb/in^2)
F_P = interlaminar compression in MPa (lb/in^2)

An analytical evaluation was completed for each bridge based on load vehicles and conditions, including the level of interlaminar compression at the time of testing. Analysis was also completed for the same load test conditions and transverse vehicle positions using AASHTO HS 20-44 truck loading (AASHTO 1992).

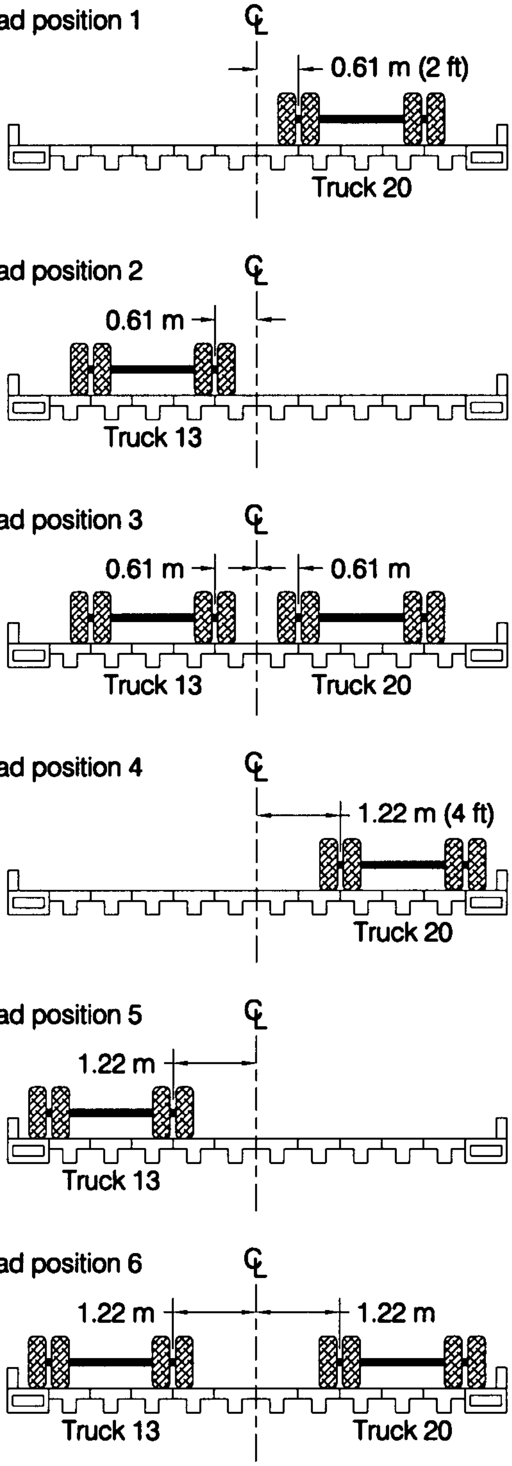


Figure 8 –Load test vehicle positions for the Mill Creek bridge (looking east). For all load positions, the truck rear axles were centered over the bridge midspan with the front axles off the span.

Condition Assessment

The general condition of each of the LVL T-beam bridges was assessed at the time of load testing. The assessments involved visual inspections, measurements, and photographic documentation of the bridge condition. Items of specific interest included the bridge geometry, condition of the LVL components, and the condition of the stressing bars and anchorage systems.

Results and Discussion

Results of the performance of the LVL T-beam bridges follow. Results for moisture content and bar force are based primarily on the Petty Creek bridge, which was continuously monitored for 2.5 years. Load test results and analysis are for the South Canal and Mill Creek bridges.

Moisture Content

All T-beam bridges were installed at a moisture content of 9%-12%. Measurements after installation indicated that the moisture content of the LVL responds relatively quickly to changes in environmental conditions. This is because the lathe checks in the veneers, which facilitate preservative penetration, also allow rapid moisture movement. For the Petty Creek bridge, the average moisture content increased from approximately 12% at the time of construction to approximately 26% at the conclusion of the 2.5-year monitoring program. During this time, variations in moisture content of 5% to 10% were noted on an annual basis as a result of seasonal climatic changes. The 12% increase in moisture content over the monitoring period is due in part to the sheltered location of the bridge, which hinders the drying of the deck, and the last and greatest moisture content readings were taken following the rainy period of the year.

Bar Force

The average bar force for the Petty Creek bridge is shown in Figure 9. At the time of load cell installation in December 1990, the bar force was approximately 112.1 kN (25,200 lb) or 0.97 MPa (140 lb/in^2) interlaminar compression. After increasing slightly, the bar force declined to approximately 90.3 kN (20,300 lb) or 0.78 MPa (113 lb/in^2) interlaminar compression in July 1991. For the remaining 2 years of the monitoring period, bar force remained relatively stable with fluctuations following seasonal climatic changes, which affected the moisture content and dimensional stability of the LVL. At the end of the monitoring period, the average bar force was 82.7 kN (18,600 lb), which is approximately 0.71 MPa (103 lb/in^2) interlaminar compression.

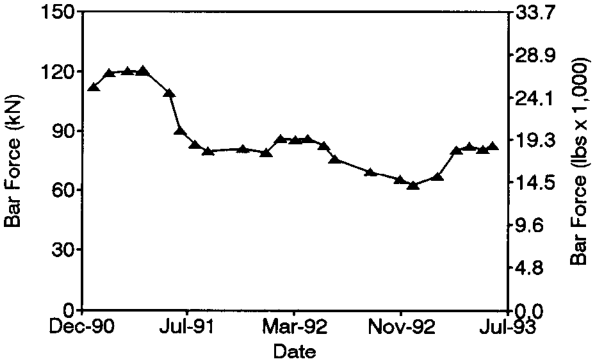


Figure 9–Average trend in bar force for the Petty Creek bridge.

For all the LVL T-beam bridges, the design interlaminar compression of 1.15 MPa (167 lb/in^2) is substantially greater than the 0.69 MPa (100 lb/in^2) commonly used for stress-laminated sawn lumber decks. At this high level, the bar force initially declines due to stress relaxation in the LVL, then stabilizes or increases slightly as the LVL absorbs moisture and expands. Based on the high initial interlaminar compression and initial swelling of the LVL, it is expected that future bar tensioning will not be required for the LVL T-beam bridges.

Load Test Behavior

Load test transverse deflections for the South Canal and Mill Creek bridges are presented in Figures 10 and 11, respectively. The interlaminar compression at the time of the testing was 0.94 MPa (137 lb/in^2) for the South Canal bridge and 1.19 MPa (172 lb/in^2) for the Mill Creek bridge. For both bridges, the deflection plots are similar to the orthotropic plate behavior of stress-laminated deck bridges constructed of sawn lumber (Ritter et al. 1995). At the South Canal bridge, the maximum deflection for load position 1 measured 19 mm (0.75 in.) and occurred under the north wheel line. For load positions 2 and 3, the deflection profiles are approximately symmetrical with maximum deflections of 20 mm (0.78 in.), occurring adjacent to the wheel line at the bridge centerline, and adjacent to the north wheel line, respectively.

At the Mill Creek bridge, the maximum measured deflections for load positions 1 and 2 measured 14 mm (0.56 in.) and occurred at the interior T beam adjacent to the outside wheel line. With both vehicles on the bridge for load position 3, the maximum measured load test deflection of 17 mm (0.69 in.) was adjacent to the interior wheel line in the south lane. For load positions 4 and 5, the maximum deflections measured 15 mm (0.59 in.) and 14 mm (0.56 in.), respectively, and occurred adjacent to the outside wheel line. The maximum deflection for load position 6 was in the same relative position and measured 15 mm (0.59 in.).

Assuming linear elastic behavior, the sum of the Mill Creek bridge deflections for load positions 1 and 2 and load positions 4 and 5 should equal the deflections of load position 3 and load position 6, respectively. Using superposition, comparative plots of these deflections are shown in Figure 12. As shown, the plots are very similar with only minor differences that are generally within the accuracy of the measurements.

Analytical Evaluation

Comparisons of the measured load test results to the analytical deflections are shown in Figures 13 and 14 for the South Canal and Mill Creek bridges, respectively. As shown, the analytical deflections are very similar to those measured. The apparent differences generally result from analytical deflections greater than those measured with maximum differences of 2 to 3 mm (0.08 to 0.12 in.). Given the accuracy of the load test measurements, the plots indicate that the analytical model accurately represents bridge behavior.

Using the same load test analytical parameters and transverse vehicle positions, the maximum deflection for AASHTO HS 20-44 truck loading for the South Canal bridge was 16 mm (0.63 in.) and occurred for load positions 2 and 3 at the same location as the test vehicle maximum deflection. For the Mill Creek bridge, the maximum HS 20-44 deflection was 26 mm (1.02 in.) and occurred in the two T-beams nearest the bridge centerline for load position 3. Represented as a fraction of the bridge span measured center-to-center of bearings, these deflections are approximately L/482 and L/344 for the South Canal and Mill Creek bridges, respectively.

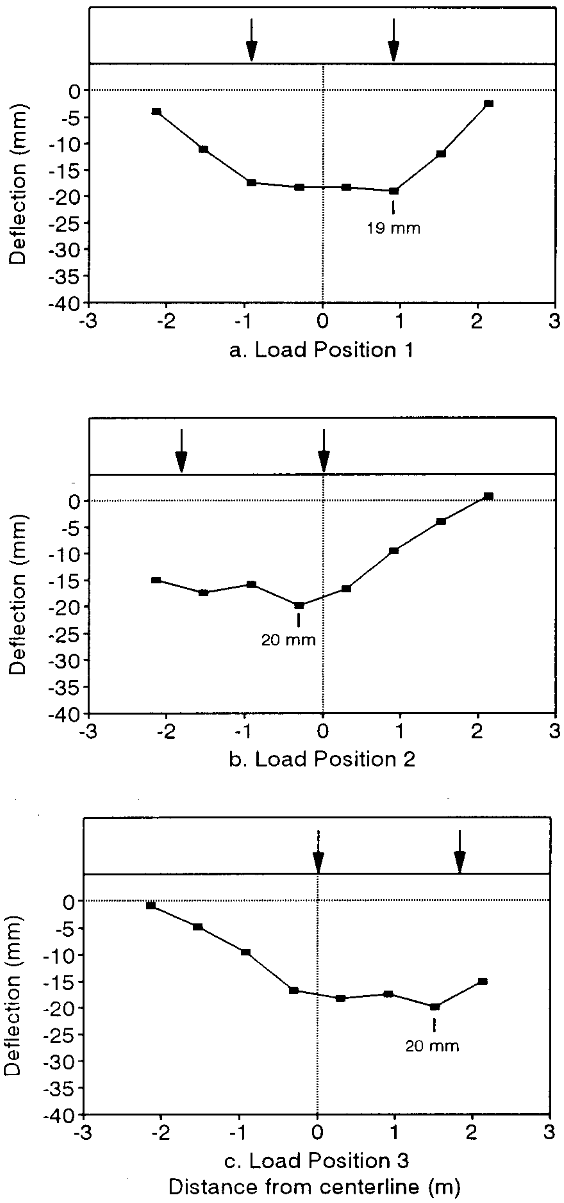
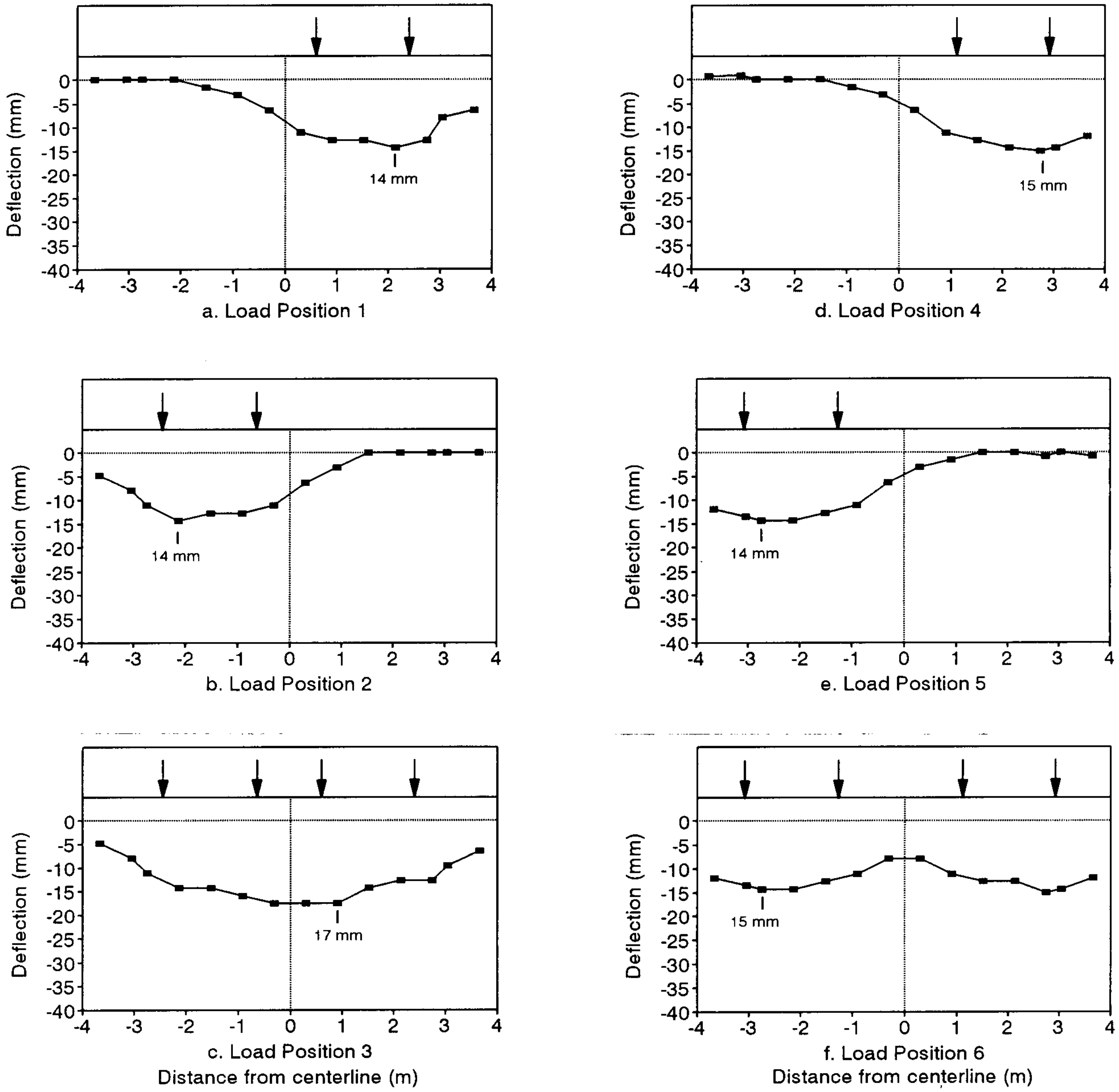


Figure 10–Load test deflection measurements for the South Canal bridge, with the maximum measured deflection noted for each load position (looking west). Truck wheel line positions are noted with arrows.

Condition Assessment

Condition assessments of the LVL T-beam bridges indicated that performance was good, and no significant deficiencies were noted. Inspection of the LVL components showed no signs of deterioration or delamination, and there was no evidence of wood preservative loss or preservative or solvent accumulations on the wood surface. At the Kenally Creek bridge, which was unpaved and did not include the LVL box beams along the edges of the bridge, a slight dimensional distortion was noted in the outside T-beams and the web was raised slightly above the bearing. This was attributed to moisture content changes in the LVL and was not evident in any of the other bridges. For all bridges, the exposed steel stressing bars and hardware showed no visible signs of corrosion or other distress, and there was no indication of the bar anchorage crushing into LVL.



a. Load Position 1

b. Load Position 2

c. Load Position 3

d. Load Position 4

e. Load Position 5

f. Load Position 6

Figure 11 –Load test deflection measurements for the Mill Creek bridge, with the maximum measured deflection noted for each load position (looking east). Truck wheel line positions are noted with arrows.

Concluding Remarks

Field evaluation of six stress-laminated LVL T-beam bridges indicates that structural and serviceability performance is good, and the bridges should provide many years of acceptable service. Based on monitoring results, the following conclusions can be made.

- It is feasible and practical to construct stress-laminated bridges using LVL T-beams.
- The moisture content of the T-beams at installation is typically 9%-12%. After installation, the LVL responds relatively quickly to changes in environmental conditions. The moisture content of one bridge in the monitoring program increased from 12% to 26% during 2.5 years.
- Loss of bar force has not been a problem with stress-laminated LVL T-beams. Swelling of the LVL as the material gains moisture tends to maintain a relatively high bar force, despite the effects of wood stress relaxation.

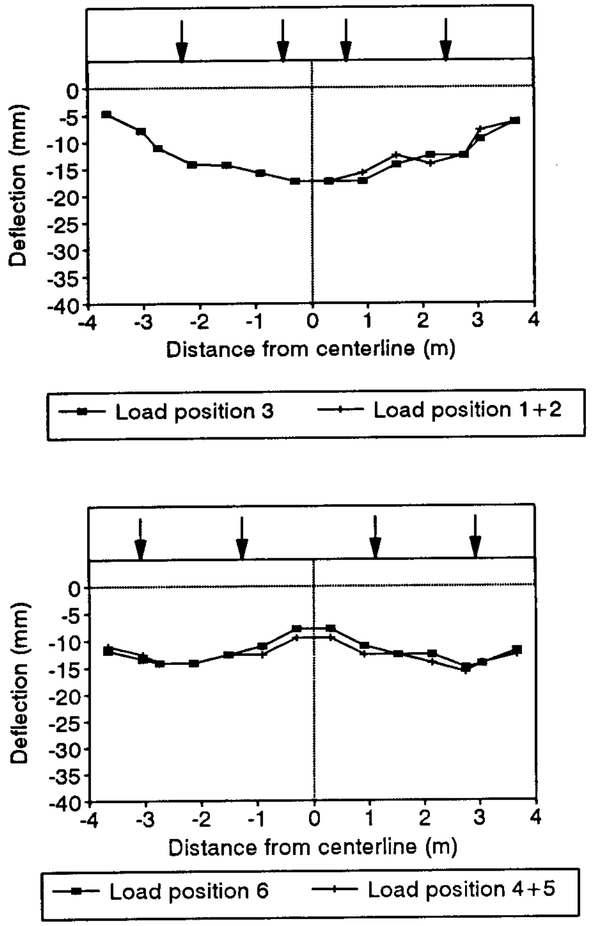


Figure 12–Load position comparisons for the Mill Creek bridge, showing load positions 1 and 2 compared with load position 3 and load positions 4 and 5 compared with load position 6 (looking east).

- Response of the bridges to static truck loading is linear elastic and similar to that for stress-laminated decks constructed of sawn lumber.

- The static load behavior of stress-laminated LVL T-beam bridges can be accurately modeled using a transformed section and orthotropic plate analysis.

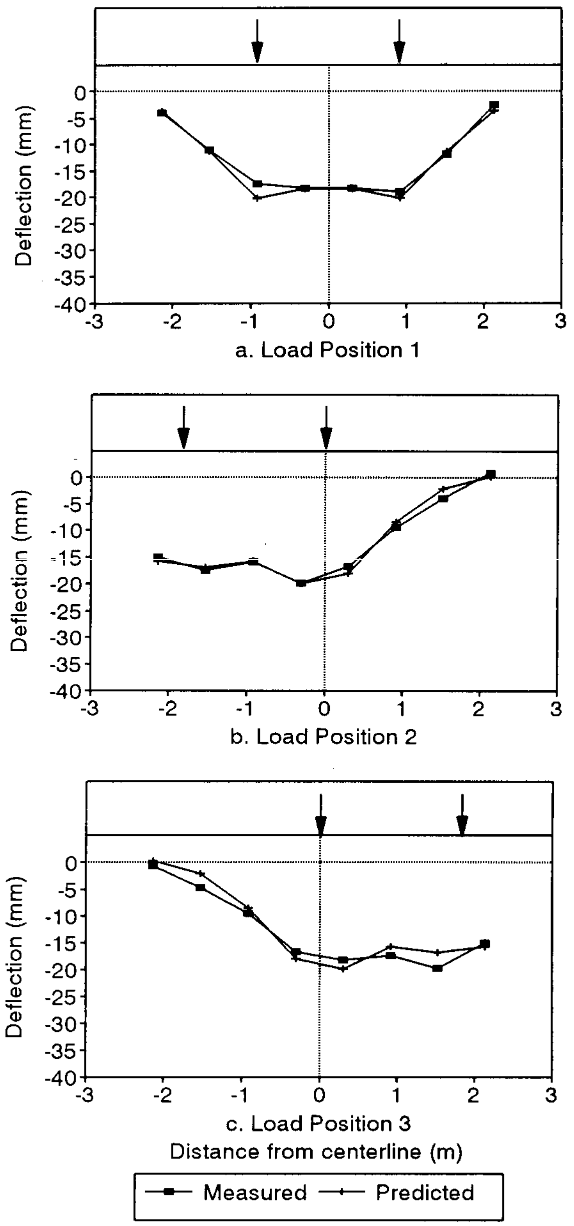
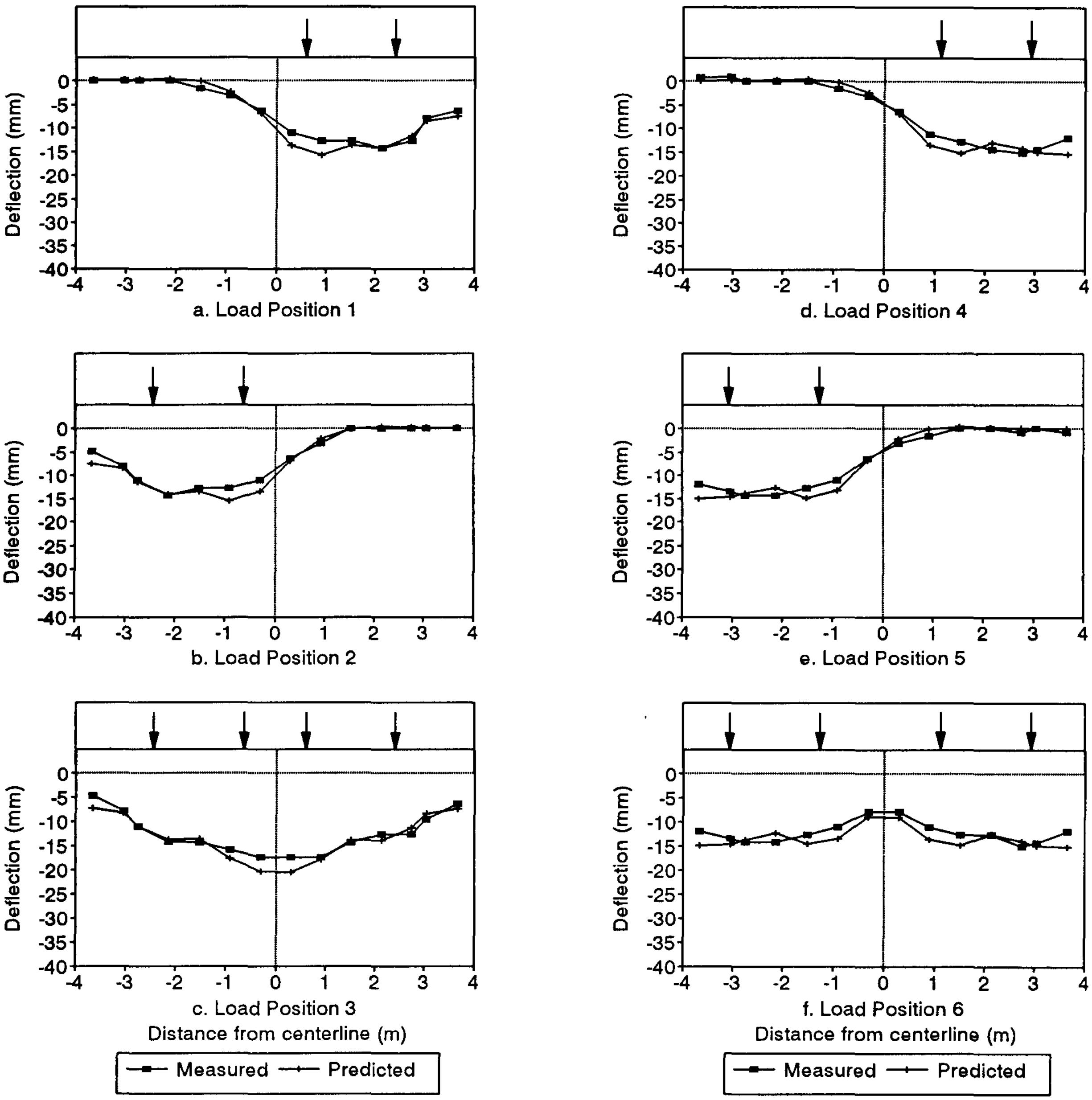


Figure 13–Comparisons of the South Canal bridge measured deflections to the analytical deflections based on orthotropic plate analysis (looking west).



a. Load Position 1

d. Load Position 4

b. Load Position 2

e. Load Position 5

c. Load Position 3

f. Load Position 6

Figure 14—Comparisons of the Mill Creek bridge measured deflections to the analytical deflections based on orthotropic plate analysis (looking east).

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