Design, Construction, and Evaluation of Timber Bridge Constructed of Cottonwood Lumber

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The Cooper Creek bridge was constructed February 1992 in the city of Centerville, Iowa. The bridge is a two-span continuous stress-laminated deck structure with a length of 12.8 m and a width of approximately 8.1 m. The bridge is unique in that it is one of the first known stress-laminated timber bridge applications to use eastern cottonwood lumber. The performance of the bridge was monitored continuously for 28 months beginning at the time of installation. Performance monitoring involved gathering and evaluating data relative to the moisture content of the wood deck, the force level of stressing bars, the deck vertical creep, and the behavior of the bridge under static load conditions. In addition, comprehensive visual inspections were conducted to assess the overall condition of the structure. On the basis of field evaluations, the bridge is performing well with no structural or serviceability deficiencies.

In 1988, the U.S. Congress passed legislation known as the Timber Bridge Initiative (TBI). The objective of this legislation was to establish a national program to provide effective and efficient utilization of wood as a structural material for highway bridges. Responsibility for the development, implementation, and administration of the timber bridge program was assigned to the U.S. Department of Agriculture (USDA) Forest Service. Within the program, the Forest Service established three primary program areas: demonstration bridges, technology transfer, and research. The demonstration bridge program, which is administered by the Forest Service Timber Bridge Information Resource Center (TBIRC) in Morgantown, West Virginia, provides matching funds on a competitive basis to local governments to demonstrate timber bridge technology through the construction of demonstration bridges (*1*). TBIRC also maintains a technology transfer program to provide assistance and state-of-the-art information about timber bridges. One objective of these program areas is to encourage innovation through the use of new or previously underutilized wood products, bridge designs, and design applications.

As the national wood utilization research laboratory within the USDA Forest Service, the Forest Products Laboratory (FPL) was assigned responsibility for the research portion of the TBI program. As a part of this broad research program, FPL has taken a lead role in assisting local governments in evaluating the field per-

formance of timber bridges, many of which employ design innovations or materials that have not been previously evaluated. Through such assistance, FPL is able to collect, analyze, and distribute information on the field performance of timber bridges to provide a basis for validating or revising design criteria and further improving efficiency and economy in bridge design, fabrication, and construction.

This paper describes the development, design, construction, and field performance of the Cooper Creek bridge located in Appanoose County, Iowa. The bridge is a two-lane, two-span continuous stress-laminated deck with a length of 12.8 m. Built in 1992, the Cooper Creek bridge was constructed entirely with local funds on the basis of technical assistance provided through the Forest Service TBI program. The bridge is unique in that it is one of the first known applications that utilizes Eastern Cottonwood lumber in a stress-laminated deck superstructure.

Objective and Scope

The objective of this project was to design, construct, and evaluate the field performance of the Cooper Creek bridge over a minimum 2-year period beginning at bridge installation. The project scope included data collection and analysis related to the modulus of elasticity (MOE) of bridge laminations, wood moisture content, stressing bar force, vertical deck creep, bridge behavior under static truck loading, and general structure performance. The results of this project will be used to formulate recommendations for the design and construction of similar stress-laminated cottonwood bridges in the future.

Background and Development

The Cooper Creek bridge site is located in Centerville, Iowa, in Appanoose County. The bridge is on West Cottage Street, which serves as the primary access road to a large community park surrounding the Centerville reservoir. The bridge crosses Cooper Creek, which carries daily flow from the backwashing of city water supply filters and occasional overflow from the nearby reservoir dam. The approach roadway is a two-lane gravel road. Traffic is mostly light passenger vehicles with an estimated average daily traffic of 200 vehicles per day.

The Cooper Creek bridge was originally constructed in the 1940s and consisted of steel stringers with a concrete deck supported by concrete abutments. Inspection of the bridge in the mid-1980s indicated that the concrete deck was in poor condition and the steel stringers were badly corroded. Replacement of the bridge, along with another bridge in the reservoir area, was subsequently included within a large waterworks project at the Centerville reservoir. This project was made possible through a grant from the Chariton Valley Resource Conservation and Development (RCD) council to the state of Iowa and was initiated to improve the city water supply system. In the initial stages of the project, both bridges were scheduled to be constructed using reinforced concrete. However, information obtained through the TBIRC prompted the Chariton Valley RCD to change the Cooper Creek bridge to a timber structure using the relatively new stress-laminated deck design concept. A timber bridge was considered the best option by RCD because there was an opportunity to use native Iowa materials and the aesthetics of a timber bridge would blend well into the natural park setting.

As the waterworks project progressed at the Centerville reservoir, difficulties were encountered in the design of the Cooper Creek bridge. Because the concept of stress-laminating timber bridges was new in the United States, little information was available on design criteria and construction specifications. To provide assistance in this area, FPL was contacted for technical advice. Through a series of meetings with state, local, and FPL representatives, options were discussed, and it was determined that a stress-laminated deck bridge constructed of Iowa eastern cottonwood lumber was feasible for the site. Subsequent to these meetings, an agreement was drafted for the design, construction, and field evaluation of the Cooper Creek bridge involving a cooperative effort between the City of Centerville, Chariton Valley RCD, Iowa Department of Transportation, Forestry Division of the Iowa Department of Natural Resources, Iowa Department of Economic Development, TBIRC, and FPL.

Design, Construction, and Economics

The design and construction aspects of the Cooper Creek bridge involved a mutual effort between the City of Centerville, Appanoose County Engineering, which served as the engineering representative for the City of Centerville, and FPL. Construction assistance was also provided by the Centerville Municipal Waterworks. An overview of the design and construction process, as well as cost information for the bridge superstructure, are presented in this section.

Bridge Design

Design of the Cooper Creek bridge superstructure was completed by FPL in collaboration with Appanoose County Engineering. At the time of the design, early

1990, national design specifications for stress-laminated timber bridges did not exist. Those aspects of the design dealing specifically with stress laminating were based primarily on research completed by the University of Wisconsin and FPL (*2,3*). Additionally, FPL experience with stress-laminated decks from an ongoing field evaluation program contributed to the design details. All other aspects of the superstructure design were based on AASHTO's Standard Specifications for Highway Bridges (*4*).

Design requirements for the Cooper Creek bridge called for a crossing of 12.8 m with an out-to-out bridge width of 7.9 m. The bridge was to carry two lanes of AASHTO HS 20–44 loading with a maximum design live-load deflection of 1/360 of the bridge span. In addition to these geometry and loading requirements, several other design requirements were related to the eastern cottonwood lumber laminations. Because of limitations on local supply and fabrication, lamination length was limited to 5.5 m. It was also considered economically advantageous to limit the deck depth to a maximum of 305 mm, although a maximum deck thickness of 356 mm was feasible on the basis of lumber availability.

The first step in the design process was to identify material design values for the Eastern Cottonwood lumber laminations. Because Eastern Cottonwood was not commonly used for structural applications, design values were not included in AASHTO and referenced design values in the National Design Specification for Wood Construction (NDS) (*5*) were limited to material 51 to 102 mm thick and 51 to 102 mm wide. Because the bridge laminations would be greater than 102 mm wide, the NDS values were not entirely applicable to the bridge design. Further examination indicated that the NDS also included design values for Black Cottonwood in widths greater than 102 mm. Subsequent review by FPL of the green, clear wood material properties for the two similar species indicated that modulus of rupture and MOE properties for eastern cottonwood were greater than those for Black cottonwood (ASTM D2555–88). Thus, the decision was made to use the NDS tabulated design values for bending strength and MOE based on black cottonwood, which would result in a slightly conservative design. The design value for compression perpendicular to grain was based on tabulated values for eastern cottonwood, which is independent of member size. The results were tabulated bending design values for visually graded lumber of 5.2 and 4.5 MPa for material graded Numbers 1 and 2, respectively, and MOE values of 8,268 and 7,579 MPa for the same grades. The tabulated value for compression perpendicular to grain was 2.2 MPa for all grades.

Given the required bridge length and limitations on material size, a two-span continuous structure with equal span lengths was selected for the final design (Figure 1). The layout of the bridge laminations was based on available lamination lengths of 1.2 to 5.5 m in 0.6-m increments. To meet span requirements for the continuous deck, a transverse butt joint frequency of one joint every four laminations with a 1.2-m-longitudinal spacing between joints in adjacent laminations was used (*3*). As with most stress-laminated timber bridge decks, it was anticipated that bridge stiffness rather than strength would control the design. After adjusting tabulated design values for wet-use conditions and other applicable modification factors required by AASHTO, it was determined that a full-sawn deck 305 mm thick would meet design requirements if visually graded Number 1 lumber was used. Using this configuration, the calculated design live-load deflection for HS 20–44 loading was 13 mm, or 1/473 of the bridge span. A check of bending stress indicated that the applied stress of 6.4 MPa was less than the allowable of 6.7 MPa.

The stressing system for the Cooper Creek bridge was designed to provide a uniform compressive stress of 0.69 MPa between the lumber laminations. To provide this interlaminar compression, high-strength stressing bars 16 mm in diameter were spaced 610 mm on-center, beginning 305 mm from the bridge ends. The tensile force required in the bars for the 0.69-MPa interlaminar compression was determined to be 128 kN. The bars were specified to comply with the requirements of ASTM A722–86 and provide a minimum ultimate tensile strength of 1 034 MPa. The bar anchorage system was the discrete plate anchorage system consisting of steel bearing plates 254 by 254 by 19 mm with steel anchorage plates 51 by 127 by 25 mm. To provide additional strength in distributing the stressing bar force into the deck without damaging the eastern cottonwood laminations, it was determined that the two outside laminations along the deck edge would be northern red oak sawn lumber.

Following initial deck design, the bridge railing was designed and specifications were summarized. The bridge railing design was a sawn lumber curb and glued laminated timber rail that was based on a crash-tested rail system developed by FHWA (*6*). Specifications for wood members required that all components be pressure treated after fabrication with creosote in accordance with American Wood Preservers' Association Standard C14. To provide protection from deterioration, all steel components including hardware, stressing bars, and anchorage plates were galvanized per AASHTO specifications (*7*).

Construction

Construction of the Cooper Creek bridge was completed by personnel from the city of Centerville, Ap-

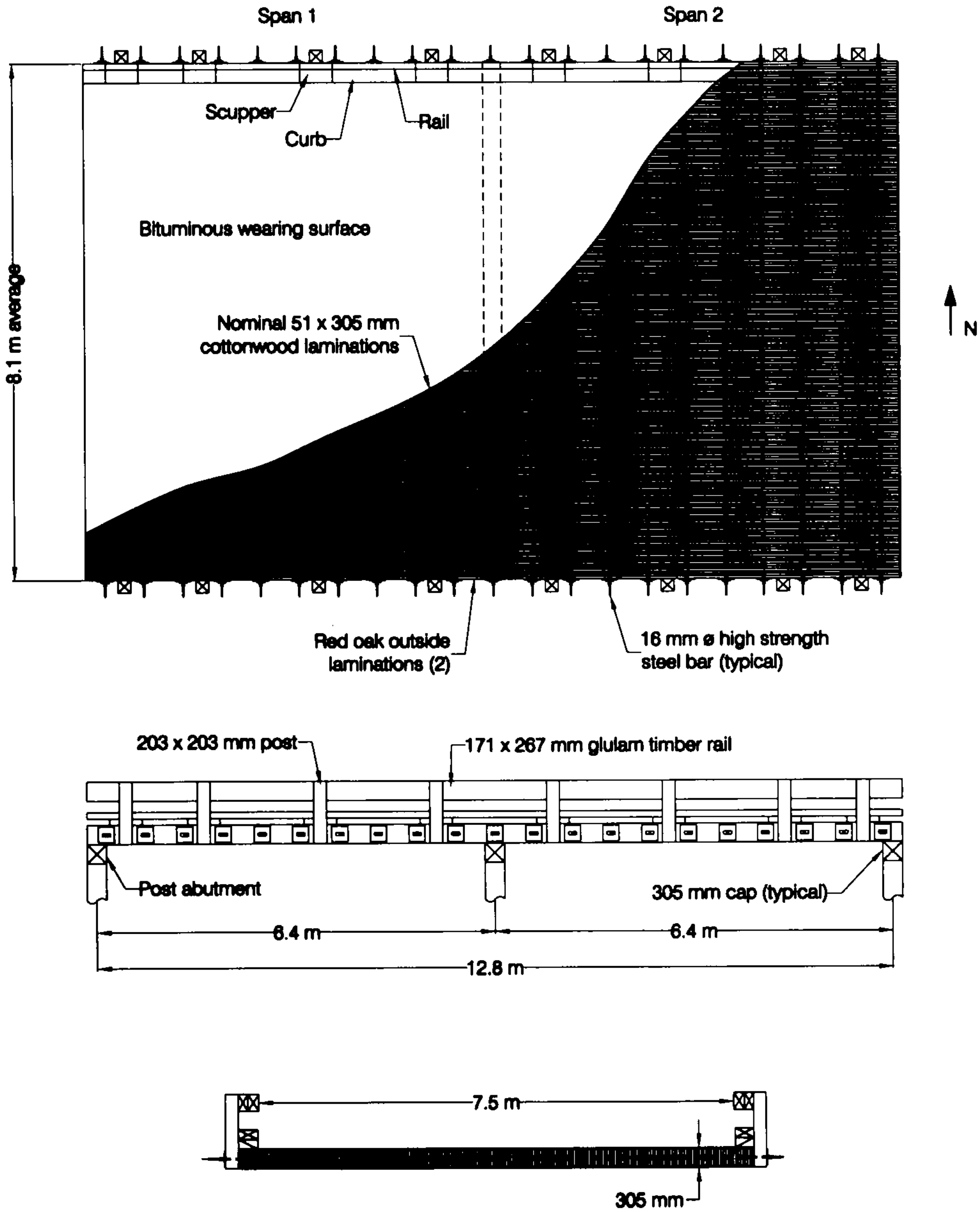

FIGURE 1 Design configuration of Cooper Creek bridge.

panoose County Engineering, the Centerville Municipal Waterworks, and FPL. After the work on the approach roadway, and the design and construction of the sawn lumber post and sill abutments and center bent by Appanoose County Engineering was completed, construction of the bridge superstructure commenced on February 25 and was completed on February 28. The construction process was slowed by rain and cold temperatures, which made work conditions difficult but did not adversely affect the construction process. Construction of the bridge railing and backfill of the approach roadways was completed shortly after the superstructure construction.

Superstructure construction began with delivery of the bridge laminations and other materials to the bridge site. The bridge laminations arrived in banded bundles and were stacked approximately 60 m from the substructure. The laminations had been prefabricated at a local mill in Centerville and were sent to a pressure-treating facility in Nebraska for the creosote treatment. Inspection of the laminations at the site indicated that the material had not been surface planed to a uniform thickness and measurements of lamination ends indicated a range in thickness of 45 to 60 mm. This presented a potential problem for construction at the deck butt joints where uniform contact is required between

laminations for load transfer. To account for this variation, the end thickness of each lamination was measured and written in chalk on the lamination end. The order of lamination placement was then scheduled so that the end thickness of the two laminations at a butt joint was the same. Laminations with odd thicknesses that could not be matched, which were generally 55 mm and thicker, were positioned over the abutments.

The construction of the Cooper Creek bridge involved a unique construction methodology that had not been widely used in the past. Rather than prefabricating the deck in sections, which is common practice for stress-laminated decks with butt joints, scaffolding was erected between the substructures, and laminations were individually placed on the scaffolding supports. This methodology was considered to be the most cost-effective because of the unavailability of a large crane to lift prefabricated bridge sections into place. The scaffolding consisted of a full floor under the deck that was supported by temporary stringers between the bridge abutments and center bent. The elevation of the floor was approximately 1.5 m below the cap elevations of the abutments and bent. Lumber supports were erected on the floor to support the laminations in their final positions as they were placed. Construction access to the scaffolding was provided by plywood ramps that were constructed between the scaffolding floor and the ground.

The deck construction process began by placing approximately 305-mm width of laminations along the south bridge edge (Figure 2*a*). The laminations were nailed together, and wood dowels were inserted into the bar holes to maintain the relative lamination alignment. Stressing bars were then inserted through the bar holes approximately 2.5 m toward the bridge centerline (Figure 2*b*). The bar overhang away from the bridge was supported by a wood frame to prevent excessive bending and damage to the bars (Figure 2*c*). After approximately 2 m of deck width was erected, the bars were pulled through the laminations so that they extended across the bridge width. Bridge construction progressed by sequentially adding laminations. This involved placing the bars through lamination holes and sliding the laminations along the temporary construction supports to the completed deck section (Figure 2*d*). Laminations were sequentially added in this manner until the bridge width was completed and ready for bar tensioning (Figure 2*e* and *f*).

Initial stressing of the bridge occurred immediately after all laminations were in position and steel plates and nuts were placed on stressing bar ends. Bar tensioning was accomplished with a single hydraulic jacking system consisting of a hydraulic pump, a hollow core jack, and a stressing chair (*8*). The stressing operation involved tensioning the first bar at an abutment, then sequentially tensioning all other bars along the bridge length. However, before beginning the stressing, visual inspection of the deck indicated that there were gaps between the laminations at several locations caused by warp in the laminations. To minimize deck distortion across the bridge width during stressing, it was determined that the bar force should be applied gradually over several passes. During the construction process, a total of six passes were completed. The first pass tensioned bars to 25 percent of the design level and was intended to bring all laminations into direct contact. The second pass brought bar force to 50 percent of design. The remaining four passes were at the full design level and were required to bring all bars to a uniform tension. Between the first and final stressing, the deck width narrowed approximately 25 mm as a result of the compression introduced between the laminations.

After the initial stressing, the bridge was restressed several times and the timber railing and asphalt wearing surface were placed. The bridge stressing followed an accelerated procedure, which has not been widely used for other bridges. It is general practice in stress-laminated deck construction to stress the bridge three times: at the time of initial construction, 1 week later, and 6 to 8 weeks after the second stressing (*3*). The Cooper Creek bridge was stressed four times: at construction and at 4, 7, and 14 days after construction. This accelerated procedure was completed because of limitations on equipment availability and provided an opportunity to evaluate bar force loss using an alternative stressing sequence. After the final stressing, the timber curb and rail system were installed. Placement of the asphalt wearing surface occurred approximately 4 months later in early July 1992. The completed bridge is shown in Figure 3.

Cost

Costs for the fabrication and construction of the Cooper Creek bridge superstructure, railing, and asphalt wearing surface totaled $34,200. On the basis of an average deck area of 104 m^2, the cost per square meter was approximately $329.

Evaluation Methodology

Through mutual agreement with the cooperating parties, a bridge monitoring plan for the Cooper Creek bridge was developed and implemented by FPL. The plan included stiffness testing of the lumber bridge laminations before bridge construction and performance monitoring after construction of the deck moisture con-

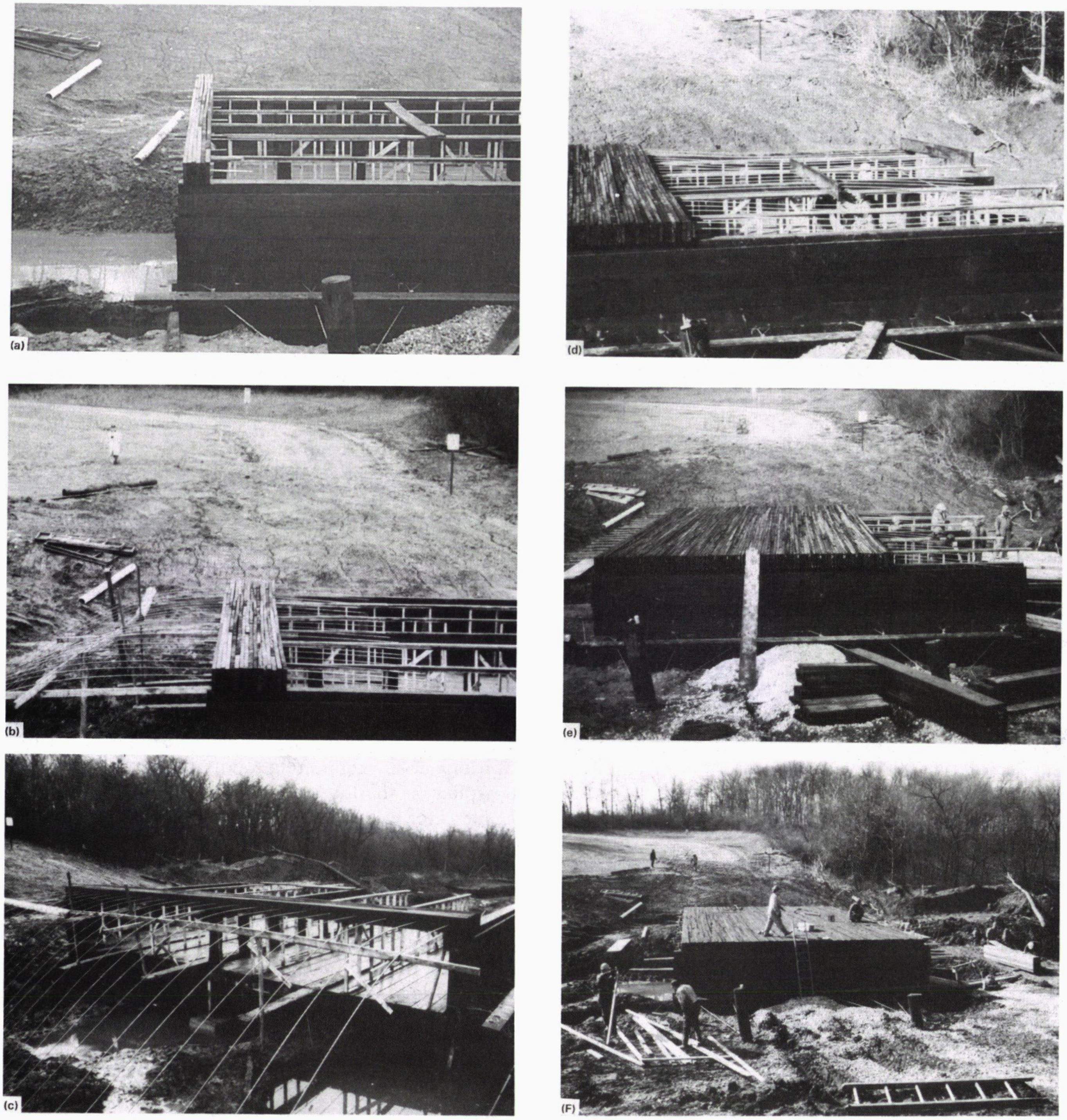

FIGURE 2 Construction sequence for Cooper Creek bridge: (*a*) placement of laminations along south bridge edge; (*b*) insertion of stressing bars; (*c*) support of bar overhang by wood frame; (*d*) sequential addition of laminations; (*e, f*) completed bridge width ready for bar tensioning.

FIGURE 3 Completed Cooper Creek bridge (two views).

tent, stressing bar force, vertical bridge creep, static load test behavior, and general bridge condition. The evaluation methodology used procedures and equipment previously developed and used by FPL on similar structures (*8,9*).

Lamination MOE

At the time of the Cooper Creek bridge design, eastern cottonwood lumber was not widely used for structural applications, and verification of the assumed design MOE was considered necessary. To measure actual lamination MOE values, portable equipment was taken to the bridge site and a group of laminations were tested just before bridge construction using the transverse vibration method (*10*). Using this method, laminations are placed flatwise on instrumented supports and impacted to induce a transverse vibration. On the basis of the vibratory response, the natural frequency of the lamination is measured and converted to MOE. For the Cooper Creek bridge, a total of 50 laminations were tested using this method, 10 each in lengths of 2.4, 3, 3.7, 4.3, and 4.9 m.

Moisture Content

The moisture content of the Cooper Creek bridge was measured using an electrical-resistance moisture meter with 76-mm probe pins in accordance with ASTM D4444-84. Measurements were obtained by driving the pins into the deck underside at depths of 25 to 76 mm, recording the moisture content value from the unit, then adjusting the values for temperature and wood species. Moisture content measurements were taken at the time of bridge installation, approximately 6 months after installation, and at the end of the monitoring period. In addition to the electrical resistance readings, core samples were removed from the bridge deck at the conclusion of the monitoring period to determine moisture content by the oven-dry method in accordance with ASTM D4442-84.

Bar Force

To monitor bar force, four calibrated load cells were installed on the Cooper Creek bridge when the bridge was constructed. Two load cells were placed on each span on the third and seventh stressing bars from each abutment. Load cell measurements were obtained by local personnel by connecting a portable strain indicator to a plug on the load cell. Strain measurements from the indicator were then converted to force levels, on the basis of the laboratory calibration, to determine the tensile force in the bar. Measurements were taken on approximately a bimonthly basis during the monitoring period. 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.

Vertical Creep

Vertical creep of the bridge was measured at the beginning and the end of the monitoring period. Vertical measurements were recorded to the nearest 3 mm by reading the centerspan elevations along deck edges relative to a stringline between supports.

Load Test Behavior

Static load testing of the Cooper Creek bridge was conducted at the end of the monitoring period to determine

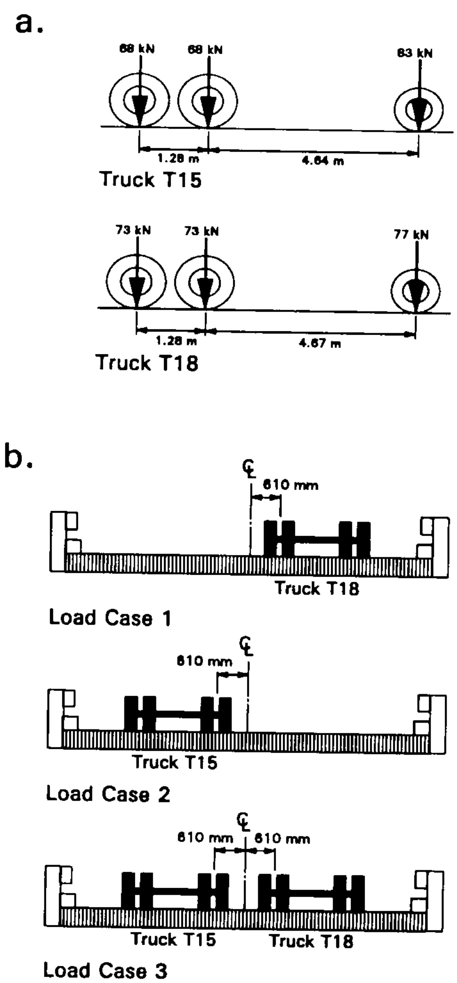

FIGURE 4 **(*a*) Load test truck configurations and axle loads (the transverse vehicle track width, measured center to center of the rear tires, was 1.83 m); (*b*) transverse load positions (looking west). For all load cases, the two rear axles were centered over the bridge centerspan with front axles off the span.**

the response of the bridge to full truck loading. In addition, an analytical assessment was completed to determine the predicted bridge response using computer modeling and current design recommendations.

Load Testing

Load testing involving positioning fully loaded trucks on the bridge spans and measuring the resulting deflections at a series of locations along the centerspan and abutments. Measurements of each span from an unloaded to loaded condition were obtained by placing calibrated rules at data points on the deck underside and reading values with a surveyor's level to the nearest 0.5 mm. Measurements were taken prior to testing (unloaded), for each load case (loaded), and at the conclusion of testing (unloaded).

Two trucks were used for load testing: Truck T15 with a gross vehicle weight of 219 kN and Truck T18 with a gross vehicle weight of 223 kN (Figure 4*a*). Each of the two spans was tested separately using designated positions in the longitudinal and transverse directions to produce the maximum live-load deflection in accordance with AASHTO recommendations (*4*). Longitudinally, the trucks were positioned with the rear axles at centerspan and the front axles off the span. On Span 1 (west span), the trucks were facing west; on Span 2 (east span), the trucks were facing east. Transversely, the trucks were positioned for three different load cases (Figure 4*b*). For Load Case 1, Truck T18 was positioned in the north lane with the center of the inside wheel line 610 mm from the bridge centerline. For Load Case 2, Truck T15 was positioned in the south lane with the center of the inside wheel line 610 mm from the bridge centerline. Load Case 3 consisted of positioning both trucks on the span in the positions used for Load Cases 1 and 2.

Analytical Assessment

At the conclusion of load testing, the bridge behavior was modeled for load test conditions and AASHTO HS 20–44 loading using an orthotropic plate computer program developed at FPL. In addition, the HS 20–44 predicted deflection was computed using the recommended design method given by the AASHTO Guide Specification for the Design of Stress-Laminated Wood Decks (*11*).

Condition Assessment

The general condition of the Cooper Creek bridge was assessed on five different occasions during the monitoring period. The first assessment occurred at the time of installation. The second through fourth assessments took place during intermediate site visits. The final assessment occurred during the final load test at the conclusion of the monitoring period. These assessments involved visual inspections, measurements, and photo documentation of the bridge condition. Items of specific interest included the bridge geometry and the condition of the timber deck and rail system, asphalt wearing surface, and stressing bar and anchorage system.

Results and Discussion

The performance monitoring of the Cooper Creek bridge extended for 28 months from February 1992

through May 1994. Results and discussion of the performance data follow.

Lamination MOE

Results of individual lamination MOE testing provided a mean flatwise MOE for the eastern cottonwood lumber of 9,299 MPa. The flatwise MOE was converted to an edgewise value by applying a flatwise adjustment factor of 0.965 (*12*). This resulted in an average edgewise MOE of 8,878 MPa. After adjustment for wet-use conditions (moisture content greater than 19 percent), the design-tabulated MOE of 8,268 MPa resulted in an allowable design value of 8,020 MPa. Thus, the actual material MOE exceeded by approximately 11 percent the assumed design value for black cottonwood lumber.

Since completion of the Cooper Creek bridge design, the NDS was revised in 1991 to include tabulated design values for the cottonwood species group, which includes eastern cottonwood (*13*). For visually graded Number 1 material, the revised design MOE for wet-use conditions is 7,441 MPa. The actual material MOE measured for the Cooper Creek bridge exceeds this value by approximately 19 percent.

Moisture Content

Electrical resistance moisture content readings taken at the beginning of the monitoring period indicated an average 25 percent in the outer 25 mm of the deck underside. At the conclusion of the monitoring period, there was a decrease in the average electrical resistance moisture content at the same locations to 22 percent. Moisture content measurements obtained at the end of the monitoring period based on coring and the ovendry method indicated a relatively uniform average moisture content of 26 percent for the inner 51 through 178 mm of the deck underside. It is expected that the outer portions of the laminations will continue to lose moisture toward an equilibrium level but will undergo seasonal fluctuations as a result of climatic variations. The inner portions of the laminations, which remain at a relatively high moisture content, will change more slowly. On the basis of the open exposure of the site and regional climatic conditions, it is estimated that the eventual equilibrium moisture content of the deck will be 16 to 18 percent.

Bar Force

The average trend in bar tension force measured from the load cells indicated that the first three bar stressings ranged from 10 to 15 percent below the design level. The final stressing was approximately 6 percent below the design level at 120 kN (0.65 MPa interlaminar compression). After the final stressing, the bar force decreased rapidly during the first 100 days to 75 kN (0.40 MPa interlaminar compression), which is 58 percent of the design level. During the remainder of the monitoring period, bar force gradually decreased to 60 kN (0.32-MPa interlaminar compression), which is approximately 46 percent of the design level.

The loss in bar force for the Cooper Creek bridge is likely the result of stress relaxation in the wood laminations as a result of the applied compressive force. The slight decrease in average lamination moisture content also contributed to wood shrinkage and a minor loss in bar force. Although the bar force decreased approximately 50 percent during the monitoring period, it did not drop below acceptable levels. However, it was probable that the gradual decrease would continue; therefore, the bridge was restressed at the conclusion of the monitoring period.

The bar force retention for this bridge is similar to or better than that compared with numerous other bridges in the FPL monitoring program (*14*). Thus, it does not appear from the data that the accelerated stressing sequence significantly affected bar force retention. However, a conclusion in this area cannot be justified until additional research is completed on other structures.

Vertical Creep

The laminations of the Cooper Creek bridge were approximately straight between supports after construction. At the conclusion of the monitoring period, the laminations remained in approximately the same position, and there was no measurable sag in the spans.

Load Test Behavior

Results of the static-load test and analytical assessment of the Cooper Creek bridge are presented here. For each load case, transverse deflection measurements are given at the bridge centerspan as viewed from the east end (looking west). No permanent residual deformation was measured at the conclusion of the load testing, and there was no detectable movement at bridge supports. At the time of the tests, the average bridge prestress was approximately 0.32 MPa, which is relatively close to the minimum recommended long-term prestress of 0.28 MPa (*3*).

Load Testing

Transverse deflection plots for Spans 1 and 2 are shown in Figure 5. For Span 1, Load Case 1 resulted in a maximum deflection of 7 mm under the outside wheel line nearest the north deck edge (Figure 5*a*). The maximum deflection of 7 mm for Load Case 2 was measured under the outside wheel line nearest the south deck edge (Figure 5*b*). For Load Case 3, the maximum deflection of 9 mm occurred under the inside wheel line of Truck T18, 610 mm from the span centerline (Figure 5*c*). As could be expected for the same loading on similar spans, the results for Span 2 were similar to those for Span 1. Load Case 1 resulted in a maximum deflection of 7 mm under the outside wheel line nearest the north deck edge (Figure 5*d*). The maximum deflection of 7 mm for Load Case 2 occurred under the outside wheel line nearest the south deck edge (Figure 5*e*). For Load Case 3, the maximum deflection of 9 mm occurred under the inside wheel line of Truck T18, 610 mm from the span centerline (Figure 5*f*).

Analytical Assessment

Results of the actual versus predicted bridge response based on orthotropic plate analysis for Load Case 3 are shown in Figure 6*a*. As seen from the figure, the predicted response is close to the actual response with minor variations at the bridge edges. This was expected because the model included no provisions for edge stiffening, but the actual bridge edges were stiffened with a curb and rail system. Further orthotropic plate analysis assuming two lanes of AASHTO HS 20-44 loading resulted in a maximum predicted live-load deflection of 10 mm at the span centerline (Figure 6*b*). This deflection is equivalent to 1/630 of the span length measured center-to-center of bearings. Deflection computed using AASHTO recommended design procedures was 13 mm or approximately 1/490 of the bridge span.

Condition Assessment

Condition assessments of the Cooper Creek bridge indicated that structural and serviceability performance was good. Inspection results for specific items follow.

Deck Geometry

Measurements of the bridge width at numerous locations indicated that the bridge was approximately 200 mm narrower over the center bent than at the abutments. This is most likely attributable to the lamination layout for consistent thickness at butt joints, which resulted in the placement of the thickest odd-size laminations over the abutments.

Wood Condition

Inspection of the wood components of the bridge showed no signs of deterioration, although minor checking was evident on rail members exposed to wet-dry cycles. In several locations on the curb and railing, bolt heads were slightly crushed into the wood. The crushing did not damage the preservative envelope and was likely caused by bolt overtightening at construction. For all wood components, there was no evidence of wood preservative loss, and preservative or solvent accumulations were not present on the wood surface.

Wearing Surface

The asphalt wearing surface remained in good condition with no cracking or other deterioration. A substantial amount of gravel and other debris was present on the surface from the unpaved road, which could potentially lead to premature deterioration of the surface.

Stressing System

The stressing bar anchorage system performed as designed with no significant signs of distress. There was no indication of crushing of the discrete plate anchorage into the outside oak laminations and no measurable distortion in the bearing plate. The exposed steel stressing bars, hardware, and anchorage plates showed no visible signs of corrosion or other deterioration.

Observations and Recommendations

After 28 months in service, the Cooper Creek bridge is performing well and should provide many years of acceptable service. On the basis of extensive bridge monitoring conducted during that period, the following observations and recommendations were made:

1. It is both feasible and practical to design and construct stress-laminated timber decks with eastern cottonwood lumber.
2. The measured flatwise MOE of the eastern cottonwood laminations resulted in an average edgewise value of 8 878 MPa. This is approximately 19 percent greater than the wet-use value currently specified in the NDS.
3. Stress-laminated decks can be constructed in place using temporary scaffolding for lamination support before bridge stressing. This method of construction is labor intensive but can be a viable option when large equipment required for prefabricated bridge placement is not available.
4. The use of red oak for outside edge laminations enhanced the performance of the discrete plate stressing

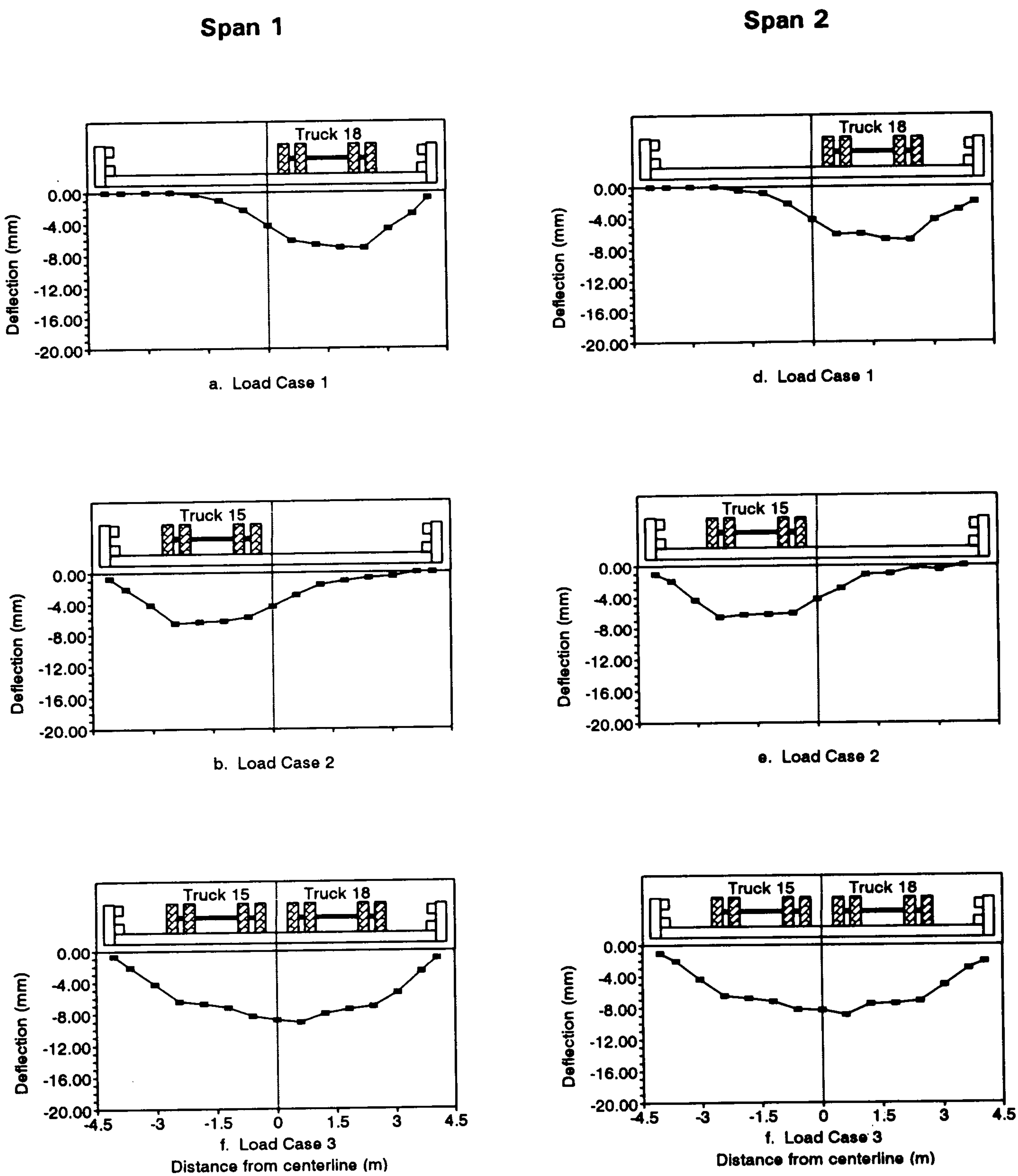

FIGURE 5 Transverse deflection plots for the Cooper Creek load test, measured at the bridge centerspan (looking west). Bridge cross sections and vehicle positions are shown to aid interpretation and are not to scale.

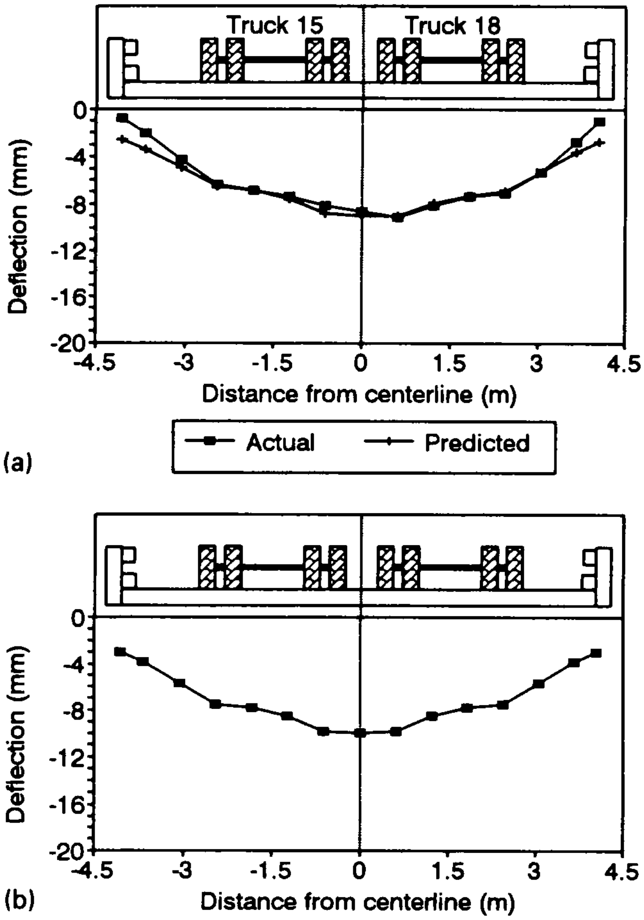

FIGURE 6 (*a*) **Comparison of the actual measured deflections for Load Case 3, Span 1, compared with the predicted deflection using orthotropic plate analysis;** (*b*) **predicted deflection profile at the bridge centerspan for two HS 20–44 trucks, each positioned 610 mm on either side of the bridge longitudinal centerline. Both plots are shown looking west.**

bar anchorage system. The oak provided sufficient strength to adequately distribute the bar force into the deck without wood crushing or anchor plate deformation.

5. The average trend in deck moisture content in the lower 25 mm of the laminations indicates that moisture content changes are occurring slowly, with an average 3 percent decrease during the monitoring period. The average moisture content in the inner 51 to 178 mm of the deck underside is 26 percent, which is expected to slowly decrease as time passes.

6. Stressing bar force decreased approximately 50 percent during the monitoring but remained within acceptable limits. The decrease is primarily attributable to transverse stress relaxation in the wood laminations. The bar force should be checked biannually and restressed as necessary until it reaches a constant level.

7. Creep measurements of the bridge deck indicate that there has been no detectable vertical displacement during the monitoring. The deck remains approximately straight between supports.

8. Load testing and analysis indicates that the Cooper Creek bridge is performing as a linear elastic orthotropic plate when subjected to truck loading. The maximum deflection of two lanes of AASHTO HS 20–44 loading is estimated to be 10 mm, which is approximately 1/630 of the span length measured center-to-center of bearings.

9. Wood checking is evident in the exposed end grain of bridge rail posts and other components. It is likely this would not have occurred if a sealer or cover had been placed over end grain at the time of construction.

10. There are no indications of corrosion on the stressing bars, hardware, or plates.

REFERENCES

1. *The Timber Bridge Initiative.* Fiscal Year 1991 Status Report. USDA Forest Service, State and Private Forestry, Northeastern Area, Radnor, Pa. 1991.
2. Oliva, M. G., A. G. Dimakis, M. A. Ritter, and R. L. Tuomi. *Stress-Laminated Wood Bridge Decks: Experimental and Analytical Evaluations.* Research Paper FPL-RP-495. USDA Forest Service, Forest Products Laboratory, Madison, Wisc., 1990.
3. Ritter, M. A. *Timber Bridges: Design, Construction, Inspection and Maintenance.* EM 7700-8. USDA Forest Service, 1990.
4. *Standard Specifications for Highway Bridges,* 14th ed. AASHTO, Washington, D.C., 1989.
5. *Design Values for Wood Construction.* A Supplement to the 1986 Edition of the National Design Specification. National Forest Products Association, Washington, D.C., 1988.
6. *Memorandum on Crash Tested Bridge Railings.* File Designation HNG-14. FHWA, Washington, D.C.
7. *Standard Specifications for Transportation Materials and Methods of Sampling and Testing,* Vol. 1: *Specifications.* AASHTO, Washington, D.C., 1990.
8. Wacker, J. P., and M. A. Ritter. *Field Performance of Timber Bridges: 1. Teal River Stress-Laminated Deck Bridge.* Research Paper FPL-RP-515. USDA Forest Service, Madison, Wisc., 1992.
9. Ritter, M. A., E. A. Geske, W. J. McCutcheon, R. C. Moody, J. P. Wacker, and L. Mason. Methods for Assessing the Field Performance of Stress-Laminated Timber Bridges. *Proc., 1991 International Timber Engineering Conference.* London, England, Sept. 1991.
10. Ross, R. J., E. A. Geske, G. R. Larson, and J. F. Murphy. Transverse Vibration Nondestructive Testing Using a Per-

sonal Computer. Research Paper FPL-RP-502. USDA Forest Service, Madison, Wisc., 1991.
11. *Guide Specification for the Design of Stress-Laminated Wood Decks.* AASHTO, Washington, D.C., 1991.
12. Williams, G. D., D. R. Bohnhoff, and R. C. Moody. Bending Properties of Four-Layer Nail-Laminated Posts. Research Paper FPL-RP-528. USDA, Forest Service, Madison, Wisc., 1994.
13. NFPA. 1991. *Design Values for Wood Construction. A Supplement to the 1986 Edition of the National Design Specification.* National Forest Products Association, Washington, D.C., 1991.
14. Ritter, M. A., E. A. Geske, L. Mason, W. J. McCutcheon, R. C. Moody, and J. P. Wacker. Performance of Stress-laminated Bridges. *Wood Design Focus*, Vol. 1, No. 3, pp. 12–16, 1990.