Hardwood Glued Laminated Timber Bridges

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Design standards and specifications for 5.5- to 27.4-m (18- to 90-ft) clear span hardwood glued-laminated (glulam) highway bridges have been developed and are available from the Pennsylvania Department of Transportation. Resin systems, preservative treatment processes, laminating procedures, and key structural properties have been determined and incorporated into the standards for three commercially important hardwood species: northern red oak, red maple, and yellow poplar. The keys to successfully bonding the hardwoods are proper open assembly time and clamping pressure. Pressure treatment cycles to attain 160.2 to 192.2 kg/m^3 (10 to 12 pcf) retention of creosote in northern red oak, red maple, and yellow poplar glulam girders had no adverse effect on the flexural strength or stiffness.

Standard designs and specifications for hardwood glued-laminated (glulam) timber highway bridges have been developed at the Pennsylvania State University for the Pennsylvania Department of Transportation (*1*). The designs and specifications are similar to those for softwood glulam bridges (*2,3*) but are specifically developed for glulam bridges fabricated with northern red oak, red maple, and yellow poplar lumber. Development of the standards required identification, qualification, or development of resin systems and laminating processes for fabricating the glulam structural elements, preservative treatment processes, allowable design strengths and stiffnesses, and fastening systems. This paper summarizes the research forming the basis of the standards, the hardwood bridge standards, and the design and performance of a hardwood glulam bridge.

RESIN SYSTEMS AND LAMINATING PROCESSES

Three hardwood species with good potential for development of hardwood glulam timber bridges are northern red oak, red maple, and yellow poplar (*4*). Gluing and preservative treatment processes that satisfy quality assurance standards established by the American Institute of Timber Construction (*5*) and the American Wood Preservers' Association (*6*) were developed for each species.

A comprehensive discussion of the requirements for glued joints in hardwood glulam construction, selection and use of adhesives for hardwood glulams, selection and preparation of hardwood lumber for lamination, lay-up of hardwood laminated assemblies, adhesive edge and end joint connections, adhesive face lamination procedures, and clamping pressure is presented by Manbeck et al. (*4*). The recommendations in the report provide guidance to glulam fabricators and engineers when modifying procedures for quality assurance for hardwood glulam members. Only minor deviations from softwood manufacturing technology are needed for acceptable hardwood glulam timbers. Lamination procedures, which significantly influence the bonding process, must be properly adjusted for higher-density hardwoods. Higher-density substrates of red oak and red maple, in comparison to bonding of softwoods, require greater attention to lamination surface quality and applied clamp pressures. Laminators should have minimum difficulties in utilizing yellow poplar with existing manufacturing technology. Red oak and red maple will require some modification or refinement of existing softwood-based gluing practices. Hardwood glulam manufacture should not represent a significant added production expense or capital investment for most established lamination operations. Slightly higher production costs over softwood glulam should be anticipated until hardwood materials are available as standard-dimension lumber. Higher hardwood glulam costs are related in part to the loss in production efficiency when dealing with semiprocessed S2S hardwood lumber instead of standard finished nominal-sized lumber products. Costs should decrease as an infrastructure develops for nominal dimension and graded hardwood lumber. Production costs are increased because more costly resorcinol formaldehyde (RF) adhesives are used. However, most softwood operations using phenol resorcinol formaldehyde (PRF) resins can easily convert to RF face lamination adhesives. Capital investments by the laminator will be required if the glulam operation needs to update clamping assembly processes to achieve higher clamping pressures. The fabricator may also need to upgrade the planer to obtain more stringent surface quality requirements. Lamination procedures must be monitored for glulam manufacturers who have limited experience bonding higher-density hardwood lamination stock. Laminators with no experience must show evidence of their ability to conform with ANSI A190.1 (*7*).

Research also indicated that either vertical or horizontal finger-joint orientations with melamine adhesive are effective for end-joint fabrication meeting the AITC qualification criteria. Qualification data indicated that finger-joint performance was adequate for glulam manufacture with a 16.54-MPa (2,400-psi) or greater beam design value. Experimental results indicated that melamine formaldehyde (MF) was a viable adhesive for hardwood finger-joint assembly with good bonding performance. Testing has shown that MF formulations can provide acceptable performance for the three hardwoods even after exposure to high-moisture conditions.

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PRESERVATIVE TREATMENT

Oil-borne preservative treatments, such as creosote and pentachlorophenol, are required for hardwood glulam members used in bridge applications. On the basis of criteria such as service life and availability of treating facilities, creosote was selected as the preservative for hardwood glulam bridge members.

A comprehensive discussion of the requirements for preservative treatment of northern red oak, red maple, and yellow poplar glulam bridge members is presented by Manbeck et al. (*4*). The report includes discussions of preservative retention requirements and performance, treatment cycles, penetration of preservative, and glueline performance after treatment. The results of the treatment studies are as follows:

- Average weight creosote retention levels were 179.8 kg/m^3 (11.2 pcf), 293.4 kg/m^3 (18.3 pcf), and 257.2 kg/m^3 (16.1 pcf) for northern red oak, red maple, and yellow poplar, respectively.
- Assay retention ranges were 121.8 to 181.0 kg/m^3 (7.6 to 11.3 pcf), 309.2 to 406.9 kg/m^3 (19.3 to 25.4 pcf), and 147.4 to 302.8 kg/m^3 (9.2 to 18.9 pcf) for northern red oak, red maple, and yellow poplar, respectively.
- Minimum depths of penetration were 2.5 mm (0.1 in.) on the edge and 20.3 mm (0.8 in.) on the face for northern red oak, 27.9 mm (1.1 in.) on the edge and 25.4 mm (1.0 in.) on the face for red maple, and 7.6 mm (0.3 in.) on the edge and 10.2 mm (0.4 in.) on the face for yellow poplar.
- The effect of the preservative treatment cycle on glue bond performance, as measured by shear tests, was not significant.
- Northern red oak, red maple, and yellow poplar glulam beams may be treated with creosote to acceptable AWPA levels (*6*) in commercial operations. The treatment cycle will depend on the commercial operation and treatment facility. The creosote treatment does not adversely affect shear strength or percent wood failure. The three species will pass the cyclic delamination test with selected resins before creosote treatment provided that the gluelines in the untreated glulam beams are sound.

Posttreatment cycles have also been developed to minimize bleeding of preservative from treated glulam bridge members. Cycle details are described by Manbeck et al. (*4*).

ALLOWABLE DESIGN VALUES

Overview of Research Goals

Allowable design values (ADVs) were determined for northern red oak, red maple, and yellow poplar glulam beams loaded perpendicular to the plane of the laminations (bending about the x-axis in Figure 1a) and loaded parallel to the plane of the laminations (bending about the y-axis in Figure 1a). Allowable flexural strengths (F_{bx}) and stiffness (E_x) were calculated from experimentally measured modulus of rupture (MOR) and modulus of elasticity (MOE) data for at least one lamination lay-up for each species. Allowable flexural strengths (F_{by}) and stiffness (E_y) were also experimentally obtained for one lamination lay-up of northern red oak and red maple. All other ADVs, including those for shear and bearing strength, were estimated and deduced from published values for the predominant grade of the species lumber used in the beam lamination lay-up. The girders and deck panels used in hardwood timber bridges are treated with creosote, after fabrication. To obtain the treatment retention levels required by AWPA (*6*), normal treatment pressures and temperatures had to be modified. Thus, it was necessary to determine whether the postfabrication treatment of hardwood glulam beams with creosote to AWPA retention levels adversely affected the strength or stiffness. An experiment was conducted to test the hypothesis that preservative treatment had no effect on the strength or stiffness of northern red oak, red maple, or yellow poplar glulam beams.

Research was also conducted to determine whether (*a*) the methods outlined in ASTM 3737 (*8*) to predict the flexural strength and stiffness of softwood glulam beams are applicable to hardwood glulam beams, (*b*) it is technologically feasible to design and fabricate hardwood glulam beams with F_{bx} = 16.5 MPa (2,400 psi) and E_x = 12.4 GPa (1.8 × 10^6 psi), and (*c*) the volume reduction effect for hardwood glulam beams is the same as that defined for softwood glulams in the *National Design Specification for Wood Construction* (NDS) (*9*). This phase of the study focused on red maple and yellow poplar.

Combination A lay-ups, as defined in the NDS (*9*) and AITC-119 (*10*), were used for all the northern red oak studies (Figure 1a). Treatment effects for red maple and yellow poplar glulam beams were also evaluated using Combination A lay-ups. ADVs for red maple and yellow poplar were measured and predicted by ASTM 3737 (*8*) for the lay-ups shown in Figure 1b for red maple. Yellow poplar lamination lay-ups were similar, but not identical, to those in Figure 1b.

Summary of Results

Comprehensive discussions of the methods and results of the treatment effect and ADV research are included in several research reports and articles (*4,11–13*). The key results are as follows:

- Postfabrication treatment with creosote to retention levels specified by AWPA (*6*) did not adversely affect the flexural strength or the stiffness of northern red oak, red maple, and yellow poplar glulam beams.
- The dry-use flexural strength (F_{bx}) of Combination A northern red oak glulam beams, as calculated from experimental MOR data from test beams, exceeded the values published in the NDS (*9*) for generic red oak. Calculated allowable flexural strength for 40 beams was 23.6 MPa (3,420 psi); the published value for red oak glulam (*9*) is 15.4 MPa (2,240 psi). An allowable value of 16.5 MPa (2,400 psi) is recommended for design.
- The dry-use stiffness (E_x) of Combination A northern red oak glulam beams, as calculated from experimental MOE data from test beams, exceeded the NDS (*9*) published value for generic red oak. The measured allowable stiffness was

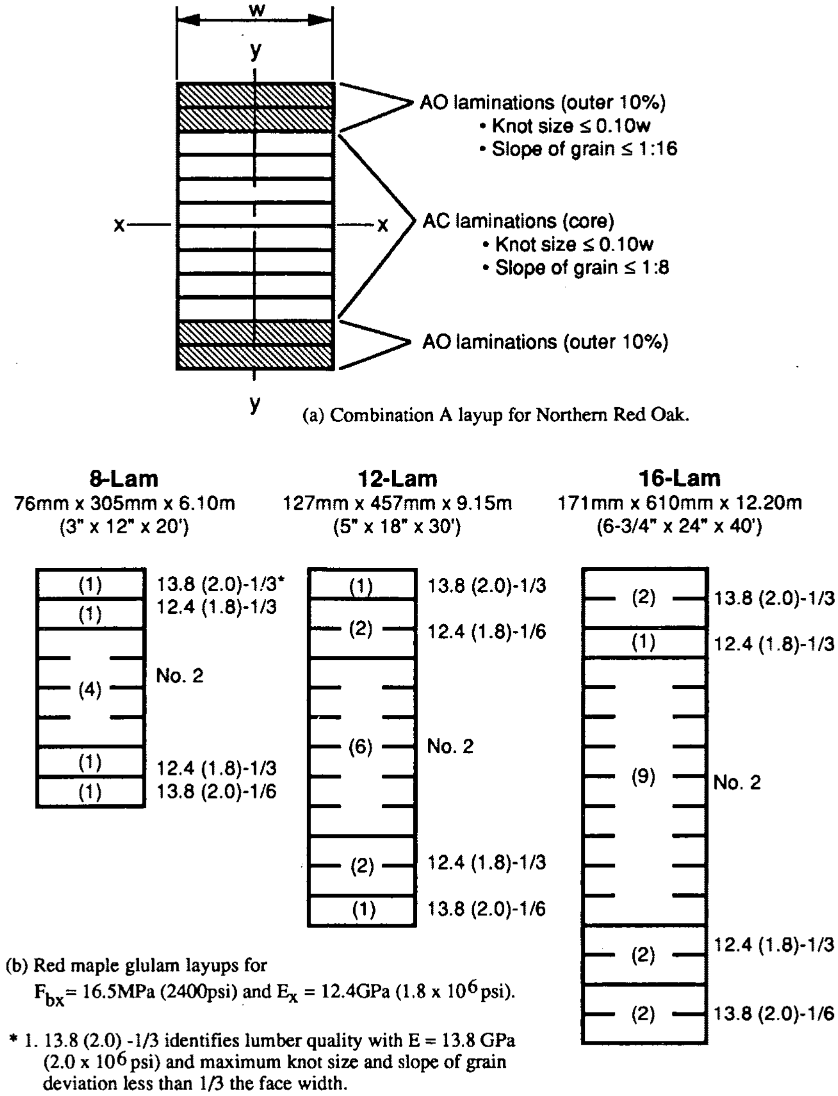

FIGURE 1 Glulam beam configurations.

13.1 GPa (1.9×10^6 psi); the published value for red oak (*9*) is 11.0 GPa (1.6×10^6 psi). An allowable value of 12.4 GPa (1.8×10^6) psi is recommended for design.

- The allowable dry-use flexural strength (F_{bx}) of both red maple and yellow poplar with lamination lay-ups similar to those shown in Figure 1b both exceeded 16.5 MPa (2,400 psi) and were satisfactorily predicted by the methods outlined in ASTM 3737 (*8*).
- The allowable dry-use stiffness (E_x) of both red maple and yellow poplar lamination lay-ups shown in Figure 1b equaled 12.4 GPa (1.8×10^6 psi) and was satisfactorily predicted by the methods outlined in ASTM 3737 (*8*).
- ASTM 3737 (*8*) can be used to design red maple and yellow poplar glulam beam cross sections with specified strength and stiffness.
- The volume effect for red maple and yellow poplar glulam beams is similar to that for softwood glulam beams. That is, flexural strength (F_{bx}) declines as beam volume increases. Stiffness (E_x) is unaffected by volume. The volume reduction factor (C_v) is defined by Equation 1 for both red maple and yellow poplar beams:

$$C_v = \left(\frac{b_0}{b}\right)^x \left(\frac{L_0}{L}\right)^y \left(\frac{d_0}{d}\right)^z \tag{1}$$

where

b_0 = 130 mm (5.125 in.),
b = cross section width (mm),
d_0 = 305 mm (12 in.),
d = cross section depth (mm),
L_0 = 638 m (21 ft),
L = beam length (m), and
$x = y = z$ = 0.071 (red maple and yellow poplar).

- Recommended dry-use ADVs for each species are summarized in Table 1 for the conditions specified in the footnotes to the table.

TABLE 1 Recommended Allowable Design Values for Hardwood Glulam Bridge Design[1,2]

Property	Axis of Bending[3]	Species		
		Northern Red Oak	Red Maple	Yellow Poplar
Flexural Strength (F_{bx})[4]	x	16.5 MPa	16.5 MPa	16.5 MPa
Stiffness (E_x)[4]	x	12.4 GPa	12.4 GPa	12.4 GPa
Flexural Strength (F_{by})[5]	y	12.4 MPa	12.4 MPa	9.6 MPa
Stiffness (E_y)[6]	y	11.0 GPa	11.7 GPa	9.6 GPa
Shear Strength (F_{vx}, F_{vy})[7]	x or y	1.5 MPa	1.4 MPa	1.0 MPa
Compressive Strength Perpendicular to Grain (F_{cp})[8]	x or y	6.1 MPa	4.2 MPa	2.9 MPa

1 Divide entries by 6.89 x 10^{-3} to convert MPa to psi; divide entries by 6.89 x 10^{-6} to convert GPa to psi.
2 All values are for dry-use conditions.
3 See Figure 1 for definition of x- and y-axes.
4 Northern red oak value is for Combination A lay-up; red maple and yellow poplar value for lamination lay-up similar to those described in Figure 1b or verified by ASTM 3737 procedures to have F_{bx} = 16.5 MPa (2400 psi) and E_x = 12.4 GPa (1.8 x 10^6 psi).
5 F_{by} values are for single grade lamination lay-ups of VSR No. 1 and No. 2 lumber of each species and for nominal deck panel thicknesses of 100 mm (4 in.) and 150 mm (6 in.). Values estimated by multiplying F_{by} of single laminations by 1.32 and 1.58 for 100 mm (4 in) and 150 mm (6 in) decks, respectively. Resulting F_{by} values were exceeded in tests at Penn State (4).
6 E_y for northern red oak is mean value of the conservative value in the NDS for single members on edge and the value from northern red oak glulam beam tests conducted at Penn State; red maple values from in-grade sampling of red maple from two locations in Pennsylvania from PennDOT Project No. SS-047 (14); yellow poplar value is average of published values for combination A lay-ups and for single members loaded on edge, NDS (9).
7 Shear strengths for each species are 1.944 times published F_v-value, NDS (9) for individual pieces of dimension lumber of the predominant lamination grade.
8 All values are the bearing strength of individual pieces of dimension lumber of the grade found in the face lamination, NDS (9).

NORTHERN RED OAK DEMONSTRATION BRIDGE

A demonstration bridge project has been under way in Pennsylvania for the past several years. The goals of this effort are to design, construct, and monitor hardwood timber highway bridges throughout the state, thus demonstrating the suitability of hardwoods for structural components in highway bridges. To date several hardwood transverse-stressed-longitudinal-deck, both unreinforced and steel-plate reinforced, demonstration bridges have been completed. At least three of the proposed demonstration bridges are to be hardwood glulam bridges, one each of northern red oak, red maple, and yellow poplar. The objective of the remainder of this section is to summarize the design and field performance of a northern red oak hardwood glulam demonstration highway bridge that was completed and opened for traffic in November 1991. Design details are further described by Manbeck et al. (*15*).

Project Team

The project was a cooperative effort of several organizations under the leadership of a Penn State University research team. The Penn State team was responsible for all quality control matters and specifications related to wood procurement, processing, grading, and fabrication. Gwin Dobson and Forman, Inc., of State College, Pennsylvania, designed the substructure and superstructure and supervised construction; Unadilla Laminated Products, Inc., of Sidney, New York, fabricated the glued laminated structural members and fastener hardware; Koppers, Inc., of Muncy, Pennsylvania, treated the glulam members, and Kamtro Construction of Osceola Mills, Pennsylvania, constructed the bridge. The bridge owner is Ferguson Township in Centre County, Pennsylvania.

Design Requirements and Procedures

A northern red oak glulam girder and deck was designed to replace a 44-year-old reinforced concrete tee beam bridge with a 107-kN (12-ton) rating on Township Road T-330 in Ferguson Township in Centre County, Pennsylvania. The bridge superstructure was erected on the existing stone abutments. The bridge skew, at 45 degrees, was severe.

The design requirements for the bridge were as follows: loads, HS25 or ML80 live load; deflections, live load deflection less than span/500; materials, all superstructure, railings, and parapets to be glulam northern red oak; clear span between centerline of abutments, 10.69 m (35 ft ½ in.); and overall deck width, 8.54 m (28 ft).

All structural components were designed in accordance with the 1986 edition of the *National Design Specifications for Wood Construction* (*16*), the 1988 edition of the *Supplement to the National Design Specification* (*17*), the AASHTO *Standard Specifications for Highway Bridges* (*18*), and PennDOT's *Design Manual 2* (*19*). All the girders were specified as Combination A lay-ups (Figure 1a) with the following unadjusted structural properties: F_{bx} = 15.4 MPa (2,240 psi), F_v = 1.5 MPa (230 psi), and E = 11.0 GPa (1.6 × 10^6 psi). The girders were braced laterally by two endwall diaphragms, midspan diaphragms, and the glulam deck, which was fastened to the girders every 0.30 m (12 in.) on center. The glulam deck panels were specified as Combination A northern red oak with F_b = 15.4 MPa (2,240 psi), F_v = 1.5 MPa (230 psi), and E = 11.0 GPa (1.6 × 10^6 psi).

Bridge Design

The bridge superstructure has nine 203- by 743-mm (8- by 29¼-in.) girders spaced 965 mm (38 in.) on center (Figure 2). All girders were fabricated with 38-mm (1.5-in.) laminations. The deck, which is 152 mm (6 in.) thick, consists of panels 914 mm (36 in.) and 1220 mm (48 in.) wide by 8.54 m (28 ft) long. All panels are spaced approximately 13 mm (½ in.) apart to accommodate anticipated in-service moisture expansion, because the panels were fabricated at 12 ± 2 percent moisture content and are expected to equilibrate over the stream at approximately 19 percent moisture content. The 152-mm (6-in.) deck was designed as a noninterconnected deck (*18,20*). However, one-half of the bridge was constructed with dowels 32 mm (1¼ in.) in diameter to observe performance differences, if any, between the asphalt paving over the interconnected panels and the noninterconnected panels. The endwall diaphragms were 152 mm (6 in.) wide by 743 mm (29¼ in.) deep and extended the full 12.08-m (39.6-ft) skew length. Midspan diaphragms, 150 by 743 mm (3 by 29¼ in.), were installed perpendicular to the span between each pair of girders for lateral stability.

The girders were attached to the abutment with 19-mm (¾-in.) anchor bolts (all bridge hardware was galvanized). The bearing design allowed vertical adjustment for proper leveling of the top surfaces of the nine beams. The deck panels were fastened to the girders with 19- by 229-mm (¾- × 9-in.) galvanized lag bolts. The heads were recessed into the deck. The diaphragms were connected to the girders with three 19- by 229-mm (¾- × 9-in.) galvanized lag bolts at each girder.

Oakum was installed between deck panels to prevent asphalt paving from filling the space. Before paving, a waterproof geotextile membrane was installed over the deck.

The railings and parapets design consists of 254- by 305-mm (10- × 12-in.) glulam posts spaced 1.83 m (6 ft.) on center, two 152- by 203-mm (6- × 8-in.) glulam rails, and 254- × 305-mm (10- × 12-in.) glulam curbs. The rail system is fastened with galvanized bolts and drift pins and is similar in design to that tested by Ritter et al. (*21*).

Fabrication and Construction

Most hardwood lumber is not structurally graded or available in standard sizes. This is a major challenge to the use of hardwoods in glulam applications. However, traditional hardwood manufacturers have shown interest in producing structurally graded dimension lumber.

The Penn State team procured the northern red oak logs, arranged for primary processing and drying of the lumber, and then sorted and graded the lumber in accordance with AITC's hardwood laminating specifications (*10*). The team also supervised and oversaw the fabrication of the girders, deck panels, and railing materials at Unadilla Laminated Products, Inc., in Sidney, New York. As part of the fabrication process, Unadilla planed and cut all the glulam members to the required finished dimensions to minimize field

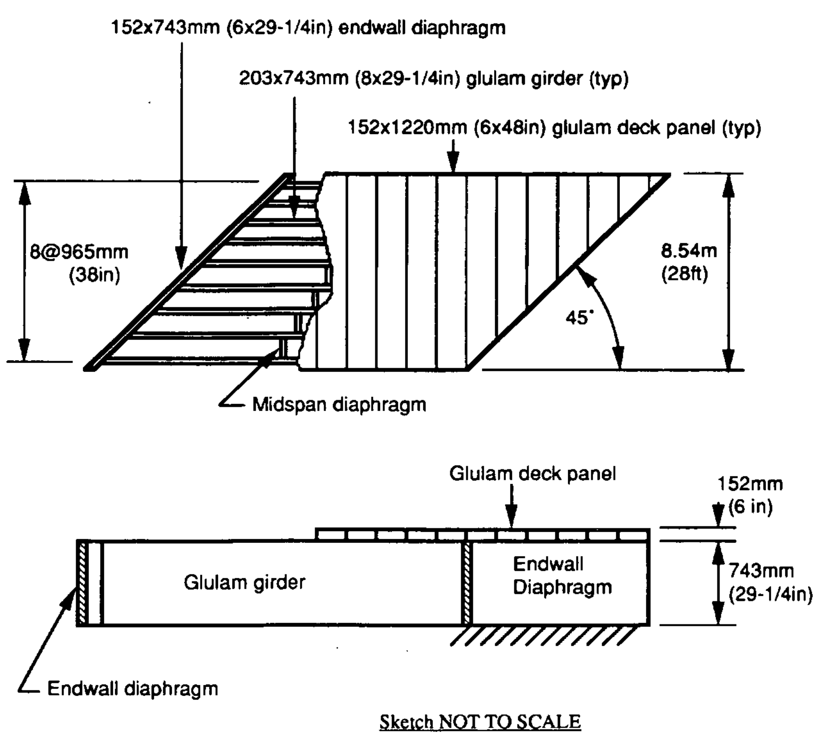

FIGURE 2 Superstructure layout for the 10.69-m (35-ft ½-in.) clear span northern red oak glulam demonstration bridge.

cutting after preservative treatment. The following holes were predrilled at Unadilla before preservative treatment: the deck holes for the deck-to-girder fastening; the girder holes for the girder-to-midspan diaphragms; the backwall holes for the backwall-to-girder connections, and the holes in the railings, posts, and curbs. All other holes were field drilled and field treated with creosote. Field-drilled holes were swabbed thoroughly with creosote and subsequently filled with asphaltic roof cement before inserting the fastener. All bridge connection hardware was fabricated and supplied by Unadilla, Inc. The team then shipped the laminated materials to Koppers, Inc., Muncy, Pennsylvania, where they were treated with creosote to a retention level of approximately 192.2 kg/m^3 (12 pcf) with a minimum depth of penetration of approximately 6 mm (0.25 in.). Finally, the glulam members and hardware were transported to the bridge site.

The notice to proceed for construction was given on September 6, 1991. Demolition of the existing concrete bridge began on September 9, 1991. The bridge bearing seat caps were reconditioned by September 23. Much of the riprap and gabion work was completed by September 30. The girders were set and diaphragms attached by October 4, 1991. Railings and parapets and all paving were completed by October 28. On October 30, the bridge was load tested with two 75,000-lb triaxle trucks. On November 1, 8 weeks after the notice to proceed, the road was reopened to traffic.

Special care was necessary in the construction phase to ensure proper mating of the deck to the girder. All deck panels had to be properly mated to the girder before insertion and tightening of the lag bolts. This can be accomplished by careful sequencing of the fastener application and by preloading the deck panel with construction equipment before fastening and properly torquing the lag bolts.

Dimensional stability was also a concern in the fabrication/construction phase. Laminating procedures require lumber to be at moisture content less than 16 percent. In service treated lumber in the deck panels is expected to equilibrate at approximately 19 percent moisture content. Thus, adequate spacing, the magnitude of which is somewhat species dependent, must be specified between deck panels. Because some expansion occurs during creosote treatment, panel widths at the site should be measured before installation for necessary panel spacing adjustments in the field.

Cost

The total cost of the bridge, including all materials, development, and monitoring costs, was approximately $250,000. The design, construction, and engineering costs, which totaled $140,000, were higher than normal for a "spec" bridge. Laminating costs were $40,000. Since this bridge was a demonstration/experimental bridge, it was the first of its kind. Consequently, uncertainties with respect to design, fabrication, and construction procedures required more time and effort. Once the standard designs and specifications are available in 1993, these costs should decline significantly, thus making timber bridges more cost competitive. In addition, these costs include evaluation of the bridge's structural responses and overall performance over a 3-year period.

Performance Test Results

The predicted live load deflection, assuming no composite behavior between the deck and girder, girder E-value of 11.0 GPa (1.6×10^6 psi), and an HS25 or ML80 load, was 22 mm (0.85 in.). A load test with two 33.4-kN (75,000-lb) triaxial trucks, located to produce maximum deflection, produced an actual maximum deflection of 14 mm (0.55 in.). Lower actual versus predicted deflection is probaby due to (*a*) neglecting composite action, (*b*) using an E-value that is somewhat lower than found in previous work [Shaffer et al. (*11*) reported E-values of 13.1 GPa (1.90×10^6 psi) for northern red oak beams], and (*c*) using an E-value that is considerably lower than that found in the actual bridge stringers by test [the average E-value, determined by static loading, of each board used in the bridge girders was 15.5 GPa (2.2×10^6 psi)]. Predicted live load deflection using an E-value of 13.1 GPa (1.9×10^6 psi) and 15.5 GPa (2.2×10^6 psi) equals 18 mm (0.72 in.) and 16 mm (0.62 in.), respectively. Fourteen months' data indicate that creep deflections are negligible (less than 1 mm).

Some small reflective cracks have formed in the bituminous paving directly above the interface between adjacent deck panels. There is no noticeable difference in the amount of cracking in the doweled and nondoweled ends of the deck. The cracking is most likely due to the expansion spacing 13 mm (0.5 in.) wide provided between deck panels during construction. Dimensional changes in the deck panels have been observed and measured monthly since construction was completed. After 1 year, the spacings have reduced to approximately 40 percent of the original width. This observation suggests that the spacing between deck panels may be reduced to 6 mm (0.25 in.).

HARDWOOD GLULAM BRIDGE STANDARDS

In May 1993 the Pennsylvania Department of Transportation published the BLC-560 series *Standards for Hardwood Glulam Timber Bridge Design* (*1*) for clear spans of 5.49 to 27.4 m (18 to 90 ft). The standards include designs and specifications for the design, fabrication, treatment, handling, and erection of components and assemblies for hardwood glulam bridge substructures and superstructures. The standards are flexible and include provisions for hardwood or nonhardwood substructures used in conjunction with hardwood superstructures. The standards also include selection tables for 100 and 150 mm (4 and 6 in.) deck panel thickness and several glulam girder widths. Notable features of the BLC-560 series are a worked design example and design worksheets.

SUMMARY

The technological basis for designing hardwood glulam timber highway bridges of northern red oak, red maple, or yellow poplar has been developed. A demonstration highway bridge using northern red oak glulam members for the superstructure, including parapets and railings, has been successfully designed, fabricated, erected, and load tested. Standard designs (BLC-560 series) have been developed for northern red oak, red maple, and yellow poplar glulam bridges with clear spans ranging from 5.49 to 27.4 m (18 to 90 ft). The standards are available from the Pennsylvania Department of Transportation.

ACKNOWLEDGMENTS

The research was funded by the Pennsylvania Department of Transportation and the Pennsylvania Agricultural Experiment Station. Key industrial partners, including Unadilla Laminated Products, Inc., of Sidney, New York, Koppers Industries, Inc., of Muncy, Pennsylvania, and Indspec, Inc., of Pittsburgh, Pennsylvania, provided technical support for the project. The significant contributions of Keith R. Shaffer, William Kilmer, Kevin Kessler, and Maria DiCola at Penn State are gratefully acknowledged.

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