Yellow Poplar Glued-Laminated Timber: Product Development and Use in Timber Bridge Construction

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Abstract

This paper outlines the research efforts involved in incorporating yellow-poplar *(Liriodendron tulipifera)* as a viable resource for structural glued-laminated timber (glulam). The development of an efficient combination of yellow poplar glulam is presented, along with a description of how this was implemented in the industry standard for hardwood glulam. A case study is then presented that utilized this new technology by constructing a timber bridge.

Keywords: Yellow Poplar, Glulam, Timber Bridge, E-Rated Lumber

Introduction

Glued-laminated timber (glulam) is a vital element for many proposed timber bridge designs, and one key issue in bridge research is the use of local hardwood species that are underutilized for these type of applications. The efficient utilization of a hardwood species, such as yellow poplar, has been limited because established design methodologies for hardwood glulam are highly conservative.

Much research has been conducted to show that yellow poplar possesses properties that make it feasible for use in structural applications. In addition, technological advances in nondestructive testing has allowed for lumber to be graded on the basis of its mechanical properties, rather than visual grading alone (Green and others 1994). With the abundance of yellow poplar that grows in the northeastern United States, it would be logical to utilize this species to further extend the available forest resource.

Background

Provisions for the design of glulam timbers made from hardwood species of lumber have been available in a specification published by the American Institute of Timber Construction, AITC 119 (AITC 1985). The homogeneous combinations in this standard were available for five different levels of lumber quality. Design stresses applicable to yellow poplar are shown in Table 1.

These homogeneous combinations of glulam are referred to as axial combinations. In axial combinations, all laminations are subjected to similar stresses, such as tension or compression, or in bending members that have loading applied parallel to the wide faces of the laminations. For glulam made from softwood lumber, design properties for these types of combinations are available in the standard AITC 117-Design (AITC 1993). In the case of bending members that have loading applied perpendicular to the wide faces of the laminations, referred to as bending combinations, the opportunity arises to use lower quality lumber in the inner laminations because of the reduced stresses. For glulam made from

Table 1—Design properties for homogeneous combinations of glulam. Yellow-poplar glulam from AITC 119 standard (AITC 1985) and Southern Pine glulam from AITC 117 standard (AITC 1993).

Combination symbol	Ratio of size of maximum permitted knot to finished width of lamination	Number of laminations	Extreme fiber in bending)		Horizontal Shear	Modulus of elasticity
Properties for yellow-poplar glulam						
			(MPa) (lb/in^2)	Steepest grain slope	(Pa) (lb/in^2)	(GPa) (x10^3 lb/in^2)
A	0.1	4 to 14	11.0 (1600)	1:16	1030 (150)	10.3(1,500)
	0.1	15 or more	11.0 (1600)	1:16	1030 (150)	10.3 (1,500
B	0.2	4 to 14	10.6 (1540)	1:16	1030 (150)	10.3(1,500)
	0.2	15 or more	11.0 (1600)	1:16	1030 (150)	10.3(1,500)
C	0.3	4 to 14	8.3(1200)	1:12	1030 (150)	9.3 (1,350)
	0.3	15 or more	9.1(1320)	1:12	1030 (150)	9.3 (1,350)
D	0.4	4 to 14	6.2 (900)	1:8	1030 (150)	8.3 (1,200)
	0.4	15 or more	7.2(1040)	1:8	1030 (150)	8.3 (1,200)
E	0.5	4 to 14	4.1 (600)	1:8	1030 (150)	8.3 (1,200)
	0.5	15 or more	5.2 (760)	1:8	1030 (150)	8.3 (1,200)
Properties for Southern Pine glulam[a]						
No.1D	0.27	4 or more	15.9 (2300)	1:10	1380 (200)	13.1(1,900)
No.2M	0.35	4 or more	12.1 (1750)	1:8	1380 (200)	9.7 (1,400)

[a] No.1D is combination number 50, and No.2M is combination number 47 (AITC 1993).

softwood lumber, available bending combinations are published in the standard AITC 117-Manufacturing (AITC 1993a), and their design properties are published in AITC 117-Design (AITC 1993). For glulam made from hardwood lumber, bending combinations were not recognized in the standard. As hardwoods were not recognized in AITC 117, and those combinations in AITC 119 used the same grade of lumber throughout, there were no opportunities for utilizing high and low grades of hardwood to develop efficient bending combinations.

Note that for combination A, Table 1, the maximum permitted knot is 10 percent of the finished width of the lamination. This knot restriction produces a lamination grade that exceeds Select Structural yellow poplar lumber, which allows a 20-percent maximum edge knot (NELMA 1991). For comparison purposes, the design properties for two grades of Southern Pine glulam are also included in Table 1. Note that design values for bending strength and stiffness are highly conservative for yellow poplar glulam, when compared with Southern Pine glulam having similar grade characteristics. A comparison between similar-knot categories, No.lD Southern Pine glulam (0.27) and combination C yellow-poplar glulam (0.3), shows that Southern Pine has a design bending strength that is approximately 1.92 times greater and design modulus of elasticity (MOE) that is 1.40 times greater. This comparison between No.2M Southern Pine glulam (0.35) and combination D yellow poplar glulam (0.4) yields ratios of 1.94 and 1.17, respectively.

Considering the large cost differential between hardwood and softwood lumber, and the limitation of the existing hardwood glulam standard, it would be difficult to justify the use of hardwood glulam other than for specialty applications. If yellow poplar glulam was available with properties similar to Southern Pine glulam, then it would have a better chance of being a competitive structural product. Better utilization of the hardwood lumber resource and establishing design properties of hardwood glulam that are competitive with those of softwood glulam is desirable.

Glulam Beam Research

In an effort to utilize yellow poplar as a structural material for glulam manufacture, a cooperative research project with West Virginia University (Moody and others 1993) was conducted to develop an efficient bending combination using the existing design methodology established for softwood species of lumber (ASTM 1992).

Glulam Beam Design

The combination, shown in Figure 1, utilized E-rated lumber in the outer laminations and visually graded lumber in the core laminations. For stiffness, the outer 10 percent of the laminations was sorted for an average modulus of elasticity (MOE) of 13.8 GPa (2.0 x 10^6 lb/in^2) and the next inner 15 percent of the laminations was sorted for an average MOE of 12.4 GPa (1.8 x 10^6 lb/in^2). The remaining 50 percent of the core laminations was made from visually graded No.2 lumber. To ensure strength, edge-knot criteria were imposed on the E-rated lumber grades. For the bottom 10 percent of the laminations on the tension side, a maximum edge knot of 1/6 the width of the cross section was imposed; this is approximately equivalent to a Select Structural visual grade. All remaining E-rated lumber zones had a 1/3 edge-knot criteria, which is approximately equivalent to a No.2 visual grade (NELMA 1991). Thus, 90 percent of the cross section was made from No.2 and better lumber. These criteria followed the pattern found to be efficient in research that formed the basis for E-rated bending combinations in AITC 117 (AITC 1993a).

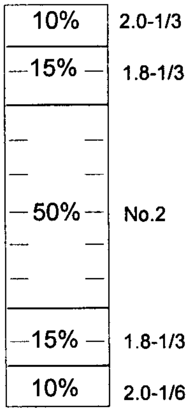

Figure 1--Layup of yellow-poplar glulam beam made from E-rated outer laminations and visually graded core laminations.

The standard design procedures for softwood glulam (ASTM 1992) indicated that the design values for this combination would be 12.4 GPa (1.8 x 10^6 lb/in^2) for MOE and 16.5 MPa (2,400 lb/in^2) for bending strength.

Glulam Beam Evaluation

To evaluate the performance of this design, Moody and others (1993) evaluated a total of 45 glulam beams having the combination shown in Figure 1. Three sizes were targeted: 8-, 12-, and 17-lamination beams made from nominal 51- by 102-mm, 51- by 152-mm, and 51- by 203-mm (2- by 4-in., 2- by 6-in., and 2- by 8-in.) lumber, respectively. Total length of these three sizes were 6.1, 9.1, and 12.2 m (20, 30, and 40 ft), respectively. In addition, samples of the end-jointed yellow-poplar lumber were also tested.

Table 2 gives the results of the yellow poplar glulam beams that were tested. The important properties to note are average MOE and the 5th percentile modulus of rupture (MOR) values, adjusted to a standard size of 130 mm wide, 305 mm deep, and 6.4 m long (5.125 in. wide, 12 in. deep, and 21 ft long).

Table 2—Results of yellow poplar glulam beam tests.

	Laminations		
Property	8	12	17
Sample Size	15	15	15
Moisture content (%)	8.2	7.5	8.0
MOE			
Average, GPa	13.0	13.4	12.3
(x10^6 lb/in^2)	(1.89)	(1.94)	(1.79)
COV (%)	4.5	3.3	3.4
MOR			
Average, MPa	55.6	52.1	45.3
(lb/in^2)	(8,060)	(7,560)	(6,570)
COV (%)	17.3	16.1	18.0
5th percentile, MPa	38.9	37.5	31.2
(lb/in^2)	(5,640)	(5,440)	(4,530)
Adjusted 5th, MPa	17.4	18.8	17.0
(lb/in^2)	(2,520)	(2,730)	(2,470)

In summary, all three beam sizes met or exceeded the targeted design levels of 12.4 GPa (1.8 x 10^6 lb/in^2) for MOE and 16.5 MPa (2,400 lb/in^2) for design bending strength (adjusted 5th). Thus, it was shown in this study that yellow poplar is a viable resource for structural glulam timber manufacture. Nondestructively testing the laminating lumber, or E-rating, enabled the utilization of lower grade lumber. An additional result of this study was that the existing methodology for designing softwood glulam beam combinations was applicable to hardwood glulam timber.

Hardwood Glulam Standard

This research on yellow poplar glulam was part of a combined research effort on hardwood glulam that enabled the American Institute of Timber Construction to take action on updating the existing hardwood glulam standard (AITC 1985). Studies by Manbeck and others (1993) and Janowiak and others (1995) on red maple and a study by Shedlauskas and others (1996) on red oak also showed that efficient bending combinations of hardwood glulam could meet the targeted 2400F-1.8E design level.

As a result of these studies, the AITC 119 hardwood glulam standard was revised so that efficient bending combinations were included. Table 3 shows two revised layups: 14F-Vl, which corresponds to combination B from Table 1, and 24F-E3, which corresponds to the targeted combination shown in Figure 1. Note that as the beam depth increases, stricter requirements are implemented in the tension laminations, which occupy the outer 5 percent of the laminations in the outer tension zone.

Table 4 shows the established design values for this combination. Note that for the 24F-E3 combination, the newly established design values for bending strength (tension zone stressed in tension) and bending stiffness are 50 and 20 percent larger, respectively, than the highest values available in the previous version of the standard (Table 1). In addition, the design shear strength value was adjusted to 1.07 MPa (155 lb/in^2), to be consistent with ASTM D3737 procedures.

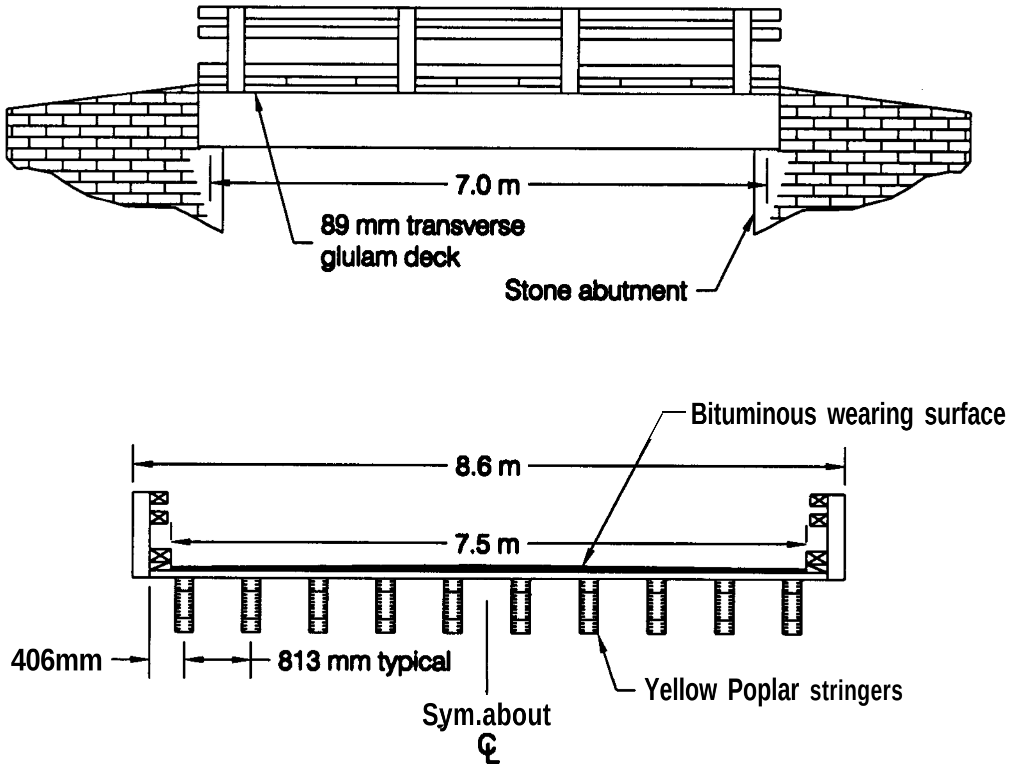

Figure 2-Overall dimensions of McFarland Road bridge

Table 3—Revised bending combinations for yellow-poplar glulam (AITC 1996).

			Minimum grade of lamination				
			Percent/Grade/Species—Each Zone				
Combination symbol[a]	Depth of member	Tension lamination	Outer tension zone	Inner tension zone	Core zone	Inner compression zone	Outer compression zone
14F–V1	4 lams to <305 mm (<12 in.)	302-20	25% SS	--	N2	--	25% SS
	305 to 381 mm (12 to 15 in.)	302-22					
	>381 mm (>15 in.)	302-24					
24F–E3 Yellow Poplar	4 lams to <305 mm (<12 in.)	302-20	10% 2.0 E6/YP	15% 1.8 E3/YP	N2/YP	15% 1.8 E3/YP	10% 2.0 E3/YP
	305 to 381 mm (12 to 15 in.)	302-22					
	>381 to 572 mm (>15 to 22½ in.)	302-24					
	>381 mm (>22½ in.)	302-26					

[a]The following combination is not balanced and is intended for simple-span-members.

Table 4—Design values for yellow-poplar glulam bending combinations (AITC 1996)

	Bending about X-X axis					
	Loaded perpendicular to wide faces of laminations					
	Extreme fiber in bending, F_{bx}		Compression perpendicular to grain, $F_{c\perp y}$			
Combination symbol	Tension zone stressed in tension (MPa) (lb/in^2)	Compression zone stressed in tension (MPa) (lb/in^2)	Tension face (MPa) (lb/in^2)	Compression face (MPa) (lb/in^2)	Shear parallel to grain (Horizontal), F_{vx} (MPa) (lb/in^2)	Modulus of elasticity, E_x (GPa) (x10^6 lb/in^2)
YP						
14F–V1	9.7 (1400)	4.8 (700)	2.8 (405)	2.8 (405)	1.07 (155)	9.0 (1.3)
24F–E3	16.5 (2400)	8.3 (1200)	4.1 (590)	4.1 (590)	1.07 (155)	12.4 (1.8)

Thus, based on this research, the industry standard for hardwood glulam timber has been revised to include efficient bending combinations. These combinations have design properties equal to those for existing softwood glulam combinations, which provides designers the flexibility to choose a species that may be abundant to their particular region.

Timber Bridge Case Study

The timber bridge described in this case study is located on McFarland Road in Washington County, Maryland. This bridge was constructed in 1995 through the Demonstration Timber Bridge Program of the USDA Forest Service, administered by the Timber Bridge Information Resources Center in Morgantown, West Virginia. The timing of the recently revised hardwood glulam standard, along with the abundance of yellow poplar in the surrounding area, provided the opportunity for this bridge to be the first timber bridge to be designed using the efficient bending combinations of yellow-poplar glulam shown in Figure 1.

This project was a rehabilitation of an existing concrete-slab bridge. The deck had been severely deteriorated, having large sections of exposed rebar in some areas. In a previous attempt to extend the service life of the bridge, a temporary steel panel bridge had been placed on top of the existing concrete slab deck. This added to the height of the deck surface, which required that the approaches be raised to the new deck elevation, requiring a 16.1 km/h (10 mph) speed limit posting. With time, the steel panels became severely rusted as a result of annual exposure to road salts, and the bridge had substantial section loss at many points.

The rehabilitation project consisted of replacing the deck structure and using the existing substructure. The existing substructure consisted of cut-stone abutment stems and wingwalls with concrete caps. The depth of the abutment is approximately 5.5 m (18 ft), which provides ample hydraulic opening. The new deck superstructure (Fig. 2) consisted of 10 longitudinal glulam stringers, which were 7-m- (23-ft-) long and 89- mm- (3-1/2-in.-) wide yellow-poplar glulam diaphragms (Fig. 3). The bridge had an out-to-out width of 8.6 m (28.3 ft), with a road clearance of 7.5 m (24.7 ft). A 76-mm (3-in) bituminous wearing surface was applied to the surface of the 127-mm (5-in.) transverse yellow-poplar glulam deck.

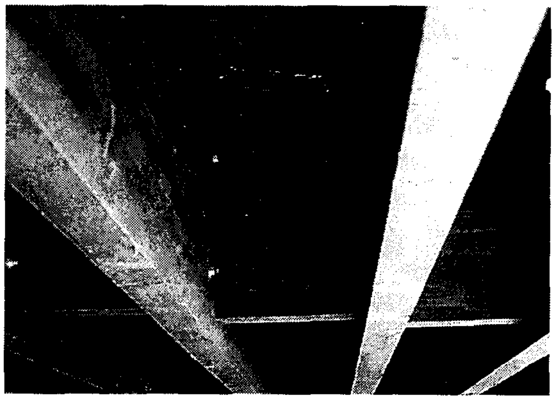

Figure 3—Placement of glulam diaphragms.

Figure 4—Yellow-poplar glulam bridge railing

This structure is a two-lane timber bridge that was designed to carry legal loads (HS20) and meet AASHTO requirements of L/500 for live-load deflections (AASHTO 1989). The design life of the superstructure is 50 years, and all components are treated with creosote. The preservative-treated beams were steam treated prior to erection to prevent bleeding.

The bridge railing, which was also made of yellow-poplar glulam timber, had an overall height of 838 mm (33 in.) (Fig. 4).

Figure 5–Final construction of McFarland Road Bridge.

Concluding Remarks

The development of efficient glulam combinations using yellow poplar provides another option for the construction of timber bridges using locally available underutilized wood species. Although there is little doubt that bridges constructed from this material will provide many years of acceptable service, the economics of hardwood glulam will be a determining factor in future acceptance.

The bridge in McFarland County was one of the first hardwood glulam bridges constructed, and costs were significantly greater compared with similar glulam bridges constructed of primary softwood species. This was expected and is typical when new materials and technology are initially introduced. As time passes and more bridges of this type are constructed, it is hoped that economics will improve and yellow poplar glulam will be a viable bridge material (Fig. 5).

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