Portable Glulam Timber Bridge Design for Low-Volume Forest Roads

S.E. Taylor, K.P. Keliher, and J.D. Thompson, *Auburn University*
M.A. Ritter, *Forest Products Laboratory, USDA Forest Service*
G.L. Murphy, *USDA Forest Service, Atlanta, Georgia*

Improved stream crossings are needed to reduce construction and maintenance costs and reduce the environmental impacts from low-volume forest roads and skid trails. New designs of timber bridges are cost-effective alternatives for portable stream crossing structures. This paper discusses design criteria for portable timber bridges and presents one design for a portable, longitudinal glued-laminated (glulam) deck timber bridge. Design criteria for portable bridges generally should not be as conservative as those used in the design of permanent highway bridges. The longitudinal glulam deck bridge has performed well in service, and load test results demonstrate that highway bridge design procedures are conservative for portable bridge systems.

T he development, harvesting, and maintenance of U.S. forest resources require an extensive roadway network over a wide spectrum of geographical conditions. In general, these roads are designed for low-volume traffic conditions and are often single lane and unpaved. Because forest management activities are both diverse and sporadic, traffic volumes and loads can vary significantly. During resource development and maintenance periods, traffic volumes are low and consist primarily of light passenger vehicles. However, dur-

ing harvesting operations, roadways may be subjected to higher-volume truck traffic with loads in excess of the maximum legal highway load. In either case, roadway use is commonly limited to short periods over a relatively long forest management period. For example, roadway access may be required for only a 6-month period over a 10-year cycle. As a result, there is a trend to close these roads when they are not needed for management activities.

Forest roads typically require a large number of structures to cross streams and other topographical features. Rothwell *(1)* and Swift *(2),* in separate studies on forest roads and skid trails, found that stream crossings were the most frequent sources of erosion and sediment introduction into streams. Fords and corrugated-metal or concrete culverts have been common stream crossing structures on forest roads for many years. Using fords may introduce sediment into the stream as vehicles drive across. While culverts alleviate this problem, considerable sediment loads appear to be introduced into the stream during the excavation and fill work that accompanies culvert installation. Results reported by Swift *(2)* show that the cumulative amount of soil placed in a stream at the road-stream crossing during the construction period was over 10 times greater than the sedimentation during logging operations. In addi-

tion, culverts may clog with debris and then be washed out during heavy runoff periods, thereby introducing additional sediment into the stream. In the case of roads or trails that are not permanent, the stream crossing structure may be removed after logging operations or other activities are complete. Removal of a culvert also appears to introduce heavy sediment loads into the stream.

Historically, bridges for low-volume forest roads have been of two types: temporary or permanent. A common temporary bridge has been the log stringer bridge that is either removed or left to deteriorate at the end of the use period. The use of temporary log stringer bridges has substantially declined over the last decade because it has become increasingly difficult to locate logs of the size and quality required for bridge construction. In addition, if the temporary bridge is not installed or removed properly, there may be adverse impacts to water quality. Permanent bridges, which are constructed of wood, steel, or concrete, depending on span requirements and economic considerations, are typically designed for service lives of 40 to 50 years. These permanent bridges are not economically feasible for short periods and often require expensive maintenance for continued service. In addition, permanent bridges for limited-use, low-volume forest roads are commonly designed to a lower standard than most public access facilities and can be a potential liability to the bridge owner if public access is possible.

One potential solution to short-term bridge needs on low-volume forest roads is the concept of portable bridges. If properly designed and constructed, portable bridges can be easily transported, installed, and removed for reuse at multiple sites. This ability to serve multiple installations makes them much more economically feasible than a permanent structure. In addition, if they are installed and removed so that disturbance to the site is minimized, they can alleviate many potential water quality problems.

Many of the advantages of timber bridges, which include using locally available materials, having long service lives, being relatively lightweight and easy to fabricate, and being prefabricated, make them ideal for temporary stream crossings. The objectives of this paper are to discuss design criteria for portable bridges and review the design and performance of a portable longitudinal glued-laminated (glulam) deck timber bridge.

BACKGROUND

A variety of temporary or portable bridge designs have been constructed from steel, concrete, and timber. The following paragraphs briefly summarize these concepts.

Steel Bridges

Temporary steel bridge designs include modular steel girder bridges, hinged steel bridges, railroad flatcars, bridges made of steel truss panels (similar to the military's Bailey bridges), pipe fascine systems, and trailer- or armored military vehicle-launched bridges. The spans for these steel bridges range from 5 to 75 m (15 to 250 ft). Of these designs, the most common are the modular girder and the hinged steel bridges.

Two examples of portable modular steel girder bridges are the EZ Bridge sold by Hamilton Construction Company of Springfield, Oregon, and those sold by Big R Manufacturing Company, Inc., of Greeley, Colorado. These bridges have modular sections constructed of steel I-beams that run longitudinally under a transverse steel or timber deck. The bridges typically come in two sections and are bolted together when installed. These bridges can be designed to meet vehicle loads specified by AASHTO or the U.S. Department of Agriculture (USDA) Forest Service. Since these bridges are prefabricated, the y can be installed quickly. Forestry equipment can be used to install shorter span bridges; however, heavy construction equipment is required for long span bridges.

Another commercially available portable steel bridge design has been used successfully on many low-volume roads and logging operations. These bridges, which are manufactured by ADM Welding and Fabrication in Pennsylvania, are constructed of steel stringers with a timber deck. One of the smaller designs is 3.5 m (11 ft) wide and 7.9 m (25 ft) long and can be constructed to support either log skidder or truck traffic. Other bridges of this type have been constructed for spans up to 16.8 m (55 ft). These bridges have a unique hinged design that allows them to be folded in half and thus meet the legal width limit for highway transport. Bridges classified for log skidder and truck loads are advertised with capacities of 13600 kg (30,000 lb) and 45400 kg (100,000 lb), respectively.

Concrete Bridges

Alt (3) discussed the use of a portable prestressed concrete bridge for logging operations. A forest products company in Florida used this bridge for log truck traffic. It was constructed with three reinforced concrete slabs 1.2 m (4 ft) wide, 381 mm (15 in) deep, and 10.7 m (35 ft) long. Although this bridge was very cost-effective, its weight of 35400 kg (78,000 lb) made it necessary to use heavy construction equipment for installation and removal. Therefore, this design is probably not suitable as a portable bridge for forest operations.

Timber Bridges

Timber bridge designs include log stringer bridges, timber mats or "dragline" mats, modular timber truss bridges, longitudinal stringer with transverse deck bridges, and longitudinal glulam or stress-laminated deck bridges. The difficulties with log stringer bridges were mentioned earlier. Many loggers use timber mats; however, most are not engineered products and are not advertised as bridge components by their manufacturers. Although log stringer bridges and timber mats have been used successfully for many years, the recent advances in timber bridge technology include several engineered designs that can be easily adapted for use as portable bridges.

Probably the most promising designs for spans up to 12 m (40 ft) consist of longitudinal glulam or stress-laminated decks that are placed across the stream. These longitudinal deck designs are relatively simple to construct, are somewhat lightweight, and have comparatively thin cross sections. They can be prefabricated into large sections that can be quickly and easily installed at the stream crossing site with typical forestry equipment, such as hydraulic knuckleboom loaders or skidders. Also, it may be possible to install these bridges without operating the equipment in the stream, which minimizes the site disturbance and associated erosion and sediment load on the stream.

Hassler et al. *(4)* discussed the design and performance of a portable longitudinal stress-laminated deck bridge for truck traffic on logging roads. This bridge was constructed of untreated green mixed hardwoods. It was 4.8 m (16 ft) wide, 12.2 m (40 ft) long, 54 mm (10 in) thick, and was fabricated in two 2.4-m (8-ft) wide modules. The bridge was installed to assist timber harvesting activities on the West Virginia University Forest and was placed directly on the existing stream banks without abutments. The bridge was installed with a typical hydraulic knuckleboom loader and a skidder and performed satisfactorily under load tests. No significant water quality changes occurred as a result of the bridge installation.

Taylor and Murphy *(5)* presented another design of a portable stress-laminated timber bridge. This bridge was designed for logging truck traffic and consisted of two separate stress-laminated panels 1.4 m (4.5 ft) wide. The panels could be constructed in lengths up to 9.7 m (32 ft). Each panel was designed to be stressed separately and then placed adjacent to the other panel with a 0.6 m (2 ft) space between panels. The overall width of the complete bridge was 3.3 m (11 ft). The deck panels could be placed on a mud sill that would sit directly on the stream bank, Curb rails ran the length of the bridge. This bridge has not yet been tested; however, various companies are currently fabricating similar portable stress-laminated timber bridges.

DESIGN CRITERIA

General Considerations

Important characteristics that must be considered in the design and selection process for portable bridges include the design life, traffic type, and volume. The designer uses these characteristics to select the initial design concept and determine many important design criteria. For example, if the average daily traffic (ADT) is less than 50 vehicles per day and consists primarily of light vehicular traffic, it may be possible to use a curb instead of a full guardrail. Also, for many types of low-volume road bridges with short design lives, installing a wear surface on the bridge deck or using high levels of preservative treatments may not be necessary. However, if the bridge is expected to carry heavy off-highway vehicles, design loads must be accurately determined.

Table 1 gives examples of different design criteria that should be considered for three traffic volume categories: sub-low-volume, low-volume, and high-volume. The sub-low-volume road category might include skid trails and other temporary roads constructed during harvesting or management activities. These types of roads may be used by very light vehicles or by heavy off-highway vehicles. The low-volume road might include major haul roads carrying higher volumes of truck traffic. The high-volume roads consist primarily of public highways where temporary bridges are needed during construction or replacement of permanent bridges. The authors invite comments on these example criteria or suggestions for additional criteria.

A portable timber bridge should have several other general design characteristics to be a viable alternative for temporary stream crossings. The most important of these considerations may be the ease with which the bridge can be assembled, installed, removed, and transported. Ideally, field fabrication requirements should be kept to a minimum. The portable bridge design should facilitate installation and removal with typical forestry or light construction equipment. Many knuckleboom loaders or small cranes can lift bridge components weighing less than 3200 kg (7,000 lb) with lengths less than 10 m (32 ft). At sites where loader or crane use is not possible, forwarders or skidders can be used to drag bridge components to the stream and winch them into place. Regardless of the equipment used to place the bridge, provisions should be made to attach rigging materials to the components so they can be handled without damage. Also, it is important to design the bridge so that it can be transported on common log trucks or equipment trailers. Temporarily placing bridge sections on wheels and towing them to the site may be possible if roads are suitably constructed.

TABLE 1 Suggested Design Criteria for Portable Bridges Installed on Various Road Types

Criterion	Sub-Low Volume	Low Volume	High Volume
Design Life	≤ 5 years	≤ 15 yearn	> 20 years
Traffic Type	1. Off-highway 2. Light vehicles	1. Trucks 2. Light vehicles	ʟ Highway
Average Daily Traffic Flow	75	100	Unlimited
Design Speed	8-16 kph	8-16 kph	>40 kph
Load Criterion	Off Highway Loads	Off Highway Loads or Highway Loads	AASHTO HS20 or HS25
Load Application Period	6 months	24 months	36 months
Deflection Criterion	None	None	AASHTO Criterion
Span Type	Simple	Simple	Simple
Span Length	< l0 m	≤ 10 m	≤ 25 m
Width	4 - 5 m	4 - 5 m	≤ 9 m
Rail	Curb or None	Rail or Curb	AASHTO Rail
Wear Surface	Wood or None	Wood or None	Asphalt

1 kph = 0.6 mph   1 m = 3.3 ft

Design Procedures

Design procedures for highway timber bridges can be found in the AASHTO standard specifications *(6)* and the publication by Ritter *(7)*. Little previous research, however, has been conducted on appropriate design procedures for portable timber bridges on low-volume roads. Knab et al. *(8)* studied military theater-of-operations glulam bridges with design lives of 2 to 5 years. They concluded that using civilian design procedures, which are generally based on design lives of 50 to 75 years with relatively high levels of reliability, could result in unnecessarily conservative and uneconomical designs for the limited performance needs of temporary bridges. Using results from reliability analyses, they developed new design procedures and modification factors for allowable stresses that would result in adequate levels of structural safety for glulam girder bridges. They concluded that modification factors could be used to increase allowable bending, shear, and compression stresses for these temporary military bridges.

Other work by GangaRao and Zelina *(9)* examined the design specifications for low-volume civilian roads.

They concluded that the use of urban highway standards for low-volume road bridges results in overly conservative and uneconomical designs. They defined low-volume roads as those with maximum two-directional average daily traffic (ADT) of 200 vehicles or maximum two-directional average daily truck traffic (ADTT) of approximately 30 trucks per day. They suggested that allowable stresses for steel and concrete structures might be increased for such roads and that deflection limits might be relaxed for steel bridges. They did not recommend changing the deflection criteria of L/400 and L/300, where L is the bridge span, for low-volume concrete or timber bridges, respectively.

These research results *(8,9)* indicate that applying AASHTO design procedures to portable bridges on low-volume roads may result in overly conservative designs. The designer must consider that, in many cases, the design life of such a bridge may only be 5 to 10 years. Therefore, it may be possible to make changes such as increasing the load duration factor above that currently specified by AASHTO. However, additional research is needed before suggesting other changes in design procedures.

Strength Criteria

The designer of a portable bridge must determine the applicable loads and load combinations for the specific situation. For portable timber bridges that will carry highway truck traffic, including logging trucks, AASHTO standard vehicle loads, such as the HS20-44 (HS20), should be sufficient in most cases. However, in situations where heavier off-highway vehicles are used, the USDA Forest Service uses several additional standard vehicle overloads, such as the U80 or U102 truck *(7)*.

If the portable bridge is to be used only on skid trails and will only carry lightweight forestry equipment, alternate vehicle loading configurations may be used for design vehicle loads. Table 2 gives various types and sizes of forestry equipment with approximate vehicle weights and wheelbases and the results of calculations to determine the approximate maximum bending moments and shear forces for a bridge with a simple span

of 9.1 m (30 ft). These design loads vary depending on the actual vehicle weight and the assumption used for load distribution. If the bridge is subjected only to these types of loads, values such as those given in Table 2 may be used for design. Since these values are all less than the value for the HS20 truck load, using such a load for design may be overly conservative.

Serviceability Criteria

Ritter *(7)* provided a discussion of timber bridge serviceability. Deflection in bridge members, which is one of the primary concerns in serviceability, is important for performance and aesthetics. In general, excessive deflections cause fasteners to loosen and wear surfaces, such as asphalt or concrete, to crack. Also, bridges that sag below a level plane can give the public a perception of structural inadequacy. Excessive deflections from moving vehicle loads also produce vertical movement

TABLE 2 Design Moments and Shear Forces for Various Types of Forest Harvesting Equipment Based on 9.1-m Span (AASHTO H20 and HS20 loads included)

Vehicle Type	Overall Wheelbase (m)	Approximate Loaded Total Weight (kg)	Maximum Moment for the Vehicle (kN-m)	Maximum Vertical Shear (kN)
John Deere 770B Motor Grader	6.0	15,205	214.1	112.4
John Deere 450E Crawler Tractor	2.1	7,045	139.9	61.2
Caterpillar D5H Track Skidder	2.7	19,318	367.6	160.8
Caterpillar 528 Grapple Skidder	3.3	14,091	222.3	115.8
John Deere 540D Cable Skidder	2.9	10,000	164.0	83.8
John Deere 748E Grapple Skidder	3.4	15,682	242.6	127.6
Tree Farmer C6D Forwarder	5.3	17,500	215.5	126.9
AASHTO H20-44	4.2	18,182	334.6	161.4
AASHTO HS20-44	variable	32,727	382.8	220.4

1 m = 3.3 ft   1 kg = 2.2 lb   1 kN-m = 737 lb-ft   1 kN = 225 lb

and vibration that may annoy motorists. Since most portable bridges will not need an asphalt or concrete wear surface, deflection concerns are not as great as in highway bridges.

The 1993 edition of the AASHTO bridge specifications *(6)* recommends a deflection criterion of L/500 for highway timber bridge superstructures. Previously recommended deflection criteria ranged from L/2OO to L/1200 *(7)*. Ritter *(7)* recommended maximum deflections of L/360 for short-term loads and L/240 for the combination of live and dead loads. In many portable bridge applications, it may be possible to relax these criteria as shown in Table 1.

Design, Construction, and Cost

Design

A portable timber bridge consisting of longitudinal glulam deck panels was designed and fabricated for use in a study at Auburn University to document water quality impacts from different types of stream crossing structures on temporary forest roads. This bridge was designed for AASHTO HS20 loading with relaxed deflection restrictions and is 4.9 m (16 ft) wide and 9.1 m (30 ft) log. It uses four southern pine Combination 47 glulam deck panels *(12)* 1.2 m (4 ft) wide and 267 mm (10.5 in) thick. Sketches of the bridge are shown in Figure 1. More detailed plans are available from the authors. The bridge was designed to be installed on a mud sill with the bridge deck extending 0.6 to 1.5 m (2 to 5 ft) on either side of the stream banks, and leaving an effective span of approximately 6.1 to 7.9 m (20 to 26 ft). Transverse glulam 16F-V5 stiffener beams *(12)* 171 mm wide by 140 mm deep by 4.9 m long (6.75 in by 5.5 in by 16 ft) are bolted on the lower side of the deck as shown in Figure 1. Glulam 16F-V5 *(12)* curb rails on glulam curb risers 216 mm wide by 127 mm deep (8.5 in by 5 in) are bolted to the outside deck panels. These glulam combinations are balanced layups, that is, neither side of the beam is designated as the tension or compression side, thereby reducing the possibility of installing the beam incorrectly.

The deck panels can be installed directly on the stream banks with no abutments. However, a mud sill or spread footer is recommended for placement under each end of the bridge to prevent differential settling of the deck panels into the soil. The current design specifies a southern pine Combination No. 46 *(12)* glulam mudsill that is 384 mm wide by 76 mm deep by 4.9 m long (3 in. by 15.125 in. by 16 ft). One advantage of this small sill is that less soil and aggregate material are required to build approaches to the bridge; however, larger sills may be required depending on the site con-

ditions. All glulam components were precut and predrilled and then treated with creosote to retentions of 194 kg/m³ (12 lb/ft³) in accordance with American Wood Preserver's Association (AWPA) specification C14 *(10)*.

The original design specified attaching galvanized ASTM A36 steel angles 203 mm by 152 mm by 12.7 mm thick by 4.3 m long (8 in. by 6 in. by 0.5 in. by 14 ft) to each end of the bridge to prevent wear on the ends of the deck panels because of vehicle traffic. These wear plates were attached with lag screws. The stiffener beams, bearing pads, and steel angles provide additional continuity to the bridge system. An additional plank or steel plate wear surface may be installed on the bridge deck depending on use conditions. Galvanized steel tie-down brackets were also provided at each of the four bridge corners to prevent bridge movement from longitudinal vehicle loads and from lateral and buoyancy forces should flooding occur. Wire rope was used to connect the steel brackets to nearby trees (deadmen could also be used to anchor the bridge). All bolts were galvanized and complied with the requirements of ASTM A307.

Construction

After the bridge components were fabricated and treated with preservative but before installation, the curb rails were attached to the deck panels to minimize the amount of erection time at the site. The bridge components were then transported to the site on a flatbed equipment trailer. Each of the panels weighs approximately 2500 kg (5,500 lb) and can be easily lifted by most knuckleboom loaders or small truck-mounted cranes. The final step in the installation process was to use a crawler tractor or skidder to level an area on each stream bank for the mud sills. The mud sills were then placed on the soil surface by using a crane or winching them into place with a skidder or crawler tractor. Then the deck panels were set in place with the same truck-mounted crane. At some sites, the soil conditions were unsuitable for the crane truck to operate safely. In these cases, a crawler tractor equipped with a winch was used to pull the panels to the stream crossing. The tractor then crossed the stream and winched the panels into place. This task could also have been accomplished by securing a snatch block on the opposite side of the stream and winching the panels across the stream. The transverse stiffener beams were then bolted in place on the bottom side of the deck panels. Although many timber bridges on low-volume roads use a plank runner wear surface, we chose not to install one on this bridge. The bridge can be installed in approximately 6 hr. In addition to a loader or crane operator, at least two people are required
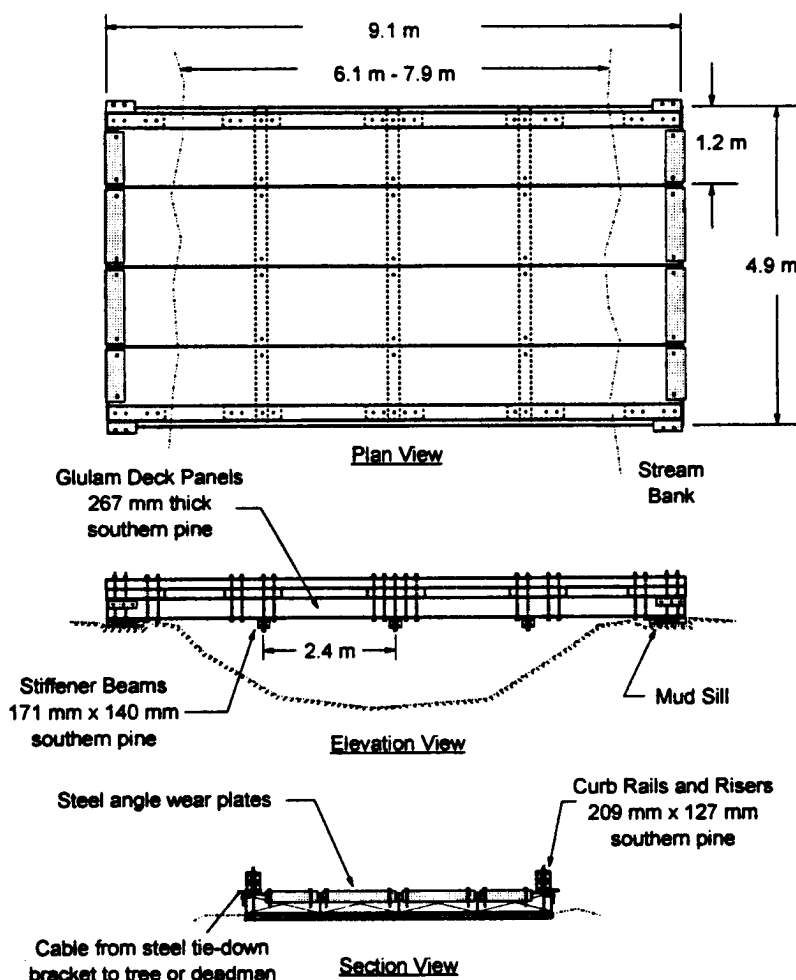
FIGURE 1 Design configuration of portable longitudinal glued-laminated timber deck bridge.

to place the components and bolt them together. The bridge can be removed in approximately 3 hr.

Cost

The total cost of the deck panels, curbs, stiffener beams, mud sills, and connectors for this bridge was $15,500 in 1993. Based on a total deck area of 44.6 m^2(480 ft^2), the cost per square meter was $347 ($32/ft^2). A conservative estimate for the cost of one installation and removal, including transportation to and from the site, equipment operations costs, and labor to install and re-move the bridge, was approximately $1,000. Distrib-uting these costs over 10 bridge installations, the bridge would cost $2,550 per installation, which is competitive with the cost of installing a permanent corrugated metal culvert for most streams. This cost is also competitive with the commercially available steel and concrete bridges discussed previously.

EVALUATION METHODOLOGY

The monitoring plans for the bridge called for stiffness testing of the individual lumber laminations, the com-pleted glulam deck panels, and stiffener beams before bridge construction. Also, load test behavior and bridge condition were assessed. These evaluation procedures are discussed in the following sections.

Stiffness of Bridge Components

Modulus of elasticity (MOE) tests were performed at the laminating plant to determine the stiffness of each lumber specimen used in the glulam deck panels before gluing. Then, after the panels and stiffener beams were glued together, similar tests were performed to deter-mine their respective MOE's. All of these tests were con-ducted using commercially available transverse vibra-tion equipment.

Load Test Behavior

Information obtained from load tests of bridges is important in improving current design procedures for both permanent and portable timber bridges. To determine the load test behavior of this bridge, static load tests were conducted at one installation of the bridge. The tests consisted of positioning a load on the bridge deck and measuring the resulting deflections at a series of locations along the bridge centerspan and at the ends of the bridge deck panels. Measurements were taken before loading, during load application, and after the load was removed. The load used in the test was a dual-axle dump truck with a combined rear axle weight of 190.4 kN (42,800 lb). The vehicle was positioned longitudinally to the bridge so that the centroid of the rear axles was aligned with the bridge centerspan (front axles were off the bridge). Two tests were performed: one with the vehicle facing north and one with the vehicle facing south on the bridge. The vehicle was positioned transversely so that the centerline of the truck was aligned with the bridge centerline. This position resulted in an application of the wheel loads directly to the two interior deck panels; that is, the wheels did not contact either of the two outside deck panels. Measurements of bridge deflection from the unloaded to loaded condition were obtained by placing a surveying rod on the deck underside and reading values with a surveyor's level to the nearest 1.5 mm (0.06 in.). Deflection readings were taken at 8 locations across the bridge width.

Condition Assessment

The general condition of the bridge components was assessed periodically during the monitoring period. These assessments involved visual inspection of the bridge components, measurement of moisture content of the bridge components with a resistance-type moisture meter, and photographic documentation of bridge condition. Items of specific interest included the condition of the top surface of the deck panels, the curb system, the stiffener beams, the mud sill, and anchorage systems.

RESULTS AND DISCUSSION

General Performance

The glulam bridge was installed and used at two different stream crossing sites on temporary logging roads near Auburn, Alabama, during 1993 and 1994. The bridge has performed satisfactorily under traffic loads of trucks hauling logs and chips, skidders, feller bunch-

ers, crawler tractors, and whole-tree chippers. Although this bridge is 4.9 m (16 ft) wide, bridges used for log truck traffic might be fabricated in smaller widths. However, a narrower bridge requires additional length of straight approach roadway for proper truck tracking on the bridge.

The mud sill provided adequate support; however, the soil under the mud sills experienced as much as 152 mm (6 in.) of permanent deformation immediately after traffic began using the bridge. In sites with weak bearing capacities, a larger sill or spread footer may be necessary to prevent excessive differential settling of the deck panels.

One modification was made in the steel angle attached to the ends of the deck panels. Originally, this angle was a single piece of steel 4.3 m (14 ft) long. Although it helped provide additional stiffness and continuity to the bridge system, it was difficult to handle during installation and removal of the bridge. Therefore, before the bridge was moved the first time, the angles were removed and cut into four separate pieces. Each of these pieces was then permanently reattached to the deck panels, thereby eliminating the need to remove them during transport. Also, in case the panels needed to be skidded into place, a short loop of steel chain was welded to the vertical face of the angle.

The transverse stiffener beams provided excellent load distribution and continuity among the deck panels. The current design uses a through bolt to attach them to the deck panels as shown in Figure 1. However, this stiffener beam configuration is difficult to install in the field because it is hard to position the deck panels so that all of the bolt holes are in line. Therefore, there is a need to develop alternative panel connection methods or use other stiffener beam configurations like those described by Ritter *(7)* that do not use the through bolts.

Stiffness of Bridge Components

The lumber used to fabricate the glulam deck panels was nominal 50 mm by 305 mm (2 X 12) No. 1 southern pine. Results of MOE tests on this lumber before gluing indicated that it had a mean flatwise MOE of 13652 MPa (1.98×10^6 psi) with a coefficient of variation of 19 percent. The design value of MOE for this grade of lumber is 11 722 MPa (1.7 X 10' psi) *(11)*.

Tests of the four laminated deck panels resulted in a mean flatwise MOE of 13 307 MPa (1.93×10^6 psi). This value is in contrast to the design MOE value for Combination 47 southern pine glulam timbers, which is 9653 MPa (1.4×10^6 psi) *(12)*. The discrepancy between the panel design MOE value and the actual MOE values may have resulted from using higher quality lumber than specified by the American Institute of Timber

Construction *(12)*. Figure 2 shows the close relationship beween lumber and deck panel MOE by plotting deck panel MOE versus mean MOE of the lumber used to fabricate each respective deck panel.

Tests of the three laminated stiffener beams resulted in a mean flatwise MOE of 16 479 MPa (2.39 X 10^6 psi). This resulted in a mean stiffness value (MOE multiplied by the moment of inertia) of 25270 kN-m (223,670 kip-in.), which is considerably higher than the minimum value of 9038 kN-m (80,000 kip-in.) recommended by Ritter *(7)*.

Load Test Behavior

The following results are for the maximum deflections recorded under both vehicle orientations. Also, the bridge deck deflections presented account for measured deflection at the bridge supports. When subjected to the axle load of 190.4 kN (42,800 lb) placed at the bridge centerspan, the vertical deflection of the deck panels at centerspan ranged from 10.7 to 28.9 mm (0.42 to 1.14 in.). Using an effective span of 8.7 m (28.6 ft) from center of bearing to center of bearing, this maximum deflection of 28.9 mm (1.14 in.) is equivalent to L/300. As expected, the maximum deflection occurred under one of the interior deck panels near the centerline of the bridge, and the minimum deflection was recorded at the outer edge of one of the exterior deck panels. No permanent residual deformation was observed in the bridge deck at the conclusion of the tests.

Predicted Bridge Behavior

Design procedures listed in the AASHTO specifications for highway bridges *(6)* can be used to determine the lateral distribution of live load bending moment for longitudinal glulam timber decks. The live load bending moment for each panel is determined by applying to the panel a fraction of the wheel load (WLF), where the WLF for one traffic lane is the minimum of

$$WLF = \frac{3.28\,W_p}{4.25 + \dfrac{L}{8.53}} \quad \text{or} \quad \frac{W_p}{1.68} \tag{1}$$

where

WLF = portion of the maximum bending moment produced by one wheel line of the vehicle that is supported by one deck panel,
W_p = panel width (m), and
L = length of the span, measured center to center of the bearings (m).

The maximum deflection also can be predicted by applying the same wheel load fraction to the panel. The predicted live load deflection of each glulam panel, Δ_{LL}, is equal to the maximum deflection produced by one wheel line, Δ_{WL}, applied to a single deck panel, times the WLF. The deflection can be computed using standard methods of elastic analysis, the full moment of inertia of the deck panel, and the panel MOE adjusted for wet use conditions. Using an actual MOE of 13307 MPa (1.93 x 10' psi), an axle load of 190.4 kN (42,800 lb), and an effective span of 8.7 m (28.6 ft), the predicted deflection at centerspan from one wheel line, Δ_{WL}, is 51.6 mm (2.03 in.). Using a panel width of 1.2 m (4 ft) and a span of 8.7 m (28.6 ft), the resulting WLF is 0.76. Therefore, when Δ_{WL} is multiplied by WLF, the predicted maximum deflection of the bridge deck, using AASHTO procedures, would be 39.1 mm
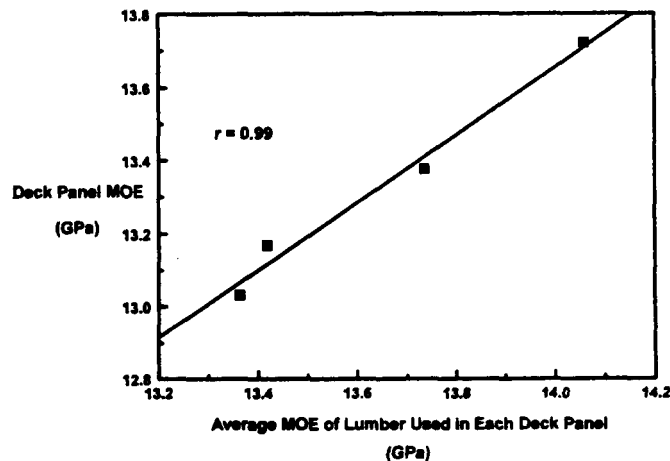

FIGURE 2   Glulam deck panel MOE versus mean MOE of lumber used to manufacture each deck panel for longitudinal glulam deck bridge.

(1.54 in.). If the recommended moisture adjustment factor of 0.833 is used, the predicted deflection now becomes 47.0 mm (1.85 in.). In both cases, the predicted deflection is considerably greater than the measured deflection of the bridge.

This discrepancy between predicted and actual deflection may have been caused by load sharing among deck panels that was greater than that predicted by AASHTO procedures. Using AASHTO procedures, the proportion of the total wheel load that should be carried by a single longitudinal deck panel is 76 percent. However, using the actual deflection data from the load tests, the equivalent proportion of the wheel load that was apparently carried by a single deck panel was approximately 56 percent.

Condition Assessment

After 12 months of use, the condition assessment of the bridge indicated that structural and serviceability performance was good. Discussion of inspection results for specific items follows.

Wood Components

Inspection of the wood components of the bridge showed no signs of deterioration. Minor checking was observed on the curb rail members and on the upper side of the deck panels because they were exposed to more wet-dry cycles. Also, very minor checking was observed in the end grain of some of the deck panels within a month after fabrication and treatment. The depths of these checks did not appear to penetrate the preservative treatment envelope of the components. Rough handling during installation and removal of the bridge resulted in minor damage to some components; however, the damage did not reduce the structural adequacy of the bridge.

Moisture content of the bridge deck panels and the stiffener beams was monitored during the use of the bridge. Although the components had a mean moisture content of 12.2 percent after fabrication at the manufacturing plant, the mean moisture content increased to 15.2 percent after 12 months. In general, the moisture content of the top surface of the deck panels was 1 to 3 percent higher than the lower surface.

There were excess creosote accumulations on the surface of the deck panels and curb rails that may have been caused by a creosote retention higher than that specified [assay results from the treatment plant showed an actual retention of 292 kg/m^3 (18 lb/ft^3) in the deck panels instead of the 194 kg/m^3 (12 lb/ft^3) specified]. Other preservatives, such as chromated-copper arsenate

(CCA) or pentachlorophenol, maybe more desirable for a bridge that will be handled several times. The primary advantage of creosote over the other treatments is its ability to form an envelope that prevents the wood from absorbing water.

Bridge Deck Surface

The steel angle wear plates installed on the ends of the deck panels appeared to be preventing damage from traffic as it drove onto the bridge deck. But, since the bridge deck was constructed without an additional wear surface, particular emphasis was placed on observing damage to the top surface of the deck panels. Gravel and other debris carried onto the bridge by traffic have left numerous gouges in the surfaces of the deck panels; however, none of these gouges are deep enough to reduce the structural adequacy of the bridge and none of them have penetrated the preservative treatment envelope. Therefore, an additional wear surface does not appear to be needed.

SUMMARY AND CONCLUSIONS

Cost-effective portable bridge designs are needed for temporary low-volume roads. Although there is much new technology in timber bridges, little research has applied this technology to portable bridge systems. Many of the advantages of timber bridges, which are lightweight and easy to fabricate and install and which can be prefabricated, make them ideal for temporary stream crossings on low-volume roads.

Previous research on glulam military bridges and on bridges for low-volume roads indicates that, although using the AASHTO design procedures for portable timber bridges is safe and conservative, it may result in overly conservative and uneconomical designs. A matrix of proposed design criteria presented here suggests that many of the AASHTO criteria can be modified for portable bridge systems. However, additional research is needed on design procedures and strength and serviceability criteria for portable timber bridges.

The design of a portable longitudinal glulam timber deck bridge was presented in this paper. Based on tests of this bridge over a period of 12 months, the following specific conclusions are given:

1. It is economically feasible to fabricate and use portable timber bridges for temporary stream crossings on low-volume roads.

2. Portable timber bridges can be successfully installed, used, and removed without sustaining substantive damage.

3. Load testing and analysis indicate that the longitudinal glulam bridge system is stiffer than AASHTO design procedures predict. The predicted deflection at the bridge midspan was 47.0 mm (1.85 in.), and the actual deflection was 28.9 mm (1.14 in.), or L/300, under an axle load of 190.4 kN (42,800 lb).

4. Greater distribution of vehicle loads than predicted by AASHTO appears to be occurring among the deck panels in the longitudinal glulam deck system. When load test data were used, the apparent WLF was 0.56; when AASHTO procedures were used, the WLF was 0.76.

5. The bridge deck panels have withstood abuse from vehicle traffic without needing an additional wear surface.

REFERENCES

1. Rothwell, R. L. Erosion and Sediment Control at Road-Stream Crossings. *Forestry Chronicle,* Vol. 23, 1983, pp. 62-66.
2. Swift, L. W. Forest Road Design to Minimize Erosion in the Southern Appalachians. In *Proceedings, Forestry and Water Quality: A Mid-South Symposium* (B.G. Black-mon, ed.), Cooperative Extension Service, University of Arkansas, 1985, pp. 141-151.
3. Alt, B. C. *Portable Pre-Stressed Concrete Logging Bridge.* American Pulpwood Association Technical Release 91-R-64. American Pulpwood Assoc., Washington, D. C., 1991.
4. Hassler, C. C., M. P. Wolcott, B. Dickson, R. E. Driscole, and W.B. Perry. A Modular Timber Bridge for Temporary Stream Crossings. In *Proceedings of the 13th Annual Meeting of the Council on Forest Engineering* (A. E. Hassan and E. L. Deal, eds.), North Carolina State University, 1990, pp. 190-194.
5. Taylor, S. E., and G. L. Murphy. *Portable Timber Bridge Designs for Temporary Forest Roads.* ASAE Technical Paper 92-4559. ASAE, St. Joseph, Mich., 1992.
6. *Interim Standard Specifications for Highway Bridges. AASHTO,* Washington, D.C., 1993.
7. Ritter, M. A. *Timber Bridges: Design, Construction, Inspection, and Maintenance.* USDA Forest Service, Washington, D. C., 1990.
8. Knab, L. L, R. C. Moody, W. W. Sanders, and H. A. Elleby. *Design Criteria for Theater of Operations Glued-Laninated Timber Highway Bridges,* Vol. L Technical Report No. M-198. U.S. Army Engineer Construction Engineering Research Laboratory, Champaign, 111., 1977.
9. GangaRao, H. V. S., and T. R. Zelina. Development of Low-Volume Road Bridges. *Journal of Structural Engineering,* ASCE, Vol. 114, No. 9, 1988, pp. 1941-1961.
10. *Standards.* American Wood Preserver's Association, Woodstock, Md., 1991.
11. *Design Values for Wood Construction: A Supplement to the 1991 Edition of the NDS.* American Forest and Paper Association, Washington, D. C., 1991.
12. *AITC 117-93 Design, Standard Specifications for Structural Glued-Laminated Timber of Softwood Species.* American Institute of Timber Construction, Englewood, Colo., 1993.