DEVELOPMENT AND TESTING OF PORTABLE GLULAM TIMBER BRIDGE SYSTEMS

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ABSTRACT

Interest in portable bridge systems has increased due to heightened awareness for reducing environmental impacts and costs associated with road stream crossings. To illustrate the effectiveness of timber bridges used in portable applications, this paper presents case studies of portable bridges constructed with longitudinal glued-laminated timber decks. Also, the paper discusses the need to account for dynamic loading effects in bridge design procedures. Longitudinal timber deck superstructures appear to be the most attractive option for use as portable bridges. The example glulam bridges performed well and were cost effective. Superstructure costs ranged from \$347/m^2 to \$414/m^2 with total costs ranging from \$325 to \$2,760 per site. Results from dynamic loading tests showed mean dynamic amplification factors ranged from 1.15 to 1.64 and 95th percentile values ranged from 1.31 to 1.88. Therefore, portable bridge design procedures need to account for dynamic effects from vehicle loads.

Keywords: portable bridge, dynamic loading, glulam

INTRODUCTION

Portable or temporary bridges have been used traditionally in military or construction applications. In construction applications, portable bridges are used when permanent highway bridges are being replaced and temporary bypasses are needed. Also, portable bridges serve as temporary structures during disaster situations, e.g. when floods wash out highway bridges. There are other situations where temporary access is needed across streams in remote areas for utility structure construction or maintenance.

Currently, portable bridge interest is high in forestry and related natural resource industries. This interest results from efforts to reduce environmental impacts from forest road construction. Stream crossings are the most frequent sources of erosion and sediment introduction into forest streams (I). Of the stream crossing structures used on forest roads, several studies showed that proper installation of portable bridges significantly reduced sediment production compared to low-water crossings and culverts (1). If properly designed and constructed, portable bridges can be easily transported, installed, and removed for reuse at multiple sites, which makes them more economically feasible than permanent structures.

Many timber bridge advantages, which include being lightweight and easy to prefabricate, make them ideal for temporary stream crossings. Recent work at Auburn University and the USDA Forest Service focused on developing portable timber bridge systems. Several prototype bridges using longitudinal glued-laminated timber (glulam) decks were developed and tested. Specific objectives of this paper are to: 1) review general design criteria for portable timber bridges; 2) review portable glulam bridge case studies; and 3) discuss the need to account for dynamic loads in portable bridge design.

PORTABLE BRIDGE DESIGN CRITERIA

Timber bridge design procedures for permanent highway applications can be found in American Association of State Highway and Transportation Officials (AASHTO) (2) and Ritter (3). Little research, however, has been conducted on appropriate design procedures for portable timber bridges. Previous research (4) indicated that applying AASHTO design procedures to portable bridges on low-volume roads may result in overly conservative designs. It was concluded that using civilian design procedures, which are generally based on high traffic volumes and design lives of 50 to 75 years, could result in unnecessarily conservative designs for temporary bridges.

To insure efficiency of portable bridges, Taylor et al. (5) proposed a matrix of design criteria for different portable bridge types, depending on intended use. The matrix was developed for bridges used on three different road types. Franklin et al. (6) modified this matrix (Table 1) to include four classes of bridge applications: two cases of sub-low volume, and one case each of low-volume and high-volume roads. Sub-low volume bridges, Case 1, include bridges used by forestry machines such as wheeled skidders. Sub-low volume bridges, Case 2, include bridges used by log truck traffic, with very low traffic rates (e.g., a single logging operation). Low volume bridges are for main forest roads with higher traffic rates. High-volume bridges are for highway applications where they are bypasses for bridges under construction. Several prototype bridges suitable for each category were constructed and tested.

PORTABLE GLULAM BRIDGE CASE STUDIES

Timber bridge superstructures are constructed in several configurations. However, for portable bridge use, longitudinal decks appear to be the most desirable alternative. Longitudinal timber decks can be lifted or winched into place and generally require less installation time than other bridges.

Traditional Longitudinal Glulam Deck Bridge for Truck Traffic

Design

Taylor et al. (5) presented a portable longitudinal glulam deck bridge for logging trucks (Figure 1). This bridge is similar to longitudinal glulam decks used in highway applications. It could be used for low-volume or high-volume portable bridge categories. The design vehicle was an AASHTO HS20 truck (2) with a deflection limitation of L/240, where L represents bridge span. The bridge is 4.9 m wide and 9.1 m long. It uses four Combination 47 (7) glulam deck panels, 1.2 m wide and 267 mm thick. It was designed to be installed on timber sills, with the bridge deck extending 0.6 to 1.5 m on either side of the stream banks, thereby leaving an effective span of approximately 6.1 to 7.9 m. Transverse glulam stiffener beams of combination 16F-V5 glulam (7) measuring 171 mm wide, 140 mm deep, and 4.9 m long were bolted on the lower side of the deck. Glulam combination 16F- V5 curb rails on glulam curb risers measuring 216 mm wide and 127 mm deep were bolted to the outside deck panels. All wood components were treated with creosote to a retention of 194 kg/m^3.

Although deck panels could be installed directly on stream banks without abutments, placement of timber sills or spread footers under each bridge end prevented differential settling of deck panels into the soil. A wearing surface was not installed on the bridge deck; however, steel angles were attached to each bridge end to prevent wear on the panel ends. Steel tie-down brackets were provided at each bridge corner to allow it to be secured to nearby trees. Securing the bridge was important since flood waters rose over the bridge several times. All steel hardware was galvanized.

Installation and Removal

The bridge was installed in less than six hours and removed in less than three hours by typical forestry or construction equipment. It was lifted into place using excavators or truck-mounted cranes and it was winched into place using a crawler tractor. To lift panels, slings or chains were attached to eye bolts placed through the deck panels. Installation and removal activities were accomplished without operating equipment in streams or disturbing stream channels or banks. Therefore, based on visual appraisal, there were no adverse impacts on water quality during construction.

Cost

Bridge components had an initial cost of $15,500. Based on deck area of 44.6 m^2, cost per square meter was $347. Average cost to transport, install and remove the bridge was approximately $1,000 per site. Distributing costs over 10 sites, the bridge would cost $2,550 per site, which was competitive with installing permanent culverts or fords (5).

Performance

The bridge performed satisfactorily under periodic use in logging operations. It was easily installed and removed with typical forestry or construction equipment. Results from static load tests indicated that maximum bridge deflections at mid-span were approximately L/300 at 119% of design bending moment. When deflection data were compared to those predicted using AASHTO design procedures, there was more apparent load distribution among deck panels than predicted using AASHTO procedures. Vehicle traffic on the unprotected bridge deck surface did not result in significant damage, thereby supporting the decision not to use a wear surface. If the bridge could be reused on at least ten sites, its cost was equivalent to typical costs for installation of culverts or constructed fords. In addition to being installed with no adverse impacts on water quality, the bridge produced less sediment after installation than that of a nearby culvert crossing, based on water samples taken upstream and downstream of the crossings during storm events (I). One area identified for potential improvement was the use of transverse stiffener beams. Installation and removal times could be reduced with easier methods of attaching stiffeners or by using alternatives to them.

Simple Longitudinal Glulam Deck Bridge for Off-Highway Vehicles

Design

Taylor et al. (8) described a longitudinal glulam deck bridge designed for off-highway vehicle traffic. The bridge, which is in the sub-low volume class, was used for rubber-tired log skidders (Figure 2). The design vehicle was a 15,454 kg skidder with a 3 m wheelbase. This bridge consists of two Combination 48 (7) glulam panels 1.2 m wide, 216 mm thick, and 8 m long.

Discussion of the previous bridge mentioned that transverse stiffeners were cumbersome to attach and remove. Therefore, to simplify installation, deck panels in this bridge were not interconnected and each panel was designed to carry one vehicle wheel line. Also, no curb or rail was used since relatively rough service would have damaged them quickly. Panels were treated with creosote to a retention of 194 kg/m^3.

After preservative treatment, 6 mm thick steel plate was attached to panel ends and sides to prevent damage from skidder grapples. Also, steel lifting brackets with chain loops were attached at panel centers to facilitate loading and unloading by typical knuckleboom loaders. Instead of using bolts to attach steel hardware to the glulam, 19 mm diameter steel dowels were placed through the glulam panels, welded to the steel plate, and ground flush. This attachment method eliminated exposed bolt heads that could be damaged during skidding operations. Since this bridge had a five-year projected service life, steel hardware was not galvanized. Instead, a primer coat of paint was applied to steel after installation.

Installation and Removal

Bridge panels were placed by using skidder grapples to pick up the panels, back over the streams, then lower the panels onto the stream banks. Panels could also be winched into place. A gap was left between panels so that wheel lines of skidders matched center lines of each panel. Logs were placed between panels to prevent excessive debris from falling into streams during skidding operations. A conservative estimate for total time to install and remove the bridge was 2 hours. This includes skidding the bridge to stream crossing sites, placing bridge deck panels, placing logs between panels, removing panels and logs, and skidding panels back to a loading area. Actual time required to place panels at streams was approximately 30 minutes. The bridge was installed by one person and since the stream channel and stream banks were not disturbed during installation, there were minimal impacts on stream water quality based on visual observation.

cost

Initial cost of the finished prototype glulam panels was $9,300. However, current estimates for fabricating the bridge panels are approximately $8,000. Based on actual deck area of 19.3 m^2, the cost would be approximately $414/m^2. Transportation, installation, and removal costs are estimated at approximately $165 per site. This type of bridge is intended for applications where the bridge will only be used for a few days in one location. Therefore, it should be used at many more locations than the bridges in the other two case studies. If the bridge was installed at 50 different sites, cost per site would be $325.

Performance

In its initial use period, the bridge performed well and was easy to install and remove. In early installations, skidder grapples damaged the glulam panel sides in areas not protected by steel plates. This damage did not affect structural adequacy of the bridge or expose untreated wood. Subsequently, additional steel plates were added along the sides of the deck panels. Future bridges for skidders might include continuous coverage of steel plating around all sides of the panels. Also during use, some of the chain loops used in lifting failed. To repair the lifting brackets, steel clevises were welded in their place and steel shackles were placed through the clevises.

Using measured panel stiffnesses, predicted bridge deflection under the design skidder was approximately L/173. Recent tests (6) showed bridge panel deflections were approximately L/196 under actual wheeled skidder loads very similar to the design load. These deflections were essentially unnoticed by skidder operators as they drove across the bridge. Overall, the bridge was well received by forest landowners and loggers because it was easy to install and remove and it appeared to reduce environmental impacts at stream crossings.

Prototype Longitudinal T-Section Glulam Deck Bridges for Highway Vehicles

Design

The portable longitudinal deck designs discussed previously were limited to spans of approximately 9 m due to practical limitations on deck panel thickness. However, more efficient technology is needed for spans up to 15 m. Therefore, two prototype longitudinal glulam deck bridges were designed and constructed in a double-tee cross section to test the feasibility of achieving longer spans for portable bridges while retaining the concept of a longitudinal deck bridge (8.9) (Figure 3). These bridges would be in the low-volume or high-volume bridge categories.

The first bridge was purchased by Georgia Pacific Corporation and was designed for log trucks. The bridge consisted of two longitudinal panels 12 m long and 1.8 m wide giving a total bridge width of approximately 3.6 m. The second bridge was 10.7 m long and was purchased by the Morgan County, Alabama Forestry Planning Committee and was also designed for log truck traffic. The design vehicle for both bridges was an AASHTO HS20 truck with no specified deflection limitation. The panels were not interconnected; therefore, each panel carried one wheel line of the design vehicle. Panels were placed side by side on timber sills, which were placed directly on stream banks. Vertically-laminated flanges were 171 mm thick and 1.816 m wide and were fabricated using No. 1 Southern Pine nominal 50 by 203 mm lumber. Two 286 mm wide and 314 mm thick webs were horizontally laminated to the lower side of the flange. Webs were fabricated using Southern Pine nominal 50 by 305 mm lumber that met specifications for 302-24 tension laminations (7). The designers did not necessarily intend that future bridge webs would be constructed using all 302-24 lumber. However, the laminator had a large supply of lumber in this size and grade and therefore chose to use it in this prototype bridge. At bridge panel ends, flanges extended 0.6 m beyond the web ends. This flange extension was to facilitate placement of bridge panels on the sills.

Interior diaphragms measuring 286 mm wide and 210 mm thick were placed between the webs at three locations along the panel lengths: one at each end, and one at midspan. To provide additional strength in the flanges weak axis, 25 mm diameter ASTM Grade 60 steel reinforcing bars were epoxied into the glulam flanges and diaphragms. Reinforcing bars were placed in holes drilled horizontally through the flanges at panel third points. Additional reinforcing bars were placed horizontally through the diaphragms near the panel ends.

At each panel end, 19 mm diameter bolts were installed through the horizontal axis of the flange. At the flange inside edge, a 152 by 152 by 13 mm steel plate was attached to the bolts. At the flange outside edge, a 305 mm long, 152 by 152 by 13 mm steel angle was attached to the bolts. Chain loops were welded to the square plates and the steel angles to facilitate panel lifting and securing. The angles served as supporting brackets for curb rails that extended the bridge length. Additional curb brackets were provided at third points along the outside edge of the flange. Curb rails consisted of 140 mm deep, 127 mm wide, and 11.6 m long Southern Pine Combination 48 (7) glulam beams. The curbs were intended only for delineation purposes; not as structural rails.

Wearing surfaces were not provided on the bridges. However, a 1.8 m long 152 by 102 by 13 mm steel angle was attached with three 19 mm diameter lag screws to the top face of each flange at each bridge end to prevent damage as vehicles drove onto the bridge. In addition, to prevent damage during bridge installation, a 6 mm thick steel plate was attached to the end of each web with 19 mm diameter bolts. To facilitate lifting of the bridge panels, lifting eyes were placed 0.9 m from either side of the bridge panel midspan. A primer coat of paint was applied to all steel hardware before installation.

Steel hardware was installed on the finished deck panels before they were shipped from the laminating plant. The deck panels were then shipped to a treating facility where they were treated with creosote to 194 kg/m. The steel hardware did not affect preservative penetration or retention in the wood. Installation of hardware before shipping to the treating facility allowed the finished bridge to be installed with no further fabrication or assembly.

Installation

The bridges were installed by lifting in place with excavators or by skidding into place with crawler tractors. Both bridges were placed on timber sills, which rested directly on stream banks. Sills were 762 mm wide and 4.9 m long and were constructed from nominal 152 by 152 mm Southern Pine timbers that were bolted together with 19 mm diameter bolts. The timbers were preservative treated with Chromated Copper Arsenate.

Typical installations began by placing timber sills on both sides of the stream. The excavator carried bridge panels to the stream and placed them on the sills. At most sites, equipment did not operate in the stream during installation. Therefore, there were minimal water quality impacts during installation. At sites where distance between the top edges of the stream banks was slightly wider than bridge length, supplementary footings were constructed by placing rip rap on stream banks, then timber sills were placed on the rip rap. On wider streams, the excavator was placed in the center of the stream channel and used to lift bridge panels into place.

Clearing stream banks and placing bridge panels was completed in an average time of 2 hours. After panels were in place, wire ropes were secured to chain loops at each bridge comer and to nearby trees to prevent bridge movement during flood events. Securing bridges required an additional hour. Additional time was required to complete final road approaches. Bridge removal was accomplished similar to installation and required an average time of two hours.

Cost

<u>Georgia Pacific Bridge</u>

Cost for materials, fabrication, treating, and shipping of the glulam bridge was $17,000. Based on a deck area of 44.6 m^2, the cost was approximately $381/m^2. Cost for sills was $600. Average cost for labor and equipment to install and remove the bridge was $1,000, which included $540 for the excavator, $300 for trucking, and $160 for additional labor. Therefore, total cost to install this bridge one time was $18,600. Projected total cost to transport, install, and remove the bridge at 10 different sites was $10,000. When this was added to initial bridge cost, estimated total costs of the bridge system, distributed over 10 sites, was $27,600 or $2,760 per site.

<u>Morgan County Bridge</u>

Cost for materials, fabrication, treating, and shipping of the glulam bridge was $14,000. Based on a deck area of 39.0 m^2, the cost was approximately $359/m^2. Cost for the sills, cable and associated hardware was $825. Cost for labor and equipment to install and remove the bridge was $1095. Therefore, total cost to install and remove this bridge the first time was $15,920. Projected total cost to transport, install, and remove the bridge at 10 different sites was approximately $10,950. When this was added to the initial bridge and sill costs, the estimated total cost of the bridge system, distributed over 10 sites, was $25,775 or $2,578 per site.

Performance

Based on static bending tests of finished bridge panels, all deck panels exhibited linear elastic behavior and had apparent modulus of elasticity values ranging from 14,962 MPa to 16,341 Mpa (9). When actual lumber properties data were used to predict panel stiffness, a transformed section model overpredicted stiffness by approximately 10.5% while a finite element model overpredicted stiffness by approximately 15.5%.

Field load tests of the bridges showed acceptable stiffness levels. For the Georgia Pacific bridge, maximum midspan deflection values were approximately L/975 at 55% of design bending moment. For the Morgan County bridge, maximum midspan deflection values were approximately L/2400 at 52% of design bending moment.

When handled properly, the bridges performed well with minimal damage. Rough handling during one bridge removal damaged curbs and steel hardware on the Georgia Pacific bridge. Checks developed at several locations on the bridges, and the checks appeared to be related to holes drilled in the webs and flanges during panel fabrication. However, they do not appear to have affected structural adequacy of the bridges.

DYNAMIC LOAD TESTING OF PORTABLE BRIDGES

Design procedures for timber bridges account for both strength and serviceability criteria. Since portable bridges may not use additional wearing surfaces, deflection limitations are not as critical as in highway bridge design. However, strength criteria are of utmost concern in any design.

Current design methods for highway timber bridges only account for static vehicle loads because historically, structural wood components were considered to resist impact loads sufficiently to preclude the need to account for impact in bridge design. However, recent work (10) presented data on dynamic response of timber bridges to vehicle live loads. These data indicated bridge deflections could be significantly greater under dynamic loading than under static loading. Therefore, to insure safe portable bridge design procedures, dynamic loading tests were conducted on two of the bridges described earlier: 1) the off-highway vehicle bridge, and 2) the Morgan County T-section bridge.

Descriptions of Test Conditions

For dynamic load tests of the off-highway vehicle bridge, it was installed in a location specifically for the tests. A pit was constructed so that the bridge panels could be placed as if they were crossing a stream. The pit was constructed to allow placement of panels on timber sills and to allow placement of deflection sensors underneath the bridge panels. The pit measured 8.2 m long by 4.3 m wide by 0.6 m deep. After preparing the pit, timber sills measuring 127 mm thick by 457 mm wide were placed on the soil surface with a clear span between inside edges of the sills of 7.3 m. Bridge panels were then placed on the sills with a gap between panels of 0.9 m as in typical installations. Approaches were leveled with a motorgrader before testing began. The Morgan County T-section bridge was tested as it was installed two years earlier. Ends of the T-section deck flanges were placed on timber sills that were laid on the stream banks. However, the ends of the webs of the T-section also were resting on the stream banks and therefore provided additional support for the bridge. Distance between edges of the bearings was approximately 6.9 m.

Instrumentation

Dynamic response of bridge panels was recorded during repeated passage of a wheeled skidder over the off-highway vehicle bridge and a tandem-axle truck over the T-section bridge. Bridge panel deflections were measured at midspan and at locations immediately adjacent to bearings using direct current displacement transducers (DCDTs). At each of the three transducer locations (i.e., midspan and at each bearing), multiple transducers were placed across the width of the bridge panels. A PC-based data acquisition system was used to record deflection values from each DCDT at 45 Hz.

Test Procedures

Dynamic deflection behavior for the bridges was determined using two different vehicles operating at three different speeds with two bridge entrance conditions. A Caterpillar 525 wheeled grapple skidder was used as the test vehicle for the off-highway vehicle bridge. This skidder had an operating weight of 15,331 kg and a wheelbase of 3.5 m. The maximum static bending moment resulting from this vehicle was approximately 90% of the design moment for the bridge. Test runs were made for two different bridge entrance conditions: smooth and rough. An artificial rough bridge approach was created by forming an earthen bump measuring approximately 200 mm wide by 100 mm thick and placing it approximately 300 mm away from the bridge panel end. Test runs were made at 9.2 kph, 13 kph, and 23.5 kph with wheel lines were centered over the longitudinal axis of the bridge panels. Five test runs were made at each speed and entrance condition for each bridge panel.

A tandem-axle truck was used for T-section bridge tests. The truck had a wheelbase of 5.0 m and a gross weight of 17,600 kg. The maximum static bending moment resulting from this truck was approximately 52% of design moment. Test runs were made for smooth and rough bridge entrance conditions. An artificial rough bridge approach was created by using a sawn timber measuring 200 mm wide by 100 mm thick and placing it approximately 300 mm from the bridge end. Smooth condition test runs were made at 8 kph, 16 kph, and 24 kph with truck wheel lines centered over the longitudinal axis of the bridge panels. Rough condition test runs were made at 8 kph only. Ten test runs were made at each speed and entrance condition for each panel.

To obtain reference conditions for comparison with dynamic deflection values, static load tests were conducted for both bridges. In these tests, vehicles were moved very slowly across the bridges and deflection values were recorded for all DCDTs. The maximum net deflection recorded at midspan was used as the static deflection.

Data Analysis

Plots of bridge deflection versus time were created for each DCDT in each test run and the static load tests. To obtain true net deflection at midspan, deflection readings from the bearings were subtracted from midspan deflection values. Using dynamic and static deflection data, a Dynamic Amplification Factor (DAF) was determined for each data stream recorded for each DCDT located at bridge midspan. The DAF was found by:

$$\text{DAF} = \frac{\text{Maximum Dynamic Deflection}}{\text{Static Deflection}} \qquad (1)$$

Dynamic Test Results and Discussion

Examples of typical dynamic deflection plots are shown in Figure 4 for the bridges. The plots illustrate how bridge deflection increased under dynamic loads exerted by moving vehicles compared to values recorded in static load tests. These deflection increases indicate that the bridges experienced dynamic loads considerably higher than those exerted by a static vehicle.

The plots also illustrate that in the dynamic bridge - vehicle systems, there were two primary vibration modes present. The first mode was a relatively high-frequency, low-amplitude vibration that was the fundamental vibration mode of the bridge deck panel. The second mode was a relatively low-frequency, high-amplitude vibration mode due to vehicle bounce and pitch. Dynamic deflection plots for test runs with rough approaches show that amplitude of vehicle vibration was significantly greater when vehicles encountered rough bridge entrance conditions.

Deflection data from each test run were used to calculate values of DAFs. Table 2 includes summary statistics for DAFs determined for the off-highway bridge and the T-section bridge tests. Also, Figure 5 contains relative frequency histograms of the DAF data for the skidder bridge and the T-section bridge. These data indicate that, overall, levels of bridge deflection resulting from dynamic loads were greater than those measured in static tests.

The table contains quantile information that may be used to modify the current design procedures. For example, to safely consider effects of actual dynamic loads in portable bridge design, a dynamic load adjustment factor may be used to increase static vehicle loads. To choose an appropriate value of DAF, a value in the upper tail of its probability distribution should be considered. If, for example, the 95th percentile is chosen for the dynamic amplification factor, this would result in increasing current static design loads by a factor of approximately 1.65 or 1.7. However, upon closer examination of test conditions, skidder bridge tests that were conducted at higher speeds were not representative of common operating speeds for wheeled skidders. Therefore, if only the tests conducted at speeds of approximately 8 kph were considered, the 95th percentile of DAF for both smooth and rough conditions was approximately 1.37, which would suggest use of a DAF of approximately 1.4 for designing sub-low volume bridges. After examining test data from the T-section bridge, which would typically be used in the low or high volume bridge categories, the 95th percentile of DAF for all speeds and approaches was 1.64. Since it is conceivable for this bridge to experience all of the speeds and entrance conditions tested, it may be advisable to use the higher DAF value of approximately 1.6 for design purposes.

Using these suggested values of DAF to adjust design loads would be a significant increase over current design loads; therefore, additional study is necessary before recommending a final dynamic amplification factor. The tests of the off-highway vehicle bridge used a vehicle very similar to the design vehicle while the tests of the T-section bridge used a truck that produced static bending moments that were approximately 52% of the design moments. Additional tests using vehicles that are much heavier than the design vehicle may be needed to document values of DAF at the higher loads. However, based on test data presented here, it is clear that bridge designers should not ignore higher levels of vehicle loads due to dynamic effects.

Design procedures for wood structures adjust values for wood strength properties based on the cumulative amount of time the design load is applied. If the dynamic load is used for design, the assumed duration of load will be shorter than what is currently assumed for static loads. This shorter duration of load will allow the designer to use a corresponding increase in wood strength values. Additional research is needed to determine the appropriate levels of load duration factors to use in conjunction with different levels of DAF.

CONCLUSIONS

Based on several years of development and testing, longitudinal glulam deck timber bridges have performed well as portable bridges in temporary stream crossing applications. The following specific conclusions can be made at this time:

1. It is feasible and practical to construct and install portable longitudinal glulam deck timber bridges.
2. The total time to install the bridges ranged from 30 minutes to six hours. Installations were easily accomplished using common construction equipment, with minimal disturbance of the stream channels.
3. Bridge superstructure costs ranged from $347/m^2 to $414/m^2. Estimated total costs (including transportation, installation, and removal) ranged from $325 to $2,760 per site.
4. When handled properly, the bridges performed well with minimal damage.
5. The bridges exhibited levels of stiffness acceptable for portable bridges. Maximum deflections during static load tests ranged from L/193 for the off-highway vehicle bridge (at design bending moment) to approximately L/2400 for the T-section bridge (at 52% of design bending moment).
6. Bridge deflections under dynamic loading were greater than under static loading. Under smooth bridge entrance conditions, mean DAF values ranged from 0.99 to 1.22 while 95th percentile values of DAF ranged from 1.31 to 1.73. Under rough entrance conditions, mean DAF values ranged from 1.22 to 1.64 while 95th percentile values of DAF ranged from 1.37 to 1.88.
7. Based on dynamic load test results, design procedures for portable timber bridges need to account for dynamic loading effects. However, additional research is needed to determine appropriate levels of load duration factors to be applied with any dynamic loading adjustment.

REFERENCES

1. Taylor, S.E., R.B. Rummer, K.H. Yoo, R.A. Welch, J.D. Thompson. What we know - and don't know - about water quality at stream crossings. Journal of Forestry Vol. 97 No. 8. 1999. Pp. 12-17.

2. American Association of State Highway and Transportation Officials (AASHTO). Standard specifications for highway bridges. AASHTO, Washington, DC. 1993.

3. Ritter, M.A. Timber bridges, design, construction, inspection, and maintenance. USDA Forest Service, Washington, DC. 1990. 944 p.

4. Knab, L.I., R.C Moody, W.W. Sanders, and H.A. Elleby. Design criteria for theater of operations glued-laminated timber highway bridges, Volume I. Technical Report No. M-198, Construction Engineering Research Laboratory, Champaign, IL. 1977. 19 p.

5. Taylor, S.E.; K.P. Keliher; J.D. Thompson; M.A. Ritter; and G.L. Murphy. Portable glulam timber bridge design for low-volume forest roads. In Proceedings of the Sixth International Conference on Low-Volume Roads. Transportation Research Board. National Academy Press. 1995. Vol. 2:32-338.

6. Franklin, J.M., S.E. Taylor, P.A. Morgan, M.A. Ritter. Design criteria for portable timber bridge systems: static versus dynamic loads. ASAE Technical Paper No. 99-4208. ASAE, St. Joseph, MI. 1999. 19 pp.

7. American Institute of Timber Construction (AITC). AITC 117-93 Design, standard specifications for structural glued-laminated timber of softwood species. Englewood, CO. AITC, 1993. 44 p.

8. Taylor, S.E., M.A. Ritter, K.P. Keliher, and J.D. Thompson. Portable glulam timber bridge systems. In Proceedings of the Fourth International Conference on Wood Engineering. Edited by V.K.A. Gopu. Omnipress, Inc. Madison, WI. 1996.

9. Morgan, P.A., S.E. Taylor, M.A. Ritter, J.M Franklin. T-section glulam timber bridge modules: modeling and performance. ASAE Technical Paper No. 99-4207. ASAE, St. Joseph, MI. 1999. 22 pp.

10. Wipf, T.J., M.A. Ritter, and D.L. Wood. Dynamic evaluation of timber bridges. In Proceedings of the National Conference on Wood Transportation Structures, Ed. By M.A. Ritter, S.R. Duwadi, and P.D. Lee. Gen. Tech. Rep. FPL-GTR-94. USDA Forest Service, Madison, WI, USA. 1996. Pp. 114-119.

TABLE 1. Suggested categories for portable timber bridges and their respective general design criteria.

Criterion	Case 1	Case 2	Case 3	Case 4
	Sub-Low Volume A	Sub-Low Volume B	Low Volume	High Volume
Design Life	5 years	5 years	10 years	25 years
Traffic Type	Off-highway / Forestry Vehicles	Off-highway / Trucks	Trucks / Light Vehicles	Unlimited
Average Daily Traffic	50	15	100	500
Design Speed	8 kph	8 kph	8 kph	40 kph
Load Type	Off-highway vehicles	HS 20 or greater	HS20 or greater	HS20 or greater
Load Application Period	6 months	24 months	24 months	36 months
Deflection Limitation	none	none	none	AASHTO or reduced level
Span Type	simple	simple	simple	simple

TABLE 2. Summary statistics for Dynamic Amplification Factor from tests of the off-highway vehicle bridge and the T-section bridge.

Off-Highway Vehicle Bridge	9.2 kph Smooth	9.2 kph Rough	13 kph Smooth	13 kph Rough	23.5 kph Smooth	23.5 kph Rough	All Speeds Conditions
n	30	30	30	30	30	30	180
Mean	1.15	1.22	1.22	1.36	1.20	1.64	1.29
Coefficient of Variation	10.9%	9.1%	5.6%	6.8%	11.8%	10.0%	15.7%
95^{th} Percentile	1.31	1.37	1.34	1.49	1.37	1.88	1.71
T-Section Bridge	**8 kph Smooth**	**8 kph Rough**	**16 kph Smooth**		**24 kph Smooth**		**All Speeds Conditions**
n	80	80	80		80		280
Mean	1.16	1.53	1.18		0.99		1.17
Coefficient of Variation	12.4%	11.8%	20.6%		19.6%		21.8%
95^{th} Percentile	1.42	1.83	1.73		1.37		1.64

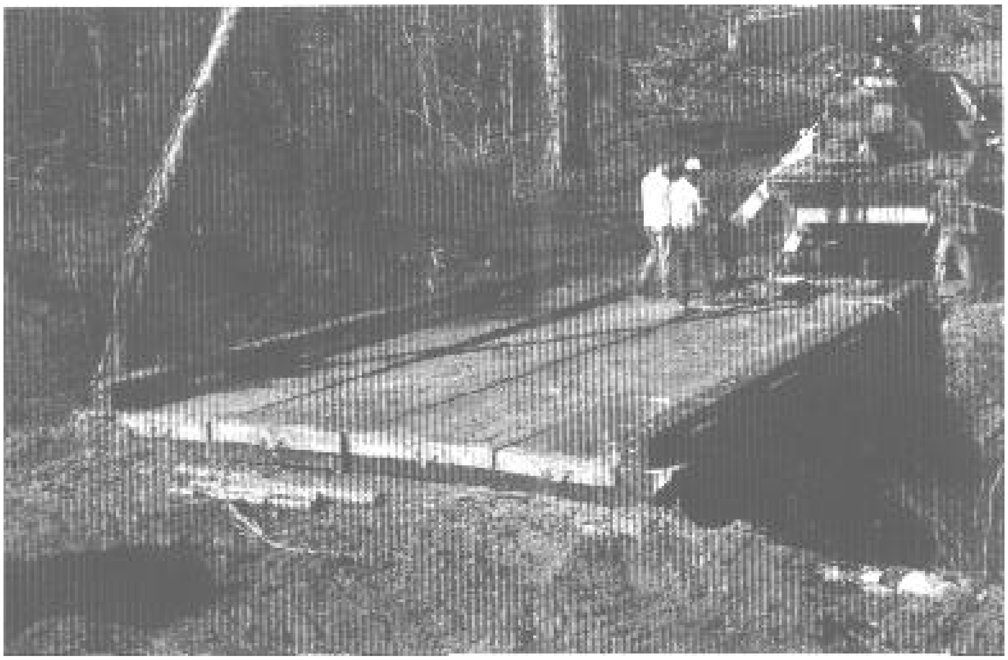

Figure 1. Portable longitudinal glulam deck bridge for truck traffic.

Figure 2. Portable longitudinal glulam deck bridge for off-highway vehicles.

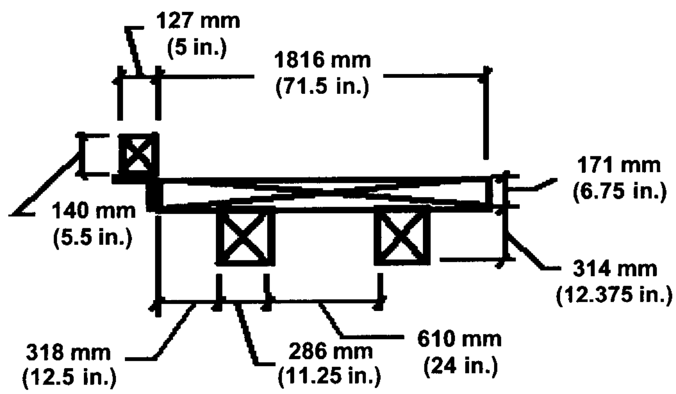

Figure 3. Portable T-section longitudinal glulam deck bridge.

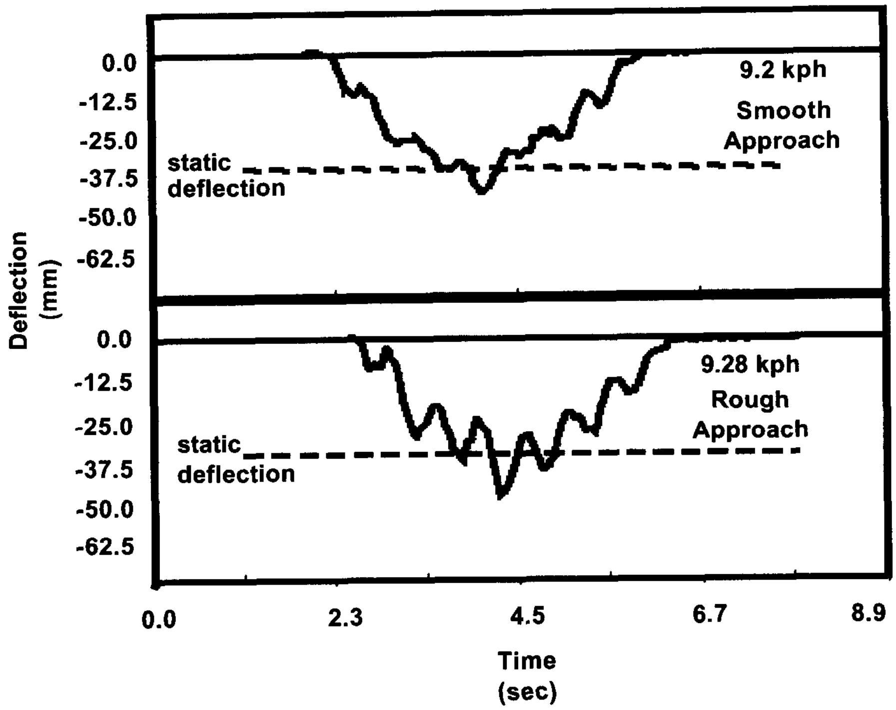

Figure 4. Typical deflection plots from dynamic load tests of the off-highway vehicle bridge.

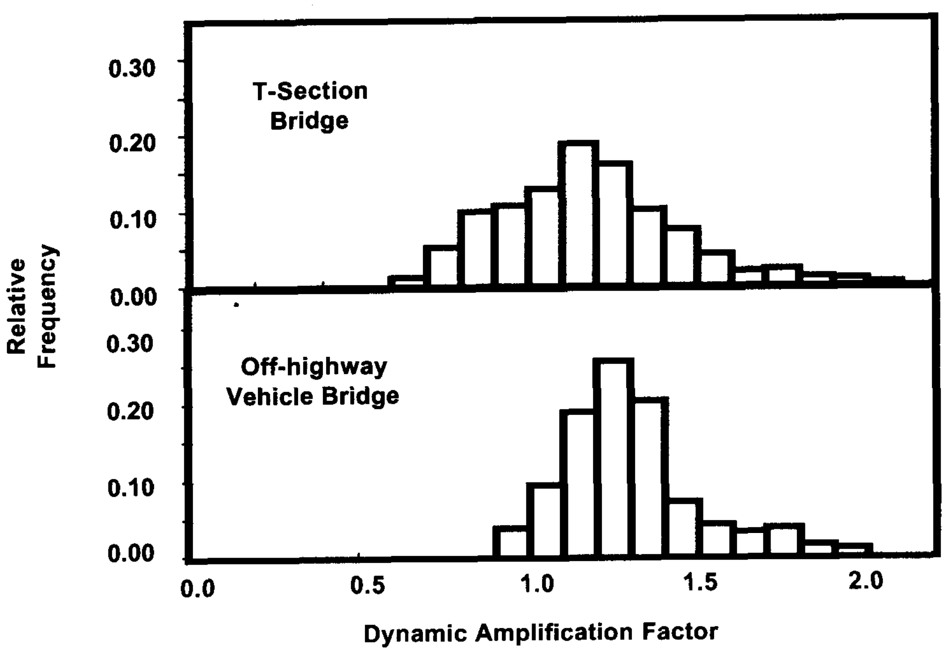

Figure 5. Relative frequency histograms of Dynamic Amplification Factors. All speeds and entrance conditions are included.