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INTERNATIONAL COUNCIL FOR BUILDING RESEARCH STUDIES AND DOCUMENTATION

WORKING COMMISSION W18-TIMBER STRUCTURES

STATE OF THE ART REPORT:
GLULAM TIMBER BRIDGE DESIGN IN THE U.S.

by

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ABSTRACT

Structural glued laminated timber has been successfully used as a highway bridge material in the United States for approximately 50 years. From the mid 1940's to the mid 1980's, virtually all of these bridges were longitudinal girder or arch type glulam superstructures with a nail-laminated wood deck or some form of composite concrete deck. The next evolution of these bridges occurred between the early 1970's and the late 1980's, when the large majority of these bridges were constructed using longitudinal glulam girders and transverse glulam decks or longitudinal glulam deck superstructures manufactured from conventional softwood lumber species. Recently, highway bridge applications employing glued laminated timber have been expanded to include alternative wood species and new designs utilizing the concept of stress-laminating. Additionally, current research using composite plastic materials in injunction with glulam may lead to future innovations in timber highway bridges.

INTRODUCTION

Structural glued laminated timber (glulam) is an engineered, stress-rated product of a timber-laminating plant. It consists of selected and prepared lumber laminations that are bonded together on their wide faces with structural adhesives. Glulam has been successfully used as a structural building material in Europe since the 1890's. In the United States, it has been used in buildings since approximately 1935. The introduction of wet use adhesives in the mid 1940's allowed the uses of glulam to be expanded to include exposed applications such as highway and railway bridges, transmission facilities and other structures.

Glulam is a versatile stress-rated wood material that provides several distinct advantages for bridge construction. Because it is a manufactured product glulam can be produced in a wide range of shapes and sizes to fit virtually any end use requirements. Most glulam used in bridges involves straight members, but curved members have also been used successfully in a number of applications. For example, the Keystone Wye bridge was built in 1968 in South Dakota as a unique hi-level interchange using both a straight girder glulam bridge and a long span glulam arch structure. The upper bridge structure has an overall length of 88 meters with an arch span of 49 meters. This high visibility bridge structure has performed well for almost 25 years with only minimal maintenance being required such as re-staining the glulam members to preserve the aesthetic appearance of the structure.

Recent installations of glulam arch highway bridges have been constructed in Colorado and Michigan and other states with several of these modem structures winning awards in a national Timber Bridge Awards program. This national awards programs acknowledges outstanding achievements in timber bridge design in four categories, these being, long span vehicular, short span vehicular, light vehicular/pedestrian and rehabilitation of an existing timber bridge.

Another advantage of glulam as compared to sawn lumber is related to the laminating process which randomly disperses the strength-reducing characteristics (src), such as knots, throughout the member. This random dispersal of src’s, results in reduced material properties variability and increased strength characteristics. Glulam also provides better dimensional stability because it is manufactured from dry lumber.

For horizontally laminated bending members, glulam is manufactured using selective lamination placement so that higher quality material can be positioned in the top and bottom of the beam, where bending stress is greatest, and lower quality material can be placed in the inner layers of the beam, where bending stress is lowest. This practice helps to extend the available lumber resource and improves the economy of the final glulam product.

While the majority of the glulam bridges built in the United States have been conventional girder-deck or longitudinal deck superstructures (Ritter, 1990), there has been considerable research activity since the late 1980's to extend the use of glulam for bridge applications into several innovative areas. This paper will briefly describe the evolution of modem glulam bridge design in the U.S. including the development of vertically laminated deck systems, the use of alternative species for glulam manufacture, the introduction of technology for glulam stress-laminated decks, T and box sections and the development of crash tested timber guardrail systems.

GLULAM DECK PANEL TECHNOLOGY

During the late 1960’s, research engineers at the USDA Forest Products Laboratory, in cooperation with Forest Service regional bridge engineers and the glulam industry undertook a research program to develop a glulam deck panel to replace the traditional nail-laminated deck system. The concept was to use a vertically laminated glulam member spanning transversely across the longitudinal bridge girders. The length of the deck panel was equal to the overall width of the bridge with the thickness of the panel being dependent on the grade and species of laminating lumber and the spacing of the deck panels. In order to facilitate handling of these deck panels at the manufacturing facility, during transportation and on the jobsite, an arbitrary decision was made to fabricate these deck panels in widths of approximately 122 cm.

In order to achieve plate action for this deck system along the longitudinal direction of the bridge and to minimize the differential deflection at the joints beyond the individual panels, several alternative load transfer mechanisms between panel interfaces were evaluated. The most efficient was the use of a steel dowel inserted in holes pre-bored at the middepth of each panel face. While hundreds of bridges were successfully constructed using this dowel system, problems were encountered in the field when attempting to pull the individual panels together.

To provide the required load transfer between panel edges but not require the close construction tolerances associated with the steel dowel system and it’s associated pre-bored deck panel holes, the Weyerhaeuser Company developed a cast aluminum bracket. This bracket was positioned in grooves pre-routed in the side of the glulam girders prior to pressure treating and was attached to the deck panels with a single through bolt as shown by Figure 1. Since the bracket is manufactured from aluminum, this eliminates concerns of corrosion, The use of this deck bracket essentially replaced the steel dowel and became the state of the art for this system.

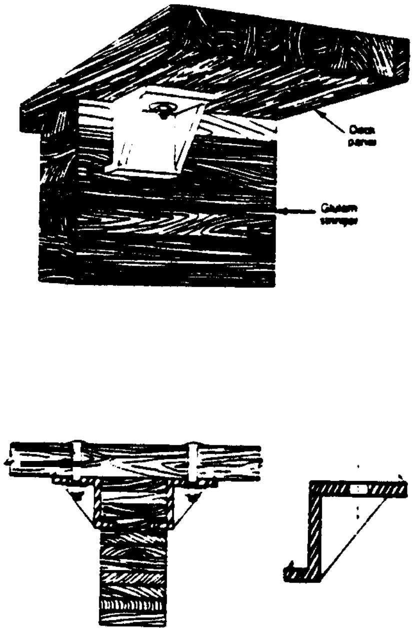
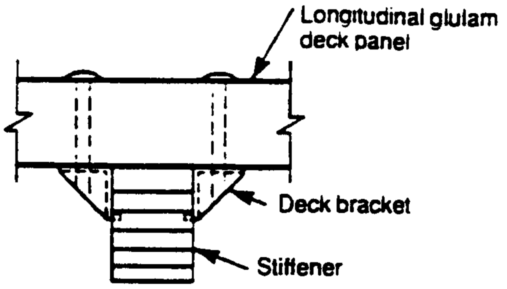


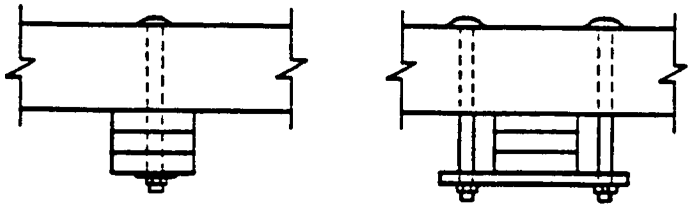
Figure 1 Cast Aluminum Deck Bracket Installation

A natural evolution of the transverse glulam deck panel was to use these members as vertically laminated beams spanning longitudinally between supports. However, the load distribution provisions in the American Association of State Highway and Transportation Officials (AASHTO) Specificatons for Highway Bridges were not favorable to the use of these longitudinal deck panels. The glulam industry sponsored an extensive test program of this system which was conducted at Iowa State University. The results of this study led to more favorable and realistic distribution factors for this type of deck system which were adopted in the AASHTO standards.

As with the transverse deck panels, the longitudinal deck panels are also manufactured in widths of 122 cms. This created a necessity to develop a mechanism for transferring loads transversely between these longitudinal panels. Thus, in addition to developing new load distribution factors for the longitudinal glulam deck panel system, the Iowa State research also led to design provisions for stiffener beams which are beams (glulam or other materials such as steel W or I sections) positioned transversely beneath the longitudinal deck panels at approximately 2.45 meters on center. These stiffener beams can be attached to the deck panels with a variety of mechanical fastening devices as shown by Figure 2. One of the most successful has been the use of the same cast aluminum deck bracket used to attach transverse deck panels to longitudinal stringers as shown in the top detail of Figure 2.

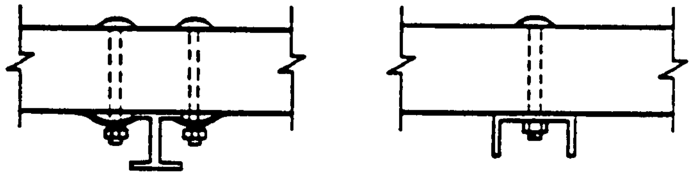


Glulam stiffener and aluminum bracket



Glulam stiffener and thru-bolt

Glulam stiffener and steel plate



Steel I-beam and C-clips

Steel channel and thru-bolt

Figure 2 Attachment of Stiffener Beams to Longitudinal Glulam Decks

STRESS-LAMINATED GLULAM DECKS

Due to the general lack of availability of laminating lumber in sizes greater than 2x12's or 2x14's the use of the vertically laminated longitudinal deck systems was limited to spans of approximately 10 meters Thus, an alternative system was sought which would permit the construction of longitudinal deck systems (those without girders) for spans greater than 10 meters. It was conceived that one such solution would be to apply the concept of stress-laminating to a series of longitudinal glulam beams placed side by side.

Stress-laminating has been an evolving technology in both Canada and the U.S. for the past 5-10 years and has achieved considerable success in highway bridge construction. The idea of using stress-laminating techniques for the rehabilitation of existing timber bridges and for the construction of new timber bridges was first introduced in Canada. The first use of this emerging technology in the U.S. was in the late 1980's. Since that time, over 150 bridges have been constructed in the U.S. using sawn lumber laminations, and a guide specification for the design of this type of timber bridge has been published by the American Association of State Highway and Transportation Officials (AASHTO, 1991).

Stress-laminated decks are typically constructed by placing sawn lumber laminations (either 2x, 3x or 4x material) on edge and stressing the laminations together on the wide face with high-strength steel bars threaded through the laminations (Ritter, 1990). The compression stress existing between the laminations serves to transfer load between the laminations by friction, causing the deck to act as a large orthotropic wood plate.

In 1989, the concept of stress-laminating decks was expanded to use glulam beams as the deck laminations, rather than sawn lumber as shown by Figure 3. Using this approach, glulam beams of variable width, which are continuous between supports, are stressed together to form the bridge deck. The first known example of this type of construction was the Teal River bridge constructed in Wisconsin (Wacker and Ritter, 1992). Since construction of this bridge, several other structures have been built including a second bridge in Wisconsin and one in West Virginia.

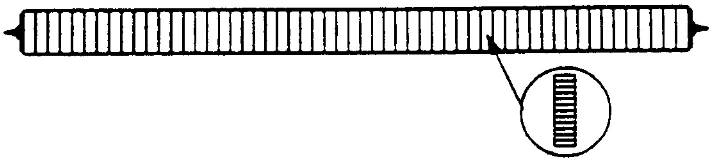


Figure 3 Stress-laminated Deck Using Glulam Beams

Bridges using glulam in stress-laminated deck applications have demonstrated excellent performance. Because horizontally laminated glulam beams allows for deeper sections, longer bridge spans are possible. Additionally, the glulam beams can be manufactured to be continuous over the bridge length and butt joints, which can reduce the bridge strength and serviceability of sawn lumber stress-laminated decks, are not required. These continuous long length beams can also be used to span across intermediate supports resulting in very high stiffness multiple span bridges, further reducing bridge deck deflections.

One of the most noteworthy advantages of glulam use has been the force retention in the p-stressing bars. Because the glulam members are dry when installed (moisture content of 16% or less), the beams typically absorb moisture slowly and the deck swells slightly as it moves toward an equilibrium in-service moisture content. As a result this minimal swelling offsets force loss in the pre-stressing rods due to stress relaxation in the wood and the net loss in bar force is minimal. Extensive monitoring of these bridges by the U.S. Forest Service has verified this performance characteristic.

STRESS LAMINATED T-BEAM AND BOX-BEAM SECTIONS

In the mid 1970’s, an extensive test program was conducted at Colorado State University to determine the degree of T-beam action which could be expected in a longitudinal girder and transverse glulam deck system. Full size double T-sections spanning 12 meters were tested under simulated AASHTO truck loading. These test sections used conventional 122 cm wide transverse deck panels with steel dowels used to provide load transfer between adjacent panels. The deck panels were attached to the stringers using steel lag screws. While there was approximately a 10-15% decrease in stringer deflection, the degree of T-beam action was limited by the effectiveness of the mechanical connections and the associated slip which occurred during loading. Due to the potential varaibility in the degree of fastener slip which might be expected to occur on in-service bridges, it was decided not to pursue a revision to the AASHTO Bridge Specifications to provide for the T-beam action which invariably occurs to some degree in these bridges.

However, the advent of stress-laminating offered new opportunities for achieve more reliable composite T-beam action between the deck and stringers without being dependent on the mechanical fasteners between the deck and stringers. The clear span of glulam bridges is typically controlled by design considerations related to the depth of the superstructure and by economical limitations on the bridge depth. Creating T-section, Bulb T and other composite configurations allowed designers to overcome these limitations, thus permitting much greater span capabilities for glulam bridges.

Two types of experimental composite bridges that have been successfully used in the U.S. are the T-section and box-beam bridges as shown schematically in Figure 4. T-beam bridges can be instructed using vertical glulam web members with flanges constructed of sawn lumber or glulam deck panels. The composite action between the flange and the web is developed through friction by stress-laminating the section with stressing bars through the flanges and webs. The box section is similar to the T-section, but with flanges and stressing bars added to the bottom of the section to create a higher overall section modulus and moment of inertia.

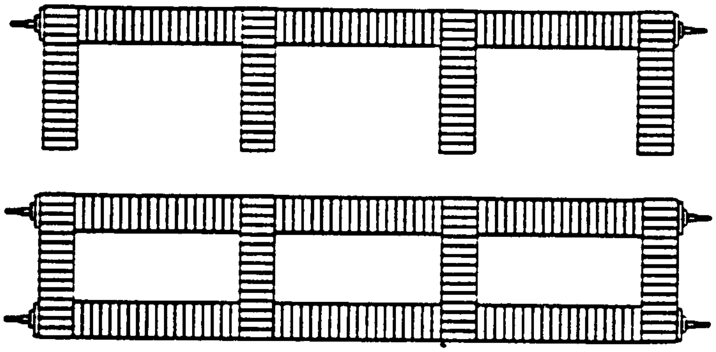


Figure 4 Stress-laminated T-beam Box-beam Bridge Schematics

The concept of stress-laminated T-section and box-beam bridges has been well received and more than 30 bridges have been built over the past 3 years in the U.S. The longest span structure to date is a 27 meter span stress-laminated T-beam bridge, which was built in Arkansas in 1993. Most research work regarding these glulam superstructure configurations was completed at West Virginia University, in cooperation with the Federal Highway Administration (FHWA) and the U.S. Forest Products Laboratory, and used a modular construction approach (Barger, et al., 1993; Davalos, et al., 1993).

In addtion to continued research on stress-laminated T-section and box-beam bridges using glulam webs and sawn lumber flanges, research is underway at the University of Wisconsin, in cooperation with the U.S Forest Products Laboratory and the U.S. Federal Highway Administration, to develop systems instructed completely from glulam panels (Oliva and Rammer, 1993). It is estimated that glulam bridges built using this technology will be able to dear span over 30 meters with structural sections less than 106 cm in depth.

Research and field evaluation are continuing on the structural performance of these systems. Draft specifications for the design and construction of stress-laminated T-section and box-beam bridges are currently being developed for submission to AASHTO.

ALTERNATIVE SPECIES

Glulam can be manufactured from virtually any softwood or hardwood species provided the end product meets necessary strength and stiffness requirements. In actuality, most of the glulam manufactured in the U.S. during the past 60 years has utilized either Douglas Fir-Larch or Southern Pine lumber. However, with continuing changes in the availability of worldwide wood resources, and with increased emphasis on using underutilized local wood species, there has been a growing interest in the U.S. towards developing new glulam layups utilizing both hardwood and softwood species, Over the past 4 years, most of the work on alternative species for glulam has centered on the utilization of hardwood lumber, but several secondary softwood species have also been evaluated.

Recent glulam research completed at the Pennsylvania State University, West Virginia University, and the U.S. Forest Products Laboratory has been directed at developing glulam layups using red maple, red oak and yellow poplar (Manbeck, et al., 1993; Shaffer, et al., 1991; Moody, et al., 1993). Although an industry glulam standard for the use of hardwood species has been available for many years, the standard neither uses currently available structural hardwood lumber grades nor provides for efficient *use* of various grades throughout the beam cross-section as is done with softwoods. Recent full scale tests of glulam beams manufactured using red maple, red oak and yellow poplar indicate that bending design values comparable to those achieved with the traditional Douglas Fir-Larch and Southern Pine softwoods can be attained for these hardwood species.

In addition to developing specifications for glulam produced from hardwood species, efforts to develop high strength and cost efficient glulam layup combinations utilizing secondary softwood species have also been successful. A project in Wisconsin using a combination of red pine and Southern Pine to manufacture glulam beams resulted in the construction of a stress-laminated deck bridge in 1989 (Wacker and Ritter, 1992). These beams used Southern pine for the outer tension and compression zones with the red pine being used for the core of the beams. The resultant beams had similar bending strength and stiffness characteristics as beams manufactured from all Southern pine laminations. This further led to the design and construction of a stress-laminated bridge using glulam manufactured exclusively from red pine lumber. Other projects using secondary softwoods, such as Eastern hemlock, Ponderosa pine and cottonwood, are planned for the future.

CRASH TESTED RAIL SYSTEMS

One ongoing concern expressed by bridge designers in the U.S. has been related to the need for cost efficient crash-worthy timber bridge guardrail systems. AASHTO and the Federal Highway Administration have a program underway which will require all highway bridges guardrail systems to be fully crash tested. Several levels of guardrail performance are being considered in this program ranging from resisting the impact of passenger vehicles to that of large over the road commercial trucks.

Both the U.S. Forest Products Laboratory and the Federal Highway Administration have completed full scale crash test programs to evaluate the performance of various timber bridge guardrail systems on both longitudinal glulam deck and longitudinal glulam stinger and transverse deck bridge configurations.

These crash tests have been conducted using a variety of test vehicles ranging from passenger cars to pick-up trucks to larger commercial trucks. Rail systems tested have included (a) single glulam rail with wood posts, (b) single steel rail with wood posts, (3) glulam rail, wood wheelguard and wood posts and (d) other combinations of guardrail system components. To date, all of the guardrail systems tested in these two research studies have met the crash test requirements established by AASHTO and the Federal Highway Administration. Reports describing these various guardrail crash tests are expected to be available in late 1994. The availability of fully crash tested guardrail systems will provide a major impetus to the further *use* of glulam highway bridge systems in the U.S.

EMERGING TECHNOLOGIES

In virtually all instances, the bending strength of glulam is controlled by the tensile strength of the lumber or the end joints on the tension side of the beam. The potential for increasing the bending strength of glulam by reinforcing the outer tension zone has been evaluated by many investigators during the past 30 years using a variety of materials. Recent developments in fiber-reinforced plastic (FRP) suggest that this high-performance material offers the possibility of being bonded to the wood laminations under factory conditions thus providing this tension reinforcement.

Forming a composite beam by using a relatively small amount of FRP to reinforce the outer tensile zone offers the potential for significantly increasing the bending strength of glulam beams. However, the use of this reinforcement material may have limited effect on increasing overall stiffness when used in the relatively small percentages required to achieve the increased tensile performance.

Recent work has been completed using various types of fibers in FRP products to reinforce glulam (Tingley, 1990). At a poster session at the 1993 Forest Products Society Meeting in Cleawater, Florida, Tingley and other researchers from Oregon State University reported highly favorable results by reinforcing the tension zone of glulam using FRP with high-strength fibers. Cooperative research is underway between West Virginia University and the U.S. Forest Products Laboratory to investigate similar uses of FRP bonded to either the tension side only or to both the tension and compression sides of beams.

These research efforts could soon lead to the instruction of experimental bridges using composite glulam and FRP beams, Reinforced beams have the greatest opportunity of showing economic advantages in applications where either (a) bending strength controls the design, (b) it is critical to minimize beam depth, or (c) the beams are part of a composite structure where the added strength provides substantial benefits.

CONCLUSIONS

Beginning in the late 1960's, extensive research was undertaken in the U.S. to advance the technology for using glulam in highway bridge construction. This research, which has been ongoing since that time, has resulted in many innovative technologies that have been successfully incorporated in numerous glulam highway bridge applications throughout the U.S. Continuing research will undoubtedly expand on existing technologies and lead to new technologies which will create additional opportunities for the use of glulam and other wood products in highway bridge construction.

It is further hoped that much of the glulam bridge technology developed in the U.S. over the past 25 years may have application in other countries where the use of timber in bridge construction is a design option. For example, although not located in the U. S., one of the most striking examples of the innovative use of glulam in highway bridge construction is the recently completed cable-stayed glulam bridge constructed near the airport in Hiroshima, Japan. This two lane wide bridge has a total length of 145 meters with a center clear span between support towers of 84 meters. This bridge uses a glulam truss configuration for the suspended superstructure. Although constructed in Japan, the glulam components for this unusual timber bridge were all manufactured, prefabricated for all connections and pressure preservatively treated at manufacturing facilities in the U.S.

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