WOOD IN INFRASTRUCTURE: ANALYSIS OF RESEARCH NEEDS AND GOALS

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Abstract

Two related government initiatives, the Intermodal Surface Transportation Efficiency Act and the Wood in Transportation Program, have resulted in significant activity in research and technology transfer for using wood for transportation structures. This paper reviews accomplishments and activities and suggests research needs for wood transportation structures. It also describes research needs for related structures such as waterfront and utility applications.

INTRODUCTION

Prior to the 20th century, most transportation structures in North America were made of wood. During this century, concrete and steel have replaced wood in many applications. Advances in alternate materials have played a major role in these changes. For example, timber bridges amount to about 10% of the total bridges in the United States, and another significant percentage of bridges have timber decks. Many of these structures containing wood are old and have exceeded their design life.

Although wood has been recognized by some as a viable material for short-span bridges, prior to 1988 little emphasis was placed on improving the structural and economic efficiency of bridges and other wood transportation structures. Recognizing the potential for wood to meet some needs for revitalizing the transportation infrastructure, Congress passed the Timber Bridge Initiative in 1988. This was followed by the 1991 Intermodal Surface Transportation Efficiency Act (ISTEA). Both of these national programs included provisions for research, demonstration, and technology transfer. The Timber Bridge Initiative, which has become the Wood in Transportation Program, is the responsibility of the U.S. Department of Agriculture, Forest Service (Cesa and Russell 1996); ISTEA is the responsibility of the U.S. Department of Transportation, Federal Highway Administration (FHWA) (Duwadi and Wood 1996).

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The Forest Service and the FHWA formed a joint research program to address needs for improved wood utilization in transportation structures (Wipf et al. 1993). Activities in the United States have renewed international interest in the use of wood bridges. Cooperative research programs with several countries were described at the 1996 International Wood Engineering Conference (Gopu 1996). Results of U.S. research between 1988 and 1996 have been periodically reported (Duwadi and Ritter 1995, Ritter and Moody 1991, Ritter et al. 1994, 1996e) and were summarized at a recent conference co-sponsored by the Forest Products Laboratory of the USDA Forest Service and the FHWA; international activities are also described in the proceedings (Ritter et al. 1996a).

These two major initiatives have focused on highway structures, recognizing that many results could apply to other transportation structures as well as other exterior uses. The objective of this paper is to provide a general assessment of the present state of knowledge and research needs as they apply to all types of transportation structures and other related structures such as waterfront and utility applications. Basic references included (the assessment of research needs in 1983 (Gutkowski and Williamson 1984), (2) results of the initial research needs assessment (Wipf et al. 1993), (3) results of a 1994 workshop on research needs for engineered wood products for transportation structures (Dickson 1996), and (4) proceedings of the 1996 National Conference on Wood Transportation Structures (Ritter et al. 1996a).

The scope of this report includes structures for highways, railroads, utilities, and waterfronts. The report also addresses material property research needs that apply to structures for many uses. It does not include a thorough analysis nor ranking of these needs. More detailed analysis is needed with input from a broad user-based audience.

HIGHWAY STRUCTURES

Bridges

General– advances have been made in developing design criteria for the stress-laminated deck system (Crews et al. 1994). Results of extensive field evaluation of stress-laminated decks after several years service are being reported (Hislop and Ritter 1996, Kainz et al. 1996b, Lee et al. 1996b, Ritter et al. 1996b, l996d. Wacker et al. 1996, Wacker and Ritter 1992, 1995a, l995b), and design procedures and construction practices have been recommended (Ritter et al. 1995c, Ritter and Lee 1996e). The field evaluations demonstrate that a variety of wood materials can be used for this type of bridge (Hernandez et al. 1996, Kainz and Hill 1996a, Lee et al. 1996a, Manbeck et al. 1996a, Ritter et al. 1995b, 1996c, Taylor and Ritter 1996). Innovative approaches are still being evaluated. For example. experimental bridges have been built using metal plate-connected trusses similar to those used for residential roof systems (Dagher et al. 1996a. Triche and Ritter 1996). Several types of T-beam and box systems have been utilized: one type uses a stress-laminated deck (Apple and Woodward 1996, Crews and Bakoss 1996, Dickson and GangaRao 1996) and another, components that are fully glued (Ritter et al. 1996c. Taylor and Ritter 1996). Detailed technical reports are being prepared for these various systems that should form the basis for determining whether and what additional research is needed.

Load distribution–The assumed distribution of vehicle loads on highway bridges is a key element of design that can significantly affect size, cost, and performance. Thus, accurate load distribution criteria are critical to structural efficiency and economics. Field evaluations of various types of bridges that include load tests are providing valuable information on load distribution. These data need to be compared with present design criteria to determine if design efficiencies can be improved. Research is needed on options for improving load distribution in systems such as plank decks and structural glued laminated timber (glulam) panel decks.

Dynamic performance–design criteria for timber bridges do not require an increase in loading to account for the dynamic effect of moving vehicles, as is required for other materials. Recently, this practice has been questioned and some design engineers believe that a dynamic factor is applicable to timber bridges. Questions about the performance of bridges under dynamic and impact loading are being addressed through analysis of full-scale test results (Wipf et al. 1996), which will result in more accurate design criteria related to the performance of timber bridges under dynamic loading.

Rail systems–Many bridges built today must be provided with crash-tested railings. Although numerous railings have been crash tested for steel and concrete bridges, relatively few have been developed for timber bridges. Full-scale crash testing of rail systems for a number of timber bridges with longitudinal decks has resulted in FHWA acceptance (Faller et al. 1996). Detailed drawings are available for the rail types commonly required for longitudinal timber decks on secondary road systems (Ritter et al. 1995a). Rail systems have also been developed and have met criteria for low-volume roads (Faller et al. 1995). Two rails for transverse timber decks have been investigated, but results have not yet been published. Research is needed on additional options for using transverse decks on secondary roads.

Capacity assessment–Guidlines are being developed for using stress-wave technology to determine in-place capacity of bridge components(Pellerin et al. 1996). Similar techniques have been shown to be applicable for timber piling, which supports many bridge abutments (Anthony and Pandey 1996) , and for measuring the stiffness of bridge decks (Ross et al. 1996). Additional research underway is examining alternate techniques. Many composite concrete-wood bridges systems have been built, and methods are needed to determine their in-place capacity.

Maintenance/rehabilitation –There is a significant inventory of short-span timber bridges that continue to meet the needs of many highways. Economical methods are needed for maintaining and rehabilitating these bridges. Virtually no research has been devoted to this subject during the past several years, and the state-of-the-art remains as described by Ritter (1990).

Sound Barriers

Wood products have been popular choices for sound barriers along highways in urban areas. However, some materials and designs have resulted in serviceability problems. Research is underway to determine successful combinations of materials and designs that meet desired performance and aesthetic requirements (Boothby et al. 1996). Additional research should be based on the results of that study. Some material options to consider would he the possible advantages of wood-nonwood composites, possibly including recycled materials, as well as improved structural panels. This general area is addressed in the section on Material Properties.

Sign and Rail Posts

Information on performance is needed to improve acceptance criteria. Alternative or improved wood-nonwood composites may offer advantages for the performance of sign and rail posts upon impact. Another potential research area is techniques for improving the durability of the posts.

Retaining Walls

Retaining walls is another area where wood-nonwood composites and recycled materials may offer some advantages. Standardized designs would enhance use and acceptance of both wood and wood-nonwood composites.

Other Areas for Research

Portable crossings changing approach to forest operations such as harvesting will likely result in less permanent roads and bridges. Portable bridges are proving to be an economical and environmentally sound solution for crossing streams and unstable areas (Hislop 1996, Taylor et al. 1996, Taylor and Ritter 1996). Improved and standardized designs could enhance their acceptance.

Pedestrian bridges is a popular material for pedestrian bridges because of both economics and aesthetics. Several demonstration bridges have been built as part of the Forest Service program, hut there has been no formal research effort in this area. An effort is need to develop several standardized design approaches.

RAILWAY STRUCTURES

Throughout most of the 20th century, wood has been used for railroad ties, and timber structures have been extensively used by the railroads for crossing streams, lowlands, and highways. Countless miles of timber trestle bridges continue to carry increasing tonnage each year. Railway engineers are facing a challenge in dealing with an aging inventory of structures, many of which are more than 50 years old, while being asked to upgrade the structures to carry heavier loads. Many of these structures consist of heavy timbers in sizes that are no longer readily available. Thus, replacement is a major challenge, in addition to upgrading.

Bridges

Some new systems being investigated for highway bridges provide for better load distribution. Using these systems to rehabilitate or replace railway bridges could increase their capacity. Also, improved grading methods for existing timbers that result in increased design properties could enhance upgrading of structures (see Material Properties). Dynamic loading is also a concern on railway bridges (see Highway Structures). Efforts are also needed to include the latest design criteria adopted for wood highway bridges and wood buildings in railroad specifications.

Ties

Improving the performance of railroad ties is particularly challenging because of the relatively low cost of existing ties, most of which have a long service-life. Most problems develop in the connections between the rail, tie plate, and tie. The primary failure mechanism is in either compression perpendicular-to-grain, splitting, or spike withdrawal. Compression perpendicular-to-grain could be improved by modifying surface properties by laminating or using a wood-nonwood composite. Fastener performance can be improved through redesign of the fastener or modification of the fastened area, by laminating or using a wood-nonwood composite. The challenge will be to obtain improvements and maintain needed bending strength in a cost-effective manner compared to sawn treated timber ties. Extending service life will become more important as disposal of used ties becomes more difficult.

UTILITY STRUCTURES

Wood poles and crossarms represent the major support structures that have carried electricity, phone service, and cable TV service to our homes and businesses. With the types of changes that are occurring in these areas, it would be easy to predict the demise of the present infrastructure of poles and lines. For example, underground cables, wireless phones, and satellite dishes have the potential for replacing the old infrastructure and likely will in some areas. However, overhead lines continue to be the most economical method for transmitting and distributing electric power. Thus, power transmission and distribution systems are likely to continue to require poles and crossarms to support the lines.

Wood poles have always had a competitive advantage for distribution systems and some designs have been used for transmission structures. However, alternative materials are becoming more competitive. Improvements could improve the efficient use of wood in these applications (see Material Properties). Values applicable for design of many pole species, glulam timber, and Douglas-fir crossarms are presently given in ANSI standards (ANSI 1992,1995, 1996). There is a continuing need to ensure that these values are applicable to the changing resource. Research is need to establish values for design of other species for crossarms, notably Southern Pine. Maintenance of the existing inventory of wood poles is a high priority with many utilities. Technology for estimating the in-place capacity of existing poles is available (Anthony et al. 1992). Repair and strengthening techniques are needed.

WATERFRONT STRUCTURES

Our waterfront structures have historically been made using wood, most of it heavily treated with preservatives using a pressure process. In salt water environments, this treated wood has resisted both decay and marine borers. However, as a result of progress in improving the environmental quality of waterfront areas, two new problems have arisen: leaching of some preservative may not be acceptable, and the cleaner water has permitted the reintroduction of some types of marine borers that attack treated wood. Thus, new developments in either materials or protection are needed to meet the needs of waterfront structures (see Material Properties).

MATERIAL PROPERTIES

A wide variety of species and grades of wood can be used for bridges and other transportation structures. New grading procedures for hardwood lumber and for hardwood and softwood timbers provide for more efficient use of the resource (Green and McDonald 1993, Green et al. 1994,1996, McDonald et al. 1993,1996). Field trials are needed to demonstrate the advantages of improved grading to producers and users. Research has demonstrated that several hardwoods can be used to manufacture glulam having design properties comparable to those for Douglas-fir and Southern Pine, species widely used for glulam (Manbeck et al. 1993,1996, 1996c, Moody et al. 1993).

For some transportation applications, particularly short-span bridges, shear strength controls the size of members. Research on the shear strength of glulam timber and sawn lumber has provided a better understanding of the variables affecting this strength property (Soltis and Rammer 1994, Rammer 1996, Rammer and Soltis 1994, Rammer and McLean 1996a,1996b, Rammer et al. 1996). Additional research is underway to better understand shear strength under slowly applied (static) loads. Research is needed to determine applicable shear design properties for use under the cyclic loading environment of many transportation structures. Research is also needed on applicable design properties in bending and shear for structural composite lumber products under the loading and environment of transportation structures.

The combination of wood with new synthetic fibers can greatly increase the bending strength of wood beams and potentially reduce the cost of major load-carrying members. Tingley et al. (1996) described a bridge constructed with fiber-reinforced plastic as a reinforcement for glulam. Development of that particular product is described in other references (Tingley 1990, Tingley and Cegelka 1996). Other research using various synthetic materials has also been described (Dagher et al. 1996b, Davalos et al. 1994, Galloway et al. 1996, Sonti et al. 1995). Research is needed to confirm the long-term satisfactory field performance of these new products.

Using recycled wood and fiber products in transportation structures would help alleviate predicted fiber shortages and provide an outlet for discarded preservative-treated material. Reuse of materials should be given priority; methods are needed to predict residual capacity. Combining wood in some form (strands, flakes, fibers) with other materials can provide a product with unique properties. Of particular importance in some transportation structures may be energy-absorption capability, such as demonstrated by a wood-cement composite (Wolfe and Gjinolli 1996). Wood-plastic composites have creep characteristics that may prohibit their use in applications with relatively high constant stress; however, their energy-absorption capability may he advantageous for rail posts.

For nearly all transportation structures, preservative treatment is necessary for long-term serviceability. Research has addressed treatability and durability of heartwood of some softwood species (Wang and DeGroot 1996) and several eastern hardwoods (Blankenhorn et al. 1996) used in demonstration bridges. Studies are also underway on new types of preservatives (Crawford and DeGroot 1996, DeGroot et al. 1996, Laks et al. 1996). Research is needed to accurately assess the environmental impacts of various types of preservative-treated

TECHNOLOGY TRANSFER NEEDS

A high priority need has been standard plans for highway bridges. Standard plans have been prepared for several types of Southern Pine bridge deck systems (Lee et al. 1995), hardwood glulam bridges (Manbeck et al. 1996b), and crash-tested rail systems for longitudinal deck bridges (Ritter et al. 1995a). Standard plans are being prepared for bridge system superstructures (Lee and Wacker 1996c). Similar information is needed for bridge substructures, pedestrian bridges, and portable bridges. An interactive computer program is being prepared for analysis, design, rating, and drafting of highway bridge superstructures (Thomas and Puckett 1996). Additional efforts in this area should build on the information being developed.

Transferring technology for railway, waterfront, and utility applications presents unique challenges. Initially, priority will be given to participation on technical committees that prepare design standards for these uses. To effectively transfer existing and developing information, an Internet system is planned to link Forest Service and FHWA sites with many of the cooperators involved in the research program. Similar sites involving industry, universities, and other government agencies would be beneficial.

REFERENCES

ANSI. (1992). "Wood poles—specifications and dimensions." *ANSI O5.1*, American National Standards Institute, New York.

ANSI. (1995). "Solid sawn wood crossarms and braces—specifications and dimensions." *ANSI O5.3*, American National Standards Institute, New York.

ANSI. (1996). "Structural glued laminated timber for utility structures." *ANSI O5.2*, American National Standards Institute, New York.

Anthony, R. W., Bodig, J., Phillips, G. E., and Brooks, R. T. (1992). "Longitudinal NDE of new wood utility poles." *Rep. TR-100864*, Electric Power Research Institute, Palo Alto, Calif.

Anthony, R. W., and Pandey, A. K. (1996). "Determining the length of timber piles in transportation structures." *Proc., 1996 Natl. Conf. Wood Transportation Structures, FPL-GTR-94*, USDA Forest Service, Forest Products Laboratory, Madison, Wis., 427–436.

Apple, D. A., and Woodward, C. (1996). "Stress-laminated/steel T-beam bridge system." *Proc., 1996 Natl. Conf. Wood Transportation Structures, FPL-GTR-94*, USDA Forest Service, Forest Products Laboratory, Madison, Wis., 65–71.

Blankenhorn, P. R., Labosky, P. Jr., Janowiak, J. J., Manbeck, H. B., Webb, D. A, and Baileys, R. T. (1996). "Wood preservation—preservative treatment of hardwood glued-laminated bridges." *Proc., 1996 Natl. Conf. Wood Transportation Structures, FPL-GTR-94*, USDA Forest Service, Forest Products Laboratory, Madison, Wis., 261–269.

Boothby, T. E., Manbeck, H. B., Burroughs, C. B., Bernecker, C. A., Grgurevich, S., Cegelka, S., and Ritter, M. A. (1996). "Development of wood highway sound barriers." *Proc., 1996 Natl. Conf. Wood Transportation Structures, FPL-GTR-94*, USDA Forest Service, Forest Products Laboratory, Madison, Wis., 158–167.

Cesa, E., and Russell, K. (1996). "Wood in transportation program, technology transfer efforts." *Proc., 1996 Natl. Conf. Wood Transportation Structures, FPL-GTR-94*, USDA Forest Service, Forest Products Laboratory, Madison, Wis., 340–343.

Crawford, D. M., and DeGroot, R. C. (1996). "Evaluation of new creosote formulations." *Proc., 1996 Natl. Conf. Wood Transportation Structures, FPL-GTR-94*, USDA Forest Service, Forest Products Laboratory, Madison, Wis., 158–167.

Crews, K., and Bakoss, S. (1996). "Fundamental structural behavior of "built-up" stress laminated timber bridge decks." *Proc., 1996 Natl. Conf. Wood Transportation Structures, FPL-GTR-94*, USDA Forest Service, Forest Products Laboratory, Madison, Wis., 39–48.

Crews, K., Ritter, M., GangaRao, H., and Dickson, B. (1994). "State of the art research—stress-laminated timber bridge decks, Australia and North America." *Proc., 1994 Pacific Timber Engrg. Conf., Timber Research and Development Advisory Council*, Queensland, Australia, Vol. 2, 123–130.

Dagher, H. J., West, B., Caccese, V., Wolfe, R., and Ritter, M. (1996a). "Fatigue design criteria of MPC wood trusses for bridge applications." *Proc., 1996 Natl. Conf. Wood Transportation Structures, FPL-GTR-94*, USDA Forest Service, Forest Products Laboratory, Madison, Wis., 58–64.

Dagher, H. J., Kimball, T. E., Shaler, S. M., and Abdel-Mogid, B. (1996b). "Effect of FRP reinforcement on low grade eastern hemlock glulams." *Proc., 1996 Natl. Conf. Wood Transportation Structures, FPL-GTR-94*, USDA Forest Service, Forest Products Laboratory, Madison, Wis., 207–214.

Davalos, J. F., GangaRao, H. V. S., Sonti, S. S., Moody, R. C., and Hernandez, R. (1994). "Bulb-T and glulam-FRP beams from timber bridges." *Proc., 1994 Structures Congress*, Atlanta, Ga. ASCE 2, 1316–1321.

De Groot, R., Crawford, D., and Woodward, B. (1996). "Integrated efficacy evaluation of new preservatives in alternative wood species." *Proc., 1996 Natl. Conf. Wood Transportation Structures, FPL-GTR-94*, USDA Forest Service, Forest Products Laboratory, Madison, Wis., 379–388.

Dickson, B. (1996). "Engineered wood products for transportation structures—an overview of the obstacles and opportunities." *Proc., 1996 Natl. Conf. Wood Transportation Structures, FPL-GTR-94*, USDA Forest Service, Forest Products Laboratory, Madison, Wis., 490–494.

Dickson, B., and GangaRoa, H. (1990). "Development and testing of an experimental timber T-beam bridge." *Paper 89-0042*, U. S. Transportation Res. Board, Washington, D. C.

Duwadi, S. R., and Ritter, M. A. (1995). "Research on timber bridges and related topics." *Research Update*, Fed. Hwy. Admin., Washington, D. C.

Duwadi, S. R., and Wood, R. C. (1996). "The Federal Highway Administration timber bridge program." *Proc., 1996 Natl. Conf. Wood Transportation*

Structures, FPL-GTR-94, USDA Forest Service, Forest Products Laboratory, Madison, Wis., 333–339.

Faller, R. K., Rosson, B. T., Sicking, D. L., Ritter, M. A., and Bunnell, S. (1995). "Design and evaluation of two bridge railings for low-volume roads." *Proc., 6th Int. Conf. on Low-Volume Roads*, Minneapolis, MN. National Academy Press (2), 357–372.

Faller, R. K., Rosson, B. T., Ritter, M. A., Lee, P. D. H., and Duwadi, S. R. (1996). "Railing systems for longitudinal timber deck bridges." *Proc., 1996 Natl. Conf. Wood Transportation Structures, FPL-GTR-94*, USDA Forest Service, Forest Products Laboratory, Madison, Wis., 145–157.

Galloway, T. L., Fogstad, C., Dolan, C. W., and Puckett, J. A. (1996). "Initial tests of Kevlar prestressed timber beams." *Proc., 1996 Natl. Conf. Wood Transportation Structures, FPL-GTR-94*, USDA Forest Service, Forest Products Laboratory, Madison, Wis., 215–224.

Gopu, V. K. A. (1996). *Proceedings of 1996 InternationalWood Engineering Conference*, Dept. Civil Environ. Engrg., Louisiana State Univ. 4 vol.

Green, D. W., and McDonald, K. A. (1993). "Investigation of the mechanical properties of red oak 2 by 4's." *Wood Fiber Sci*, 25(1), 35–45.

Green, D. W., Ross, R. J., and McDonald, K. A. (1994). "Production of hardwood machine stress rated lumber." *Proc., 9th Int. Symp. Nondestructive Testing of Wood*, Forest Products Society, 141–150.

Green, D., Kretschmann, D., Wolcott, M.,and Ross, R. (1996). "Mechanical grading of timbers for transportation industry." *Proc., 1996 Natl. Conf. Wood Transportation Structures, FPL-GTR-94*, USDA Forest Service, Forest Products Laboratory, Madison, Wis., 186–191.

Gutkowski, R. M., and Williamson, T. G. (1984). "Heavy timber structures and bridges." *Proc., Structural Wood Research: State of the Art and Research Needs*, ASCE, 111–130.

Hernandez, R., Ritter, M. A., Moody, R. C., and Lee, P. D. H. (1996). "Yellow poplar glued-laminated timber: Product development and use in timber bridge construction." *Proc., 1996 Natl. Conf. Wood Transportation Structures, FPL-GTR-94*, USDA Forest Service, Forest Products Laboratory, Madison, Wis., 411–417.

Hislop, L. E. (1996). "Portable surfaces for crossing unstable roadbeds." *Proc., 1996 Natl. Conf. Wood Transportation Structures, FPL-GTR-94*, USDA Forest Service, Forest Products Laboratory, Madison, Wis., 138–144.

Hislop, L. E., and Ritter, M. A. (1996). "Field performance of timber bridges. 7. Connell Lake stress-laminated deck bridge." *Res. Pap. FPL-RP-550*, USDA Forest Service, Forest Products Laboratory, Madison, Wis.

Kainz, J. A., and Hill, C. A. (1996a). "McCurdy Road stress-laminated timber bridge: A viable option for short-span design." *Proc., 1996 Natl. Conf. Wood Transportation Structures, FPL-GTR-94*, USDA Forest Service, Forest Products Laboratory, Madison, Wis., 418–426.

Kainz, J. A., Wacker, J. P., and Nelson, M. (1996b). "Field performance of timber bridges. 9. Big Erick's stress-laminated deck bridge." *Res. Pap. FPL-RP-552.* USDA Forest Service, Forest Products Laboratory, Madison, Wis.

Laks, P. E., Gutting, K. W., Pickens, J. B., and De Groot, R. C. (1996). "Field performance of new wood preservatives in secondary timber species." *Proc., 1996 Natl. Conf. Wood Transportation Structures, FPL-GTR-94,* USDA Forest Service, Forest Products Laboratory, Madison, Wis., 389–400.

Lee, P. D. H., and Wacker, J. P. (1996). "Standard plans for timber highway structures." *Proc., 1996 Natl. Conf. Wood Transportation Structures, FPL-GTR-94,* USDA Forest Service, Forest Products Laboratory, Madison, Wis., 344–350.

Lee, P. D. H., Ritter, M. A., and Triche, M. (1995). "Standard plans for Southern Pine bridges." *Gen. Tech. Rep. FPL-GTR-84.* USDA Forest Service, Forest Products Laboratory, Madison, Wis.

Lee, P. D. H., Ritter, M. A., and Tice, E. D. (1996a). "Eastern cottonwood stress-laminated timber bridges: Enhancing rural America with underutilized species." *Proc., 1996 Natl. Conf. Wood Transportation Structures, FPL-GTR-94,* USDA Forest Service, Forest Products Laboratory, Madison, Wis., 104–113.

Lee, P. D. H., Ritter, M. A., and Wacker, J. P. (1996b). "Field performance of timber bridges. 10. Sanborn Brook stress-laminated deck bridge." *Res. Pap. FPL-RP-555,* USDA Forest Service, Forest Products Laboratory, Madison, Wis.

Manbeck, H. B., Janowiak, J. J., Blankenhorn, P. R., Labosky, P., Moody, R. C., and Hernandez, R. (1993). "Red maple glulam timber beam performance." *Res. Pap. FPL-RP-519,* USDA Forest Service, Forest Products Laboratory, Madison, Wis.

Manbeck, H. B., Blankenhorn, P. R., Janowiak, J. J., Witmer, R. W. Jr., and Labosky, P. Jr. (1996a). "Performance of red oak and red maple glued–laminated bridges." *Proc., 1996 Natl. Conf. Wood Transportation Structures, FPL-GTR-94,* USDA Forest Service, Forest Products Laboratory, Madison, Wis., 82–91.

Manbeck, H. B., Janowiak, J. J, Blankenhorn, P. B., and Labosky, P. Jr. (1996b). "Standard designs for hardwood glued-laminated highway bridges." *Proc., 1996 Natl. Conf. Wood Transportation Structures, FPL-GTR-94,* USDA Forest Service, Forest Products Laboratory, Madison, Wis., 351–360.

Manbeck, H. B., Janowiak, J. J., Blankenhorn, P. B., Labosky, P. Jr., Moody, R. C., and Hernandez, R. (1996c). "Efficient hardwood glued–laminated beams." *Proc., 1996 Int. Wood Engrg. Conf.,* Dept. Civil Environ. Engrg., Louisiana State Univ., (1), 283–290.

McDonald, K. A., Green, D. W., Dwyer, J., and Whipple, J. W. (1993). "Red Maple stress-graded lumber from factory-grade logs." *Forest Prod. J.,* 43(11/12), 13–18.

McDonald, K. A., Hassler, C. C., Hawkins, J. E., and Pahl, T. L. (1996). "Hardwood structural lumber from log heart cants." *Forest Prod. J.,* 46(6), 55–62.

Moody, R. C., Hernandez, R., Davalos, J. F., and Sonti, S. S. (1993). "Yellow Poplar glulam timber beam performance." *Res. Pap. FPL-RP- 520*, USDA Forest Service, Forest Products Laboratory, Madison, Wis.

Pellerin, R. F., Lavinder, J. A., Ross, R. J., Falk, R. H., and Volny, N. (1996). "In-place detection of decay in timber bridges—An application of stress wave technology." *Proc., 1996 Natl. Conf. Wood Transportation Structures, FPL-GTR-94*, USDA Forest Service, Forest Products Laboratory, Madison, Wis., 282–291.

Rammer, D. R. (1996). "Shear strength of glued–laminated timber beams and panels." *Proc., 1996 Natl. Conf. Wood Transportation Structures, FPL-GTR-94*, USDA Forest Service, Forest Products Laboratory, Madison, Wis., 192–200.

Rammer, D. R., and McLean, D. I. (1996a). "Recent research on shear strength in wood beams." *Proc., 1996 Int. Wood Engrg. Conf.*, Dept. Civil Environ. Engrg., Louisiana State Univ. (2), 96–103.

Rammer, D. R., and McLean, D. I. (1996b). "Shear strength of wood beams." *Proc., 1996 Natl. Conf. Wood Transportation Structures, FPL-GTR-94*, USDA Forest Service, Forest Products Laboratory, Madison, Wis., 168–177.

Rammer, D. R., and Soltis, L.A. (1994). "Experimental shear strength of unchecked beams." *Res. Pap. FPL-RP-527*, USDA Forest Service, Forest Products Laboratory, Madison, Wis., 38 p.

Rammer, D. R., Soltis, L. A., and Lebow, P. K. (1996). "Experimental shear strength of solid-sawn Douglas-fir beams." *Res. Pap. FPL-RP-553*, USDA Forest Service, Forest Products Laboratory, Madison, Wis.

Ritter, M. A. (1990). "Timber bridges: Design, construction, inspection, and maintenance." *EM 7700-8*, U.S. Dept. Agric., Washington, D. C.

Ritter, M. A., and Lee, P. D. H. (1996). "Recommended construction practices for stress-laminated wood bridge decks". *Proc., 1996 Int. Wood Engrg. Conf.* Dept. Civil Environ. Engrg., Louisiana State Univ. (1), 237–244.

Ritter, M. A., and Moody, R. C. (1991). "Timber bridge research by the USDA Forest Service, Forest Products Laboratory." *Proc., 1991 Int. Timber Engrg. Conf.*, Timber Res. Develop. Assoc., United Kingdom (3), 356–363.

Ritter, M., Moody, R., and Duwadi, S. (1994). "U.S. Timber bridge research." *Proc., PTEC 94*, Fortitude Valley MAC, Timber Res. Develop. Advisory Council, Queensland, Australia,(2), 148–155.

Ritter, M. A., Faller, R. K., Lee, P. D. H., Rosson, B. T., and Duwadi, S. R. (1995a). "Plans for crash-tested bridge railings for longitudinal wood decks." *Gen. Tech. Rep. FPL-GTR-87*, USDA Forest Service, Forest Products Laboratory, Madison, Wis.

Ritter, M. A., Wacker, J. P., and Tice, E.D. (1995b.) "Design, construction, and evaluation of timber bridge constructed of cottonwood lumber." *Proc., 4th Int. Bridge Engrg. Conf.*, National Academy Press, Washington, D.C., (2), 358–370.

Ritter, M. A., Wacker, J. P., and Duwadi, S. R. (1995c.) "Field performance of stress-laminated timber bridges on low-volume roads." *Proc., 6th Int. Conf. on Low-Volume Roads*, National Academy Press, Washington, D. C., (2), 347–357.

Ritter, M. A., Duwadi, S. R., and Lee, P. D. H. (1996a). *Proceedings of 1996 National Conference on Wood Transportation Structures, FPL-GTR-94*, USDA Forest Service, Forest Products Laboratory, Madison, Wis.

Ritter, M. A., Kainz, J. A., and Porter, G. J. (1996b). "Field performance of timber bridges. 5. Little Salmon Creek stress-laminated deck bridge." *Res. Pap. FPL-RP-547*, USDA Forest Service, Forest Products Laboratory, Madison, Wis.

Ritter, M., Lee, P. H., Kainz, J., and Meyer, C. (1996c.) "Evaluation of stress-laminated T-beam bridges constructed of laminated veneer lumber." *Proc., 1996 Natl. Conf. Wood Transportation Structures, FPL-GTR-94*, USDA Forest Service, Forest Products Laboratory, Madison, Wis., 92–103.

Ritter, M. A., Lee, P. D. H., and Porter, G. J. (1996d). "Field performance of timber bridges. 6. Hoffman Run stress-laminated deck bridge." *Res. Pap. FPL-RP-549*. USDA Forest Service, Forest Products Laboratory, Madison, Wis.

Ritter, M. A., Moody, R. C., and Duwadi, S. R. (1996e.) "Summary of U.S. research on wood transportation structures." *Proc., 1996 Int. Wood Engrg. Conf.*, Dept. Civil Environ. Engrg., Louisiana State University, (1), 81–88.

Ross, R. J., Ritter, M. A., and Schad, K. C. (1996.) "Determining in-place modulus of elasticity of stress-laminated timber decks using NDE." *Res. Pap. FPL-RP-547*, USDA Forest Service, Forest Products Laboratory, Madison, Wis., 277–281.

Soltis, L. A., and Rammer, D.R. (1994.) "Shear strength of unchecked glue-laminated beams." *Forest Prod. J.*, 44(1), 1–8.

Sonti, S. S., Davalos, J. F., Hernandez, R., Moody, R. C., and Kim, Y. (1995). "Laminated wood beams reinforced with pultruded fiber-reinforced plastic." *Proc., Composites Inst. 50th Annual Conf. and Expo '95*, SPI Composites Institute, New York.

Taylor, S. E., and Ritter, M. A. (1996). "Portable T-section bridge for low-volume roads." *Res. Pap. FPL-RP-547*, USDA Forest Service, Forest Products Laboratory, Madison, Wis., 426–436.

Taylor, S. E., Ritter, M. A., Keliher, K. P., and Thompson, J. D. (1996). "Portable glulam timber bridge systems." *Proc., 1996 Int. Wood Engrg. Conf.*, Dept. Civil Environ. Engrg., Louisiana State Univ., (2), 368–375.

Thomas, W. R., and Puckett, J. A. (1996.) "Analysis, design, rating, and drafting of wood bridge superstructures." *Proc., 1996 Natl. Conf. Wood Transportation Structures, FPL-GTR-94*, USDA Forest Service, Forest Products Laboratory, Madison, Wis., 361–370.

Tingley, D. A. (1990). "Predicting strength criteria for Kevlar and fiberglass reinforced plastic (KRP and FRP) glued laminated beams." *Proc., Int. Timber Engrg. Conf.*, Tokyo, Japan, (1), 42–45.

Tingley, D. A, and Cegelka, S. (1996). "High-strength-fiber-reinforced plastic-reinforced wood." *Proc., 1996 Int. Wood Engrg. Conf.*, Dept. Civil Environ. Engrg., Louisiana State Univ., Baton Rouge, (3), 57–66.

Triche, M. H., and Ritter, M. A. (1996). "Pole Creek metal-plate-connected truss bridge." *Proc., 1996 Natl. Conf. Wood Transportation Structures, FPL-GTR-94*, USDA Forest Service, Forest Products Laboratory, Madison, Wis., 49–57.

Wacker, J. P., and Ritter, M. A. (1992). "Field performance of timber bridges. 1. Teal River stress-laminated deck bridge." *Res. Pap. FPL-RP-515*, USDA Forest Service, Forest Products Laboratory, Madison, Wis.

Wacker, J. P., and Ritter, M. A. (1995a). "Field performance of timber bridges. 3. Birchlog Run and Tumbling Rock Run stress-laminated deck bridges." *Res. Pap. FPL-RP-538*, USDA Forest Service, Forest Products Laboratory, Madison, Wis.

Wacker, J. P., and Ritter, M. A. (1995b. "Field performance of timber bridges. 4. Graves Crossing stress-laminated deck bridge." *FPL- RP-539*, USDA Forest Service, Forest Products Laboratory, Madison, Wis.

Wacker, J. P., Ritter, M. A., and Conger, D. (1996). "Field performance of timber bridges. 8. Lynches Woods Park stress-laminated deck bridge." *Res. Pap. FPL-RP-551*, USDA Forest Service, Forest Products Laboratory, Madison, Wis..

Wang, J. Z., and De Groot, R. (1996). "Treatability and durability of heartwood." *Proc., 1996 Natl. Conf. Wood Transportation Structures, FPL-GTR-94*, USDA Forest Service, Forest Products Laboratory, Madison, Wis., 252–260.

Wipf, T. J., Ritter, M. A., Duwadi, S. R., and Moody, R. C. (1993). "Development of six-year research needs assessment for timber transportation structures." *Gen. Tech. Rep. FPL-GTR-74*, USDA Forest Service, Forest Products Laboratory, Madison, Wis.

Wipf, T. J., Ritter, M. A., and Wood, D. L. (1996). "Dynamic evaluation of timber bridges." *Proc., 1996 Natl. Conf. Wood Transportation Structures, FPL-GTR-94*, USDA Forest Service, Forest Products Laboratory, Madison, Wis., 114–121.

Wolfe, R. W., and Gjinolli, A. E. (1996). "Assessment of cement-bonded wood composites as a means of using low-valued wood for engineering applications." *Proc., 1996 Int. Wood Engrg. Conf.*, Dept. Civil Environ. Engrg., Louisiana State Univ., Baton Rouge, (3), 74–81.

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