

Summary of U.S. Research on Wood Transportation Structures

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Abstract

An extensive U.S. research program to further develop wood utilization in transportation structures is currently in progress as a joint effort of the USDA Forest Service, Forest Products Laboratory, and the U.S. Department of Transportation, Federal Highway Administration. This research is funded primarily by U.S. legislation and involves cooperative research with universities, government agencies, and private industry. Within the program, research is divided into six areas: system development and design, lumber design properties, preservatives, alternate transportation system timber structures, inspection and rehabilitation, and technology and information transfer. This paper presents a brief summary of selected research program highlights within each of these areas and includes a listing of recent publications.

Introduction

Research related to the utilization of wood as a material for transportation structures has increased substantially in the United States during the past 7 years. The primary reason for this increase has been U.S. legislation directed at furthering the development and utilization of wood as a material for bridges and other transportation structures. The first legislation in this area was the Timber Bridge Initiative (TBI), which was passed by the U.S. Congress in 1988. More recently, Congress passed the 1991 Intermodal Surface Transportation Efficiency Act (ISTEA). In both cases, elements of the legislation were directed at establishing research and development programs to improve existing technology and develop

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new technology related to wood transportation systems and materials. Research leadership under the TBI was delegated to the USDA Forest Service, Forest Products Laboratory (FPL). Under the ISTEA, research leadership was assigned to the U.S. Department of Transportation, Federal Highway Administration (FHWA).

To coordinate respective research activities, the FPL and FHWA initiated a joint research program involving wood in transportation structures. By combining funding and other resources, a program has been developed and implemented, based on a comprehensive analysis of national research needs. Although wood bridges are the principal area of emphasis, the program includes other types of transportation structures, such as noise barriers, retaining walls, sign supports, and marine facilities. Research may be accomplished in staff studies by FPL and FHWA engineers but is more commonly a cooperative research effort with universities, government agencies, and private industry. Technology transfer is an integral part of this program.

Research Project Descriptions

Research activities under the joint FPL/FHWA program are divided into six general areas identified in the ISTEA legislation: system development and design, lumber design properties, preservatives, alternate transportation system timber structures, inspection and rehabilitation, and technology and information transfer. A brief summary of selected research within each of these areas and a partial listing of recent publications follows.

System Development and Design

Stress-Laminated Bridge Monitoring Program — A national bridge monitoring program is continuing to evaluate the field performance of stress-laminated wood

bridges including, deck, T-, and box-beam designs instructed of sawn lumber, glued laminated timber (glulam), and structural composite lumber. To date, monitoring has been completed on 30 + bridges and more than 15 bridges are currently being monitored. These structures are located across the United States. Monitoring activities for each bridge typically include a 2- to 5-year assessment of wood moisture content and bar force, two or more load tests, and thorough visual inspections. The information obtained from these activities is being used to improve design procedures, fabrication, and construction methodologies.

Field Evaluation of Glulam Bridges — A study is being completed with the University of Alabama to evaluate the field performance of five glulam girder bridges. The bridges consist of glulam girders with transverse glulam deck panels and range in span from 7.6 m (25 ft) to more than 31 m (102 ft). Monitoring has focused on dimensional stability, wood moisture content, general condition, and load test behavior. In addition, girders and deck panels for several bridges were tested prior to bridge construction to determine modulus of elasticity values for future analytical modeling. Field evaluation and load testing have been completed and a report is being prepared. Results from this study will be used with analytical studies, laboratory testing, and additional field evaluations to develop recommendations for revised design criteria for glulam girder bridges.

Stress-Laminated Truss Bridges using Light-Frame Metal-Plate-Connected Trusses — A study is concluding with the University of Maine to develop stress-laminated truss bridges using light-frame metal-plate-connected trusses. The study involved laboratory evaluation of cyclic moisture content, preservative treatment, and fatigue load effects on connections. It also addressed areas of connection durability under design environmental conditions, connection corrosion, reduction in static load capacity as a result of cyclic loads and moisture conditions, and effects of cyclic moisture on joint fatigue capacity. Results of the study and design recommendations are currently being compiled in a report.

Field Evaluation of Wood Bridges Constructed with Metal-Plate-Connected Trusses — A study has been completed with the University of Alabama to evaluate the field performance of the first U.S. wood bridge constructed of light-frame metal-plate-connected trusses. The bridge consists of two spans employing stress-laminated and truss girder configurations. A report on

the performance of this bridge will be completed in late 1996. A similar study is continuing with the University of Maine to evaluate several stress-laminated bridges constructed of light-frame metal-plate-connected trusses, using design technology based on research previously described. Completion of this study is scheduled for 1997.

Temperature Reduction on Interlaminar Stress Retention in Stress-Laminated Bridges — An FPL study is concluding that is investigating the effect of temperature decreases on the bar force in stress-laminated bridge decks. Laboratory testing is currently in progress on four deck specimens of various species and preservative treatments to assess temperature reduction effects at various bar force and moisture content levels. Several bridges have also been instrumented with remote sensing equipment to determine the effects of temperature reduction under field conditions. A similar cooperative study is also concluding at the University of Minnesota where several stress-laminated decks constructed of red pine are being evaluated under controlled laboratory conditions to determine temperature effects for different temperature ranges and moisture content levels. Results of these studies will be combined to formulate design recommendations for stress-laminated bridges used in cold temperature regions.

Dynamic Evaluation of Wood Bridges — A project is continuing with Iowa State University to evaluate the dynamic behavior of wood bridges. The study includes superstructures constructed both of sawn lumber and glulam and involves field and analytical evaluations. To date, dynamic load tests have been completed on nine stress-laminated wood decks and four glulam girder bridges with transverse glulam decks. Data reduction and analytical evaluations of these bridges have been completed and reports are in progress. Testing of longitudinal glulam panel bridges will be completed in 1996. Results of this study will be used to formulate recommendations for design allowances related to dynamic effects.

Load Distribution in Plank Decks — A study is continuing with the University of Michigan to determine the wheel load distribution criteria for transverse plank decks. Currently, thousands of plank decks are in service that do not meet current design criteria, yet continue to perform in an acceptable manner with no detectable structural problems. To date, analytical modeling has been completed and draft load distribution recommendations have been prepared. Laboratory testing

of various plank sizes is currently in progress and results are scheduled to be published in 1997.

Portable Wood Bridge Systems — A study is continuing with Auburn University to develop wood bridges that are portable and suitable for use in temporary applications. These bridges are intended for use on roads where temporary access is required or where a bypass is necessary for the repair or replacement of existing structures. To date, preliminary design criteria have been formulated and designs for three different portable bridges have been completed. Based on these designs, several bridges have been constructed and field evaluation is in progress. Field evaluation reports and standardized drawings for several portable wood bridge designs will be available in late 1997.

Butt Joints in Stress-Laminated Decks — A study is continuing at FPL to determine the effect of butt joints on the strength and stiffness of stress-laminated wood decks. A total of 12 decks have been tested with different butt joint frequencies and spacings to determine stiffness effects at various prestress levels. At the conclusion of stiffness testing, each deck was tested to failure to assess the butt joint effect on ultimate strength. Testing of the remaining five decks is scheduled for completion in 1996. Results from this study will be used to formulate design recommendations for stress-laminated wood bridges with butt joints.

Wood Railroad Bridges — Several studies are currently in progress with the Association of American Railroads (AAR) and Iowa State University to evaluate wood railroad bridges. Dynamic load testing has been completed on several bridges constructed of sawn lumber and glulam and additional testing is scheduled. Results of these tests will provide a basis for determining the load capacity of existing bridges and will be used to evaluate various methods of bridge rehabilitation and strengthening. Several new railroad bridge designs will also be developed and evaluated.

Alternate Stressing Systems for Stress-Laminated Bridges — An FPL/FHWA staff study has started that will examine alternate prestressing systems for stress-laminated wood bridges. Historically, prestressing has been accomplished with high strength steel bars. This study will compare the performance of steel bars to stressing systems employing steel prestressing strand and fiber-reinforced plastic (FRP) bars currently being evaluated at the University of Maine. To assess relative performance, each system will be evaluated on three

spans of a multispan bridge under the same exposure and loading conditions. Prestress retention and performance characteristics will be monitored for 3 years and construction/design recommendations will be formulated.

Stress-Laminated Wood T- and Box- Beam Bridge Superstructures — A study is currently being initiated to conduct an independent evaluation of stress-laminated wood T- and box-beam bridge research and field performance. The objective of the study is to formulate recommendations as to the technical and economical feasibility of these bridge systems and identify the potential use for wood T- and box-beam bridges relative to other commonly used wood bridge designs. The study will include a literature review of all U.S. and international research and field performance information. It will evaluate completed experimental and analytical laboratory studies to assess the adequacy and completeness of work in addressing necessary design aspects for structural and serviceability bridge performance. The study will also identify and evaluate specific field performance characteristics and trends for bridges constructed in the United States and abroad and, if appropriate, identify areas where additional research is necessary to fully develop design criteria for structural and serviceability performance.

LRFD Calibration for Wood Bridges — A study is being initiated to refine the load and resistance factor design (LRFD) criteria for wood bridges given in the American Association of State Highway and Transportation Officials (AASHTO) *LRFD Bridge Design Specifications*. The study will involve a calibration procedure similar to that completed for other materials and will include development of a statistical resistance model for wood material properties and load models for the various types of wood bridges. The study will also develop reliability analysis procedures for existing bridges designed in accordance with current AASHTO specifications and formulate a target reliability level for wood bridges based on a critical evaluation of current practice and economic analysis. The study will result in recommended revisions to the AASHTO *LRFD Bridge Design Specifications*.

Lumber Design Properties

Shear Design for Glulam Timber — A staff study to evaluate the shear strength of glulam beams has been completed and results have been published. An additional study is currently in progress to evaluate the shear capacity of glulam bridge deck panels in order to develop improved shear design procedures. A total of 200

matched specimens will be tested and analyzed to determine shear strength. Results from this study will be used to formulate proposed revisions to the AASHTO bridge design specifications.

Shear Strength of Solid-sawn Lumber Beams — A cooperative study with Washington State University is continuing to determine the shear strength of solid-sawn lumber beams. For phase 1 of the study, 400 Douglas-fir, Engelmann Spruce, and southern Pine beams were tested and analyzed in a green condition to determine the unsplit and unchecked shear strength for several beam sizes. Phase 2 consists of testing and analyzing more than 400 Douglas-fir and Southern Pine beams to evaluate the effect of checks and splits on beam shear strength. These results are currently being evaluated for possible changes in the ASTM provisions and will be used to prepare revised specification related to solid-sawn lumber beam shear design for submission to AASHTO.

Hardwood Glulam — Cooperative research with Pennsylvania State University and West Virginia University confirmed the potential of using hardwoods for high-performance glulam. Results of several studies in which more than 150 beams were evaluated formed the basis of a revised hardwood glulam specification, AITC 119-96, published by the American Institute of Timber Construction.

Preservatives

Accelerated Laboratory Testing of New Wood Preservatives; Ecosystem Studies — A project is continuing with Michigan Technological University to evaluate 10 different wood preservatives for bridge applications. Accelerated testing using small wood beams are being conducted under laboratory and field conditions to determine efficacy for protecting various softwood and hardwood species commonly used for wood bridges. The specimens are being subjected to complexes of wood degrading fungi and termites. The results of this study are necessary for the formulation of proposed treatment specifications for bridge members.

Accelerated Laboratory Testing of New Wood Preservatives; Pure Culture Studies — A project is continuing with Oregon State University to test 16 different wood preservatives for bridge applications. Accelerated testing using small wood specimens are being conducted under laboratory conditions to determine efficacy for protecting seven softwood and eight hardwood species commonly used for wood bridges. The

results of this study are necessary before field trials can be completed for code acceptance.

Treatments and Methods for Field Treating Bridge Members — A study is concluding with Oregon State University to develop treatments and methods for field treating bridge members. This project will identify and/or develop equipment, preservative formulas, and procedures for effectively treating field cuts, bore holes, and other breaks in preservative treatment encountered during bridge construction and maintenance operations. The project will result in a comprehensive users guide and video tape on the field treating of wood bridge members.

Wood Preservative Performance in Stress-Laminated Bridges — A project is continuing with Florida A&M/Florida State University to evaluate the effects of various wood preservatives and anchorage configurations on the dimensional stability and bar force retention of stress-laminated decks constructed of Southern Pine lumber. Seven different wood preservative formulations and three anchorage systems are being evaluated using full-scale stress-laminated decks. Data on bar force and temperature are being collected with a remote data acquisition system. The study will be completed and a final report published in 1997.

Copper Naphthenate Wood Preservative — Copper naphthenate is an important wood preservative that is receiving increased use in wood transportation structures. This preservative is a complex of many chemicals that can have a varying influence on preservative efficacy. A study is in progress with Michigan Technological University to develop means for the quantitative separation of naphthenic acid components to determine which components are the most biologically active against wood decay fungi. Results of the study will be used to develop recommendations on copper naphthenate preservative formulations to provide optimum wood protection.

Environmental Effects of Wood Preservatives — A study is being initiated to develop recommendations and guidelines on the potential environmental impacts associated with the use of wood preservatives in transportation structures. The study will assemble available research information, both nationally and internationally, on the environmental impacts associated with preservative-treated wood and will evaluate the applicability of available research findings to wood transportation structures over or in contact with water

and soil. The study will also identify and complete research necessary to assess the potential environmental impacts associated with the combinations of preservatives, wood species, and materials that are typically used for wood transportation structures. Results of the study will include recommendations and guidelines regarding the potential environmental impacts and risks associated with preservative-treated wood used in transportation structures.

Alternate Transportation System Timber Structures

Crashworthy Bridge Railings for Longitudinal Wood Deck Bridges — A study has been completed with the University of Nebraska to develop crashworthy bridge railings and approach railing systems for longitudinal wood decks. As a result of this study, five railings and transitions were successfully crash tested: three for AASHTO Performance Level 1, one for AASHTO Performance Level 2, and one for Test Level 4 as defined in National Cooperative Highway Research Program (NCHRP) Report 350. Reports on the railing testing and drawings of the various designs are currently available.

Bridge Railings for Low-Volume Roads — A study is concluding with the University of Nebraska and the USDA Forest Service to develop crash-tested bridge railings for low-volume roads. The study involves the development and testing of two curb systems and two railings. Evaluation of one curb was based on low-volume road criteria developed as a part of this study to represent single-lane forest roads. Evaluation of the remaining curb and railings was based on the new national criteria recently developed for low-volume roads. These evaluation levels require significantly lower loading than those commonly used for highway bridge railing crash testing and will result in more realistic and economical bridge railing designs for low-volume road applications. Testing has been completed and drawings are currently being prepared.

Wood Bridge Railing Analysis and Design — A study is continuing with the University of Nebraska to develop a procedure for evaluating and designing bridge railings for wood bridges. The procedure will be similar to that currently used for earthquake analysis and will be consistent with the philosophy and methodology of the LRFD limit states approach. Equivalent static forces will be developed for various impact conditions and railing types considering specific design details, geometric discontinuities, and retrofit options. This will provide

bridge engineers with a rational and accurate method to design new bridge railings and a reliable procedure to evaluate existing railings for replacement or retrofitting.

Crashworthy Bridge Railings for Transverse Glulam Decks — A study is in progress with the University of Nebraska to develop crashworthy bridge railings for transverse glulam decks. Two bridge railings and approach railing transitions will be designed, constructed, and crash tested in accordance with criteria established for Test Level 4 (TL-4) as outlined in NCHRP Report 350. Emphasis will be placed on railing systems that are adaptable to typical deck panel dimensions and configurations, prevent or minimize damage to the wood bridge superstructure, and are economical. Full-scale tests are scheduled to begin in late 1996.

Wood Noise Barriers — A study is continuing with Pennsylvania State University to evaluate wood noise barriers for highway applications. An evaluation of numerous designs and acoustic testing and inspection of several barriers has been completed. Based on this work, a prototype design has been developed and a full-scale prototype will be constructed and tested. Results of this study will be used to develop recommended designs and specifications for wood noise barriers.

Inspection and Rehabilitation

Wood Bridge Evaluation Using Stress Wave Technology — A project is continuing with Washington State University to develop guidelines for applying existing nondestructive stress wave technology for the in-place evaluation of wood bridges. The study will develop and present guidelines for equipment use and interpretive procedures to evaluate various bridge components based on field and laboratory research. Currently, field evaluation and laboratory work have been completed, and stress wave data for various species have been summarized. A manual on the use of stress wave nondestructive evaluation (NDE) of wood bridges will be completed in late 1996.

In-Place Stiffness of Stress-Laminated Wood Decks Constructed of Sawn Lumber — A staff study is continuing to extend existing NDE evaluation technology by developing equipment and simple procedures for determining the in-place stiffness of individual laminations within existing stress-laminated lumber bridges. This information will be used to evaluate field performance and assess structural integrity.

Wood Bridge Inspection Manual — A study is in progress with the University of Tennessee to develop a comprehensive manual for the inspection of wood bridge superstructures and substructures using traditional inspection methods. The manual will be written specifically for bridge inspectors and will include an office reference text as well as clipboard field inspection guidelines. Topics include an introduction to the properties of wood and structural wood products as they relate to bridge inspection, an overview of the mechanisms of decay and other deterioration, an indepth discussion of the methods and tools typically used for detecting external and internal deterioration in wood bridge members, and recommended wood bridge inspection procedures and recording guidelines. An introduction to current and emerging NDE technology will also be presented.

Development of Nondestructive Evaluation Methods and Equipment — A study is being initiated to develop one or more advanced NDE techniques and equipment for the inspection, condition evaluation, and in-situ strength assessment of wood transportation structure components that provides a reliable evaluation procedure through enhanced information display and image processing technology. The study will begin with an evaluation of current and emerging technologies used for steel, concrete, wood, and composite components. From this, one or more promising technologies will be developed for applications involving wood transportation structures.

Remedial Treatments for Bridge Applications — A study is being initiated to investigate new and current remedial treatments, such as fumigants and diffusible chemicals, that will stop internal decay in bridge structural components. The study will investigate the distribution and longevity of remedial treatments in glulam and solid-sawn structural wood species (including hardwoods) and will focus on identifying treatment formulations that can be easily applied in a routine bridge maintenance program. The study will also assess the effect of pressure treatment with oilborne or waterborne preservatives on the retention of the remedial treatment and emphasize treatments that do not pose unacceptable environmental hazards during application, use, and removal/disposal. Results of the study will include guidelines on the use, application, and effectiveness of remedial treatments for applications involving wood bridge members.

Moisture Protection for Wood Members — A study is being initiated to develop, refine, and evaluate a variety of coatings and coverings for protecting bridge members from moisture. The study will examine a combination of coatings and/or coverings that include or supplement wood preservatives or involve non-chemical alternatives. Emphasis will be on protecting wood members from moisture in a variety of applications, such as exposed end grain on pile and railpost tops, exposed side grain on bridge railings, concealed joints (e.g., sill-pile connections), and concealed end grain at beam or deck panel ends. The study will result in a manual that includes comprehensive recommendations for the use, application, and maintenance of protective coatings and coverings for wood members.

Technology and Information Transfer

Standard Plans for Southern Pine Bridges — A project has been completed with the Southern Forest Products Association and the University of Alabama to develop standard plans for Southern Pine bridge superstructures. The plans include stress-laminated decks constructed of sawn lumber and glulam and solid-sawn stringer bridges with plank decks and include fabrication details, materials lists, and design computations. The plans have been published and are currently available.

Standard Plans and Specifications for Wood Bridge Superstructures — A project is concluding with Laminated Concepts, Inc. to develop standard plans and specifications for wood bridge superstructures. The following superstructure types are included in the project:

- Glulam beams with transverse glulam deck**
- Longitudinal glulam deck**
- Longitudinal stress-laminated deck**
- Longitudinal spike-laminated deck**
- Longitudinal nail-laminated deck**
- Transverse nail-laminated deck**
- Wood decks on steel beams**

Plans will be completed in mid-1996 and will be circulated for review. Final publication of the drawings is scheduled for 1997.

Interactive Computer Programs for Wood Bridge Superstructures — A study is in progress with the University of Wyoming to develop computer programs for the design of the following wood bridge superstructures:

Glulam beams with transverse glulam deck
Longitudinal glulam deck
Longitudinal stress-laminated deck
Longitudinal spike-laminated deck
Longitudinal nail-laminated deck

The programs provide interactive analysis, design, and load rating using allowable stress design, as well as LRFD methods in both customary U.S. and SI units. Currently, the programs have been completed and are in initial testing. Completion of field testing and release is scheduled for 1997.

Publications

Following is a partial listing of publications related to wood transportation structures which have been published since 1994.

- Rammer, D.R.; Soltis, L.A. 1994. Experimental shear strength of unchecked beams. Res. Pap. FPL-RP-527. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 38 p.**
- Ritter, M.; Moody, R.; Duwadi, S. 1994. U.S. timber bridge research. In: PTEC 94 Timber shaping the future: Proceedings of Pacific timber engineering conference; 1994 July 11-15; Gold Coast, Australia. Fortitude Valley MAC, Queensland, Australia: Timber Research Development and Advisory Council; Vol. 2: 148- 155.**
- Ritter, M.A.; Nowak, A.S. 1994. LRFD provisions for wood bridges. In: Baker, N.C.; Goodno, B.J., ed(s). Structures Congress 12: Proceedings of papers presented at the structures congress '94; 1994 April 24-28; Atlanta, GA. New York, NY: American Society of Civil Engineers; Vol. 1: 549-554.**
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- Soltis, L.A.; Rammer, D.R. 1994. Shear strength of unchecked glue-laminated beams. Forest Products Journal. 44(1): 1-8.**
- Taylor, R.; Ritter, M. 1994. Durability in stress laminated timber bridges. In: PTEC 94 Timber shaping the future: Proceedings of Pacific timber industry conference; 1994 July 11- 15; Gold Coast, Australia.**
- Fortitude Valley MCD, Queensland, Australia: Timber Research and Development Advisory Council; Vol. 1: 686-694.**
- Triche, M.H.; Ritter, M.A.; Lewis, S.L.; Wolfe, R.W. 1994. Design and field performance of a metal-plate-connected wood truss bridge. In: Baker, N.C.; Goodno, B.J., ed(s). Structures Congress 12: Proceedings of papers presented at the structures congress '94; 1994 April 24-28; Atlanta, GA. New York, NY: American Society of Civil Engineers; Vol. 2: 1310-1315.**
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- Lee, P.D.H.; Ritter, M.A.; Triche, M. 1995. Standard plans for Southern Pine bridges. Gen. Tech. Rep. FPL-GTR-84. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 26 p.**
- Nowak, A.S.; Ritter, M.A. 1995. Load and resistance factor design code for wood bridges. In: Proceedings of 4th International bridge engineering conference; 1995 August 28-30; San Francisco, CA. Washington, DC: National Academy Press; Vol. 2: 351-357.**
- Ritter, M.A.; Wood, D.J.; Wipf, T.J.; Wijesooriya, C.; Duwadi, S.R. 1995. Dynamic response of stress-laminated-deck bridges. In: Proceedings of 4th International bridge engineering conference; 1995 August 28-30; San Francisco, CA. Washington, DC: National Academy Press; Vol. 2: 381-394.**
- Ritter, M.A.; Faller, R.K.; Duwadi, S.R. 1995. Crash-tested bridge railings for timber bridges. In: Proceedings of 4th International bridge engineering**

- conference; 1995 August 28-30; San Francisco, CA. Washington, DC: National Academy Press; Vol. 2: 395-404.
- Ritter, M.A.; Faller, R.K.; Lee, P.D.H.; Rosson, B.T.; Duwadi, S.R. 1995. Plans for crash-tested bridge railings for longitudinal wood decks. Gen. Tech. Rep. FPL-GTR-87. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 27 p.
- Ritter, M.A.; Wacker, J.P.; Tice, E.D. 1995. Field performance of timber bridges: 2. Cooper Creek stress-laminated deck bridge. Res. Pap. FPL-RP-536. Madison, WI: USDA Forest Service, Forest Products Laboratory. 17 p.
- Ritter, M.A.; Wacker, J.P.; Duwadi, S.R. 1995. Field performance of stress-laminated timber bridges on low-volume roads. In: Proceedings of the 6th International conference on low-volume roads; 1995 June 25-29; Minneapolis, MN. Washington, DC: National Academy Press; Vol. 2: 347-357.
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- Ritter, M.A.; Williamson, T.G. 1995. Maintenance practices for wood bridges. In: Sanayei, M., ed(s). Restructuring: America and beyond: Proceedings of Structures Congress 13; 1995 April 2-5; Boston, MA. New York: American Society of Civil Engineers; Vol. 1: 290-293.
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- Wacker, J.P.; Ritter, M.A. 1995. Field performance of timber bridges: 3. Birchlog Run and Tumbling Rock Run stress-laminated deck bridges. Res. Pap. FPL-RP-538. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 11 p.
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