An Overview of Timber Bridges

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ABSTRACT

This paper contains a review of literature on timber bridges. It presents recent developments and evolving concepts in timber bridge technology, including aspects concerning wood material, bridge design, construction, inspection, rating, and maintenance. This review indicates that timber bridge technology has advanced with the design and construction of a prototype of a prestressed, laminated timber bridge in Ontario, Canada. In the United States, the main effort of government and the timber industry is to promote timber bridge technology transfer.

Timber was probably the first type of material that humans used to construct a bridge. Although concrete and steel replaced wood as the major materials for bridge construction in the 20th century, the use of wood in short-span bridges remains as great as ever. Of United States bridges that have a span of more than 20 ft (6 m), 12.6 percent (or 71,200) are made of timber. In the Forest Service (U.S. Department of Agriculture) alone, approximately 7,500 timber bridges are in use, and more are being built each year. The railroads have more than 1,500 mi of timber bridges and trestles in service. In addition, timber bridges recently have attracted considerable attention from many international organizations and foreign countries, including the United Nations, Canada, England, Japan, Kenya, and Honduras (1-3).

Timber is a highly desirable raw material because it is an abundant renewable resource. It has several advantages as a material for bridge construction. Timber bridge structures present a natural and aesthetically pleasing appearance, particularly in wooded surroundings. The timber sections can be constructed in any weather, including cold and wet conditions, without experiencing detrimental effects. Timber bridges cannot be damaged by continuous freezing and thawing and are resistant to the effects of deicing agents. Because of wood's energy-absorbing ability, timber bridges are also able to sustain overloads for short periods of time. The light weight of timber allows for easier fabrication and construction since smaller equipment is needed to lift the beams into place. A timber bridge's light weight also benefits repair and rehabilitation efforts including superstructure replacements because abutments can be reused and the available load-carrying capacity of the remaining existing structure can be increased. Initial and maintenance costs of timber bridges are lower than for most other alternatives and are certainly competitive with the materials usually considered to be best (4). For example, a prestressed, treated timber bridge costs only two-thirds of its counterpart constructed with conventional steel and concrete (5).

Wood does have several shortcomings as a bridge material. First, because wood is a biological material, it is vulnerable to damage by fungi, fire, accidents, and insects. Second, the deeper beam sections may significantly reduce the hydraulic operation, reducing the flood flow capacity beneath the bridge. Third, the fabrication of glued-laminated (glulam) timber members may take longer than the construction of steel beams or concrete sections (6); however, a newly developed prefabricated modular system of production may eliminate this time delay (3).

Several studies have summarized the results of research on timber bridges. The first study was performed by the American Institute of Timber Construction in 1973 (7). This study summarized the significant advances in the engineering and construction of timber bridges that occurred in the 1950s and 1960s. The Committee on Wood in the Structural Division of the ASCE made the second attempt in 1975 (8). The ASCE endeavor compiled an extensive bibliography on timber bridge design and classified a set of selected standard specifications into primary and supplementary criteria for both glulam and wood bridge members. The third study, conducted in 1980 by the ASCE Technical Committee on Timber Bridges, presented an excellent summary on the state of the art of timber bridges and included discussions of the development of new wood composite products and manufacturing techniques, the improvements in preservative treatment methods for resisting decay, the development of new wood bridge system concepts, and the advancements in timber bridge design and analysis techniques (9).

Manufacture and design were a major concern of these reports on the state of the art of timber bridges. The studies overlooked other aspects, however, such as inspection and maintenance. Given the safety requirements under the law, methods for inspecting and maintaining a safe timber bridge are as important as a cost-effective design. The present study will review the literature on timber bridges and emphasize all the important aspects of timber bridges, including wood materials, bridge design, construction, inspection, rating, and maintenance. It is hoped that this study will enhance the transfer of technology in the use of timber bridges.

WOOD AS A CONSTRUCTION MATERIAL

One of the major concerns in using wood as a bridge building material is strength. Because wood is orthotropic, its strength properties are different in different directions--that is, longitudinal, radial, or tangential to the grain or axis of fiber orientation. Wood strength is greatest in the longitudinal, or parallel-to-grain, direction, and weakest across the grain. This strength varies among tree species (10). In addition, growth variations, defects, and manufacturing processes also affect

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strength significantly. Therefore, the strength properties of each individual board are determined by a number of wood characteristics, including slope of grain, knots and their locations, pitch, wane, density, checks or splits from uneven drying, and size variations (11).

Wood Degradation

Because wood is a biological material, it is subject to seven types of degradation: decay-causing fungi, wood-destroying insects, marine borers, discolorations, weathering, chemicals, and fire.

Decay-causing fungi produce spores that develop into very small, threadlike hyphae that spread through the wood in all directions. A favorable environment for the fungi requires four factors: (a) available moisture, (b) adequate air, (c) favorable temperature, and (d) suitable food--the wood (11). The resulting decay causes losses of density and strength, and increased permeability in the wood. The loss of strength results from the enzymatic degradation of the wood cellulose and lignin. The decayed wood rapidly loses its toughness, or capacity to withstand loading, and its resistance to bending and crushing. For example, the Forest Service's Forest Products Laboratory conducted bending tests on stringers from 12-year-old native timber bridges in Southeast Alaska and found that the strength of the decayed logs was 25 percent lower than that of fresh logs (12).

Another type of degradation, weathering, is affected by light, water, and heat. Weathering can change the equilibrium moisture content and result in changes in the strength of wood and its dimensions. As the moisture content falls below the fiber saturation point, wood shrinks. A 12-percent change of moisture content in a 12-in. piece of wood can result in a shrinkage of .25 in. Shrinkage leads to warping, checking, and splitting, which can cause connectors to loosen and reduce bridge capacity.

One of wood's distinguishing characteristics, however, is its good energy-absorbing properties. This enables the wood structure to sustain overloads for short periods of time. However, the wood's strength will decrease over time as a result of the degradation.

Wood Preservation

Chemical preservation of wood is often used to maintain the material in serviceable condition. Two main preservation methods consist of brushing, spraying, or dipping and vacuum-pressure processes (13). Brushing, spraying, or dipping provide shallow penetration, low chemical absorption, and superficial treatment of the wood surface. Vacuum-pressure processes penetrate the wood more deeply. They consist of the Bethel, Lowry, and Rueping processes, each of which uses timed pressure and vacuum treatments. Vacuum-pressure processes are referred to as full- or empty-cell processes depending on the amount of preservative solution or toxicant that remains in the wood after treatment (13). The Bethel process is a full-cell process and is applied to products such as marine piling where maximum protection is required; both the Lowry and Rueping methods are empty-cell processes and provide good distribution with a limited amount of preservative. The Rueping process is more flexible and can be used to achieve a wider range of results than the Lowry process. However, the Lowry process is simpler to perform, particularly when the wood is readily treatable.

Three groups of preservatives are used for wood treatment--creosote, pentachlorophenol (penta), and water-borne salts. Although each compound or mixture of compounds has unique characteristics, all preservatives must have the following properties:

1. They must be toxic to organisms that degrade wood, and they must have some degree of permanence.
2. They must be capable of being forced into the wood by pressures of one atmosphere or greater.
3. They must not be unduly flammable or explosive, highly poisonous to man or animals, or have an undesirable color or odor.
4. They must not be corrosive to metals.
5. They must be easy to detect by standard assay methods.

Chemical treatment makes wood resistant to most agents of deterioration, fire, swelling, and shrinking. For instance, either pressure impregnation or fire retardant wood coatings such as phosphates, zinc chloride, boric acid, and so forth, will produce some reduction in flame spread. Fire retardants may increase ignition temperatures or reduce the tendency of the wood to catch fire or to glow after flaming has ceased. In addition, treated wood cannot be damaged by continual freezing and thawing and is not affected by temperature, alkali soil, or acids. Although using water-borne preservatives and fire retardants may harm wood's stiffness and bending strength, this damage should be insignificant if modern treating practices are followed.

The preferred preservatives are creosote or penta in heavy oil because they provide a more uniform moisture content over a longer period of time. Creosote treatments are used to protect deck panels and stringers, while penta in heavy oil is a commonly specified treatment for both stringers and deck panels. The water-borne salts or penta in light solvents are better suited for bridge components, such as traffic rail elements, that may come into human contact. In temperature climates, creosote treatments can extend the serviceable life of wood considerably (14). Thus, the life expectancy of treated timber bridges can be as high as 50 years under normal conditions (6,7).

Summary

Today, much is known about wood, yet its propensities are not fully exposed. Given its many advantageous characteristics, treated wood is a good source for construction materials. Research on its cost-effective use is important and is continuing (11,13, 15-18).

DESIGN

U.S. timber bridge design follows the requirements of Section 13, Timber Structures, Division I, Design, of the thirteenth edition of the Standard Specifications for Highway Bridges (19), published by AASHTO. The AASHTO design specifications are adjusted or amended by state designers or Forest Service bridge engineers to fit local conditions based on new experience or research results (20). The AASHTO specifications include a list of allowable stresses for stress-grade lumber and glulam timber under normal loading; permanent loading; and wind, earthquake, or short-term loading conditions. The specifications provide formulas for the computation of stresses, as well as detailed design procedures for simple columns, spaced columns, pile and framed bents, and trusses. The Forest Products Laboratory also has documented in detail a design procedure for glulam bridge decks (21-23) that was adopted by AASHTO and included in the bridge specifications.

The AASHTO design code does not address the design of log bridges for trails and roads. The Forest Service often uses untreated logs for temporary structures when short-term (5 to 10 years) needs justify use. However, some of these "temporary" structures are up to 25 years old. Glulam bridges also have been designed and constructed for temporary structures in cases in which the load duration characteristics of wood (time dependency; that is, change in strength over time of use) were a consideration (24). Logs used for road bridges range in diameter at the tip from about 24 to 40 in. (61 to 102 cm). The bridge spans reach up to 80 ft (24.4 m). Although the loading varies in road designs, the minimum loading for the Forest Service is the AASHTO HS 20-44 truck. Markedly higher loads are used for logging roads. In Forest Service engineering practice, loadings for trail bridges include hikers, livestock, motorcycles, snowmobiles, and sometimes, four-wheel-drive vehicles. The usable width of trail bridges varies from 3 to 8 ft (0.92 to 2.44 m) (25).

Timber Bridge Design

Traditionally, the deck design has involved a nail-laminated assembly of nominal, 2-in. (5-cm) dimension lumber placed transverse to the supporting stringers. Connections include through-nailing of laminations and toe-nailing to the stringers. The major shortcoming of this system is that nail connectors gradually loosen as a result of the deck deflections and the shrinking and swelling caused by repeated wetting and drying cycles. Because of this problem, the deck cannot serve as a roof over the entire bridge structure, protecting the supporting members and the deck itself from the deteriorating effects of rain and snow.

Glulam Bridge Design

To overcome the deficiencies of the nail-laminated deck and to increase deck stiffness, the composite timber-concrete deck was designed and constructed in the early 1930s (9). In the 1950s, an effort was made to examine the glulam concept in terms of the effect of knot size and distribution of glulam timbers (26). Glulam is an assembly of individual wood laminations bonded together with structural adhesive. In the early 1960s, the Forest Products Laboratory further developed the glulam technique, introducing prestressed glulam (27-29). In 1976, the Ontario Ministry of Transportation and Communications used transverse prestressing for rehabilitating existing nailed decks (30). In 1979, the possible use of prestressed glulam for wood bridges was further examined by the U.S. researchers (31).

In the late 1960s and early 1970s, the Forest Products Laboratory and the glulam industry continued their research on prestressed glulam, evaluating the concept of increasing beam strength by increasing the grade requirements for the tension zone and defining the grade requirements for fabricating glulam members using lumber that has been both E-rated as well as visually graded (32). The results of this research appear in the 1973 version of AASHO design specifications (32) and in "Standard Specifications for Structural Glued-Laminated Timber of Douglas Fir, Western Larch, Southern Pine, and California Redwood" published by the American Institute of Timber Construction (33). In the late 1970s and early 1980s, the Ontario Ministry of Transportation and Communications also conducted considerable research on the design of prestressed wood decks (30,34), which resulted in a comprehensive set of design specifications (35,36). These new specifications were developed using probability-based methods of timber stress analysis and have been included in the 1983 edition of the Ontario Highway Bridge Design Code (36).

However, the analytical methods used in the specifications for AASHTO and for the Ontario design code differ. AASHTO uses allowable stress to design and evaluate timber bridges, while the Ontario design code uses probability-based methods as an analytical tool (37). The AASHTO approach does not provide for the determination of the actual safety reserve in the structure (38). However, developing a comprehensive probability-based design code would require considerable research because of the current lack of a good data base on the mechanical properties of wood (39,40).

BRIDGE LOAD-CARRYING CAPACITY

An important aspect of bridge design is analyzing the adequacy of the bridge structure to carry the expected traffic load. Nine independent elastic constants are used in the analysis: three moduli of elasticity, three shear moduli, and three Poisson's ratios. However, because of large variations in the longitudinal modulus of elasticity of wood, actual values of dead and live load moment and shear stresses in timber bridges are difficult to determine. Many methods have been used to estimate the longitudinal modulus of elasticity, such as the orthotropic plate theory (21,30,41,42), the Grillage analogy (43,44), the AASHTO simplified approach (19,45), the statistical approach (46), and probability-based methods (38). These methods were developed based on various assumptions. For example, in the orthotropic plate theory, the bridge structure is considered to be a plate of uniform thickness that has different flexural and torsional properties in two orthogonal directions. In the grillage analogy analysis, bridges are considered to be idealized grillages. The analytical procedure is similar to that used in nontimber bridges, except for the discretization of the structure and the calculation of the properties of idealized members. The statistical approach is to calculate mean values of longitudinal moments and shears and their coefficients of variation by assuming a uniform value for the longitudinal moduli of elasticity of various longitudinal members. Probability-based methods use several mathematical models to compute reliability indices, for instance, using the Rackwitz and Fiessler procedure for single beams and Monte Carlo simulations for whole bridges. This method allows the investigation of a structure's limit states (47).

Overload behavior is a major concern in the timber bridge design (48). In several cases, overloading caused shear failures in laminated-timber bridge girders (49). Some early investigations of load distribution on timber bridges centered on structures with decks and timber girders (50-54), while others concerned wood floors on steel joists (55) or timber deck and steel girders (56). The Forest Products Laboratory and the FHWA conducted tests on the strength of log bridge stringers and piles (13, 57-61).

In the past two decades, researchers have investigated the behavior of layered wood systems. In the late 1960s, glulam wood was treated as steel and reinforced concrete material and analyzed for stress based on an assumption that the material properties of the individual layers are constant along the entire span (62,63). In the 1970s, researchers studying glulam bridges applied a finite-element approach, based on the principle of minimum potential energy (64, and an unpublished analysis of stiffened deck panel systems by Weyerhauser Company, Tacoma, Washington, in 1977), to define key factors such as gaps between individual deck panels and interlayer slip at the deck-stringer interface that have significant effects on the system performance (65). The result of this research indicated that the composite design of glulam bridges can add strength and stiffness to working loads because layered systems perform at maximum structural capacity if the individual components interact as a single unit. Thus, the finite-element approach is becoming an important tool for evaluating the deck systems performance (66).

A recent study conducted by the researchers at Iowa State University verified this finding and recommended that the existing load distribution criteria for glulam longitudinal deck bridges as shown in the current AASHTO bridge specifications (19) be updated according to the distribution behavior defined by the finite-element method (67). In this recent study, finite-element analysis was used to develop an analytical model for studying the load distribution behavior of glulam longitudinal deck bridges.

CONSTRUCTION

The thirteenth edition of AASHTO Standard Specifications for Highway Bridges (19) sets forth the requirements for constructing glulam timber bridges. The specifications cover materials; timber connectors; holes for bolts, dowels, rods, and lag screws; pile and frame bents; nail-laminated or strip floors; wheel guards and railing; and so forth. In United States practice, some of these specifications apply to other types of bridges, such as log bridges and prestressed glulam timber bridges. However, the construction procedures for log bridges and prestressed glulam timber bridges differ from those for glulam timber bridges. Therefore, the AASHTO standard specifications are adjusted or amended by bridge engineers in state and forest service based on the local environment (20,68).

Log bridge construction is simple. The logs are normally greater than 10 in. in diameter and are all as nearly equal in size as possible so that they will uniformly support the 2-in.-thick flooring. They are placed perpendicular to the stream channel. The number of logs varies from two for wheel-tracking spacing to three or more equally spaced for a solid bed of logs. In some cases, dirt fill or gravel is used to cover the plank flooring, which permits smoother truck crossing. Depending on the size of the bridge, constructing a log bridge may require a two- to three-man crew for a period ranging from 2 days to 2 weeks (69).

The fabrication and construction of the longitudinal, laminated-deck timber bridge is also simple (26,70), requiring a small crew consisting of a carpenter foreman, a machine operator, and one or two laborers. The construction does not require much sophisticated equipment or many highly skilled workers (71).

Although the concept of prestressed timber bridges has been studied for 20 years, it was not until 1981 that the world's first bridge of this kind was constructed--in Ontario, Canada (5). The Ontario experience indicated that constructing a 37-ft prestressed timber bridge took several weeks with a crew consisting of three experienced construction workers and three supplemental laborers. In this project, all steel hardware was hot-dip galvanized for protection. All wood materials were cut and drilled before undergoing pressure preservative treatment with creosote, except for the holes in the deck that were drilled on site.

The process for the fabrication of the frame geometry used in Ontario differs from the prestressing routine used by timber craftsmen (72). It enables the prestressing of the entire bridge to be done at the same time and allows the legs and deck to be constructed as an integrated, prestressed, laminated system. The Ontario experience also indicates that the cost of prestressed, treated timber bridges is one-third lower than that for conventional steel and concrete bridges.

A recent investigation has found that a weak glue bond may fail in shear. The weak glue bond is caused by a premature curing of the glue before final clamping. When a girder is assembled during hot, dry weather, the extended "layup" time caused by its large size may cause this effect (49).

INSPECTION

Federal and state legislation require that highway and railroad bridges periodically be inspected, evaluated, and rated as to their safe load-carrying capacity. Inspections cover physical and mechanical properties of timber, such as strength, porosity, anisotropy, impact resistance, durability, fire resistance, and so forth. The purpose of the inspections is to ensure the early detection of damage or deterioration and to prevent structure failure (73-75).

Inspections are also important in developing economic plans for bridge replacements or rehabilitations. Bridge engineers, therefore, need reliable data for assigning priorities and scheduling maintenance on timber bridges. These data come from tests conducted on a bridge during an inspection. The techniques used for testing fall into two categories: destructive and nondestructive. Destructive testing includes probing and core sampling. Nondestructive testing consists of visual inspection, sounding, radar, ultrasonic technique, infrared thermography, microseismic survey, resistivity survey, and electronic potential. They are described below.

Destructive Testing Methods

Destructive testing methods can be classified into probing and bore or core sampling. The probing sampling approach detects external decay using a pointed tool, such as an awl, an ice pick, or a prospector's rock pick. The bore or core sampling method detects and defines the limits of internal decay using such instruments as an electric drill or an increment borer.

These destructive sampling tests can impose undue strain on the tested members and increase the loss of cross-sectional areas at the location where the test takes place. Impairing the usefulness of wood material is the major disadvantage of destructive testing methods. Another shortcoming of these sampling techniques is the assumption that the tested pieces represent the entire population not tested. If the sample is not truly representative, then the results of the test are not accurate (76).

Nondestructive Testing Methods

Any inspection technique that does not impair the usefulness of the material under examination is categorized as a nondestructive method. Visual inspection, sounding, radar, ultrasonic technique, and infrared thermography are discussed in the following paragraphs. Other methods, such as microseismic survey, resistivity, and electronic potential, have been detailed in other reports (77,78). Some of these nondestructive methods are applied to timber and others may have potential for the application.

Visual Inspection

Visual inspection of timber bridges is based on two groups of visual indicators (79). The first group includes three visual indicators of the presence of decay: (a) characteristic fungus fruiting structures, (b) abnormal surface shrinkage or sunken faces, and (c) insect activity. The second group of visual indicators is used to identify six conditions conducive to decay. The indicators are

1. Excessive wetting (evidenced by water marks or stains);
2. Rust stains on wood surfaces;
3. Growth of vegetation on bridge members;
4. Accumulation of soil on any wood surfaces, which can trap water and increase decay hazard;
5. Joint interfaces, mechanical fasteners, field fabrication, and wood adjacent to other water-trapping areas, which are potential sites of decay fungi growth; and
6. Water-catching seasoning checks in exposed wood faces. Of these, the first condition is probably the most common and noticeable indication of the development of decay.

The advantage of visual inspection is its simplicity and quickness. However, it depends a great deal on the inspecting engineer's judgment. This method has two major limitations. First, it is less accurate for inspecting internal decay; for example, a timber pile may be completely decayed even though the external material appears sound. Second, members immersed in water or covered by asphalt or concrete are difficult to inspect. However, a newly developed photographic technique could overcome the difficulty of inspecting underwater bridge components (80). The equipment allows divers to obtain clear, underwater photographs under typical inspection conditions.

Sounding

The sonic technique has been used to locate the relatively severe delaminations of concrete bridges by monitoring the audible sounds that result from striking the deck surface of a bridge. Sounding relies on subjective judgments of hollow sound that are produced when concrete is struck with a hammer or when a chain is dragged across the deck surface. Interference from traffic noises may result in an inaccurate judgment (78,81). To overcome this difficulty, the Delamtec, a delamination detector, may be used to monitor the sound. The Delamtec uses piezoelectric hydrophones to characterize vibration waves generated by steel tapping wheels striking delaminated areas. This device is faster than the hammer or chain drag and provides a graphic record of distressed areas.

The use of sonic instruments, which were developed in the 1960s, to inspect piles of timber bridges is still in the experimental stage (82). In the simplest version of the sounding method, an inspector strikes a wood member with a rock pick and listens to the sound produced. A dull or hollow sound may indicate internal decay (79). The approach is economical, but its accuracy is much in doubt. The application of sonic techniques to covered timber decks has not been reported in the literature. One shortcoming of sounding is its inability to identify the areas of debonding (78,83).

Radar

A pilot test using low-power, high-resolution, ground-penetrating radar (GPR) to detect deterioration in concrete bridge decks was performed in 1977 (84). After this pilot test, additional work was done to improve the accuracy of the technique (85-87).

The GPR system consists of a monostatic antenna, a control console that contains a transmitter and receiver, and an oscilloscope. This system transmits impulses of microwave frequency into an overlaid concrete bridge deck and detects the extent of deterioration based on the reflection from the surfaces of the bituminous concrete, the portland cement concrete, and the reinforced concrete slab. When the concrete slab is delaminated, there is an additional reflection from the deteriorated area. The more severe the delamination, the more pronounced is the resulting reflection.

Recent studies indicate that radar can be used to survey the condition of overlay decks and decks that have their original surfaces (78,83). Although the speed and accuracy of the technique need improvement, the experiment of concrete bridges indicates that radar can be a potential tool for inspecting timber bridges. It should be noted, however, that like other nondestructive techniques, radar is not adequately capable of identifying the areas of debonding. Also, the radar technique requires further development to automate data collection and analysis and to improve the interpretation of signals.

Ultrasonic Technique

Ultrasonic technique has been used to detect defects and to measure the strength of concrete for many years (88-93). The technique involves the use of propagated high-frequency sound waves to test materials based on the relationship between the wave velocity in a material and its properties. For example, undamaged wood is an excellent transmitter of these waves, whereas damaged and decayed wood delays transmission. The technique, therefore, requires accurate measurements of the velocity of the propagated stress wave.

A recent study (76) indicated that the velocity of propagation of the waves parallel to the grain V_L and in the radial direction V_N (normal to the grain) in an orthotropic material with a Poisson's ratio for transverse strain in the longitudinal direction, when stress is applied in the radial direction, in the range of 0.01 to 0.04, is approximately

$$V_L = (E_L/p)^{1/2}$$

and

$$V_N = (E_N/p)^{1/2}$$

where E_L and E_N are the dynamic modulus of elasticity in the longitudinal and radial directions, respectively, and p is the material mass density. Factors affecting the velocity of waves include type of wood, effect of treatment, direction of grain, density of wood, degree of decay, and moisture content.

In the late 1960s and 1970s, the Forest Products Laboratory made two efforts to apply the ultrasonic scanning technique to detect defective wood (94,95). Although the results were encouraging, these two applications were merely experimental. It was not until 1984 that an ultrasonic wave propagation method was used to test wood bridge piles in Maryland (76). The results of the Maryland test were satisfactory. The difference between the calculated average crushing strength and the actual measured strength was about 11 percent. The study indicated that the ultrasonic technique can determine if damage is occurring or has occurred and to what extent, thus enabling the inspector to predict the true performance of the pile.

In contrast, the application of ultrasonic technique to detect the deterioration of asphalt-covered concrete decks has yielded no meaningful results because of unknown path lengths in three different materials--the bituminous surfacing, the concrete deck slab, and the reinforcing steel (78). This problem may also exist in an overlaid timber bridge. Therefore, this technique's use on asphalt-covered timber deck inspection requires further research.

Infrared Thermography

The principle of using infrared (IR) thermography as a means of defining delaminated areas caused by corrosion of the reinforcing steel in concrete bridge decks is based on the detection of differences in the surface temperature between the sound concrete and the delaminated concrete. The concrete emits IR radiation generated by the vibration and rotation of its atoms and molecules. From an IR scanner, the temperature can be determined indirectly by measuring the intensity of the emitted IR radiation.

IR thermography has proven to be a faster and more effective method than conventional sounding methods for surveying the extent of delaminations in concrete decks that have not been overlaid with bituminous concrete (96,97). For overlaid concrete bridge decks, the application of an IR scanner is still in the experimental stage. However, two recent studies have shown encouraging results. One study indicated that the scanner detected more than 90 percent of the known delaminations, some of which were less than 6 in. (150 mm) in diameter (78). The results of the other study were not conclusive for quantity estimates, but the applicability of IR equipment to general rehabilitation programming is warranted (98,99).

A number of commercial IR systems have been tested using various configurations of the equipment, including aerial and van-mounted apparatus. Between the two, the van-mounted equipment, which provides simultaneous recordings of the infrared scan and a video of the actual surface appearance, is more practical. The results of recent tests have concluded that the optimum height above the deck for the scanner is in the range of 13 to 20 ft (4 to 6 m) (78,97,98).

Although IR thermography is a promising tool for bridge inspection, it has limitations. First, detecting the point of debonding or the lateral extent of debonding with any degree of accuracy is difficult. Second, there are difficulties associated with isolating and identifying hot spots, such as bituminous patches, crack sealers, and tire marks. The presence of these affects the quality of interpretation and requires appropriate visual records to complete the interpretation. Third, a better definition is needed of the weather conditions under which IR thermography is most effective. Finally, IR thermography requires the development of software to produce a scaled hard copy from videotape.

The application of IR scanners on timber bridges has not been reported on in the literature. However, the successful use of IR scanners to develop a remote sensing technique for tree stress surveys (100) and the satisfactory results of the use of scanners on concrete bridge decks indicate that IR thermography has great potential for detecting the deterioration of timber bridges, including piles and decks.

Summary of Inspection Techniques

The application of nondestructive approaches to timber bridge inspection has been minimal. The review of the use of these methods on concrete bridges shows that the technology in this area has advanced significantly in the last decade. This new technology, particularly in radar and IR thermography, has great potential for use in routine operational procedures for detecting the deterioration of timber bridges. However, at present, the nondestructive techniques are better suited to the rapid assessment of the overall condition of a large number of bridges for developing rehabilitation programs than to the provision of detailed information for the replacement or repair of individual bridges.

RATING

As discussed previously, the field inspection establishes the extent of deterioration in load-carrying members of bridges. After inspection, the information gathered must be rated so that the bridge engineers can make safety decisions about the repair, rehabilitation, posting, closing, or replacement of an existing bridge. The rating of bridge strength generally follows procedures similar to the AASHTO design code, including checks for specified design loads, girder distribution and impact factors, and allowable stresses. Therefore, bridge rating is an important step in producing acceptable safety.

Most bridge rating methods were developed for steel and concrete bridges. Some of these methods use load spectra (101), and others apply the pragmatic approach for rating (102). The pragmatic approach uses a procedure to rate highway bridges for regulation loads without causing yielding of the bridge materials. Federal and state governments have developed several computer systems that inventory the actual conditions of bridges (103,104). These systems may provide a data base for rating and selecting a preferred bridge maintenance program (105-107).

There is not however, a well-developed rating method for timber bridges. The Forest Service has developed a system for bridges and major culverts (BMC) to be used in conducting inventories of forest road structures (108). Implemented several years ago, this national system is progressively being enhanced. Because most Forest Service bridges are timber bridges, the BMC is considered to be a timber bridge inventory system. A major element of this system is composite rating, in which a numerical rating, ranging from 0 to 9, is assigned to the condition of the bridge as a whole. This rating reflects the inspector's evaluation of the more critical features of the bridge affecting safety and cost.

The rating scores rely partly on the mathematical ratings for load capacity and on the inspecting engineer's judgment. Scientific approaches for timber bridge rating have yet to be developed.

MAINTENANCE

Based on the field inspection and the rating, a bridge maintenance program can be developed. Government agencies use numerous methods to develop bridge maintenance programs. For example, the Minnesota Department of Transportation has employed a systems approach as a planning tool (109,110), while the Wisconsin Department of Transportation has used the linear programming method (111) to minimize maintenance costs.

Timber bridge maintenance can be classified into three categories: replacement, repairs, and preventive maintenance. As indicated previously, the age of a structure is a major factor in the deterioration of a bridge. However, a thorough inspection should determine the actual condition of the structure before a decision is made on a maintenance plan.

Replacement

When the load-carrying capacity of a member has decreased by 50 percent or more of its design capacity, the member must be replaced, repaired, or strengthened by adding reinforcements (100,113). Replacement includes the replacement of timber stringers, plank decks, defective piling, and so forth. The construction procedure for replacement is documented elsewhere (114,115). In the case of a partial replacement, the replacement must extend 2 ft beyond the defective area of the member (113). Onsite preservative treatment is recommended for the area surrounding the defect and the newly exposed cutoff area.

Repairs

Repairs aim to extend the service life of a bridge, to increase or maintain the load-carrying capability of the structure, and to improve bridge safety. Repairs range from strengthening existing timber pier caps to fixing cracked or split timber stringers. Depending on the member of the structure and the severity of the damage, methods of repair include reinforcing a member, adding a sister member, stitch bolting, adding protective armors, post-tensioning, using a composite deck, repairing with epoxy, and using preservatives. The application of these methods was discussed in detail in a recent study (112). It is important to point out that after post-tensioning, the load-carrying capacity of a rehabilitated, nail-laminated deck can be increased as much as 100 percent (115). The epoxy repair method was introduced in 1976 (116) and has proved to be highly effective (117). Its applicability to glulam beams also has been demonstrated (118). This approach has great potential for timber bridge repair (119).

Preventive Maintenance

Preventive maintenance can be carried out either by field preservative treatments or by moisture control. Field preservative treatments should be applied at regular intervals to the major structural components of a bridge, such as stringers, piles, caps, and the exposed untreated surface of timber that has resulted from collision damage, delaminations, checks, and splits, to protect them from decay. Forest Service experience indicates that field treatments should be considered when decay is under way on not more than 25 percent of the structural members. Otherwise, when decay has attacked 40 percent or more of the members, a percentage of them will have to be replaced. For instance, when decay has affected 80 percent of the structural members, 14 percent of them will have to be replaced (120).

Moisture control is required at sites where bridge timber is subjected to frequent decay-causing wetting. Proper bridge surface drainage as well as a clear waterway will reduce decay or collision damage. Periodic inspections during periods of minimum moisture to ensure that no glueline separation is developing would be appropriate (121).

RESEARCH AND TECHNOLOGY TRANSFER

The outcome of the future wood utilization research will have significant impact on the research and development of timber bridges. Three major institutional groups in the United States that are involved in research and development concerning the use of wood are the federal government, the forest industry, and academic institutions. The federal government funds and performs research and development, the forest industry develops products and improves manufacturing processes, and academic institutions conduct training and basic research. [The research and development activities of the three groups are reported elsewhere (18).] Two of the groups' major concerns with respect to the timber bridge technology development are research and technology transfer.

Research

As stated in a 1983 report (9), three major research areas are (a) rationalization of limit states design for uniformity in the various structural codes; (b) incorporation of reliability-based formats; and (c) development of a systems approach to the analysis of structures. In the first area, some researchers are applying fracture mechanics theories to define the ultimate strength limit state of wood. The result of research in this area could aid in producing ingrade strength of full-size structural members of a bridge as a basis for establishing allowable design stress in the future.

Significant progress has recently been made in the second area of research. In Canada, the Ontario highway bridge code was developed from probability-based methods of analysis (36). In the United States, a set of reliability indices for single-timber bridges with deck planks and stringers was calculated using probability-based analysis (38). The results of this research are encouraging for the future development of a probability-based design code.

Research in systems approaches to structural analysis also has made headway. Recently, a systematic approach has been developed for the assessment of the reliability in wood structural systems under load (122). The method calculates performance factors in reliability-based design equations and determines reliability levels for "baseline" structures that are accepted as safe and adequate and to which the design of future structures could be calibrated. Further research needs on timber bridges have been documented elsewhere (123, and in communication notes on technical applications to Harold Strickland, Assistant Director of the Engineering Staff, Forest Service, U.S. Department of Agriculture, in 1985).

Technology Transfer

The concept of timber bridge technology transfer was initiated in the Forest Service Road Technology Improvement Program, which was designed to evaluate, develop, and adopt new concepts and technologies to improve road construction, operation, and maintenance, and, consequently, to lower transportation costs. Recently, the Forest Service, in coordination with the American Institute of Timber Construction, established an Industry-Federal Government Cooperative Program on timber bridge technology transfer (124). This cooperative program attempts to encourage the adoption of beam and deck technology and has a target to increase the use of timber bridges tenfold in 5 years (using 1983 as the base year).

It is difficult to transfer new timber bridge technology by means of education and publications. Therefore, the cooperative program devised three specific objectives, as follows: (a) to inform state, county, and township officials, as well as federal agencies, engineers, and contractors about the advantages of timber for new and replacement bridges on local and secondary road systems and federally owned properties; (b) to provide guidance on the rehabilitation of existing timber bridges; and (c) to cooperate with interested professional and industry associations, technical organizations, and government agencies to improve the nation's road systems by providing safe and economical alternatives for bridge replacement needs.

An implementation team developed six tasks for the implementation of the 5-year cooperative program as follows:

1. Develop a timber bridge design and construction manual that would have a larger scope than that developed by Weyerhauser in 1980 (125);
2. Document the economy of timber bridges by providing the requisite initial cost and life-cycle cost information;
3. Study ways to reduce the transverse load-carrying criteria or to design and test a cost-effective bridge-railing detail that meets the current AASHTO requirements (in practice, the load-carrying criteria specified by AASHTO for bridge railings exceed that used by the Forest Service);
4. Disseminate general information through bulletins, leaflets, workshops, seminars, lectures, papers, and demonstrations;
5. Select sites for constructing demonstration projects; and
6. Develop a technology transfer schedule of activities.

CONCLUSIONS

Considerable progress has recently been made on the use of wood as a construction material as follows:

1. Preservative agents may extend the serviceable life of timber considerably. Thus, the life expectancy for glulam-treated timber bridges can increase to 50 years.
2. The evolution of timber bridge design follows the progress of research on timber's load-carrying capacity. Two major approaches for analyzing load-carrying capacity are based on allowable stress, which is used in AASHTO specifications for glulam timber bridges, and on probability methods, which are used in the Ontario Highway Bridge Design Code for prestressed, treated timber bridges. A probability-based design code for glulam timber bridges is still in the development stage.
3. The construction of timber bridges is simple and economical. Procedures for constructing glulam timber bridges are defined in AASHTO specifications and Forest Service reports, while procedures for constructing prestressed bridges has been developed from the Canadian experience in Ontario. Methods for constructing prestressed bridges will require modification as construction experience for this type of bridge progresses. Compared to the costs of steel and concrete bridges, the costs of constructing prestressed treated bridges can be as much as one-third less.
4. Destructive testing approaches are still used for timber bridge inspection. However, there has been considerable research on developing nondestructive inspection methods. The results of studies in this area are encouraging. Both radar and IR thermography have great potential for application to timber bridges.
5. Timber bridge rating mainly relies on the inspecting engineer's judgment. There has been little research in this area. Recently, however, automation systems have been developed for use in conducting inventories on timber bridge conditions and providing information for use in formulating cost-effective bridge maintenance programs.
6. The methods for repairs and preventive maintenance of timber bridges also have been improved considerably. Case studies indicate that a post-tension system of rehabilitation can double a nail-laminated deck's load-carrying capacity. Several studies also have demonstrated that preventive field treatments are cost-effective.
7. The current focus on timber bridges centers on technology transfer. The Forest Service coordinates with other government agencies and the timber industry to develop the Industry-Federal Government Cooperative Program on Timber Bridge Technology Transfer. The goal of this program is to increase the use of timber bridges tenfold within 5 years.
8. The technology associated with various aspects of timber bridges continues to be developed in significant ways. The availability of this technology, along with the advantages of using wood as a construction material and the reduction of government budgets, will make timber bridges more appealing. The initiation of technology transfer by the Forest Service is timely and will have significant impact on the use of timber bridges on low-volume roads in the near future.

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Designing Timber Bridges for Long Life

FRANK W. MUCHMORE

ABSTRACT

Wood is a marvelously adaptable structural building material. When treated with a compatible preservative to prevent early decay deterioration, it is an economical and practical structural material for many short-span bridges (spans in the range of 15 to 60 ft). Timber's inertness to deicing chemicals, as well as some new design developments, such as glued-laminated deck panels and prestressed laminated decks, make it more attractive than ever for use in highway structures. Important factors in assuring long, useful lives for timber bridges include designing to avoid water-trapping details, use of effective and compatible preservative treatment, and following a systematic inspection and maintenance program. Attention to these factors will provide a lifespan that is competitive with other structural materials, such as steel and concrete, and will, in most cases, dramatically increase the useful life of timber bridges.

Timber bridges are remarkable structures--when properly designed, built, and maintained, they can (a) carry heavy loads without showing material fatigue, (b) resist the deteriorating action of deicing chemicals, (c) be constructed by unskilled labor, and (d) last for long periods of time. Timber is particularly adaptable to short-span bridges (spans up to 60 ft) and can be economically designed to carry heavy highway loads. For example, some timber bridges in western Canada routinely carry logging trucks and machinery weighing in excess of 100 t.

Wood was one of man's first building materials. However, as modern technology has yielded its wonders in mass-produced steel, aluminum, concrete, and plastic construction materials, wood has been largely overlooked as a primary structural material for bridges. Wood is still a marvelously adaptable structural material. For example, structural wood

- Is simple to fabricate,
- Is lightweight and easy to install,
- Has a high strength-to-weight ratio,
- Has excellent sound and thermal insulation properties,
- Has good shock resistance,
- Is immune to deicing chemicals,
- Has unique aesthetic qualities,
- Is a renewable resource,
- Is long-lasting (when properly protected), and
- Has good fire resistance (1).

Note that the unusual claim of good fire resistance of structural timber is well founded. When a large structural timber is exposed to fire, there is some delay as it chars and eventually flames. As burning continues, the charred layer has an insulative effect, and the burning slows to an average rate of about 1/40 in. (0.6 mm) per min [or 1-1/2 in. (38 mm) per hr], for average structural timber species. This slow rate of fire penetration means that timber structural members subjected to fire maintain a high percentage of their original

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