Table 1. Summary of test results.

Girder	Pre-Test Condition	Load Position	Predicted Ultimate Capacity (kN)	Test Collapse Load (kN)	Equivalent AASHTO Load	Apparent Loss of Strength (%)
139-S1	No apparent damage	Midspan	423	423	HS20	None
139-S2	No apparent damage	Midspan	423	423	HS20	None
171-S2	No apparent damage	⅓ point	489	498	HS20 plus	None
171-S3	Extensive corrosion	⅓ point	489	449	HS20	8
139-S3	Extensive corrosion; one bar fractured	⅓ point	311	329	HS20	33

Note: 1 kN = 224.8 lbf.

failure surface, when fracture propagates from the center of the section.

In girder 139-S3, one of the prestressed bars fractured before the girder was removed from the bridge. As expected, the girder suffered a 33 percent loss of strength as a result of the missing bar. Of the remaining two bars, one was corroded and failed by brittle fracture at near ultimate strength, and the other failed ductily with no evidence of corrosion.

Another brittle fracture occurred in girder 171-S2, although we saw no spalled or cracked concrete before the test. Here, again, the fracture was induced by corrosive pitting at the bar surface. However, the bar appeared to have reached the theoretical ultimate strength before failure.

The test results are tabulated in Table 1. The predicted ultimate capacity is the theoretical maximum concentrated load capacity for an uncorroded girder. The tabulated predicted capacity is based on flexural not shear strength, although the collapse mechanism was a combination or interaction of flexure and diagonal tension. When there was no obvious initial damage, the test capacity equaled or exceeded the predicted capacity. The equivalent AASHTO load includes consideration of load factors ($M_u = 1.5 M_{dl} + 2.5 M_{ll}$), distribution factor (1.09), and impact factor (1.30), in accordance with the AASHTO specifications. The test load for girder 171-S2 was 10 percent above the equivalent HS20 ultimate load. All other test loads were essentially the same as the equivalent AASHTO loads.

These tests indicate that on the Skyway bridge there is no immediate danger of girder collapse from corrosion. Even the 33 percent strength loss of one prestressing bar does not reduce the girder strength below that required for the AASHO design load. Furthermore, the load-deflection curves show that the girders are versatile enough ductily to redistribute the load to adjacent girders should one completely collapse.

Periodic visual inspection will reveal extensively corroded girders for selective removal and replacement. This process will provide time during which additional studies can be undertaken to evaluate remedial measures.

It is of interest to note that the corrosion occurs primarily in the end regions of the girders, where they are exposed to salt spray from waves splashing against the piers. Very little corrosion has been observed in the midspan regions even though the concrete is apparently less than 25 mm (1 in).

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Basic Evaluation of the Structural Adequacy of Existing Timber Bridges

Ben F. Hurlbut, HKM, Engineers, Billings, Montana

The properties of wood as a structural material in highway bridges are discussed. These properties give a timber bridge a very different load-carrying capability than that of a steel or a concrete bridge. Wood has the advantage of being able to sustain overloads for short time periods but is subject to decay and deterioration. By recognizing these characteristics, the engineer can determine the safe loading for the structure and can recommend procedures for prolonging its life. Guidelines are offered to assist the engineer in his work, and suggestions for presenting the information to the owner and recording it are made.

Wood is structurally very different from concrete or steel and therefore performs differently as the various components of a timber bridge. Some of the characteristics of wood that affect its structural behavior and set it apart from concrete and steel are discussed below.

WOOD CHARACTERISTICS

Wood is orthotropic in nature; that is, its strength properties differ in three directions, longitudinally, radially, and tangentially 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. The strength of timber connectors depends, then, on the direction in which the load is applied relative to the direction of the grain. Stresses for loads applied intermediately between parallel and perpendicular to grain directions are computed by the use of Hankison's formula (1).

Wood is a variable material. Each species of tree has basic structural properties unique to itself. Growth variations and manufacturing processes also produce characteristics in each individual board that control the strength properties. Sawed timbers are graded and assigned strength values according to the species and to the defects in each piece. Characteristics determined visually and used in assigning strength properties are slope of grain, knots and their locations, pitch, wane, density, checks or splits from uneven drying, and size variations—to name a few.

In the 1930s, glue-laminated structural timber came into use in this country. Selective placing of individual boards with proper gluing has resulted in a structural member of better strength properties than was previously available in solid-sawed timber. During the early years of production of glue-laminated material, manufacturing controls were rather loose, and not all of the properties of the finished product were known as they are today. In evaluating early bridges constructed with glue-laminated material, the investigator should examine and analyze this material in the light of current knowledge.

The strength of wood and its dimensions change with changes in equilibrium moisture content. As the moisture content falls below the fiber saturation point, wood shrinks in the tangential and radial directions but not in the longitudinal. In most domestic wood, moisture content will fall during service from first installation. This may be important to the behavior of the timber structure, particularly in relation to connections. Split rings and shear plates, for example, tend to cause wood members to split during drying, weakening connections in timber trusses.

Generally, strength and stiffness increase as moisture content falls. The moisture exposure conditions and the moisture content of wood members should be considered when evaluating the strength of a timber bridge. In recent years, bridge decks have been constructed of glue-laminated planks about 1.22 m (4 ft) wide. Tests by the Forest Products Laboratory in Madison, Wisconsin, indicate that this product is superior in strength to nail-laminated decks. These large panels also provide more protection to the deck-supporting members. The use of this type of deck will also influence the life expectancy of the structure.

The length of time during which a wood member is subjected to a load allows for an adjustment in the safe working stresses that may be used. The reason for this is wood's good energy-absorbing properties. The permissible stresses are higher for short load durations and lower for longer durations.

For impact loading, the permissible stresses may be doubled. For short time loads, such as wind and seismic forces, the stresses may be increased by 33 percent. For a 7-d duration stresses may be 25 percent greater, and for a 2-month duration stresses may be increased by 15 percent over those basically allowable. In contrast, for permanent loading, the stresses must be reduced to 90 percent of the allowable total. These variations are important considerations in analyzing timber bridges.

AASHTO (2) generally recognizes these variations in allowable stress. For example, impact forces need not be considered. Wind and seismic stresses are increased by one-third, similar to concrete and steel. The stresses for 7-d and 2-month duration loads are recognized by AASHTO for loadings other than traffic loads.

Before 1974, the exclusion of vehicle loads for making load duration adjustment implied that the increased stresses would be permitted for this loading. Some of these departures from recognized and published criteria for design of timber structures introduce a measure of conservatism in timber bridges that should be recognized when evaluating existing ones.

Probably the most serious drawback to timber structures is that they are subject to decay and attack by various organisms. Unprotected wood can be critically weakened by decay and insect infestation when temperature and moisture conditions are favorable. It is essential that these be properly protected against either by physical cover or preservative treatment.

EVALUATING TIMBER BRIDGES

In evaluating the load-carrying capability of a wholly or partially timber bridge, each bridge component and its connections must be investigated for strength and then the entire structure evaluated as a unit. This paper is primarily concerned with highway bridges, although the principles involved will generally apply to railroad bridges also.

The age of a bridge is important for reasons other than simply age, because the permissible stresses and grading rules for lumber have varied throughout the years. Design principles have also changed. As an example, compare the 1961 AASHO bridge specifications with current practice.

First, all of the tabular stresses and the grades of lumber are different. Some of the previously permitted stresses have been reduced, some increased. Horizontal shear is now 655 kPa (95 lbf/in^2); in 1961 it varied from 760 to 1000 kPa (110 to 145 lbf/in^2) for Douglas fir on the West Coast. Modulus of elasticity was previously set at 11 100 MPa (1.6 million lbf/in^2) for all grades of Douglas fir. Now these vary from 10 400 to 13 200 MPa (1.5 to 1.9 million lbf/in^2).

Glue-laminated timber was given only partial consideration for selective manufacture, whereas now the full values recommended by the industry are accepted. Shape factor has allowed current practice to provide for a reduction in permissible stress. This principle was known, at least in theory, as the form factor in 1954 (3).

In recent years, it has been found that, when a series of connectors such as bolts are placed in a row parallel with the applied stress, they do not develop each connector's full shear value (4). If three or more connectors are in a row, a reduction must be made in their combined strength. This could be a significant strength-reducing factor in trusses with a built-up tension cord or at-heel connections. The structure should be analyzed according to current design criteria and strength characteristics. Steel components and metal connectors in an older bridge should also be evaluated differently from when they were first installed.

Loading and traffic must be considered and compared with those when the structure was first erected if it is several years old. If it is decided that a load or speed limit should be posted, enforcement must be taken into account. Posting an unrealistic load limit is sure to cause violations. If the normal traffic that has been using the structure is heavier than the posted limit, questions are sure to be raised as to the validity of the limit. Some sort of survey of probable frequent or occasional heavy loads would be in order. Whether or not the bridge can carry single or multiple land loads will influence its load-carrying capability.

The engineer's judgment and experience will play an important role here because of the nature of timber. The engineer or person making the evaluation of a bridge must be well informed on the use of timber as a structural material and must understand its capabilities as well as its limitations. This person must also be able to recognize the species and grade characteristics of the wood components.

Accidental or unintended loads may significantly reduce the safe live load capacity of a structure or its components. A build-up of asphalt pavement or sand and gravel on the deck can seriously reduce the live load capacity of a bridge. For example, a 15.25-m (50-ft) single-lane bridge of glue-laminated stringers spaced at 1.83 m (6 ft) on centers with a laminated deck is designed for an AASHTO HS-15 loading. The application of 5 cm (2 in) of asphalt will increase the bending moment in the stringers by as much as 20 percent and will increase their reactions by about 17 percent. Therefore, it is important that all loads be considered in evaluating a timber structure and that proper maintenance be assured.

Load sharing may be considered to improve the load-carrying capability of individual members. For example, close-spaced floor joists supporting a stiff deck will assist each other by transferring the load through the deck; like members deflect in proportion to their stress. Therefore, if we control the deflection of two closely spaced members by a stiff deck, then one member cannot deflect much more than its neighbor under application of load.

Damage from abuse or decay is a frequent cause of failure and should be determined by careful inspection. Note any stress concentration defects, such as splits, indentations, or crushed wood in bending members, and determine their effects on the member. Decay, if not too extensive, may be controlled by application of preservatives or proper protection. If, for example, the ends of floor stringers are covered with dirt and debris at the abutments, decay may begin. Proper maintenance can control this. Some experimental work is currently being done on introducing preservatives into wood by fumigation (5). These studies may prove very beneficial in prolonging the life of wood structures.

A surface treatment with oil-borne creosote or pentachlorophenol is not as reliable as pressure treatment but will significantly reduce exposure to decay. Treatment of ends of members with an oil-borne preservative is particularly effective, because moisture migrates much more rapidly through the end grain than through the sides of wood members.

Well-sealed ends of members also control splitting, which both weakens the member and exposes more surface to organic attack. If decay has occurred, its extent must be known. A simple wood auger may reveal the depth of defective wood, or, if needed, there is a special tool that can drill an undisturbed core sample for further evaluation. Samples should be taken, if possible, where the member will not be weakened. The hole should be protected with preservatives and plugged after the sample has been taken.

When analyzing a timber bridge, it is helpful to obtain all the available records concerning its design, construction, maintenance, modification, and history of use. Unfortunately, this material is not always available for highway bridges, but, if the original plans and design notes can be found, the engineer's task is simplified. The design can then be compared with the materials used and actual dimensions and details of the built structure.

The key to sound performance, for all structures, is in the connections. This is particularly true for timber bridges. Many times these are not visible, and the engineer will experience some difficulty in discovering what was used. Split rings and shear plates are concealed between wood members. These significantly increase the shear strength of bolted connections. Sometimes a probe may be used to good advantage in locating these.

Guardrails for both traffic and pedestrians are usually a problem, particularly with older timber bridges. Current AASHTO standards require that traffic rails be capable of resisting a lateral force of 4.45 kN (10 000 lbf) applied 68 cm (27 in) above the roadway surface. When working with the permissible stresses specified by AASHTO, the engineer generally finds that wood rails do not conform. Judgment is needed to evaluate the adequacy of railings.

Occasionally, there may be a built-in condition that becomes a problem when the structure ages. A compression member, such as a strut in a truss or a column, may have been designed as an axially loaded member. Then, because of deformation or a connection partially failing or a later modification of the framing, the member suffers induced bending stresses. The combined bending plus axial load stresses may prove excessive even for relatively small eccentricities. Truss members must be analyzed for stress reversals from loading combinations.

Short compression members may be completely adequate normally, but, if tension occurs, connections can be inadequate. Most species of wood have higher allowable stresses for short columns than for tension. In Douglas fir this difference can be 30 percent or better in some grades. Secondary stresses in trusses should also be examined.

The discussion up to this point has dealt with bridge superstructure. Of equal importance, however, are the components of the substructure. Timber pilings, if completely covered by concrete, cannot economically be examined. The best solution here is to find out from available records what sorts of piles were used. If no settlement or other foundation defects are evident, it can reasonably be assumed that the pilings are performing adequately.

If piles are exposed above ground or to water, they can be evaluated for damage or deterioration. Cribbed timber piers or abutments, if present, should be examined with particular care. These are exposed to severe abuse both from decay and from ice or debris in the stream.

Failure of timber piers or abutments usually occurs from deterioration rather than traffic loading. Generally, potential failure is not as evident as it would be in the superstructure. If untreated timber has been used for this part of the structure, periodic inspection is advisable. Any detected movement is a reliable indication that remedial repairs are necessary.

A general evaluation of the total structure should be made. Bracing systems for lateral loads must be secure and functional. An appraisal of the weathering, deterioration, damage, modifications, and general maintenance will aid in determining the safe useful load that can be carried. The superstructure should be securely anchored to its supports, and the components of the supports should be positively fastened together. The anchorage system should be capable of resisting lateral forces.

Consider the effects of a member or a joint failing, and whether other members will take over or will collapse. As in other structures, this is an important economic consideration. A value should be placed on a secondary or backup system if such exists. Generally, temperature stresses need not be considered for timber bridges. The effects of any known traffic accidents must be analyzed. Some members may have been so severely overstressed that they are weakened.

The roadway surface should be examined for proper drainage and the effects of wear. A timber deck is not affected by the application of salts during winter, but it is subject to abrasion by tire chains and tire studs. An asphalt wearing surface over a timber deck virtually eliminates abrasion and, further, seals the deck from moisture. This also provides protection for the supporting structure under the deck.

Application of a wearing surface must be evaluated for its increased loading effects, as mentioned previously. End rotation for individual members, such as a series of simple-span beams or stringers, will adversely affect the deck at the end joints and may require remedial work. Because bridges constructed of arches or trusses can develop a permanent sag, the centerline should be measured and checked later on. Alignment of members, particularly trusses, should be observed. This can indicate loosening of connections or yielding of supports. When vehicles are passing over the bridge, observations should be made of the various components and connections for any indication of loose joints, sway, or uneven twist that is not normal for that type of structure.

PRESENTATION OF THE EVALUATION

The evaluation of the structural adequacy of a timber bridge should be logically presented and well documented. Recommendations given to the owner should relate to periodic or special inspections, maintenance, repairs, or possible replacement. A final net load limit for gross vehicle weight or a combination of axle loads should be indicated. Normal design criteria (6) should be followed in evaluating the entire bridge and its use.

A person writing a bridge evaluation should cover the following.

1. Determine the strength properties of the wood members and connections. At this time assign basic values to the various timber members based on the wood species and estimated grade. These may be adjusted for the conditions present, such as weathering or decay. If critical members are found to be unacceptable, the bridge evaluation can terminate at this point.
2. Assess stream conditions for a river crossing. Foundations and substructure conditions may limit the useful purpose of the structure; evidence that might indicate flood waters of greater volume than permitted by the stream profile could limit the bridge's usefulness.
3. Acquire necessary information on present or anticipated traffic loads. If heavy loads are anticipated and the bridge is limited to lighter loads by some key members, further studies may not be warranted at this time. Alternate routes might be considered.
4. Make a checklist or table in order to record the condition of the various components in the field. Later, the structural analysis can be used to complete this list, which can serve as a structural evaluation of each member as it affects the load capacity of the bridge. Sometimes a relatively economical repair or modification can be made to a few members or connections to upgrade the entire structure. Checklists of this sort could also be made for both the superstructure and the substructure. These would normally include an identification of each component and connection, a description of its condition, and rated load-carrying capacity as it affects the bridge. Any needed repairs could be indicated.
5. Examine and record critical defects or deficiencies that limit the useful load or life of the structure. This includes such things as sag, bracing condition, decay, damage, guardrail conditions, departure from original plans, modifications, and other items of a critical nature. Roadway surface smoothness, although not a structural item, is important for riding quality and for its effects on impact forces.

One excellent guide has been prepared (6), although some of the discussion in it should probably be expanded or modified to fit the particular situation being considered. The manual departs in several places from the AASHTO specifications, which are intended for new constructions and provide for future increased loading, deterioration, and other conditions of long continuing use regarding permissible stresses.

The evaluation of bridges as presented here and in the manual tends to eliminate some of the unknowns. This can then permit somewhat higher stresses. The manual suggests that stresses at the operating rating be 75 percent of the material yield point. This is considered the absolute maximum stress level permitted. Next, the inventory rating or working stress level is assigned as 55 percent of yield point. These values do not apply to timber because there is no yield point that can be used; each grade of a species is limited by its particular growth characteristics.

In the examples shown in the manual, a stress level for wood is set at 133 percent of the basic strength adjusted for the condition of the member. This is a good place to start but should be used with caution. A safety factor against ultimate collapse is probably a better criterion. If, for example, the bearing of a beam is highly stressed in compression perpendicular to grain, failure is not likely, but, if a truss member has a tension splice that is highly stressed, complete collapse could occur. The manual states that it is sufficient to consider only one unit of maximum weight in each lane for spans up to 61 m (200 ft). This might be better evaluated by knowing the expected traffic during the projected life of the structure. Usually, timber bridge spans are well below 61 m, so this may not be a consideration.

This presentation is quite general and obviously cannot be used as a detailed method for the structural evaluation of timber bridges. Hopefully, some new ideas and a different look at how a timber bridge can be analyzed will occur to the reader.

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