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Load and Resistance Factor Design Code for Wood Bridges

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The development of a load and resistance factor design (LRFD) edition of AASHTO's Standard Specifications for Highway Bridges is complete. A part of this effort involved the development of LRFD provisions for wood bridges. These new specifications include numerous changes and several significant departures from current allowable stress design practices for wood bridges. The live load model is based on the statistical analysis of the actual traffic data. The design load is a superposition of the traditional HS20 truck and lane loading. Dynamic load is applied to wooden components of the superstructure. Strength of material is based on the nominal values derived from in-grade tests, specified for wet-use conditions and 2-month live load duration. The resistance factors are determined consistently for all the limit states considered. The major changes in the approach to summarize the design provisions are presented.

The load and resistance factor design (LRFD) code for bridges was adopted in 1993 *(1)*. The document covers all materials, including steel, concrete, and wood. The development of a new specification for wood bridges presented several unique opportunities and challenges. Overall, this project was a rare opportunity to completely revise and update AASHTO wood bridge design requirements *(2)* which traditionally have lagged behind state-of-the-art wood design methodologies. The primary challenge for wood bridges was to develop basic design requirements and procedures for LRFD. Unlike concrete and steel, which have had an LRFD procedure available for several years, LRFD specifications for wood are in the developmental stages *(3,4)*.

The state-of-the-art data base for wood bridge design is summarized by Ritter *(5)*. There were considerable new developments in the area of structural reliability and code optimization. The parameters of load and resistance are random variables. Therefore, statistical models were derived on the basis of load surveys, material tests, bridge tests, and simulations. New data are available for modeling wood components and structures *(6)*. The approach to probability-based analysis of wood bridges *was* presented by Nowak *(7)*.

This paper summarizes selected provisions of the new AASHTO LRFD specifications as they relate to the design of wood bridges. These provisions include topics related to general design features, loads and load distribution, and wood design.

General Design Features

AASHTO's LRFD specifications *(1)* are based on a limit states design approach. As defined in the specification, a limit state represents a condition beyond which the bridge or component ceases to satisfy the provisions for which it was designed. For general bridge design, four limit states are defined; strength, service, extreme events, and fatigue and fracture. For wood bridge design, the most applicable of these limit states are the strength limit state, which is intended to ensure that the structure will provide the required strength and stability over the design life, and the service limit state, which restricts stress and deformation under regular service conditions. The extreme event limit state, which is intended to ensure structural survival in major earthquakes, floods, and vehicle collisions, will generally not control the design of most wood bridges. The fatigue and fracture limit state, which applies primarily to steel bridges, is not applicable to the design of wood components under current design practices.

In the LRFD specification, each component must satisfy the following equation for each limit state:

$$\eta\Sigma(\gamma_i Q_i) < \phi R_n \tag{1}$$

where

- η = load modifier for ductility, redundancy, and operational importance;
- γ_i = load factor;
- Q_i = load effect;
- ϕ = resistance factor; and
- R_n = nominal resistance.

Within the general provisions of the LRFD specification, two provisions that affect wood design are noteworthy. In the past, wood structures have not been subject to impact factor adjustments that increase vehicle live load to account for dynamic effects. In the LRFD specification, general requirements for a dynamic load allowance require that the static truck loads be increased 75 percent for the design of deck joints and 33 percent for the design of all other components. For wood design, these values may be reduced by one-half. Another area that has not been addressed for wood bridges in previous allowable stress design (ASD) specifications is live load deflection. The LRFD specification presents a deflection limit for wood bridges equal to the bridge span divided by 425. This deflection limit, which is based on the vehicle live load, including the dynamic allowance, is considered an optional requirement and is left to designer judgment.

Loads and Load Distribution

The major load components for bridges include dead load, live load, dynamic load (impact), environmental loads (wind, earthquake, and temperature), and special (extreme) loads and effects (vessel collision and vehicle collision).

From the statistical point of view, it is convenient to distinguish between weight of structural components and asphalt wearing surface. It has been observed that, on average, self-weight of structural components is 3 to 5 percent larger than the design value. The coefficient of variation is about 0.08 to 0.10. On the other hand, the weight of asphalt varies depending on the actual thickness of the wearing surface. The average thickness is 3.5 in. (90 mm), and the coefficient of variation is 0.25 *(8)*. For wood bridges, dead load constitutes a small portion of the total load. The weight of asphalt contributes about 10 percent of the total load.

Live load is often the most important load component for wood bridges. Live load model was derived on the basis of the actual truck survey data *(9,10)*. Most of the wood bridges are with short spans. Therefore, the maximum moment is determined by an axle or closely spaced tandem. For example, the histogram of actual axle loads measured in Michigan is shown in Figure 1. The corresponding cumulative distribution function (CDF) is shown in Figure 2 *(11)*. The CDF is plotted on the inverse normal probability scale. The average axle load is about 10 kips (45 kN), but the maximum observed values exceed 40 kips (180 kN).

The extreme effect for various periods (up to 75 years) was extrapolated from the available data. The critical load is a result of two side-by-side trucks, each representing the maximum 2-month truck. The design of superstructure components is based on the analysis of moments and shear forces, The maximum expected moments and shears, calculated for various periods, are shown in Figures 3 and 4, respectively. For an easier comparison, the moments and shears are divided by

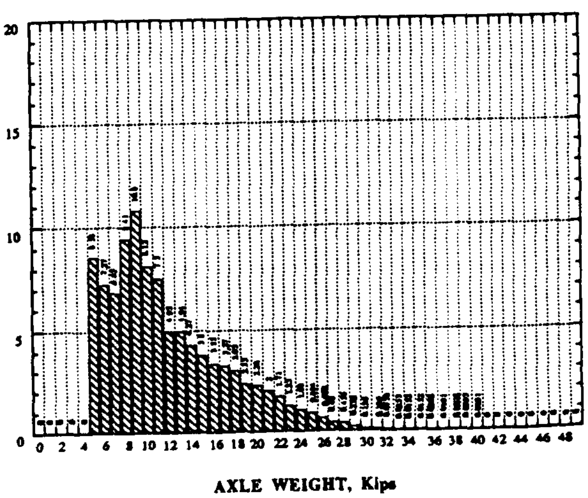

FIGURE 1 Histogram of measured axle loads (1 kip = 4.45 kN).

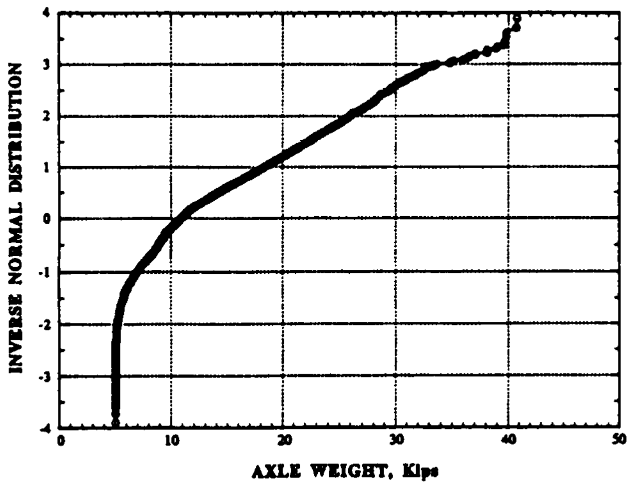

FIGURE 2 CDF of axle loads on normal probability paper (1 kip = 4.45 kN).

corresponding HS20 moments and shears *(2)*. The new live load, specified in LRFD AASHTO code, is a superposition of HS20 truck and a uniform lane loading of 640 lb/ft (9.3 kN/m). The ratio of mean to nominal is called a bias factor. The design code is expected to specify design load values so that bias factor is uniform over different spans. The bias factors for AASHTO (1992) and the new LRFD AASHTO *(1)* are shown in Figure 5 for moments and Figure 6 for shears.

The LRFD specification presents load combinations in tabular format with the specified load factors for each type of applied loading *(1)*. There are a total of 11 load combinations; 5 for the strength limit state, 2 for the extreme events limit state, 3 for the service limit state, and 1 for the fatigue and fracture limit state. Of these, two strength load combinations and one service load combination will most commonly control design for wood bridges.

Requirements for structural analysis and evaluation in the LRFD specification include guidelines for sophisticated bridge analysis and simplified approximate methods of analysis, which have traditionally been used. In general, the requirements for approximate load distribution for wood bridges are the same as those cur-

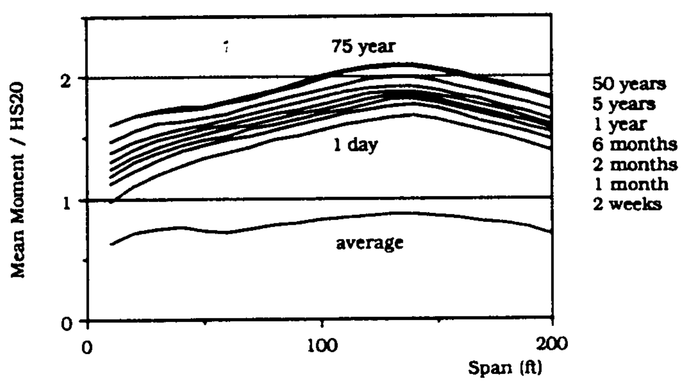

FIGURE 3 Mean maximum moments for various periods (1 ft = 0.305 m).

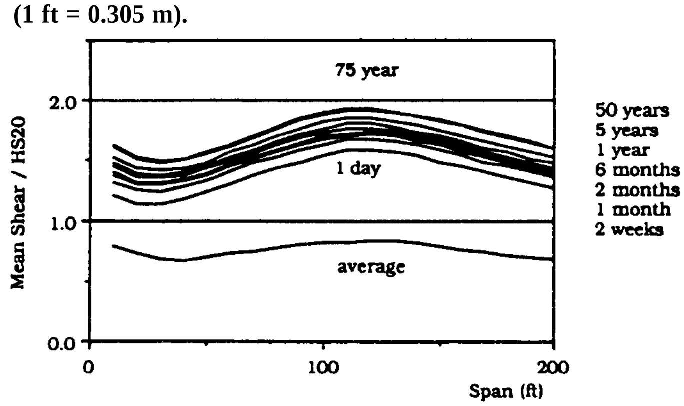

FIGURE 4 Mean maximum shears for various periods (1 ft = 0.305 m).

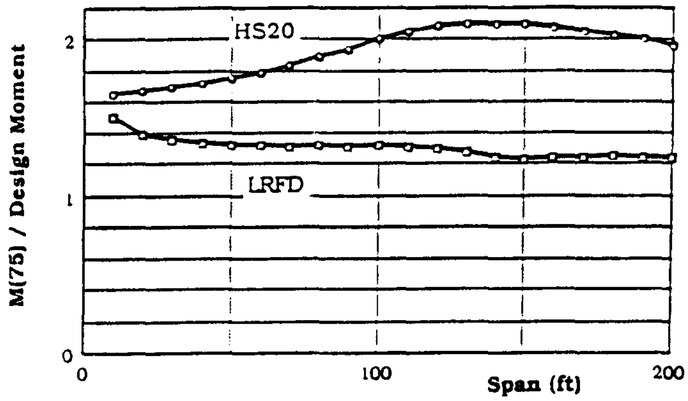

FIGURE 5 Bias factor for moments: for AASHTO *(2)* and LRFD AASHTO *(1)* (1 ft = 0.305 m).

rently presented in the AASHTO allowable stress design (ASD) specification *(2)*. An exception is the load distribution criteria for the design of slab-type superstructures. Rather than the traditional criteria based on a longitudinal distribution width as a function of tire width and deck thickness, the following equations are given for an equivalent longitudinal distribution width per lane and are applicable both to wood and concrete superstructures.

With one lane loaded,

$$E = 1.00 + 0.50(L_1 W_1)^{1/2} \quad (2)$$

With more than one lane loaded,

$$E = 7.00 + 0.12(L_1 W_1)^{1/2} < W/N \quad (3)$$

where

E = equivalent distribution width per lane (in feet) (1 ft = 0.305 m);
L_1 = modified span equal to the lesser of the actual span or 60 ft (18 m);
W_1 = modified width equal to the lesser of actual width or 60 ft (18 m),
W = physical edge-to-edge bridge width (ft),
L = physical bridge length (ft), and
N = number of design lanes.

Wood Design

Provisions for the LRFD design of wood components are presented in one chapter of the LRFD AASHTO code *(1)* and include requirements for materials, limit states, component design, bracing, and camber. From a

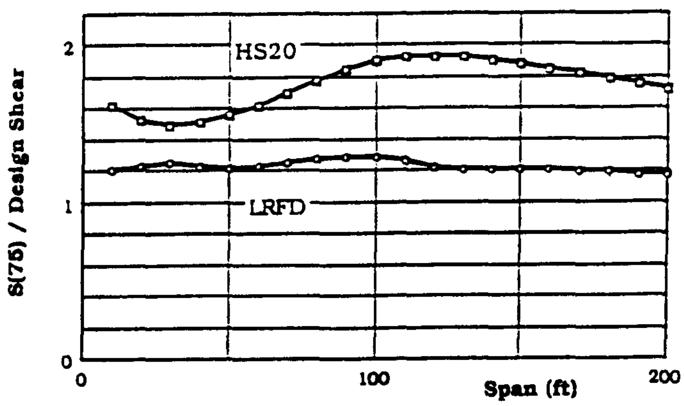

FIGURE 6 Bias factor for shears: for AASHTO *(2)* and LRFD AASHTO *(1)* **(1 ft =** 0.305 m).

design perspective, the most significant departures from the ASD method involve provisions for base and nominal resistance values for wood materials, resistance factors and the relationship of these factors to limit states and load combinations, and component design requirements.

One key wood design requirement for the AASHTO LRFD specification was the development of a procedure for obtaining base resistance values for various engineered wood products *(1)*. Given the large number of wood species, products, and grades used in bridge applications, AASHTO ASD specifications have traditionally included design values for only a limited number of the species and grades of sawn lumber, glued laminated timber, and timber piles *(2)*. These values have been obtained directly from national standards, primarily the National Design Specification for Wood (NDS) *(12)* for sawn lumber and timber piles and AITC 117-Design *(13)* for glued laminated timber. This approach has provided consistency between the design values used for bridges and those used for buildings and other structures. In addition, this approach provides the most expedient reference to current design values when industry changes are made. On the basis of these considerations, a procedure for determining base resistance values for wood products was developed that directly incorporates industry standards presented in the NDS and AITC 117-Design *(12,13)*.

The properties of material are based on the actual in-grade tests. For example, the CDFs based on the results of bending tests to determine the modulus of rupture (MOR) of Douglas fir are shown in Figure 7 for select structural and Figure 8 for Grades 1 and 2. The CDFs of MOR are plotted on inverse normal probability paper. The results are shown for several sizes. MOR indicates a considerable degree of variation, with coefficient of variation about 0.3. The average MOR is about three to four times larger than the lowest test results. However, new structural types, glulam and stressed wood, allow for a significant reduction of the coefficient of variation. The tests were carried out to determine the MOR for different widths of stressed units, each made of 2 x 8 in. (50 x 200 mm) boards. Three widths were considered: 1, 2, and 3 ft (300, 600, and 900 mm). Examples of CDFs for red pine, white pine, and hem-fir are shown in Figure 9 *(7)*. The coefficients of variation are about 0.10 to 0.13, which are considerably lower than those without prestressing.

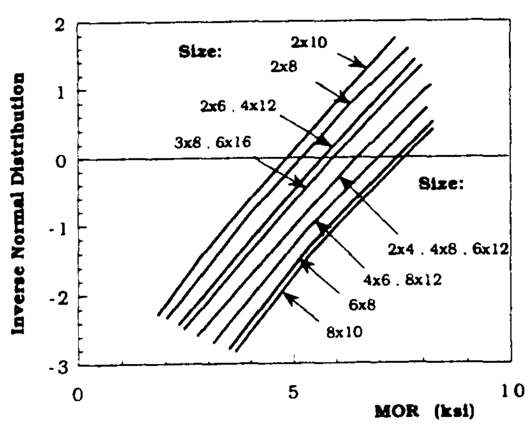

FIGURE 7 MOR for Douglas fir, select structural, on inverse normal probability paper (1 ksi = 6.9 MPa).

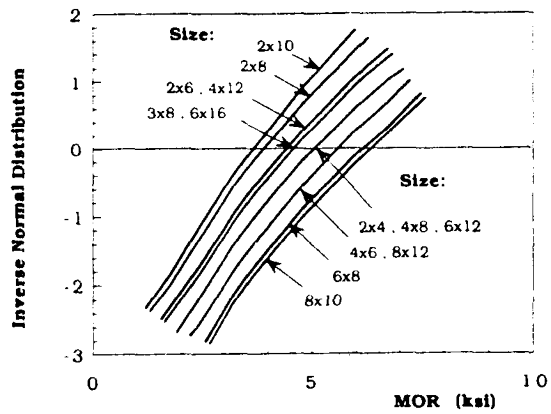

FIGURE 8 MOR for Douglas fir, Grades 1 and 2, on inverse normal probability paper (1 ksi = 6.9 MPa).

The LRFD specification includes tables of base resistance values for selected wood species and grades of sawn lumber, glued laminated timber, and timber piles that are commonly used for wood bridge design *(1)*. The base resistance is defined as a value of stress (or modulus of elasticity) that is to be used in the design. The values correspond to wet-use conditions and a 2-month load duration, which corresponds to the most common design conditions. Within these tables, base resistance values are given for flexure (F_{bo}), tension parallel to grain (F_{to}), shear parallel to grain (F_{vo}), compression perpendicular to grain (F_{cpo}), compression parallel to grain (F_{co}), and modulus of elasticity (E_o). To obtain values for species and grades not included in the tables, a direct conversion of ASD values in the NDS or AITC 117-Design *(12,13)* is specified using the following conversion factors given in Table 1.

Base LRFD resistance values obtained from the specification tables or through adjustment of ASD values are based on specific conditions and are intended to serve *as* a starting point for determining the nominal resistance values used for design. To determine nominal resistance values, base resistance values must be adjusted by factors that compensate for *(a)* differences between

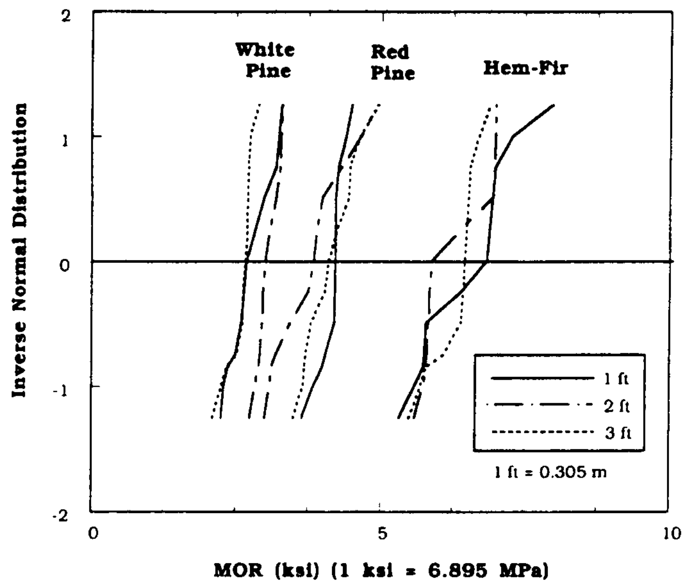

FIGURE 9 MOR for stressed wood units.

the assumptions used to establish the base resistance values and the actual use conditions, *(b)* variations in wood behavior related to the type of stress or member orientation, and *(c)* differences between the physical and mechanical behavior of wood and that of an ideal material assumed in most equations of engineering mechanics. General adjustments that are common to the design of most components are presented in the LRFD specification as follows:

$$F = F_o C_F C_M C_D \quad (4)$$

$$E = E_o C_M \quad (5)$$

where

- F = applicable nominal resistance F_b, F_t, F_v, F_{cp}, or F_c,
- F_o = applicable base resistance F_{bo}, F_{to}, F_{vo}, F_{cpo}, or F_{co},
- C_F = size effect factor based on the member size or volume,
- C_M = moisture content factor for adjustment to dry use conditions,
- C_D = deck factor applicable to the design of some deck types,
- E = nominal modulus of elasticity, and
- E_o = base modulus of elasticity.

Additional adjustments that are related only to the design of specific components are included in the component design subsections of the wood design section.

RESISTANCE FACTORS

As previously presented in the general LRFD design equation, the nominal resistance of a component is multiplied by a resistance factor ϕ. For wood design, the resistance factors for all wood products, species, and grades are as follows:

- Flexture: $\phi = 0.85$,
- Shear: $\phi = 0.75$,
- Compression parallel to grain: $\phi = 0.90$,
- Compression perpendicular to grain: $\phi = 0.90$, and
- Tension parallel to grain: $\phi = 0.80$.

For strength load combination IV, corresponding to the case governed by permanent loads, the resistance

TABLE 1 Conversion Factors for LRFD Base Resistance from NDS ASD Tables

Material	F_{bo}	F_{to}	F_{vo}	F_{cpo}	F_{co}	E_o
Dimension Lumber	2.35	2.95	3.05	1.75	1.90	0.90
Beams and Stringers and Posts and Timbers	2.80	2.95	3.15	1.75	2.40	1.00
Glued laminated timber	2.20	2.35	2.75	1.35	1.90	0.83

factors are multiplied by 0.75 to compensate for the load duration effect on wood properties when components are subjected to the long-term loading.

Component Design Requirements

Within the LRFD wood design section, subsections are provided for component design for members in flexure, shear, compression, tension parallel to grain, combined flexure, and axial loading. These subsections include specific provisions related to design, including additional adjustment factors that are applied to the nominal resistance. An example equation for nominal resistance in flexure follows:

$$M_n = F_b S C_s C_r \tag{6}$$

where

M_n = nominal resistance in flexure,
F_b = specified resistance in flexure from Equation 2,
S = section modulus,
C_s = stability factor, and
C_r = repetitive member factor.

Within the LRFD specifications, values for specific factors such as C_s and C_r are determined from equations or tables presented in the component design subsection.

Conclusions

The new AASHTO LRFD specification *(1)* presents a new approach to bridge design that differs from traditional ASD methodology *(2)*. From the perspective of wood bridge design, significant provisions of the LRFD specification include *(a)* the use of load and resistance factors, *(b)* inclusion of a dynamic load allowance for static truck loads, *(c)* a new live load deflection criteria, *(d)* revised load combinations and live load distribution requirements, and *(e)* new values for material strength (base resistance).

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