

# Reliability Analysis of Plank Decks for Bridges

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## Abstract

The major parameters which determine performance of wood structures are modulus of rupture (MOR), modulus of elasticity (MOE), and loads. These parameters are a subject to considerable variation and therefore, they are treated as random variables. The objective of this study is to develop an efficient procedure for evaluation of the structural reliability. The work will focus on wooden plank decks for highway bridges. In particular, the paper is focused on distribution of truck load to plank decks. The current AASHTO Specifications are unrealistic and too conservative in most cases. A plank element is modeled as a beam on elastic supports. Material properties, in particular MOE and MOR, are based on the actual test data. The major part of the load model is axle load, and in particular wheel load. The statistical analysis is based on the available weigh-in-motion measurements data. It was observed that truck parameters are strongly site-specific. For plank decks, live load consideration is focused on axle weights and wheel loads rather than whole vehicles. The reliability model will be used to develop rational design criteria for plank decks.

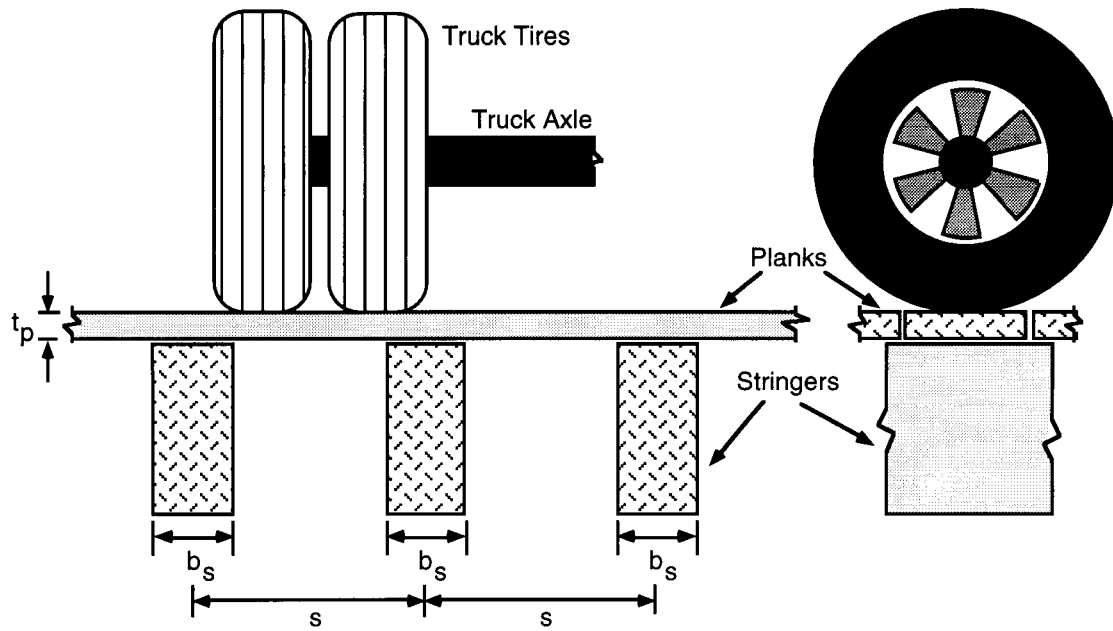
Keywords: Plank decks, Bridges, Reliability analysis, Wooden structures.

## Introduction

The objective of this study is to develop an efficient procedure to perform reliability based evaluation of plank decks for highway bridges. In particular, it has been observed that the current AASHTO Specifications (1992, 1994) provisions for load distribution for plank decks are not realistic. The problem was identified by the AASHTO Subcommittee on Bridges, Committee on Timber Bridges, as a priority item requiring an urgent solution.

A typical plank deck consists of planks placed on stringers as shown in Figure 1 and 2. There are two categories of plank decks depending on the direction of planks vs. the direction of traffic: transverse deck and longitudinal deck.

For a typical transverse plank deck the span of the deck is perpendicular to the direction of traffic. The typical span length of stringers is usually 5-6 m (16-20 ft). In older structures it can be up to 11 m (36 ft). Stringers are spaced at,  $s = 300\text{-}600$  mm (12-24 in) center-to-center, mostly 300-450 mm (12-18 in). Stringers are made of sawn lumber, typical Southern Pine size 150x450 mm (6x18 in), or Douglas-Fir (larger size).



**Figure 1 - Typical Transverse Plank Deck**

The planks are typically 100x250 mm (4x10 in) or 100x300 mm (4x12 in), and their length can be 3.5-11 m (12-36 ft). Planks are nailed to stringers.

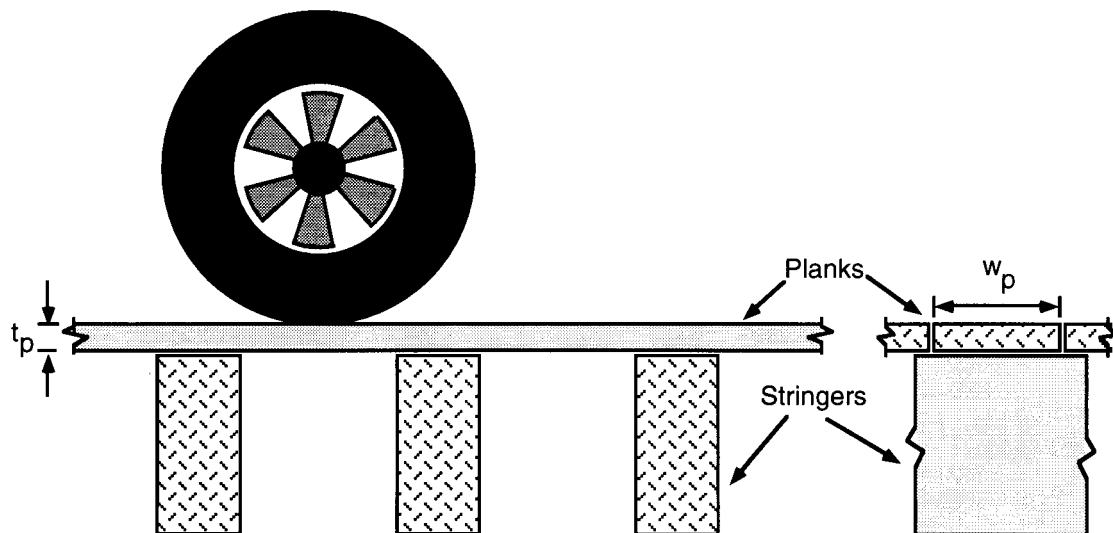
A longitudinal plank deck, as shown in Figure 2, is placed parallel to the direction of traffic. The major design parameter determined by the designer is the spacing between stringers.

The paper deals with the current design provisions for plank decks. It is assumed that stringers have an adequate load carrying capacity and that they provide a

sufficient support for planks. The design of stringers is not considered.

The evaluation procedures for plank decks are developed assuming that the design truck load is as specified in the code. Two codes are considered: AASHTO (1992) and LRFD AASHTO (1994).

The study is focused on distribution of the truck load to plank decks. A plank element is modeled as a beam on elastic supports. It is assumed that the elastic support parameters vary depending on stiffness of



**Figure 2 - Typical Longitudinal Plank Deck**

individual stringers. Material properties, in particular the modulus of elasticity (MOE) and the modulus of rupture (MOR), are based on the actual test data. Statistical models for MOR and MOE for various wood species and sizes were derived by Nowak (1983).

The major part of the load model is axle load, and in particular wheel load. The statistical analysis is based on the available weigh-in-motion measurements data (Nowak et al. 1994). The contact pressure between truck tire and road surface are modeled using the available literature.

The current design criteria's in AASHTO (1992) and LRFD AASHTO (1994) were evaluated using the procedure described in the paper.

### Current Design Provisions

Two design codes are considered: AASHTO (1992) and LRFD AASHTO (1994). Both codes specify live load as HS-20 truck. The resulting design wheel load is 16 kips.

### AASHTO Specifications (1992)

The design formula for a plank deck is

$$[D + L (1 + I)]/S < F_b \quad (1)$$

where  $D$  = dead load moment,  $L$  = live load moment,  $I$  = impact factor,  $S$  = section modulus,  $F_b$  = allowable stress. Dead load is very small compared to live load. The live load is specified as the moment due to wheel load. Impact is not considered for wood components. The section modulus is

$$S = b_p d_p^2/6 \quad (2)$$

where  $b_p$  = plank width and  $d_p$  = plank depth (thickness), in most cases it is 90 mm (3.5 in). The wheel load associated with HS-20 truck is 70 kN (16 kips). The tire contact area is defined as a rectangle shown in Figure 3. The length in direction of traffic,  $L_t$ , and width of tire,  $b_t$ , can be determined from the following two equations,

$$L_t b_t = 0.01 P \quad (3)$$

$$b_t/L_t = 2.5 \quad (4)$$

where  $P$  = wheel load in pounds. For  $P = 70$  kN (16,000 lb),  $L_t = 200$  mm (8 in) and  $b_t = 500$  mm (20 in).

It is assumed that wheel load is distributed depending on the direction of planks in relation to the direction of traffic. For transverse planks, it is assumed that the

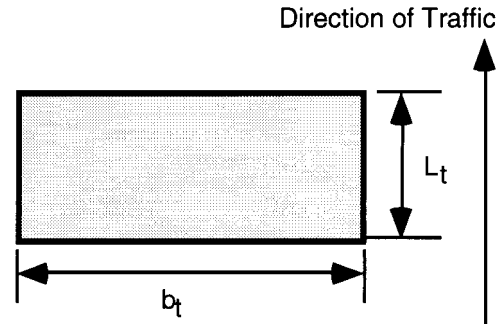
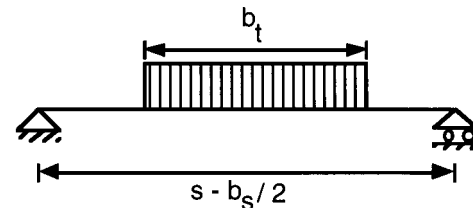
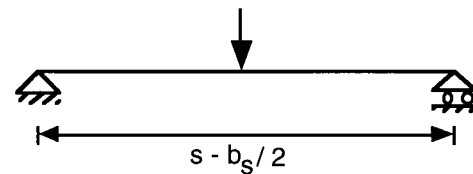


Figure 3 - Tire Contact Area

wheel load is uniformly distributed over the contact area defined as a rectangle shown in Figure 3. The live load moment is calculated for a simply supported beam, as shown in Figure 4(a), with a span equal to clear distance between the stringers plus one-half the width of one stringer. For continuous planks, the moment is taken as 0.8 of the calculated value.



(a) Transverse Planks



(b) Longitudinal Planks

Figure 4 - Load Distribution (AASHTO - 1992)

For longitudinal planks, in the direction of span, the wheel load is considered a point loading, and normal to the direction of span, the wheel load is distributed over the width of plank (Figure 4(b)). The live load moment is calculated for a simply supported beam, with a span equal to clear distance between the stringers plus one-half the width of one stringer. For continuous planks, the design moment is taken as 0.8 of the calculated value.

Following the AASHTO (1992) provisions, the maximum stress due to live load is calculated for stringer spacing from 300 mm through 600 mm (12 in through 24 in), and for plank widths 100 through 300 mm (4 in through 12 in). For transverse plank decks the maximum bending stress ranges from 1.7 MPa to

34.5 MPa (250 psi to 5000 psi). For longitudinal planks the stresses are as much as 66 MPa (9500 psi) for smaller deck sizes.

For comparison, the allowable stress for Douglas-Fir Grade 1 is 12.4 MPa (1798 psi) including a flat-wise use factor of 1.11 and a moisture compensation factor of 1.08 (from AASHTO 1992).

### LRFD AASHTO Specifications (1994)

The design formula for a plank deck is

$$1.25 D + 1.75 L (1 + I) < 0.85 F_b S \quad (5)$$

where  $D$  = dead load moment,  $L$  = live load moment,  $I$  = impact factor,  $S$  = section modulus (Eq. 2),  $F_b$  = nominal resistance (stress). Dead load is practically negligible. Live load is specified as the moment due to HS-20 truck wheel load. For longitudinal planks, live load includes the HS-20 truck load and lane load of 9.3 kN/m (640 lb/ft). Impact is 0.33 of truck load effect, but for wood components it is reduced by 50 percent, therefore,  $I = 0.165$ .

The wheel load is 70 kN (16 kips). The tire contact area is defined as a rectangle shown in Figure 3. The width of tire,  $b_t$ , is 500 mm (20 in) and the length in direction of traffic,  $L_t$ , can be determined from the following equation,

$$L_t = 1.75 (1 + I) P / 2.5 \quad (6)$$

where  $P$  is the wheel load, for  $P = 70$  kN (16 kip),  $L_t = 330$  mm (13 in). The wheel load is distributed depending on the direction of planks in relation to the direction of traffic.

For transverse planks, shown in Figure 5(a), it is assumed that the wheel load is uniformly distributed over the area of a rectangle with the length of 500 mm (20 in) plus the thickness of plank (in the direction of span) and width equal to plank width. For longitudinal planks, the wheel load is distributed over the area of a rectangle with the length 330 mm (13 in) plus the plank thickness (in the direction of span) and width equal to plank width as shown in Figure 5(b).

The live load moment is calculated for a continuous beam, with each span equal to the center-to-center distance between the stringers.

Following the LRFD AASHTO (1994) provisions, the maximum bending stress due to live load is calculated for stringer spacing from 300 mm - 600 mm (12 in through 24 in), and for plank widths 100 mm - 300 mm (4 in through 12 in). The stresses in transverse

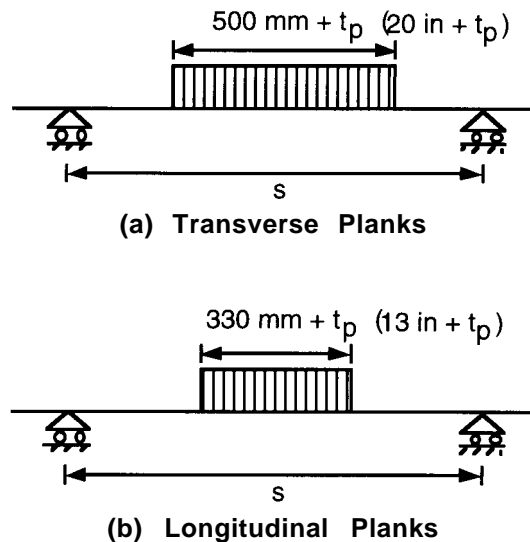


Figure 5 - Load Distribution (LRFD AASHTO - 1994)

decks vary from 2.4 MPa to 36.2 MPa (350 psi to 5250 psi). For longitudinal decks the stresses are ranging from 4.5 MPa to 50 MPa (650 psi to 7200 psi).

The nominal resistance,  $F_b$ , is a product of base resistance and the size effect factor,  $C_f$ .  $C_f$  is taken to be 1.54 for flat-wise planks. For comparison, the base and nominal resistance's for Douglas-Fir Grade 1 and 2 are 19 MPa and 30 MPa (2800 psi and 4310 psi), respectively (from LRFD AASHTO 1994),

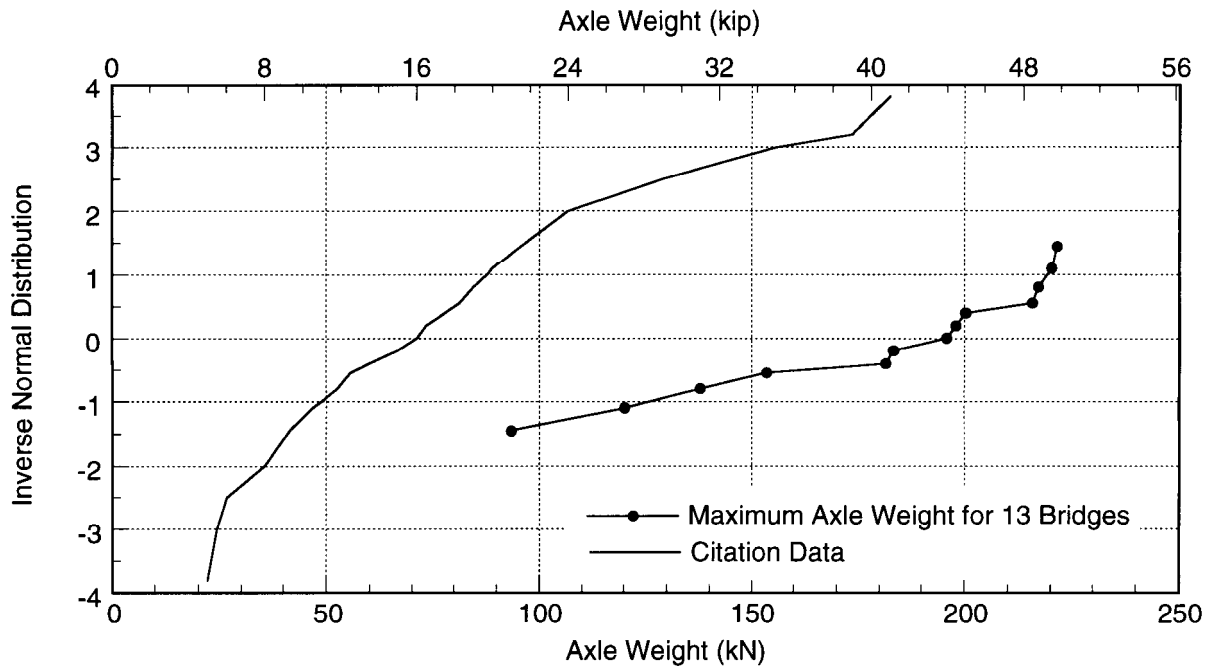
### Reliability Analysis

The structural performance of plank decks is determined by loads and resistance. Both load and resistance are random variables. Therefore, reliability analysis is used to evaluate the current design provisions. The reliability index,  $\beta$ , is considered as the measure of safety.

### Load Model

The live load model is developed on the basis of actual truck measurements. Extensive weigh-in-motion (WIM) measurements were carried out by researchers at the University of Michigan (Nowak et al. 1994). The study provided statistical data on gross vehicle weights (GVW), axle weights and axle spacings. It was observed that truck parameters are strongly site-specific.

For plank decks, live load consideration is focused on axle weights and wheel loads rather than whole vehicles. The cumulative distribution functions of axle weight from citation data are plotted on normal probability paper in Figure 6. The vertical axis is the



**Figure 6 - Cumulative Distribution Function of Axle Weight**

inverse normal distribution function and it corresponds to the probability of being exceeded. The measured axle weights vary from site-to-site. The average weights are ranging from 40 to 55 kN (9 to 12 kip). The maximum values were observed on 13 bridges. They vary from 95 to 220 kN (21 to 50 kip). The cumulative distribution function of the maximum axle weights for the considered bridges is also plotted on normal probability paper in Figure 6. Based on these results, the expected mean maximum live load is a wheel load of 51.2 kN (11.5 kip) distributed over the rectangular contact area. The coefficient of variation is 14 percent without impact, which could be reduced for smaller size planks to account for better load sharing. The wheel load for a dual tire assembly is taken to be 100 kN (23 kip).

**Contact Area**

Dimensions of the contact area are based on the available literature (Pezo et al. 1989 and Kim et al. 1989). The length of the contact area is 250 mm (10 in) in the direction of traffic and the width is 200 mm (7.5 in) in the other direction. The pressure under tire is 1 MPa (150 psi). The contact area for a two wheel unit weighing 100 kN (23 kip) is shown in Figure 7.

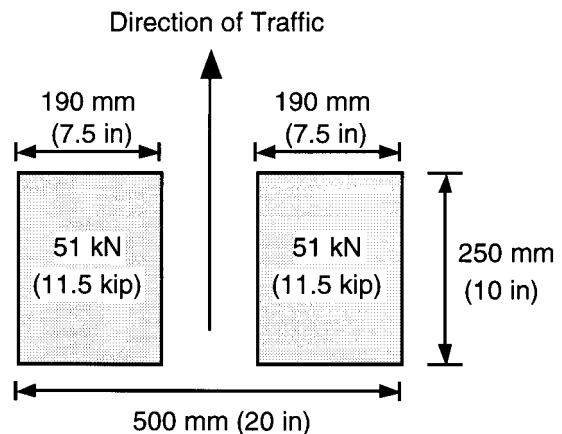
**Load Distribution**

For transverse planks (planks perpendicular to the direction of traffic), the wheel load is applied as a uniform pressure, over the area shown in Figure 7. If plank width is larger than the length of contact area, 250 mm (10 in), then it is reasonable to assume that the load is distributed over the whole plank width. If

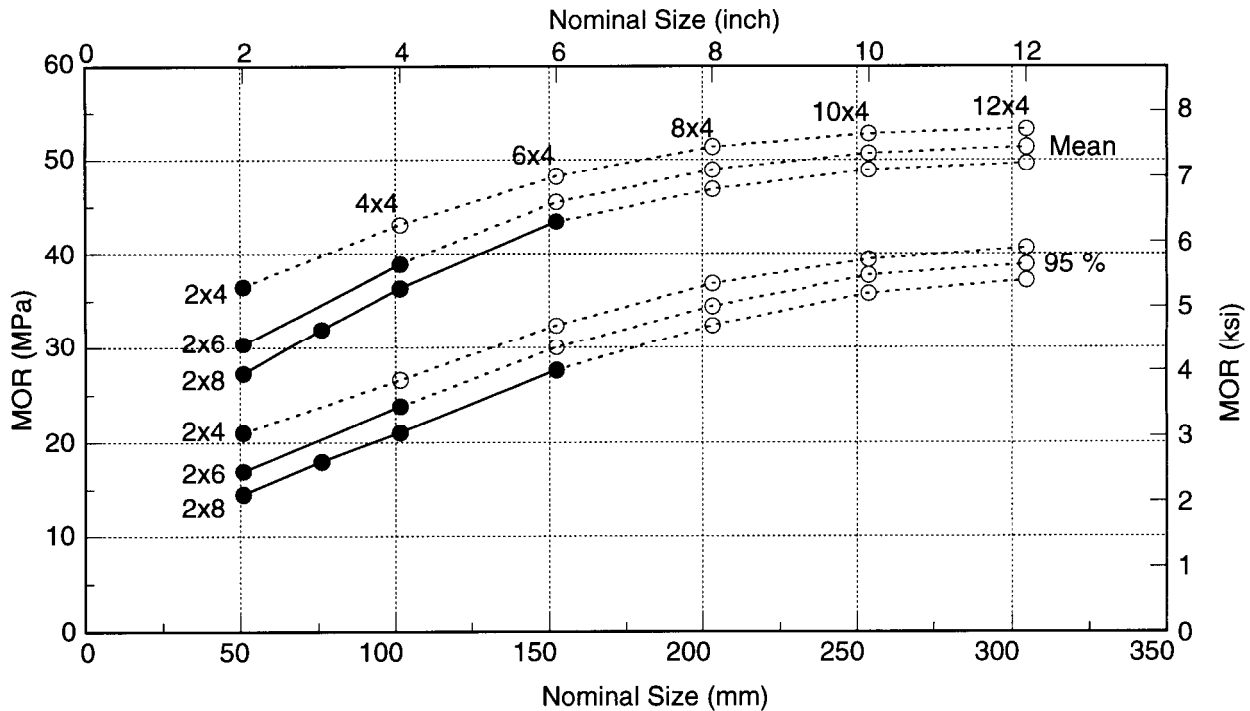
the plank width is less than 250 mm (10 in), then the plank takes only a portion of wheel load proportional to the ratio of plank width and 250 mm (10 in).

For longitudinal planks (planks parallel to the direction of traffic), the wheel load is also applied as a uniform pressure, over the area shown in Figure 7. If plank width is larger than the width of contact area, 200 mm (7.5 in), then it is reasonable to assume that the load is distributed over the whole plank width. If the plank width is less than 200 mm (7.5 in), then the plank takes only a portion of wheel load proportional to the ratio of plank width and 200 mm (7.5 in).

In practice, a transverse plank is usually resisting two



**Figure 7 - Proposed Tire Contact Area**



**Figure 7 - Modulus of Rupture for Douglas-Fir Grade 1 and 2**

wheel loads, while a longitudinal plank resists only one wheel load.

The live load moment is calculated assuming the plank is a continuous beam on elastic supports. The actual dynamic load is about 0.05 of live load. However, the flexural strength of wood is significantly larger for short duration loads, therefore, dynamic load (impact) is not considered in the analysis.

The calculations were carried out for a wide range of stringer spacings and plank widths. The flexural stresses due to a dual tire assembly with 100 kN (23 kip) on transverse planks vary from 5.5 MPa to 23.5 MPa (800 psi to 3400 psi). For longitudinal planks it ranges from 5.5 MPa to 16.6 MPa (800 psi to 2400 psi).

### Resistance Model

The resistance of wood is determined by MOR. For plank decks, the wood sections are used flat-wise. For the considered plank species, sizes and grades, the mean MOR's are available only for edge-wise use. The flat-wise MOR's are extrapolated from the available data, as shown in Figure 7. Experiments are currently being carried out at University of Michigan, to determine the actual statistical properties of wood section for flat-wise use. The resistance (MOR) has a log-normal distribution. The coefficient of variation of MOR is taken to be about 20 percent.

### Reliability Analysis

The reliability analysis is carried out using the procedure developed for calibration of the LRFD AASHTO (Nowak 1995). Reliability is measured in terms of the reliability index,  $\beta$ . The analysis is performed for plank decks designed using AASHTO (1992) and LRFD AASHTO (1994).

The dead load moment due to self weight of plank and the asphalt pavement are very small and each is about 10 percent of the total moment. The live load moment is the primary load component and it has a log-normal distribution. Hence, the total moment can also be assumed to have a distribution similar to that of the live load. Since, both the load and resistance are log-normally distributed, the reliability index,  $\beta$ , can be calculated using the following equation

$$\beta = \frac{\ln(m_R/m_Q)}{\sqrt{V_R^2 + V_Q^2}} \quad (7)$$

where,  $m_R$  and  $m_Q$  are the mean of resistance and load, respectively, and  $V_R$  and  $V_Q$  are the respective coefficient of variations.

The procedure outlined above can be used to perform reliability based evaluation of the wooden plank decks for bridges. The reliability indices were calculated for current code provisions. They show that the current

provisions have conservative load distribution, specially for the smaller sizes, because the effect of load sharing among adjacent planks is not considered. Therefore, much higher values of reliability indices are obtained for smaller sizes (4"x4" to 6"x4") as compared to larger sizes (10"x4" and 12"x4"). Which penalizes the use of wooden planks with smaller widths. Although, based on reliability analysis, the smaller sizes should be preferred as they provide better load sharing and improved redundancy. New code provisions for the design of wooden plank decks will be developed using the procedure described in this paper.

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