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Reliability Analysis of Plank Decks

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Abstract

The objective of this study is to summarize the load and resistance criteria for highway bridge plank decks, and to estimate the reliability of plank decks designed by AASHTO Code. Both transverse and longitudinal planks for a variety of typical stringer spacings and plank sizes are considered. Truck traffic load data is based on the model used to calibrate the 1994 AASHTO LRFD Code. However, for plank decks, wheel load rather than whole vehicle weight is most important, and these statistics are developed for this study. For wood planks, dead load and dynamic load are not significant. The limit state considered is flexural strength, and resistance statistics are presented for wood planks in terms of modulus of rupture. Special flat-wise use data are presented to account for section aspect ratio as well as edge of load application. The reliability analysis is carried out using the procedure developed for calibration of AASHTO LRFD. Reliability indices for both AASHTO Standard and AASHTO LRFD Code are presented for plank decks. The results indicate that there are considerable differences in plank reliability indices. Causes of inconsistencies in safety are identified.

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Introduction

In 1993 AASHTO adopted a new load and resistance factor design (LRFD) code for highway bridges. The new code provides a rational basis for the design of steel and concrete structures. Although wood bridge design was also included in LRFD format, the calibration was not carried out for these structures (Nowak 1995; 1999). Therefore, there was a concern about the consistency of the reliability level for wood structures. To this end, the need for revised design criteria for plank decks was identified by the AASHTO Subcommittee on Bridges, Committee on Timber Bridges, as a priority item requiring an urgent solution.

Previous studies have shown that the reliability index for wood bridge components can be significantly different from those for steel or concrete structures (Nowak 1991). The degree of variation for wood properties is a function of dimensions, load application, moisture content and other parameters. There is particular concern for plank decks, for which edge of load application and section aspect ratio also significantly affects results. The objective of this study is to summarize the load and resistance criteria for highway bridge plank decks, and to estimate the reliability of plank decks designed by AASHTO Code (2004 LRFD and 2002 Standard).

A typical plank deck consists of planks placed on stringers, where planks may run either transversely to or parallel to the direction of traffic. For the latter case, transverse beams are placed on top of the main stringers to carry the planks. The bridge span is usually 5-6 m (16-20 ft), while stringers are typically spaced from 300-600 mm (12-24 in). Stringers are commonly made of Southern Pine or Douglas-Fir, either glued-laminated or sawn lumber, and are often nominally 150 x 450 mm (6 in x 18 in), or larger. The planks are typically 100 x 250 mm (4 in x 10 in) or 100 x 300 mm (4 in x 12 in) and are often fastened to the stringers by nails or spikes.

Load Model

The live load model is based on that used to calibrate the 1994 AASHTO LRFD Code, and is developed from actual truck measurements. For this study, additional load data are considered and are taken from extensive weigh-in-motion (WIM) measurements that were carried out by researchers at the University of Michigan on thirteen typical highway bridges in Michigan (Nowak et al. 1994). For plank decks, live load consideration is focused on axle weights and wheel loads rather than whole vehicles. Based on the WIM data, mean axle weights varied from 40 to 55 kN (9 to 12 kips), and maximum values were observed from 95 to 220 kN (21 to 50 kips). Based on the procedure used in the calibration of the AASHO LRFD Code (Nowak 1995), the cumulative distribution function of the mean maximum axle weight is extrapolated to a 75 year design lifetime and presented in Figure 1 as a normal probability plot (Nowak and Collins 2000). Here the mean value is about 200 kN (44 kips) and the coefficient of variation (COV) is 0.25. Rear (governing) axle weight is typically a sum of four equal-weight wheel loads. Therefore, the wheel load can be calculated as one-fourth of the axle weight, or 50 kN (11 kips). The data were found to best fit a lognormal distribution.

Tire contact area is an important consideration for live load distribution to short span components. Based on the measurements reported by Pezo et al. (1989) and Sebaaly (1992), the transverse dimension (width) of the contact area is 185 mm (7.5 in) for each tire, with a 125 mm (5 in) gap between tires for a dual tire wheel. A nearly linear relationship exists between the wheel load and length of the contact area. The pressure distribution beneath the tire is known to be nonlinear, but its precise shape has an insignificant effect on maximum plank moment (the limit state of interest in this study) for typical plank spans, and it is thus treated as uniformly distributed, as customary. For a 50 kN (11 kip) wheel load, a uniform 1 MPa (150 psi) contact pressure results, with a tire length of approximately 250 mm (10 in). Therefore, in this study, the contact area for a single tire is considered as a rectangle of 180 mm x 250 mm (7.5 x 10 in), and for a dual tire, a rectangle of 250 mm x 500 mm (10 in x 20 in) (the gap is ignored), where 250 mm (10”) is in the direction of traffic.

For transverse planks (planks perpendicular to the direction of traffic), if plank width is larger than the length of contact area, 250mm (10 in), it is assumed that the load is distributed over the plank width. If the plank width is less than 250mm (10 in), then the plank is assumed to take a portion of the wheel load proportional to the ratio of plank width and 250mm (10 in). For longitudinal planks (planks parallel to the direction of traffic), if plank width is larger than the width of contact area, 200 mm (7.5 in), then it is assumed that the load is distributed over the 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 typical transverse plank is usually resisting two wheel loads, while a typical longitudinal plank resists only one wheel load. The resulting live load moment can be calculated assuming the plank is a continuous beam on elastic supports, with support stiffness based on typical plank deck stringers as designed by AASHTO Code as limited by the Code-specified strength and deflection criteria.

For the heaviest vehicles, the actual dynamic load is less than 10% of live load (Nowak and Kim 1998). However, the flexural strength of wood is significantly higher for short duration loads, therefore, dynamic load (impact) is not considered in the analysis. Similarly, plank dead load is insignificant relative to traffic load and therefore not included in the reliability analysis.

Resistance Model

Flexural strength is considered in this study. Moment failures typically govern in plank decks, and there is limited data available to compute shear resistance statistics. The major parameter which determines the flexural resistance of wood planks is the modulus of rupture (MOR). The statistical model of MOR is based on the actual in-grade tests carried out by researchers in Canada (Madsen and Nielsen 1978) and the test data were processed by Nowak (1983). The cumulative distribution functions (CDFs) of MOR for Douglas-Fir planks are shown in Figure 2 on a normal probability scale for Select Structural, and in Figure 3 for Grades 1 and 2. Statistical parameters are given in Table 1. The resistance distributions were found to best-fit lognormal.

The MOR data above were obtained by applying the load to the narrow side of the section (edge-wise). In plank decks, however, the load is applied to the broad side of the plank (flat-wise). The results of flat-wise load tests performed by Stankiewicz and Nowak (1997) and Nowak et al. (1999) are used in this study. As flat-wise use has a significant impact on resistance, the effects of which were not studied in previous code calibration efforts, a brief description of the available test data follows.

Tests were performed on pressure-treated Red Pine, the most common species for plank decks in Michigan. Nominal sizes of 100 x 150 mm (4 x 6 in), 100 x 200 mm (4 x 8 in), 100 x 250 mm (4 x 10 in), and 100 x 300 mm (4 x 12 in) were tested, where the later two sizes are most frequently used in practice. The sizes and quantities are given in Table 2. A total of 169 edge-wise and 177 flat-wise specimens were tested. The edge-wise tests were performed using a third-point loading setup. The span of tested specimens was 84 in (2,135 mm), and specimens were placed on roller bearings. In order to prevent the transverse buckling and deformation of the specimen, special side braces were provided. The load was transferred from the actuator to the specimen using a loading steel beam equipped with load bearings. The flat-wise tests were performed using a single-point loading setup. The span of tested specimens was 915 mm (36 in). The load was transferred from the actuator to the specimen using a roller. A rubber pad was used between the loading roller and the specimen to reduce the stress concentration and indentation. For all tests, a monotonically increasing, displacement controlled, linear ramp loading was applied, with the load rates selected (from 0.254 mm/sec (0.0100 in/sec) to 0.127 mm/sec (0.0050 in/sec)) to provide consistent strain rates for different specimen depths. The moisture content of each specimen was measured and it varied from 9 to 15%. For each specimen, based on the measured failure load, MOR was calculated. The resulting CDFs of MOR for edge-wise and flat-wise loading are shown in Figure 4 for 100 x 150 mm (4 x 6 in), Figure 5 for 100 x 200 mm (4 x 8 in), Figure 6 for 100 x 250 mm (4 x 10 in), and Figure 7 for 100 x 300 mm (4 x 12 in). Statistical results are presented in Table 3 for the mean value as well as the 10^{th} and 5^{th} lowest percentiles. The calculations were carried out using the actual dimensions, as measured prior to the tests. Table 4 presents the flat use factors (ratio of MOR to flat-wise versus edge-wise loading) found directly from the experimental data, as well as those used for the reliability analysis in this study and those given by AASHTO. Values recommended for design practice and used in the reliability analysis were modified slightly from the mean experimental values so that there is a smoother transition from one size to the next. Note that coefficient of variation is typically smaller for flat-wise loading as compared to edge-wise.

The curves in Figures 4 through 7 are close to straight lines, which is an indication that the corresponding CDF's are close to normal distributions. However, it is expected that for a larger sample size, the distributions will best-fit lognormal, as this was found from other MOR test results for wood specimens that considered a larger number of samples (as per Madsen and Nielsen (1978), for example), and since strength is always positive. It also can be seen that the difference between flat-wise and edge-wise CDF's increases for larger dimensions of the cross section. For 100 x 150 mm (4 x 6) specimens, for example, the difference between flat-wise MOR and edge-wise MOR is relatively small, because the thickness to depth ratio is not very large. However, for 100 x 250 mm (4 x 10) and 100 x 300 mm (4 x 12), flat-wise MOR is clearly larger than edge-wise MOR. This observation can be justified by considering a wood beam as a system of parallel fibers in the longitudinal direction. The capacity of the beam, however, is limited by the presence of defects (knots and splits) across its width. For example, a knot at the bottom of an edge-wise loaded beam can drastically reduce the load carrying capacity, because there are fewer remaining strong fibers at the extreme edge, as compared to a flat-wise loaded beam with the same size knot located at the bottom.

Comparing code flat-wise use factors to experimental values, the code becomes more conservative as plank width increases. Based on the available data, here an assumption is made that flat use and size effects are generally consistent across species, as per current NDS.

Reliability Analysis

The reliability analysis is carried our using the procedure developed for calibration of the AASHTO LRFD Code (Nowak 1995). The limit state is formed in terms of bending stress, and for this study the analysis is performed for Douglas-Fir plank decks designed using AASHTO (2002) and AASHTO LRFD (2004). Reliability index is calculated with the first order, second moment method for lognormal random variables:

$$\beta = \frac{\ln \overline{R} - \frac{1}{2}\ln\left(V_R^2 + 1\right) - \ln \overline{Q} + \frac{1}{2}\ln\left(V_Q^2 + 1\right)}{\sqrt{\ln\left(V_R^2 + 1\right) + \ln\left(V_Q^2 + 1\right)}} \qquad (1)$$

where $\overline{R}$ and $\overline{Q}$ are the mean values of resistance and load effect, respectively, and V_R and V_Q are the coefficients of variation of resistance and load effect. Results are given in Tables 5 and 6 for a range of practical stringer spacing (plank span).

The parameters involved in the design of plank decks include stringer spacing, plank thickness, species, and grade. Most often the plank thickness is 100 mm (4 in) nominal. Therefore, in this study, which considers data for 4 in thick Douglas-Fir planks, stringer spacing and grade are treated as the only design parameters. The resulting maximum allowed stringer spacings determined from the AASHTO Codes are given in Table 7 below. Table 8 presents the reliability indices corresponding to the planks and spans given in Table 7. These values are representative of current design practice. The results indicate that there are considerable differences in the reliability indices. In general, longitudinal planks have higher indices than transverse planks, grade 1 & 2 have higher indices than Select planks, and for longitudinal planks, the Standard Code results in higher indices than LRFD. Considering all cases, for the Standard Code, the lowest index is for a 100 x 250 mm (4 x 10 in) Select grade plank spanning 560 mm (22") (transversely), with β=3.6, while the highest is for a 100 x 300 mm (4 x 12) Select grade plank spanning 360 mm (14") (longitudinally), with β=7.9. For the LRFD Code, the lowest index is for the same case as is the same value as for the Standard Code, while the highest index is for a 100 x 300 mm (4 x 12 in) grade 1 or 2 plank spanning 410 mm (16") (longitudinally) with β=7.0. This range in reliability index (3.6-7.9) represents an extremely large range of failure probabilities, from approximately $1x10^{-4}$ to $1x10^{-15}$. Clearly, current procedures result in significant discrepancies in safety level and are unsatisfactory from a design perspective.

There are several sources of β variation, including discrepancies in allowable stress, size factor (effect of section aspect ratio), flat-use factor, and wheel load distribution modeling, that the Code specifies, as compared to the actual mean values (as well as non-uniformity in resistance coefficients of variation). The interaction of these discrepancies produces the range of values shown in Table 8.

Conclusions and Recommendations

Load and resistance models were developed for plank decks, and reliability indices estimated for decks designed to AASHTO Code. Significant differences in indices were found for different plank decks, however. There are several considerations which would aid in developing a more uniform level of plank deck safety:

1. Flat-use factors. Code values are conservative but not consistently so. Comparing AASHTO-referenced values to experimental values and the values used in the reliability analysis (Table 4), the Code is more conservative for wider planks.
2. Size factors. Similar to point one above, the Code-referenced values are conservative with respect to those found in the available test data. However, the degree of conservatism is not consistent, producing small but noticeable variations in reliability. Sections with aspect ratios closest to 1.0 (i.e. 100 x 150 mm or 4 x 6 in) are most conservative. Here resistance capacity discrepancies up to about 10% are observed as compared to planks with smaller aspect ratios.
3. Wheel load distribution. For transverse planks, the AASHTO Codes specify that a single plank must carry the entire wheel load, regardless of plank width. For the Standard Code, the wheel load on longitudinal planks is taken as a point load rather than a pressure patch carried by a single plank. For short spans such as plank decks, this assumption significantly increases design moment in some cases. As a group, these assumptions are inconsistently conservative, especially for longitudinal and narrow planks. Although not accounted for by Code, a smaller plank width can increase the reliability of the deck due to the load sharing

effect, as well as by reducing resistance variation by allowing multiple planks to act together in a parallel system.

Exploring the feasibility of incorporating appropriate adjustments in the AASHTO Codes to account for these discrepancies may be useful to develop design standards that result in a more consistent level of reliability for plank decks.

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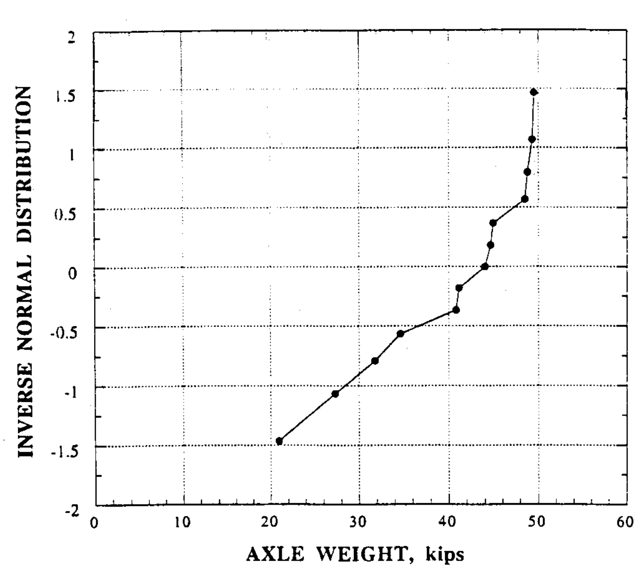

Fig 1. Cumulative Distribution Function of Maximum Axle Weight

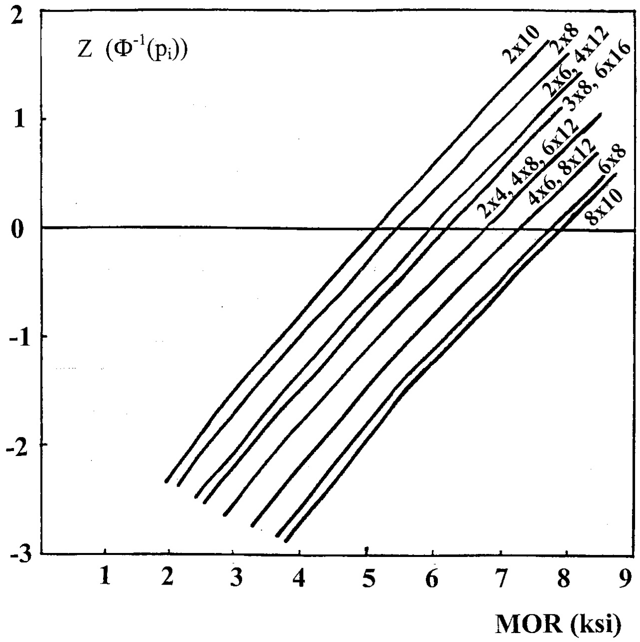

Figure 2. CDF of MOR for Douglas Fir Planks, Select Structural Grade

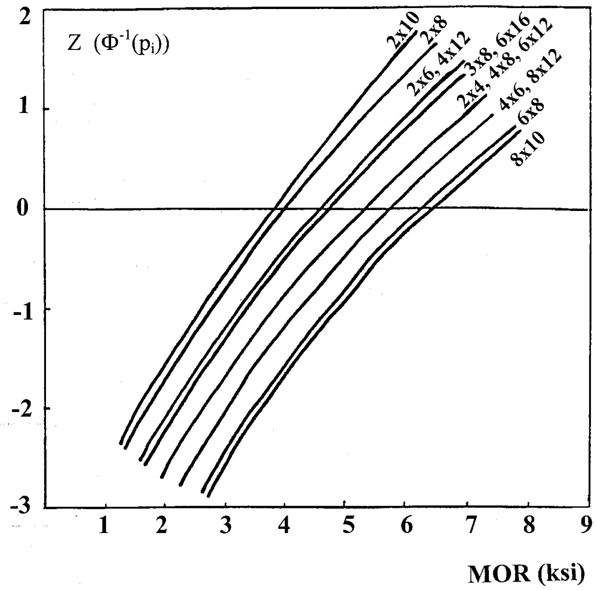

Figure 3. CDF of MOR for Douglas Fir Planks, Grades 1 and 2

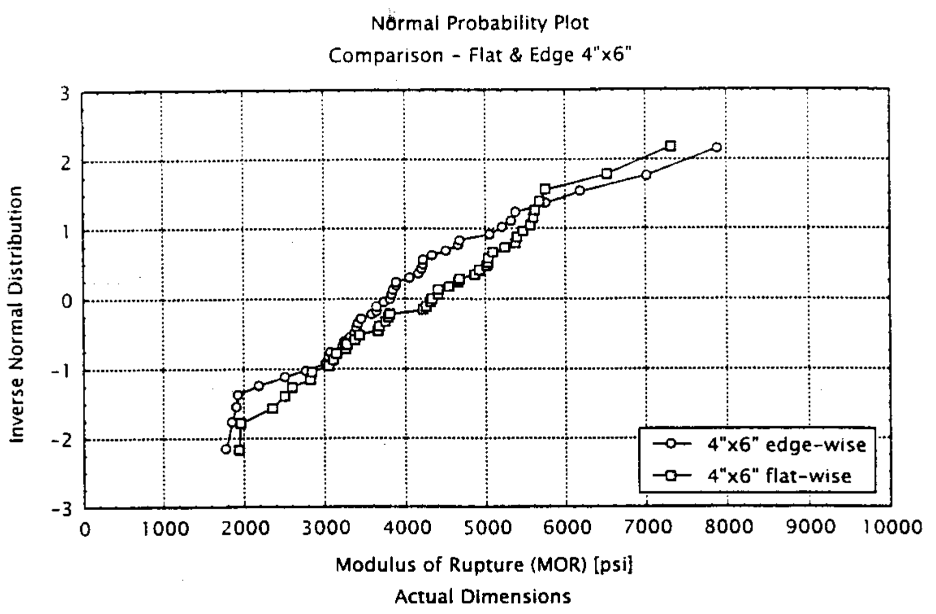

Figure 4. CDF of MOR for 4x6 Planks, Edge-wise vs Flat-wise Loading

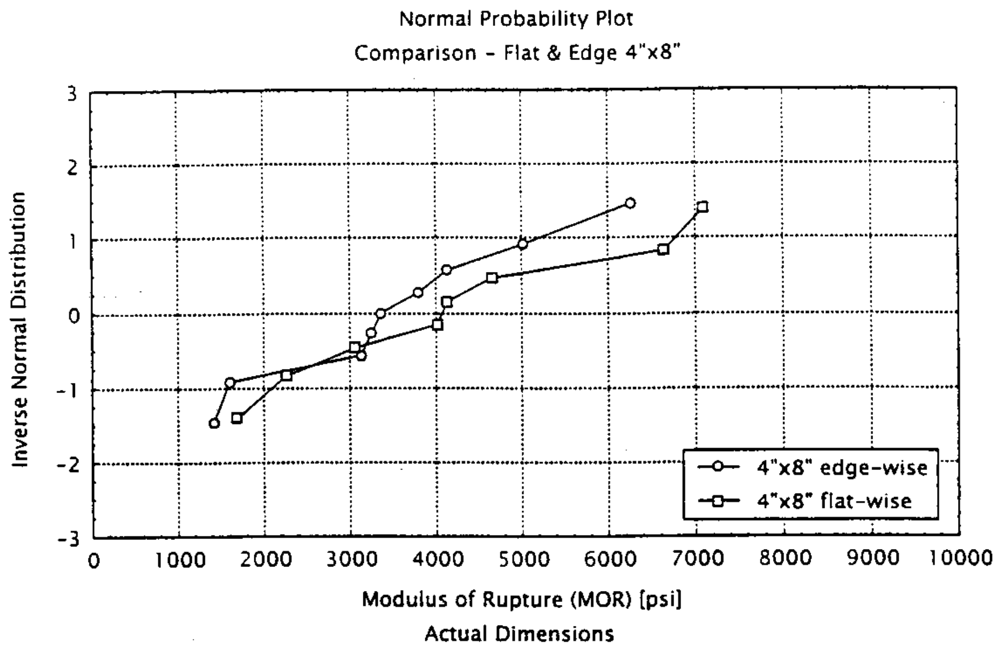

Figure 5. CDF of MOR for 4x8 Planks, Edge-wise vs Flat-wise Loading

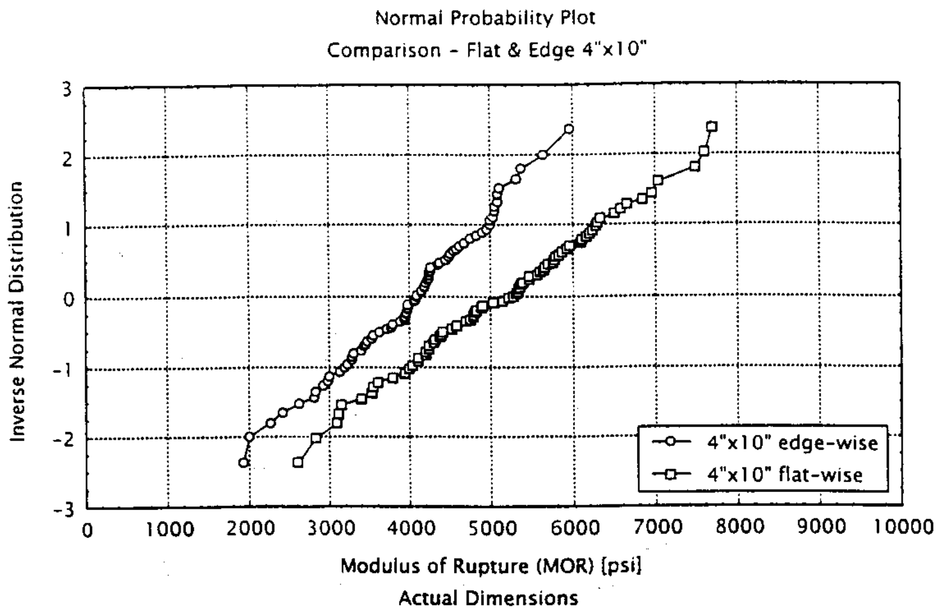

Figure 6. CDF of MOR for 4x10 Planks, Edge-wise vs Flat-wise Loading

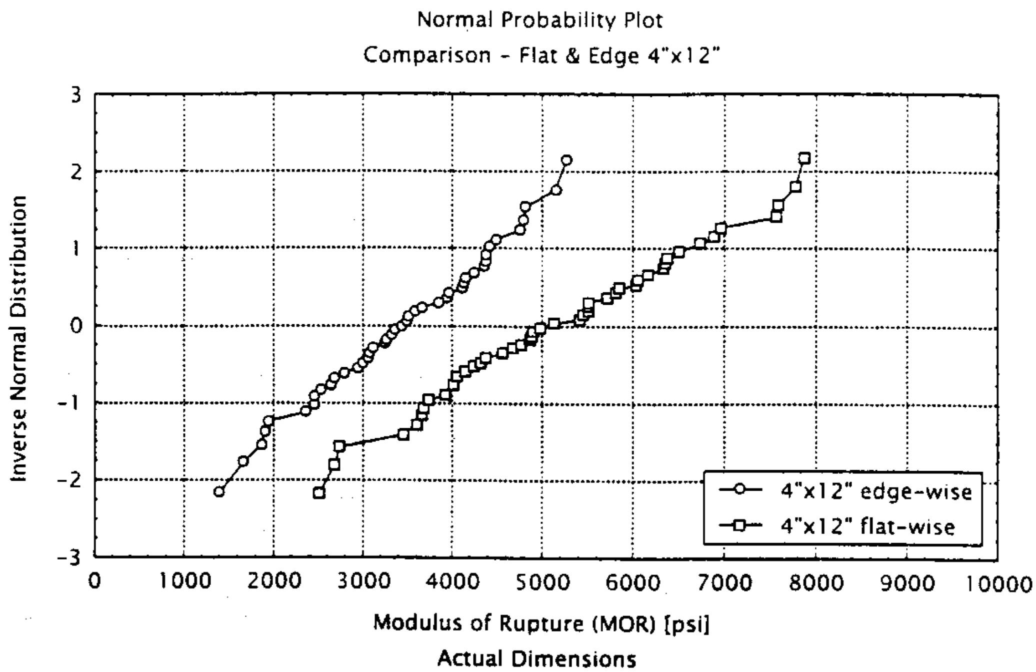

Figure 7. CDF of MOR for 4x12 Planks, Edge-wise vs Flat-wise Loading

Table 1. Statistical Parameters of MOR for Douglas-Fir Sawn Lumber.

Size, mm (in)	Select Structural		Grade 1 & 2	
	Mean, MPa (ksi)	COV	Mean, MPa (ksi)	COV
100 x 150 (4x6)	50 (7.3)	0.19	40 (5.8)	0.26
100 x 200 (4x8)	47 (6.8)	0.22	37 (5.4)	0.29
100 x 250 (4x10)	44 (6.4)	0.23	34 (4.9)	0.30
100 x 300 (4x12)	42 (6.1)	0.23	32 (4.6)	0.30

Table 2 Sizes and Quantities of Tested Planks for Flat-wise Use Factor

Nominal Size of Specimens mm (in)	Dressed Size mm (in)	Tested Specimens	
		Edge-wise	Flat-wise
100 x 150 (4 x 6)	89 x 140 (3.5 x 5.5)	43	45
100 x 200 (4 x 8)	89 x 184 (3.5 x 7.25)	9	8
100 x 250 (4 x 10)	89 x 235 (3.5 x 9.25)	74	77
100 x 300 (4 x 12)	89 x 286 (3.5 x 11.25)	43	47

Table 3. Statistical Parameters of MOR for Tested Planks

Size, mm (in)	Flat-wise MOR (MPa)				Edge-wise MOR (MPa)			
	Mean	10th	5th	COV	Mean	10th	5th	COV
100x150 (4x6)	30.0	19.3	15.5	0.31	26.2	15.9	13.5	0.30
100x200 (4x8)	25.9	12.4	8.63	0.44	22.8	10.4	6.90	0.45
100x250 (4x10)	35.2	25.9	22.1	0.22	28.3	20.0	16.6	0.24
100x300 (4x12)	35.2	23.1	20.0	0.25	16.6	17.3	12.1	0.32

Table 4. Flat Use Factors

Size, mm (in)	Experimental Values			Reliability Model		AASHTO	Recommended
	Mean	10th	5th	Mean	COV	Specified	for design use
100x150 (4x6)	1.14	1.22	1.15	1.10	0.31	1.05	1.05
100x200 (4x8)	1.14	1.20	1.25	1.15	0.30	1.05	1.15
100x250 (4x10)	1.24	1.29	1.33	1.25	0.28	1.10	1.25
100x300 (4x12)	1.50	1.63	1.66	1.50	0.25	1.10	1.50

Table 5. Reliability Indices for Douglas-Fir Planks, Select.

Stringer Spacing mm (in)	Transverse Planks				Longitudinal Planks			
	Plank Width (mm)				Plank Width (mm)			
	150	200	250	300	150	200	250	300
300 (12)	7.2	7.3	7.7	9.1	6.4	6.6	7.6	9.0
360 (14)	6.1	6.2	6.6	7.9	5.4	5.6	6.5	7.9
410 (16)	5.3	5.3	5.7	6.9	4.6	4.8	5.8	7.0
460 (18)	4.6	4.6	4.9	6.1	4.1	4.2	5.2	6.4
510 (20)	3.9	3.9	4.2	5.4	3.6	3.8	4.7	5.9
560 (22)	3.4	3.3	3.6	4.8	3.2	3.4	4.2	5.4
610 (24)	2.8	2.8	3.1	4.2	2.9	3.0	3.9	5.0

Table 6. Reliability Indices for Douglas-Fir Planks, Grade 1&2.

Stringer Spacing mm (in)	Transverse Planks Plank Width (mm)				Longitudinal Planks Plank Width (mm)			
	150	200	250	300	150	200	250	300
300 (12)	6.6	6.6	7.1	8.3	5.8	6.0	7.0	8.2
360 (14)	5.6	5.6	6.0	7.1	4.8	5.0	5.9	7.1
410 (16)	4.7	4.7	5.0	6.2	4.0	4.2	5.1	6.2
460 (18)	4.0	4.0	4.3	5.3	3.5	3.6	4.5	5.6
510 (20)	3.3	3.3	3.6	4.6	3.0	3.2	4.0	5.1
560 (22)	2.8	2.7	3.0	4.0	2.6	2.8	3.6	4.6
610 (24)	2.3	2.2	2.4	3.4	2.3	2.4	3.2	4.3

Table 7. Maximum Allowable Stringer Spacing, mm (Douglas Fir Planks)

	Transverse Planks				Longitudinal Planks			
Code:	Standard		LRFD		Standard		LRFD	
Size, mm (in)	Select	1&2	Select	1&2	Select	1&2	Select	1&2
100x150 (4x6)	410	360	410	360	n/a	n/a	300	n/a
100x200 (4x8)	510	410	510	410	n/a	n/a	360	300
100x250 (4x10)	560	460	560	460	300	n/a	460	360
100x300 (4x12)	610	510	610	510	360	n/a	510	410

Table 8. Reliability Indices for Douglas-Fir Planks Designed by Code

	Transverse Planks				Longitudinal Planks			
Code:	Standard		LRFD		Standard		LRFD	
Size	Select	1&2	Select	1&2	Select	1&2	Select	1&2
100x150 (4x6)	5.3	6.1	5.3	6.1	n/a	n/a	6.4	n/a
100x200 (4x8)	4.6	5.3	4.6	5.3	n/a	n/a	5.6	6.6
100x250 (4x10)	3.6	4.9	3.6	4.9	7.6	n/a	5.2	6.5
100x300 (4x12)	4.2	6.1	4.2	5.4	7.9	n/a	5.9	7.0