Reliability of Bolted Wood Connections

By John J. Zahn,[1] Member, ASCE

Abstract: This report analyzes the implied reliability of current practice for the design of bolted wood connections. All U.S. data available to the writer were used. The resistance distribution was taken to be normal. and the coefficient of variation was obtained by pooling data from several sources. as long as the moisture condition. grain direction. side-plate material, and species were alike. The reliability index for softwood connections is about 5; the index for hardwood connections is about 20% greater than that for softwood connections. A comparative study of data from six sources showed that reliability does not depend upon bolt length-to-diameter ratio. and the effects of wood moisture content and side-plate material (steel or wood) are minimal. Two new codes are briefly examined and compared with current practice. Both of these codes contain radically reformed design criteria for bolted wood connections. The comparison shows that both new codes maintain the present level of reliability.

Introduction

In 1989, a consortium of wood-industry interests under the auspices of the National Forest Products Association (NFPA) and the managerial control of the Wood Industry Management Committee (WIMC) began work on a load- and resistance-factor design (LRFD) specification for engineered wood construction. The primary aim of the project was to produce a specification with the factored load provisions of ASCE (*American* 1990). The starting point for this document was the ASCE prestandard report (Load 1988), which was prepared by a task committee of the ASCE Committee on Wood. The final document will appear as a joint NFPA-ASCE standard. A trial draft was being field-tested at the time this study was performed. A companion working document prepared by the NFPA task group, defines the procedures by which wood products may be assigned nominal resistance values for use in conjunction with the LRFD specification. These values are to be provided by suppliers of wood-based materials and engineered wood products.

in preparing the LRFD document, every effort was made to include state-of-the-art design criteria. Although current design practice was assessed for its reliability, no attempt was made to revise the levels of reliability that are presently in use. Instead, the reliability assessments were used for insight into the best code conversion factor that would calibrate the new code to current practice. Because many improvements other than load factors were introduced in the new document, the NFPA worked to simultaneously revise the National Design Specifications (NDS) with similar reforms (*National* 1991). As a result, the 1991 NDS and the LRFD specification will be similar in almost all respects except format.

The Forest Products Laboratory was involved in many aspects of the LRFD project. In this paper, the results of the reliability assessment of

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bolted connections are presented. In addition, a comparison of the reliability of the LRFD code and the 1991 NDS code with current practice is presented.

BASIC PARAMETERS

All the data used in this study were obtained from three-member connections. The number of samples of other types of connections was insignificant. The three-member connections examined here had two equal outer members, called side plates, and one main member. The main member was always wood, but the side members were either wood or steel.

The basic parameters of this study were species, moisture condition, side-plate material, and grain direction of main wood member. Variables also included bolt length L and bolt diameter D. (In this context, bolt length is defined as the thickness of the main member.) The variation of reliability with LID was a primary consideration in this study because uniformity is difficult to achieve.

DEFINITION OF LIMIT STATES

The limit state of interest was, of course, the ultimate limit state. In the past, design values were derived from the proportional limit load; in the future, they will be based upon the dowel bearing strengths of the fastener in the main and side members. This latter concept is part of the European yield theory, which. in its U.S. implementation, aims to achieve a target offset load for the connection. Therefore three limit states were examined—proportional limit, offset, and ultimate—whose failure events are defined as follows (Fig. 1).

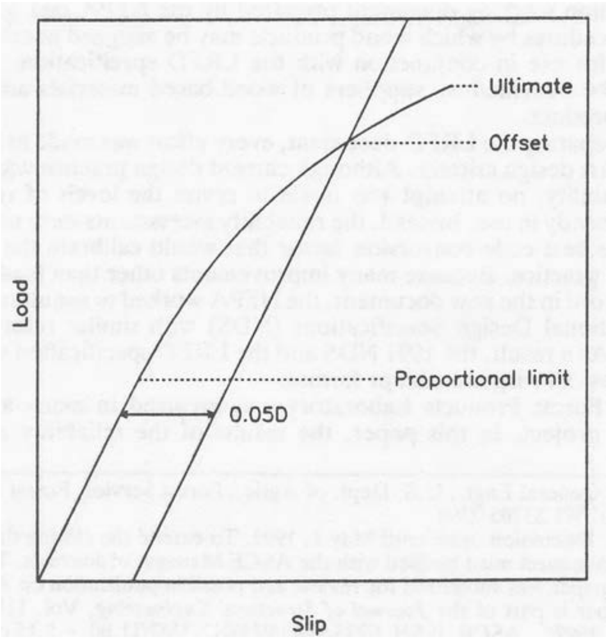

FIG. 1. Definition of Limit States

- Proportionality: Load effect exceeds the proportional limit load of the connection. X_{pl}. This is defined as the load at which the load-slip curve first departs from a straight line.
- Offset: Load effect exceeds the offset load of the connection. X_{of}. This is defined as the load at which the load-slip curve is intersected by a straight line constructed parallel to the initial linear portion of the curve with a slip offset equal to 5% of the bolt diameter. If the constructed line and the load-slip curve never intersect then the rupture load is taken as the offset load for that case. The definition of offset load is currently under consideration by the American Society for Testing and Materials (ASTM) Committee D 07.05.02 as a deformation-based limit state that has better repeatability than the proportional limit. The offset load lies between the proportional limit load and the ultimate load. It is nearly equal to the ultimate load for brittle connections. but may be as much as 40% less for very ductile connections. Such ductility is typical for large LID ratios.
- Ultimate: Load effect exceeds the ultimate load of the connection, X_{ul}. This is defined in ASTM D 1761 (''Standard''1992) as the load at which rupture occurs or the load at which the connection slip reaches 0.6 in. (15 mm), whichever occurs first. The 3.6-in. (15-mm) cutoff is included in the ASTM definition because the rupture load is not a practical measure of capacity for connections that exhibit extremely ductile behavior.

Although all the studies reported the proportional limit load, it was not always possible to obtain the other two measures of connection capacity. Where ultimate loads were measured, they are included here. Wherever load-slip curves were available, the offset load was geometrically constructed and is reported here.

METHODS

Because of the creep-rupture phenomenon, reliabilities are affected by time under load as well as by load magnitude. Traditionally, duration-of-load factors have been used to account for this. Because duration-of-load factors are currently under review and revision, all reliabilities calculated and reported herein are immediate (5-min) values. This allows unambiguous comparisons of codes, but reliabilities over longer periods will be lower than the reliabilities reported here.

The Hasofer-Lind reliability index ß was used as the measure of reliability. This index was obtained using extended level-two methods as presented in Thoft-Christensen and Baker (1982). The reliability index depends on the form of the load and resistance distributions and the amount of their separation (difference in means). Given the distributions, the separation of the means can be inferred from the code-specified relations between the nominal values and mean values, and the code-specified design equation relating the nominal values. In the 1986 edition of the NDS (*National* 1991), this design equation was

$$R_n = D_n + L_n \qquad (1)$$

in which R_n = nominal resistance; D_n = nominal dead load; and L_n = nominal floor live load.

Resistance Distribution

None of the data on the capacity of bolted connections contained large samples. Therefore, the resistance distribution is assumed Gaussian normal with a coefficient of variation (COV) estimated from data for a particular limit state. Fig. 2 shows cumulative distribution functions at all three limit states for one sample of size 15 (Soltis et al. 1986). No sample showed evidence of nonnormality at any limit state, based on an analysis of variance test for normality (Shapiro and Wilk 1965). Estimation of the COV is described in the following.

Load Distribution

In this study, the case of dead load plus floor live load with a live-to-dead load ratio of 4.0 was considered. Load distributions were taken from *American* (1990). This standard specifies that the dead-load distribution is normal with COV = 0.10 and nominal dead load equal to the mean divided by 1.05. Floor live load has a Gumbel distribution with COV = 0.25 and nominal load equal to the mean.

DATA

Data Sources

Data examined here came from six studies (Doyle 1963; Soltis et al. 1986; McLain 1981; Trayer 1932; Wilkinson 1978; Wilkinson unpublished report). Sources and values of the basic parameters are summarized in Table 1.

Some of these data contained small samples. They are listed here for completeness, but small samples had little effect on the reliabilities calculated in this study. Data of similar parameter values were grouped. and groups that contained only small samples were discarded.

Data Pooling and Selection of COV Values

Data were gathered into groups, each with the same species, moisture condition, side-plate material, and grain direction. Data from the sources

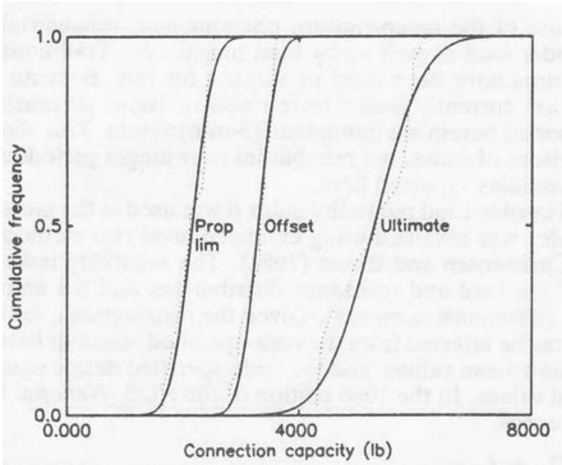

FIG. 2. Cumulative Frequency Distributions for Typical Sample of 15 Specimens. Solid Lines indicate Fitted Normal Distributions; Dotted Lines indicate Raw Data. 1 lb = 4.45 N

TABLE 1. Summary of Data Sources

Source (1)	Species (2)	Moisture condition[a] (3)	Side plates[b] (4)	Grain direction[c] (5)	Sample size[d] (6)	Total tests (7)
Doyle (1963)	Douglas-fir	both	both	both	3	66
McLain (1981)	Southern pine	dry	both	PAR	10	90
Soltis et al. (1986)	Douglas-fir	dry	wood	both	15	390
Trayer (1932)	several	both	both	both	4 or 5	449
Wilkinson (1978)	Douglas-fir	dry	wood	PAR	6	168
Wilkinson (unpublished report)	Douglas-fir	dry	steel	both	20[e]	480

[a]Wet or dry.
[b]Wood or steel.
[c]Direction of bearing load on main member. PAR = parallel to grain.
[d]Number of tests per sample.
[e]One sample was of size 40.

listed in Table 1 produced a total of 24 groups, but only 11 groups were used (Table 2). All groups of softwood data that contained only small samples were discarded as insignificant for an assessment of reliability. However. all available hardwood data were in small samples. Therefore, all hardwood groups that contained data for the ultimate limit state were retained despite their small sample size. The results for reliability of hardwood connections must, therefore, be viewed with some caution.

Because the basic parameters are equal within a group, the COV for a given limit state should be consistent. However, the COV of individual samples vaned widely. In some studies (Trayer 1932, Doyle 1963, McLain 1981), material was specially selected in ways that tended to eliminate variability. In general, larger samples showed larger COV values. Therefore, to estimate the COV of a group at a given limit state, data were pooled as follows. Each datum within a sample was divided by its own sample average and all data within a group were pooled. The COV of the pooled data was then calculated. This was repeated for each group and each limit state. Table 2 shows the COV values that resulted from this process for the 11 data groups. (The number of specimens sometimes differs between limit states because not all limit state values were available for some specimens.)

On the basis of Table 2, with due regard to source and size of each sample, the COV of the resistance variable for each limit state was estimated to be as follows:

- Proportionality: 0.19.
- Offset: 0.16.
- Ultimate: 0.15.

CALCULATION OF RELIABILITY INDEXES

For the case of dead load plus floor live load, the calculated reliability is a function of the COV of the resistance distribution and the separation of resistance and load. The ratio of mean resistance to nominal dead load was used as the measure of separation. Taking the nominal dead load D_n = 1.0, nominal live load L_n = 4.0, mean resistance ranging from 5.0 to 50.0

TABLE 2. Total Number of Specimens and Coefficients of Variation (COV) for Three Limit States

Test Parameters					NUMBER OF SPECIMENS AND COV					
					Proportionality Limits[a]		Offset		Ultimate	
Species (1)	Moisture condition (2)	Side plates (3)	Grain[b] (4)	Source[c] (5)	Number (6)	COV (7)	Number (8)	COV (9)	Number (10)	COV (11)
(*a*) Softwoods										
Douglas-fir	dry	steel	PAR	D, U	271	0.133	271	0.121	270	0.162
Douglas-fir	dry	steel	PERP	D, T, W	268	0.217	248	0.180	268	0.132
Douglas-fir	dry	wood	PAR	D, S, U	373	0.159	370	0.130	373	0.111
Douglas-fir	dry	wood	PERP	D, S	210	0.210	210	0.173	210	0.162
Southern pine	dry	steel	PAR	M	40	0.093	34	0.211	25	0.086
Southern pine	dry	wood	PAR	M	41	0.087	25	0.073	41	0.080
Sitka spruce	dry	steel	PAR	T	118	0.104	78	0.145	53	0.048
(*b*) Hardwoods										
Maple	wet	steel	PAR	T	29	0.103	—	—	19	0.065
Maple	dry	wood	PAR	T	20	0.110	—	—	20	0.061
Oak	wet	steel	PAR	T	20	0.098	20	0.073	—	—
Oak	dry	wood	PAR	T	20	0.059	4	0.022	20	0.050

[a]Proportional limit.
[b]Direction of bearing load on main member. PAR = parallel to grain; PERP = perpendicular to grain.
[c]Data sources: D = Doyle (1963); S = Soltis et al. (1986); M = McLain (1981); T = Trayer (1932); W = Wilkinson (1978); and U = Wilkinson (unpublished).

with various values of resistance COV, and using extended level-two methods (Thoft-Christensen and Baker 1982), the reliability index was plotted as a function of separation ratio (Fig. 3). This figure can be used with any design code. The code merely supplies the checking equation, such as (1), and the nominal resistance. The mean and COV of the resistance are supplied by experimental data.

Fig. 3 was used to calculate the reliability index for each sample. The mean resistance was the mean of the sample, the nominal dead load was the nominal resistance divided by 5.0 [from (1)], and the nominal resistance was obtained from the 1986 edition of the NDS (*National* 1991). These values were calculated for each limit state, using a COV corresponding to the limit state.

For the nominal capacity, the tables and methods presented in "Wood" (1987) (Forest Products Laboratory 1987) were used, which are the basis of the bolt design values of the 1986 edition of the NDS (*National* 1991) (Table 8.5A). For many specimens, the nominal capacity could be obtained from Table 8.5A. For these specimens, I found that the calculated capacity and the published capacity were usually within a few percentage points of each other and never differed by more than 10%. Because the range of

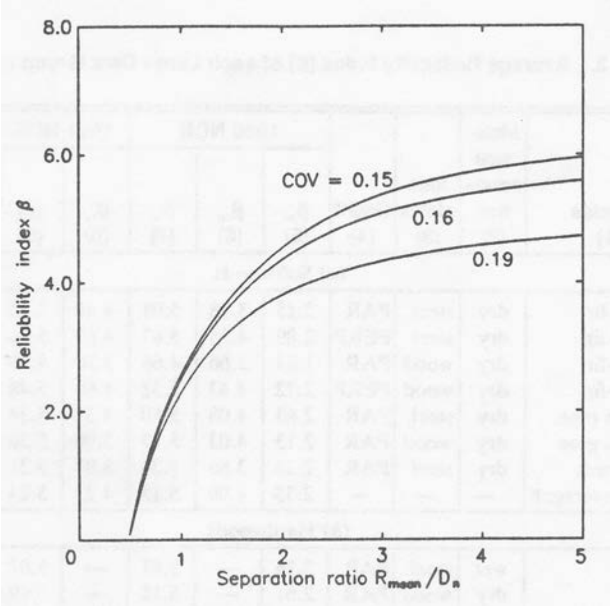

FIG. 3. Results of Reliability Analysis for Three Assumed Resistance COV Values. Load Case Is Dead Load plus Live Load at Live/Dead Ratio of 4.0. Abscissa Is Ratio of Experimental Mean Resistance to Nominal Dead Load

Table 8.5A did not cover all specimens, I decided to always use the calculated nominal. For steel side plates, only 25% increase was taken, as recommended by the American Institute of Timber Construction (AITC), rather than the more liberal increase permitted by the 1986 edition of the NDS (*National* 1991).

RESULTS

The results of the reliability calculations are shown in Table 3. This table clearly indicates that the difference between the proportional limit load and the ultimate load constituted the essential margin of safety in the current design of bolted connections.

Simply reaching the proportional limit is not in itself a very meaningful definition of failure, unless one wishes to view it as a serviceability limit state. In that case, the proportional limit load is still a poor definition because the results show a great deal of scatter. This is the inevitable result of the ambiguous meaning of the proportional limit. Its determination depends vitally upon measurement sensitivity and the scale to which measured results are plotted. The offset load. which has better repeatability, is considerably more consistent.

Trends

The data show the following trends.

1. Reliability shows no consistent trend with bolt LID ratio. Figs. 4–6 show the results of plotting reliability index versus LID. These three data

TABLE 3. Average Reliability index (3) of each Large Data Group for Three Limit States [a]

Species (1)	Moisture condition (2)	Side plates (3)	Grain[b] (4)	1986 NDS β_{pl} (5)	1986 NDS β_{of} (6)	1986 NDS β_{ul} (7)	1991 NDS β_{of} (8)	1991 NDS β_{ul} (9)	LRFD β_{of} (10)	LRFD β_{ul} (11)
(*a*) Softwoods										
Douglas-fir	dry	steel	PAR	2.15	3.98	5.01	4.41	5.30	4.06	5.05
Douglas-fir	dry	steel	PERP	2.89	4.65	5.67	4.63	5.66	4.32	5.48
Douglas-fir	dry	wood	PAR	1.84	3.66	4.66	3.76	4.75	3.32	4.38
Douglas-fir	dry	wood	PERP	2.72	4.43	5.32	4.68	5.48	4.38	5.26
Southern pine	dry	steel	PAR	2.63	4.08	5.10	4.32	5.24	3.95	4.96
Southern pine	dry	wood	PAR	2.13	4.03	5.37	3.96	5.30	3.55	5.02
Sitka spruce	dry	steel	PAR	2.26	3.86	5.24	3.97	5.21	3.57	4.93
(Grand average)[c]	—	—	—	2.33	4.09	5.13	4.27	5.24	3.90	4.97
(*b*) Hardwoods										
Maple	wet	steel	PAR	3.16	—	5.97	—	5.87	—	5.73
Maple	dry	wood	PAR	2.61	—	6.12	—	5.99	—	5.88
Oak	wet	steel	PAR	2.18	3.75	—	—	—	—	—
Oak	dry	wood	PAR	2.56	4.28	6.02	—	5.78	—	5.63
(Grand average)[c]	—	—	—	2.68	3.84	6.03	—	5.88	—	5.75

[a]Subscripts to β denote limit state: *pl* = proportional limit; *of* = offset; and *ul* = ultimate.
[b]Direction of bearing load on main member. PAR = parallel to grain; PERP = perpendicular to grain.
[c]Weighted by sample size.

groups were typical; all other groups showed similar results. Horizontal lines on these figures show the average value of the reliability index for a given group and limit state.

2. The ultimate reliability index of softwood connections is approximately 5 when the bolt is bearing parallel to grain and 5%–15%greater when it bears perpendicular to grain. Figs. 7 and 8 show that the difference between parallel and perpendicular grain is more pronounced when wood side plates are employed, at least for Douglas-fir. (No data on this effect were available for any other species.)

3. Hardwood connections appear to be much more reliable than softwood connections. based on these limited data. Fig. 9 shows a difference of about 15% in the reliability index.

4. Although the reliability of Douglas-fir connections with steel side plates is slightly greater than that of connections with wood side plates. this was not true for the other species considered here. Steel and wood side plates are compared in Figs. 10–12.

5. The only available data for the effect of moisture condition are for hardwood connections. The reliability of wet connections appears to be somewhat less than that of dry connections.

6. None of these trends is strong, in view of the wide range of results for

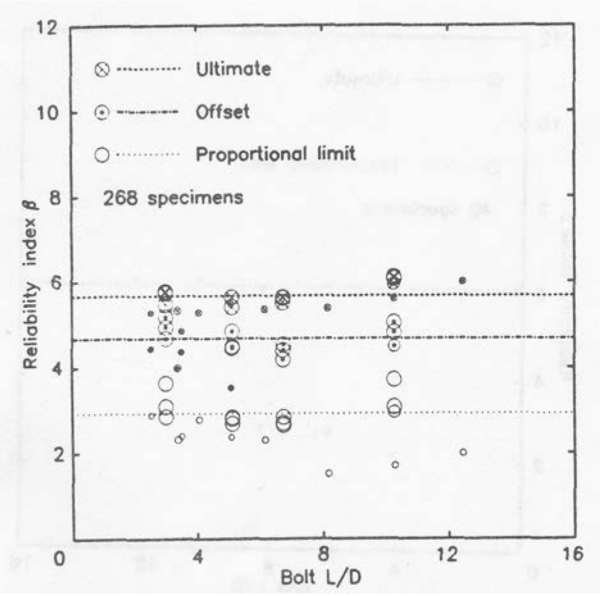

FIG. 4. Reliability Variation with Bolt *L/D* for Case of Dry Douglas-Fir, Steel Side Plates, and Bearing Perpendicular to Grain. Horizontal Lines Show Average Values

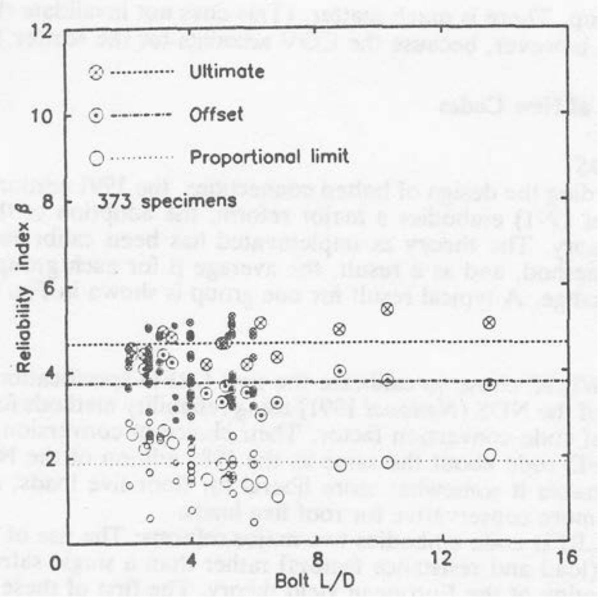

FIG. 5. Reliability Variation with Bolt LID for Case of Dry Douglas-Fir, Wood Side Plates, and Bearing Parallel to Grain. Horizontal Lines Show Average Values

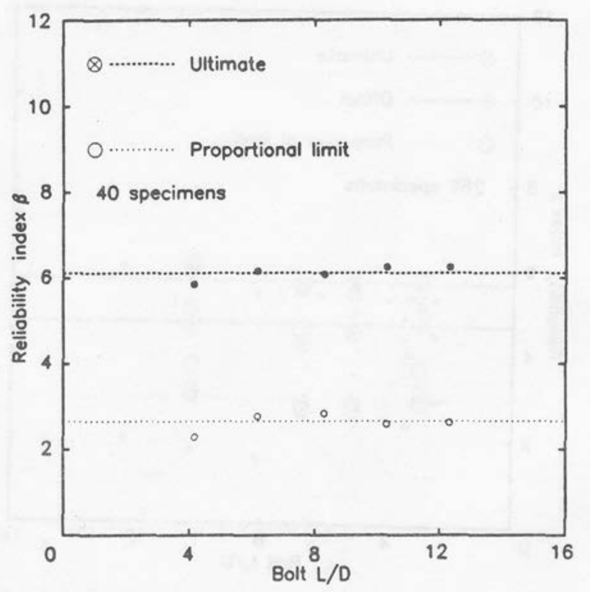

FIG. 6. Reliability Variation with Bolt *L/D* for Case of Dry Maple, Wood Side Plates, and Bearing Parallel to Grain. Horizontal Lines Show Average Values

each group. There is much scatter. (This does not invalidate the reliability analysis, however, because the COV accounts for the scatter.)

Analysis of New Codes

1991 NDS

Regarding the design of bolted connections, the 1991 edition of the NDS (*National* 1991) embodies a major reform: the adoption of the European yield theory. The theory as implemented has been calibrated to the old design method, and as a result, the average ß for each group shows little or no change. A typical result for one group is shown in Fig. 13.

LRFD

The WIMC chose to calibrate the new LRFD specification to the 1986 edition of the NDS (*National* 1991) using reliability methods for insight into choice of code conversion factor. Their choice of conversion factor keeps the LRFD code about the same as the 1986 edition of the NDS for snow loads, makes it somewhat more liberal for floor live loads, and makes it slightly more conservative for roof live loads.

The LRFD code embodies two major reforms: The use of partial safety factors (load and resistance factors) rather than a single safety factor and the adoption of the European yield theory. The first of these reforms produces more uniform reliability over all load cases. although this cannot be judged from the single load case considered here. The second has no real impact upon reliability. Its chief advantage is that it unifies the design of dowel-type fasteners by treating them all in a similar manner.

For the load case considered here, the allowable load has been increased

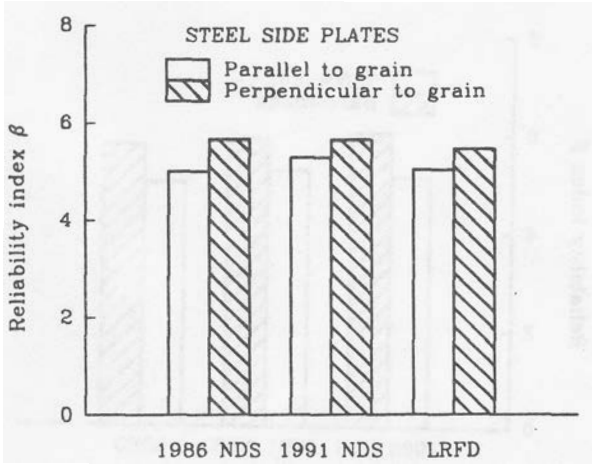

FIG. 7. Effect of Grain Direction of Wood in Main Member. Douglas-Fir with Steel Side Plates

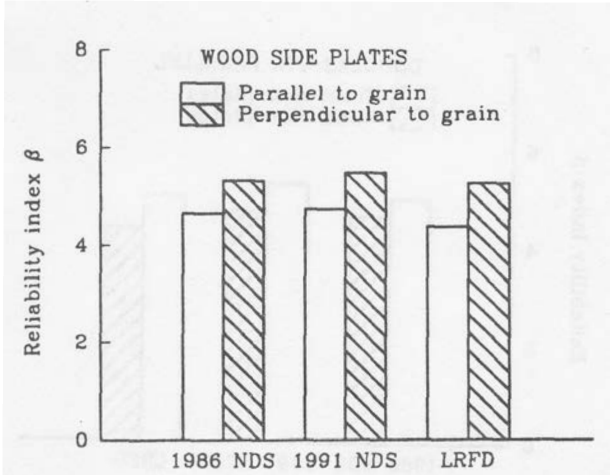

FIG. 8. Effect of Grain Direction of Wood in Main Member. Douglas-Fir with Wood Side Plates

by about 14%. However, at a reliability index of 5.0, this only decreases the reliability index by about 4%. (See Fig. 3—the curve for COV = 0.15 is not very steep at ß = 5.0.) The reliability indexes for other load cases are either unchanged or slightly increased.

Is there a need for further code reform? These data do show some variation in ß with species, but this may reflect differences between early and more recent data rather than true species effects. As mentioned. there are differences in reliability with moisture condition and between hardwoods and softwoods. However. reliability appears to be remarkably consistent, based upon these limited data. In any case, the WIMC chose to calibrate the new code rather than adjust the design values to a target reliability index at this time.

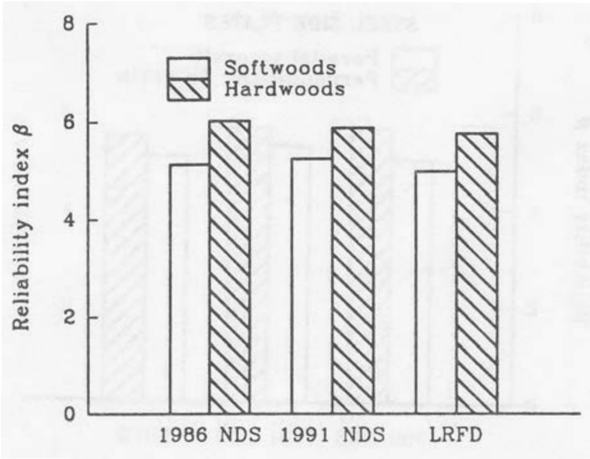

FIG. 9. Effect of Species. Comparison of Averages of All Softwoods with All Hardwoods

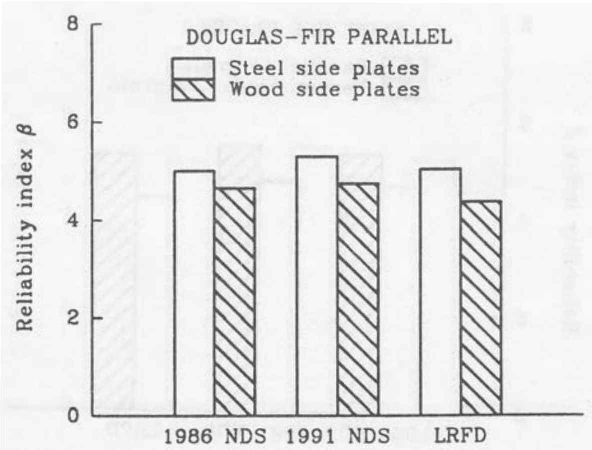

FIG. 10. Effect of Side Plate Material. Douglas-Fir with Bearing Parallel to Grain

CONCLUDING REMARKS

The reliability of bolted wood connections under the 1986 NDS was analyzed using all U.S. data available to the writer. The resistance distribution was taken to be normal, and the COV was obtained by pooling data from several sources, as long as the basic parameters were alike. The basic parameters were moisture condition (wet or dry), grain direction. side-plate material (steel or wood), and species. No consistent variation of reliability with bolt LID was noted. Wet connections may be slightly underdesigned, based on limited data for hardwoods. and connections with bearing perpendicular to grain may be somewhat overdesigned, based on data for Douglas-fir. Side-plate material had no significant effect. The rather old and meager data for hardwood connections indicate that hardwoods are apparently much more reliable than softwoods.

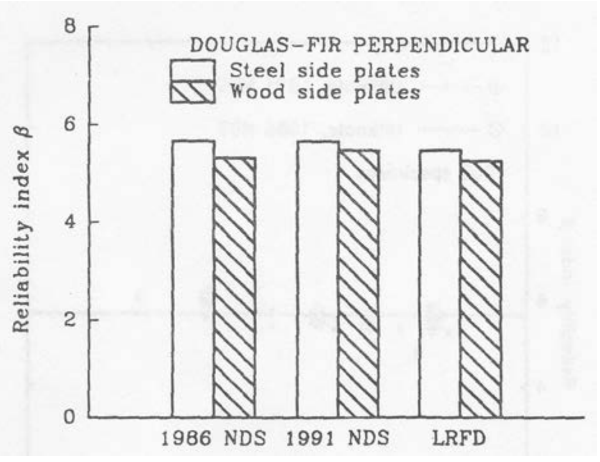

FIG. 11. Effect of Side Plate Material. Douglas-Fir with Bearing Perpendicular to Grain

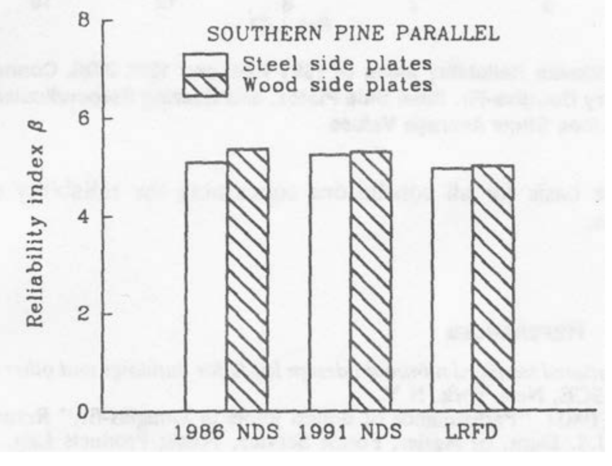

FIG. 12. Effect of Side Plate Material. Southern Pine with Bearing Parallel to Grain

The overall reliability index for bolted connections was found to be approximately 5.0. Such a large value should not be taken literally. The underlying resistance distribution is not well known. However, one can state with confidence that the overall reliability index is at least 4.0, because changing the form of the resistance distribution would not have that great an affect upon reliability index. Also, the negative tail of the assumed Gaussian normal distribution makes these reliability estimates more conservative than if that low tail had been truncated.

Of the three limit states considered, the proportional limit load showed the greatest scatter. Past design practice used this load as the basis for design values. Future design practice will use the offset load, which has better repeatability than the proportional limit. The ultimate limit state was used

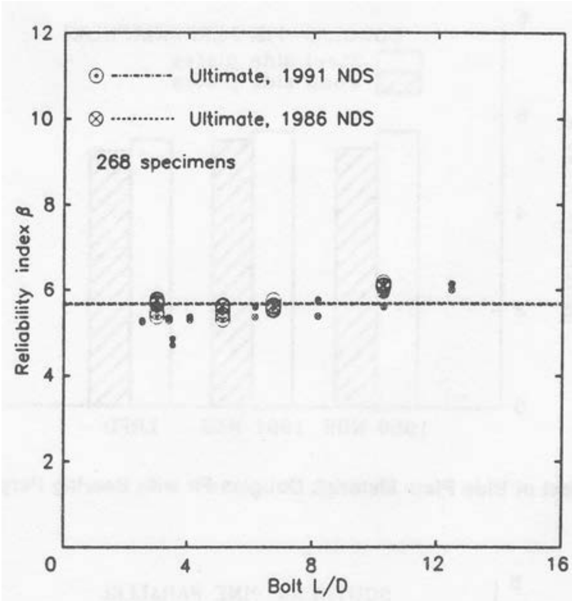

FIG. 13. Ultimate Reliability Index of 1991 NDS and 1986 NDS. Connection Parameters: Dry Douglas-Fir, Steel Side Plates, and Bearing Perpendicular to Grain. Horizontal Lines Show Average Values

here as the basis for all conclusions concerning the reliability of bolted connections.

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