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LRFD FOR ENGINEERED WOOD STRUCTURES—CONNECTION BEHAVIORAL EQUATIONS

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ABSTRACT: A new design specification for engineered wood structures has been proposed in load and resistance factor design (LRFD) format. This paper provides an overview of the proposed LRFD connections design criteria. The connections design provisions are, in part, calibrated from allowable stress design provisions. Major changes from historic practice, however, result from a change in behavioral equations to a theoretical base for predicting the lateral strength of connections using bolts, screws, and nails. New provisions for axial withdrawal of driven and turned fasteners, as well as combined axial and lateral loading criteria are also proposed. Safety levels were calibrated to historic practice, but some change in design capacity is expected due to format change, conversion to new behavioral equations. and the selection of a calibration point. The LRFD document contains substantial improvement in code clarity. simplification. and structure over the historic allowable stress specification. A clear mechanism for including design with new wood-based engineering materials is provided.

INTRODUCTION

Allowable stress design (ASD) provisions for structural wood connections are found in the *National Design Specification for Wood Construction NDS-86* (*National* 1986), known as *NDS-86,* or *National Design Specification for Wood Construction NDS-91* (*National* 1991), known as *NDS-91.* Criteria for load and resistance factor design (LRFD) of engineered wood connections have been developed. Compared to *NDS-86,* the LRFD connections criteria differ as a result of three major factors and numerous minor improvements. The first major factor is the consequence of the ASD-to-LRFD format-conversion process. This is described by Gromala et al. (1990) in more detail. A second factor is the implementation of new behavioral equations for connection strength. These equations are the result of applying European research on connection mechanics and a thorough review and compilation of data from a wide variety of sources. These behavioral equations have also been introduced into ASD in the 1991 edition of the national design specifications (*National* 1991). The third major factor is the calibration of predictions from the new behavioral equations to historic ASD strength levels.

The objective of this paper is to describe the new behavioral equations, the results of calibration to existing practice, and to identify potential changes in connection design that may be seen when comparing LRFD and ASD.

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For a simple connection, the safety-checking equation in LRFD is

$$\lambda\phi Z_n \geq Z_u \qquad (1)$$

where Z_u = required strength as determined by structural analysis for factored loads (such as 1.2D + 1.6L) acting on the structure; Z_n = nominal short-term connection strength adjusted for all in-service conditions; ϕ = 0.65; and λ = time-effect factor. The adjusted resistance Z_n is defined as

$$Z_n = n_f C_p Z \qquad (2)$$

where n_f = number of fasteners in connection; Z = reference resistance, average short-term strength of a single-fastener connection at reference conditions; and C_p = product of all factors adjusting strength from reference to end-use conditions. There are both global and fastener-specific reference conditions. Reference conditions are for connections containing untreated wood or wood-based members with 19% or less moisture content at installation, and having a density representative of the species or material. The variable Z is for short-duration loading. Each connection type, such as nails, screws, bolts, or lag screws, have additional reference conditions related to joint geometry (e.g. penetration or spacing). If end-use conditions differ from the reference levels, then the reference resistance Z, is multiplied by adjustment factors. Examples include adjustments for end-use temperature (C_{ct}), moisture content (C_{cm}), multiple fasteners (C_{cc}), and geometry (C_{cg}), among others.

The scope of the LRFD specification is limited to design of connections that use generic fasteners, such as nails, bolts, dowels, wood screws, and lag screws. In addition, connections with shear plates and split rings are covered at the same level as specified in NDS-86. Industry guidelines have been established to allow manufacturers of proprietary fastening devices to qualify their products through testing and analysis.

NEW BEHAVIORAL EQUATIONS

The NDS-86 allowable lateral strengths for nail, bolt, wood-screw, and lag-screw connections are based on empirical equations fit to varied test data. These equations were developed at different times by different workers resulting in an inconsistent basis for design loads between fastener types. Additionally, allowable connection strengths have been derived from experimental results using disparate methods. In the 1940s, Johansen (1949) developed a theoretical model of the yield strength of a laterally loaded connection using a dowel-type fastener. Larsen (1973) later published a more complete summary. These models, referred to here as european yield models (EYM), are based on the bending resistance of the fastener, the crushing strength of wood or member material, joint geometry, and assumed mechanical relationships. The EYM describe a set of possible yield modes for a single fastener under lateral load. Characteristic strength for each mode is predicted from a static analysis. assuming that members and fasteners behave as ideal rigid-plastic materials. Numerous researchers have published verification of EYM for several connection types (Soltis et al. 1986, 1987; McLain and Thangjitham 1983; Whale and Smith 1986). A typical example of predictive ability is seen in Fig. 1. EYM are the basis for design criteria in Eurocode 5 in Europe (Whale 1991) and the Canadian wood design code (*Engineering* 1989).

One primary difference between the empirically based ASD criteria

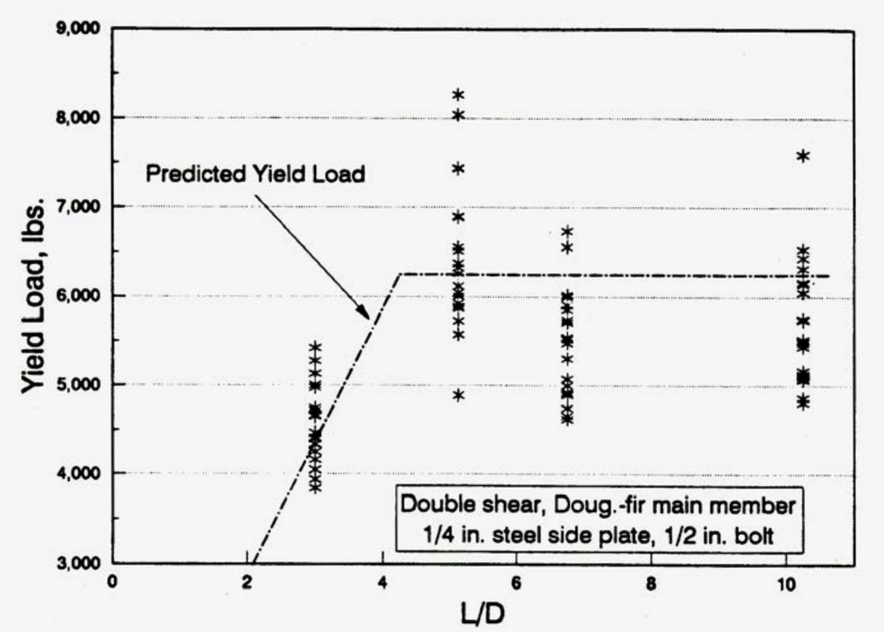

FIG. 1. Predicted Yield Strength and Experimental Observation for Douglas-Fir-Steel Plate Double Shear Connection

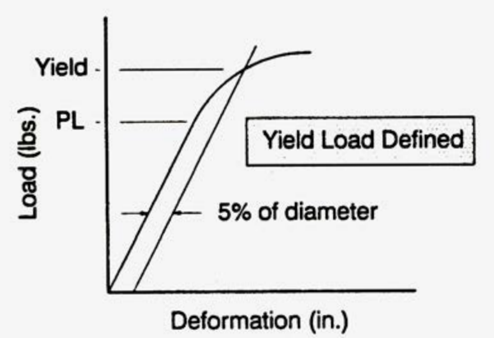

FIG. 2. Connection Yield Strength Definition

and yield theory is the definition of characteristic load. A “proportional limit” or load at a limiting deformation has been the ASD criteria. The yield theory predicts a characteristic load Z_v that lies between the connection proportional limit and ultimate strength. There have been several different definitions of joint-yield load as the European theory has evolved over the last 50 years. The definition of Harding and Fowlkes (1984) has been adopted for both the LRFD specifications and 1991 NDS. This definition, shown in Fig. 2, enables comparisons of experimental results with theoretical predictions. Yield is found by drawing a line parallel to the initial linear range of the load-deformation curve, but offset from it, by a deformation equal to 5% of the fastener diameter. The intersection of the offset line and the load-deformation curve is the 5% *D* offset-yield strength of the connection.

This definition is unambiguous and reasonably free of graphical error compared to earlier definitions of yield strength. In addition, this yield load is below the load level where microcracking is seen with transverse grain loading (Wilkinson 1991). This definition of yield differs from that chosen by the Eurocode 5 writers (Smith et al. 1988). One consequence is a slightly different implementation of EYM. This is discussed in detail by Wilkinson (1992).

As an example, Fig. 3 shows the yield modes and behavioral equations to predict Z_y for a double-shear-bolted connection. Yield strength for a specific geometry is the minimum calculated from all equations. Similar equations are developed for other connection geometries. The development of the equations is well documented by Soltis et al. (1986, 1987), McLain and Thangjitham (1983), and Patton-Mallory (1989) for bolted connections and by Aune and Patton-Mallory (1986a, 1986b) for nailed joints.

The EYM equations are easily incorporated into computer programs or calculators; alternatively, tables of design values may be readily generated. The writers of the LRFD documents clearly distinguish between the roles of specification and design aids. Both are necessary, but clarity of meaning rather than ease of use dictated the development of the specification. This distinction is expected to become more important as the computer becomes commonplace in design.

For wood screws and lag screws, the EYM are modified to account for reduced bending resistance of the threaded shank. With screws, fewer yield modes are considered than with bolts or nails, but yield may occur in either the thread or shank. McLain (1992) developed simplified equations similar to those proposed by Larsen and Reestrup (1969). Limitations are placed on fastener geometry, depth of penetration, and other joint geometry variables.

The use of yield theory assumes that the predicted yield action governs connection strength. Fastener strength and that of all steel connecting members are checked independently of EYM. Also excluded are wood failure actions, such as splitting and tear-out, and those that are brittle. rather than

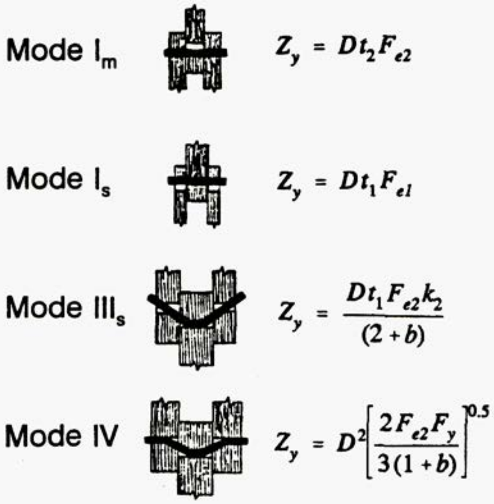

FIG. 3. **Double-Shear Connection Yield Modes**

ductile, in nature. For this reason, the specification prescribes minimum fastener spacing and other geometry restrictions on the unmodified EYM results. These geometry restrictions differ by connection type, but are considered as part of the "reference conditions" for which C_{cg} is unity. For other than reference geometries, adjustment factors are prescribed. There are lower limits on allowed variations with most cases to insure a minimum level of safety. Other corrections for geometry consider spacing, placement of fasteners with respect to member edges. and the number of shear planes acting on the fastener.

COMPONENT MATERIAL PROPERTIES

Wood-connection strength depends on both the connector and the connected materials. For example. with axial loading of lag screws, the connection may fail due to inadequate fastener-tensile strength, shank-withdrawal strength, or head pull-through resistance of the material under the head of the screw. For lateral loading of connections with dowel-type fasteners, the EYM require dowel-bearing strengths F_e for each member and fastener yield F_y.

Dowel-Bearing Strength F_e

A new material property, dowel-bearing strength (F_e), is defined as the compressive strength of the wood (or other material) under a dowel-type fastener. For connections loaded at an angle to grain, the appropriate F_e value is found by applying the well-known Hankinson's formula. This is more convenient than, and gives essentially the same results as, applying Hankinson's formula when solving for connection yield strength (Wilkinson 1993).

The dowel-bearing strength of a material may be determined through a simple compression test of a dowel into a predrilled half-hole. For large dowels (e.g. bolts or lag screws) the hole is 1.6 mm ($^1/_{16}$ in.) oversize. For small dowel (e.g. nails or wood screws) the hole is undersized to mimic the action of driving. The development of these test procedures is outlined by Wilkinson (1991). An ASTM standard has been drafted, and the methods are currently in review. With these procedures, and confirming connection tests, a manufacturer of composite structural materials may qualify products for design use.

Trayer (1932), who developed the original empirical bolt-strength equations, found that for small ratios of bolt length-to-diameter, the proportional limit stress under the fastener was a fairly constant fraction of the wood compression strength parallel-to-grain. For perpendicular-to-grain loading, Trayer modified the clear wood proportional limit stress by a factor accounting for diameter effects. Since wood compression strength is related to density, the experimentally determined dowel-bearing strength is directly related to wood specific gravity. Wilkinson (1991) developed the relationships, shown in Table 1, that are used in the 1991 NDS and the LRFD specification for solid wood products.

Note that F_e is not dependent on dowel diameter for small dowel-type fasteners, but is for large dowels. This is consistent with current practice that does not recognize differences between parallel- and perpendicular-to-grain loading of nails. spikes, and wood screws, but does for bolts and so forth. Soltis et al. (1987) show that the transition from "small" to "large" dowel effects, with respect to F_e, is diameter and species dependent. This has been considered in setting appropriate F_e values.

TABLE 1. Dowel-Bearing Strength Specific Gravity Relationshipsl

Fastener (1)	Angle to grain (2)	Equation (3)
Nails, spikes, wood screws	All grain angles	$F_e = 16{,}600G^{1.84}$
Bolts, lag screws, large dowel	Parallel-to-grain	$F_e = 11{,}200G$
Bolts, lag screws, large dowel	Perpendicular-to-grain	$F_e = 6{,}100G^{1.45}D^{-.5}$

Note: G = specific gravity on ovendry weight and volume basis. D = nominal shank diameter in inches.

Fastener Yield Strength F_y

The yield strength of the fastener F_y (on a 5960 offset basis) can be found by bending tests. In the absence of extensive data, 310 MPa (45 ksi) is assumed as the bending F_y of common steel bolts. This has been an implied assumption with ASD for over 50 years, and is not contraindicated by recent research from Soltis et al. (1986), Thangjitham and McLain (1983), and Smith and Whale (1985). Loferski and McLain (1991) and Smith et al. (1986) provide information on the bending F_y of common wire nails. Their studies concluded that for common wire nails an average bending $F_y = 896 - 58(D)$, where D is diameter in mm and F_y in MPa. ($F_y = 130 - 214(D)$, where D is diameter in inches and F_y in ksi). For a nominal 16d nail with $D = 4.1$ mm (0.162 in.), then $F_y = 130–214(0.162) = 657$ MPa 95 ksi. Note that F_y is defined on a 5% diameter offset basis.

It is interesting to note that the use of EYM, and hence F_y, does focus equal attention on the properties of the fastener and those of the connected members. This requires that construction specifications for engineered wood connections be more carefully worded with regard to fasteners, and indicates that additional dialogue with the fastener-manufacturing industry is needed to improve information available to the designer. However, use of EYM opens new opportunities for designers to take advantage of fasteners with improved properties to optimize connection design.

Specific Gravity G

Specific gravity–species relationships are important because of the breadth of species that may be used for construction in the U.S. Through G, a nominal shank-withdrawal strength or dowel-bearing strength can be assigned to each species or species group. There are two methods for identifying an average G (based on oven-dry weight and volume). For those species that were tested in the National In-grade Test Program (Jones 1989), the average G resulting from tests of select structural and no. 2 lumber grades are adopted. For groups of species, G is based on ASTM D1990 (“Standard” 1991a) grouping criteria for median properties or the average G from the lowest-density species in the group. For untested species. the mean G from clear-wood data using methods of ASTM D2555 (“Standard” 1989b) and ASTM D2395 (“Standard” 1991b) are used. When combining several untested species into a group. G may be based on the ASTM D2555 grouping criteria for MOE or the average G of the lowest-density species in the group.

DATA-BASED DESIGN CRITERIA

Allowable-stress-design provisions for connections such as nails, screws, and lag screws in axial withdrawal, shear plates/split rings under lateral load as well as most adjustment factors for moisture, and geometry factors are derived directly from empirical data.

Adjustment Factors

Most factors to adjust connection strength for end-use conditions are based directly on research results. As a part of the LRFD development effort, we revisited the data supporting these criteria and generally found no compelling reason for change in practice. The principal exceptions were minor changes in geometry factors for penetration and some simplification of moisture and temperature-effect factors. Additionally, the group-action, or multiple-fastener, factor was modified to present a more faithful interpretation of the supporting research than has been traditional. This is discussed more fully by Zahn (1991). Absent any indication that design practice was non- or overly conservative, we chose to leave the adjustments at their historic levels. We note that some of these adjustment factors now apply to yield-based criteria whereas they were established for proportional limit or other criteria. Confirmation of many adjustment factors must be placed on a future research agenda.

Axial Strength

On review of the supporting data for axial shank-withdrawal strength of nails, screws, and lag screws, we discovered that additional research information could be added to upgrade the level of confidence in the regression-based empirical models. These changes will be documented in a separate paper. One example benefit of this reanalysis is seen in Fig. 4, which shows that the predicted axial-strength nails, screws, and lag screws are consistent with respect to each other. Previously, separate development of the behavioral equations for the three fastener types resulted in some inconsistencies when comparing the strength of fasteners with similar diameter.

Interaction Equations

Combined axial and lateral loading is common for many connection types. In NDS-86, interactive effects are formally recognized only for lag screws. In the LRFD specification, two changes were made. First, an interaction criteria was instituted for nails, spikes, and wood screws. This may be expressed as

$$\frac{Z_{n,\theta}\sin^n\theta}{Z_{n,\text{lateral}}}+\frac{Z_{n,\theta}\cos^n\theta}{Z_{n,\text{axial}}}\leq 1 \quad\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

where $Z_{n,\theta}$ = nominal strength of connection loaded at an angle θ to the fastener axis, where 0° is lateral loading and 90° is axial loading; $Z_{n,\text{lateral}}$, $Z_{n,\text{axial}}$ = nominal strength of connection in lateral and axial loading, respectively, adjusted for all end-use conditions; and $n = 1$ for nails, spikes, and wood screws. An exponent of unity ($n = 1$) was recommended by DeBonis and Bodig (1975), who studied interaction effects in nailed joints. It has also been confirmed by German research (Ehlbeck 1985) on smooth-shank nails. Limited unpublished data suggests that wood screws behave like nails and spikes with respect to axial and lateral interaction strength.

If $n = 2$ in (3), then this form can be rearranged to the well-known

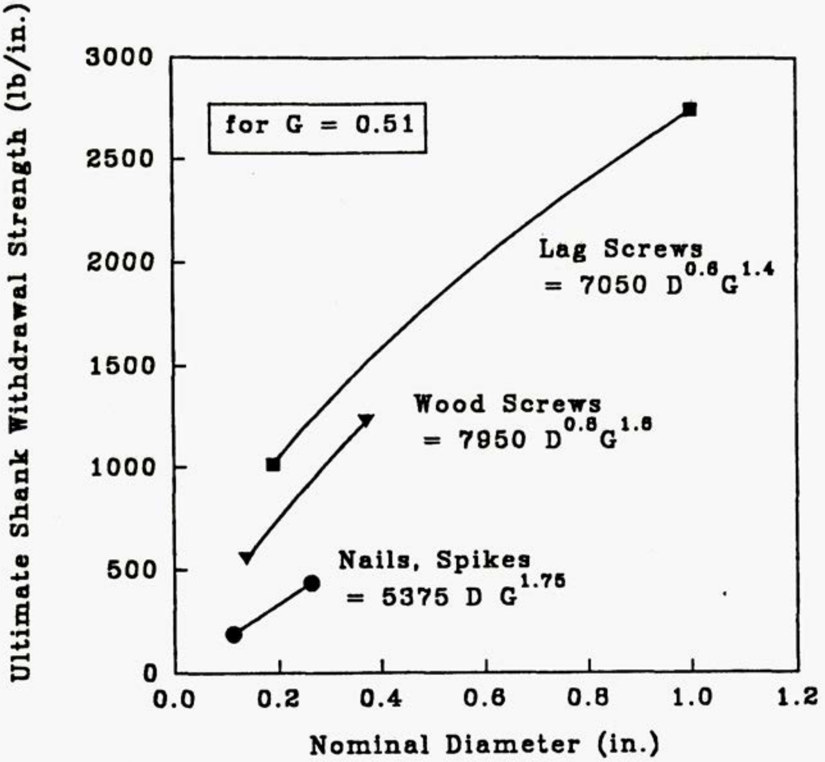

FIG. 4. Ultimate Axial Strength Predicted by New Behavioral Equations for G = 0.51

Hankinson's formula. McLain and Carroll (1990) show that this nonlinear form is more appropriate for lag-screw connections than the historic practice of using vectorial components of resultant force. This nonlinear form has been incorporated into both LRFD specification and 1991 NDS.

FORMAT CONVERSION

Design values are derived from estimates of short-term strength using the behavioral equations. Bodig et al., in press, 1993, describe the general methodology used in setting nominal resistance for wood structural elements such as beams and columns. For connections, the derivation of resistance differed from the general approach in several respects. First, no explicit reliability analysis was used to develop nominal resistance. That is, the reliability normalization factor K_r was set at unity for connections. This deviation was due, in part, to the lack of data over a broad spectrum of connection types and geometries with which to make any more than a cursory estimate of K_r. Of greater concern is the combined impact on design of changing both the behavioral equations for connection strength and the safety-checking format. As Gromala et al. (1990) point out, with format conversion alone there is only one design case where there will be exact panty between LRFD and ASD. At all other points in the design space, some change will occur. This is in addition to any changes that result from adopting new behavioral equations.

With the data available we found reasonable confidence in estimates of mean strength. However, we could not state with confidence an estimate of a lower fifth percentile strength or similar nominal low value, based on data. This is due, in part, to the limited-strength data available at reference conditions and to the observation that all adjustment factors, supported by data. are mean-based. An additional issue is that most connection-research data come from studies where variation was intentionally minimized to reduce the needed sample size. We suspect that most currently available data may not be representative of the strength of field connections, in terms of the observed variance. Consequently, distributional analysis and estimates of lower strength percentiles are suspect, except in some limited cases. Zahn (1992) examines the reliability of some bolted connections in terms of ultimate strength and one-load combination. With the adoption of EYM, future efforts may allow for additional meaningful reliability analysis.

For connections, the development of a reference nominal resistance takes the form of

$$Z = \frac{\sum \gamma_i Q_i}{\sum Q_i} \cdot \frac{\mathrm{DOL}}{\lambda \phi_c} \cdot \frac{c}{C_p} \cdot Z^* \quad \text{(4)}$$

where $\gamma_i Q_i$, Q_i = factored and unfactored load effects, respectively; DOL = ASD duration of load factor: c, C_p = cumulative product of ASD and LRFD adjustment factors, respectively; ϕ_z, = 0.65 for connections; and Z^* = nominal ASD or equivalent capacity of the connection. The resistance factor ϕ_z was set to be consistent with the resistance factors for member strength.

Defining Z^* in (4) as the ASD connection strength or its equivalent implies that the level of safety in ASD provisions is satisfactory for LRFD criteria. Development of Z was a two-step process. Step 1 was to calibrate the new behavioral equations to ASD safety levels and determine Z*. Step 2 was to apply format conversion through (4) to reach Z. Note that the first step was done in conjunction with a simultaneous change in ASD design criteria. As near as possible, common adjustment factors and behavioral equations were incorporated into both the 1991 NDS and LRFD specifications to minimize gross differences between future ASD and LRFD results.

Gromala et al. (1990) discuss the effects on design of factored loads and a shift in time effects. This is not repeated here, except to note that the same format-conversion point and time-effects factor developed for members are applied to connections. There is growing evidence that the material-based cumulative-damage concepts developed for lumber may not apply to connections. (Ellingwood and Rosowsky 1991; Leijten 1988). However, the evidence is not yet compelling enough to eliminate the conservative inclusion of A in the safety-checking equation for mechanical connections. Nevertheless, no increase in connection capacity for impact loads is allowed.

CALIBRATION TO ASD PRACTICE

The ASD connection strength, as found in NDS-91, is an estimate of a base capacity divided by a connection normalization factor K_c. The base strength varies by fastener type, but it is the proportional limit load, ultimate strength, or yield load as determined by test at reference conditions or from one of the behavioral models described earlier. The factor K_c is the aggregate of all factors required to adjust an average 5-min duration test load to an allowable load for 10-year duration. The variable K_c, shown in Table 2, includes adjustment for duration of load, safety, and some connection-specific effects. For those connection types shown in Table 2, the derivation of K_c factors is identified in the Wood Handbook (1987) or McLain (1983, 1992).

The 1991 NDS provides ASD values for laterally loaded connections with dowel-type fasteners that are based on European yield models. The predicted yield loads were adjusted using the normalization factor K_c, shown in Table 3. These factors were developed from an extensive evaluation of

TABLE 2. Connection Normalization Factor K_c Based on Ratio of Average 5 min Test Base Load to 10 Year Allowable Loads from 1986 NDS

Fastener type (1)	Loading (2)	Conditions (3)	Base load (4)	K_c (5)
Nails, spikes	Axial	Side grain	Ultimate	6.08
Wood screws	Axial	Side grain	Ultimate	4.62
Lag screws	Axial	Side grain	Ultimate	4.62
Shear plates/split rings	Lateral	Parallel-to-grain	Lesser of ultimate or prop. limit	3.33 1.33
Shear plates/split rings	Lateral	Perpendicular-to-grain	Prop. limit	1.33

TABLE 3. Connection Normalization Factor K_c Based on Ratio of Average Predicted Yield Load to Allowable Loads from 1986 NDS (Lateral Loads Only)

Fastener (1)	Yield mode (2)	Orientation to Grain: Parallel (3)	Orientation to Grain: Perpendicular (4)
(*a*) Bolts			
Double shear	I_m, I_s	4.0	5.0
Double shear	II	3.2	4.0
Double shear	III	3.2	4.0
Single shear	I_m, I_s	4.0	5.0
Single shear	II	3.6	4.5
Single shear	III_m, III_s	3.2	4.0
Single shear	IV	3.2	4.0
Single shear	I_s	4.0	5.0
Single shear	III	2.8	3.7
Single shear	IV	3.0	3.75
Single shear	All	2.2 for $D \leq 4.3$ mm (0.17 in.)	
Single shear	All	$10D + 0.5$ for 4.3 mm (0.17 in.) $< D < 6.4$ mm (0.25 in.)	
Single shear	All	3.0 for $D \geq 6.4$ mm (0.25 in.)	

the ratios of predicted 5-min yield loads to the 10-year duration strength provisions of NDS-86 (Wilkinson 1992). An example of this analysis is shown in Fig. 5. The nonlinearity of the ratio with respect to factors such as LID (ratio of bolt length in main member to bolt diameter) indicates that conversion to an EYM basis will result in some change in design practice. Because of the implied variation in the safety level over the range of bolted connection geometries, some change is desirable.

If K_c is selected as constant over the entire design space, then some very startling (and unacceptably large) changes would result. This is equivalent to using one ratio to represent all data shown in Fig. 5. We chose to directly influence relative change (and hence, safety) by defining a separate K_c for each yield mode. In that manner, we smooth out safety over the set of connection variables. For example, the loads corresponding to yield modes I_s and I_m, in most connection types, may be near ultimate strength, which can be brittle in nature. We chose a large reduction factor for connections that exhibit those modes in contrast to those that yield in the more ductile mode IV.

With this approach, for laterally loaded dowel type connections $Z^* = Z_y/K_c$, where Z_y is the predicted yield load. The resulting Z^* is equal to the ASD loads found in the 1991 NDS. This conversion may create discontinuities at transitions between modes. However, connection geometries and hence, capacities, generally come in incremental sizes (due to lumber thickness, fastener sizes, and so forth). These factors will minimize the impact of any discontinuities, but do not preclude them from appearing in design aids or tables. The variable K_c is a conversion ratio designed to minimize change in current practice. It does not directly address the basic question of what level of safety should be ascribed to design values based on a predicted connection yield strength. This approach does minimize the impact of conversion but does not solve all of the problems with inconsistent relative

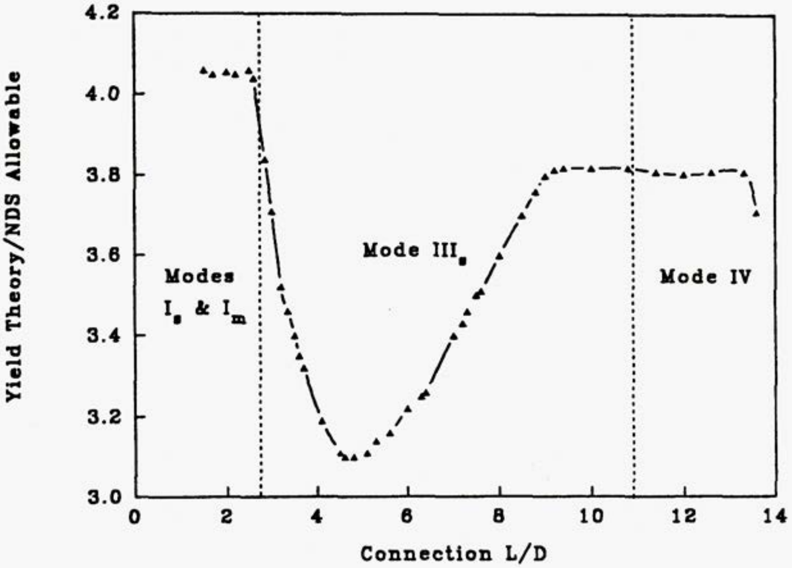

FIG. 5. Ratio of Predicted Yield Load Z, to NDS-86 Allowable Load for Double Shear Bolted Connections Loaded Parallel-to-Grain

safety levels that may exist in the current NDS. No reliability analyses were involved in selecting K_c.

In summary, with the chosen calibration point described by Gromala et al. (1990), (4) may be rewritten as

$$Z = 3.33Z^* = \frac{3.33(\text{Base short-term strength})}{K_c} \qquad (5)$$

The base strength, such as proportional limit. yield, or ultimate strength, varies with connection type and load direction.

IMPACT

Format Changes

Users of the older versions of the ***National Design Specification*** will note that the 1991 NDS is now in an equation format. While this improves clarity and ease of use. the document still blurs the distinction between specification and design aid. The proposed wood LRFD document is also in equation format but, like the *LRFD Specification for Structural Steel Buildings* (1986), design aids are separate from specification.

EYM Conversion

A natural consequence of changing behavioral equations is that the capacity of some connection geometries will change. With EYM this change is reduced by a variable K_c, but it is not eliminated. In general, the K_c for bolts and lag screws were set by calibrating to steel side-plate connections with a low-to-intermediate range of bolt length-to-diameter ratios *L/D*. Fig. 6 shows the result of this calibration on one type of bolted connection. As might be expected, the greatest change is with a wood-to-wood connection having high *L/D* ratios. The least change is typically at low *L/D* ratios and for steel-plate connections.

Values of K_c for nailed connections were set by calibrating to connections having 9.5-12.7 mm ($^3/_8$–$^1/_2$ in.) wood side members thickness or 2.67 mm

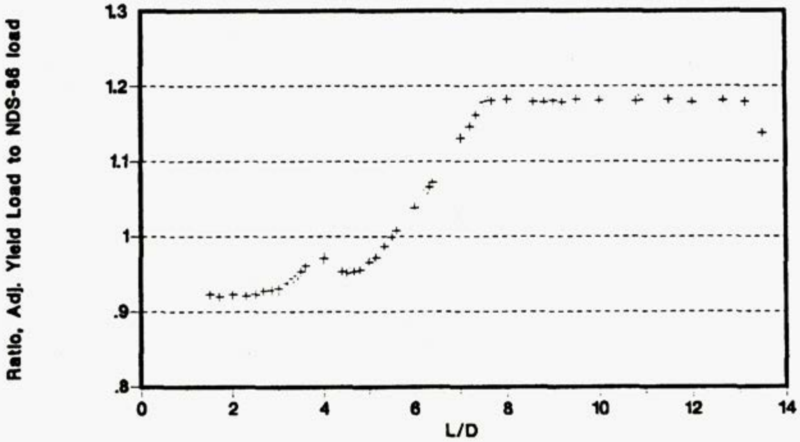

FIG. 6. Ratio of Z^* to NDS-86 Allowable Load for Single Shear Southern Pine Bolted Connections Loaded Parallel-to-Grain

(12 gage. 0.105 in.) to 1.5 mm (16 gage, 0.06 in.) steel side plates and fastened with 6–16d nails. As seen in Table 3, K_c vanes with diameter to moderate a general increase in capacity from historic loads and to develop consistency with K_c for larger dowel fasteners.

Species Effects

One other source of change is due to a conversion from discrete connection-strength groups to a more continuous relationship between strength and specific gravity. NDS-86 and prior versions provide design strength by species groups rather than by individual species. This grouping compensated for research that tested few species and the need to put bounds on empirically derived design values. Eliminating groups results in some change from historic practice. For bolted connections, the G-induced changes are negligible. For lag screws. wood screws, and nails, the principal change associated with G is not with the level chosen for a species. but with the elimination of species groupings in favor of a more continuous strength G relationship. A IO–20% difference may be seen when comparing nail or screw design values for species that were historically included in the same connection strength group.

Calibration Point

Any change in design capacity from historic practice due to format changes, yield-theory conversion, or species effects are the same in LRFD as in ASD. That is. the NDS-91 design provisions have changed capacities similar to those in the LRFD specification. Unique to the LRFD document, however, is any change in capacity due to the selection of the ASD-to-LRFD calibration point. The selection of the calibration point resulted in some connection-design changes for various loading conditions. The calibration point was chosen by considering the relative performance of a broad spectrum of wood structures. The rationale for this selection is discussed more fully by Gromala et al. (1990).

LRFD connection capacities for connections that support snow loads, roof live loads, or wind loads will be within ±8% of NDS-91 connection capacities. Connections that support occupancy live loads will have 10–15% increased capacity under LRFD provisions. Because of the ANSI/ASCE 7-88 (*Minimum* 1990) load provisions. connections that support storage live loads greater than 100 psf will have 32% increased capacity under LRFD than historically has been the case. Connections that resist seismic loads will have 11% decreased capacity under LRFD provisions.

SUMMARY

Load and resistance factor design criteria for connections in engineered wood construction have been proposed. Coincident with a format conversion. new behavioral equations for connection strength have been introduced into the specification. Similar equations have been incorporated into the allowable stress design provisions.

The new equations for laterally loaded connections using nails, wood screws, bolts, and lag screws are based on European yield theory, which explicitly considers fastener and component properties as well as geometry. Appropriate material properties have been defined, and for solid wood the values are identified. Test methods for use by manufacturers are established. Additionally. a thorough review of available strength data resulted in new equations for empirically based axial strength.

Safety levels were established by calibration to ASD criteria without use of reliability analysis. The format-conversion point for structural members was also used for connections with resistance factor $\phi = 0.65$. All connection LRFD strengths are for short-duration loads. Change in design strength of connections may be due to format conversion, new behavioral equations, or calibrations to historic practice. These effects have been minimized, but some are necessary to equalize safety levels over the design space.

APPENDIX I. REFERENCES

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