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Abstract

Recently published test data for bolted and nailed connections was evaluated to assess the structural reliability inherent in current allowable stress design procedures for connections in wood structures. Reliability indices were determined for timber connections using standard first-order, second moment (FOSM) procedures. For the connections considered in this study, reliability indices range from 2.6 to5.1, generally providing higher levels of safety than the structural members in timber structures.

Introduction

In development of load and resistance factor design (LRFD) procedures for wood structures, primary attention was given to assessing the safety/reliability inherent in design of timber members to resist typical combinations of live and dead loads (Gromala et al 1990; "Standard" 1996; "Standard" 1998a). This was possible due to an extensive database of primary strength properties (bending, tension, compression parallel to grain) for structural wood members. Sample sizes were sufficiently large to facilitate statistical distribution fitting techniques to describe test data for wood strength properties. However, LRFD connection design procedures were simply calibrated to existing allowable stress design (ASD) methods ("Standard" 1996; McLain et al. 1993; Zahn 1992), primarily due to the fact that sample sizes were insufficient to accurately fit probability distributions to connection strength data. Thus, even though structural load data could be described probabilistically, there was insufficient information to characterize connection strength data probabilistically and calculate structural reliability indices (β).

Background

Current and historical design methods for connections in wood structures are based on the static load capacity at either an offset (yield) limit state or proportional limit state (*Commentary* 1999; Zahn 1992). However, reliability assessment of connection capacity should be based on the ultimate limit state of the connection. The offset limit state equations specified in current wood design literature are effective at identifying characteristic yield modes for connections subjected to overload conditions (McLain et al. 1993). Due to plastic hinge formation in fasteners, connections which exhibit yield modes III (one hinge per shear plane) and IV (two hinges per shear plane) behave in a relatively ductile fashion, resulting in considerable connection displacement and energy dissipation prior to reaching ultimate failure. In contrast, connections which exhibit modes I and II (no plastic hinges in fastener; only member yielding) behave in a brittle manner, resulting in relatively low levels of connection ductility and energy dissipation prior to fracture of wood members in the connection.

Recent reliability analyses for laterally-loaded connections in timber structures have emphasized calibration to historic proportional limit states (McLain et al. 1993; Zahn 1992). Extension of these procedures to ultimate limit states has proven difficult since many historical connection tests were halted at predetermined levels of connection displacement, thus precluding accurate assessments of maximum load capacity, ductility and energy dissipation. Sample sizes for specific connection test configurations have historically ranged between five and fifteen since mean (average) trends in strength data were of primary interest. As a result, probability distributions could not be characterized for key connection performance parameters due to the small sample sizes of test data available. This situation recently prompted the U.S. wood engineering community to simply "soft convert" connection design provisions in the new "Standard for Load and Resistance Factor Design (LRFD) for Engineered Wood Construction" (1996), rather than conduct comprehensive connection reliability analyses ("Standard" 1998a).

Zahn (1992) employed first order, second moment (FOSM) techniques to provide preliminary assessments of bolted connection reliability for wood structures. In particular, when structural loads (S) and connection resistance capacities (P) are independent, normally distributed random variables related in a simple linear limit state function, the probability of failure (p_f) can be determined in the following manner using FOSM techniques:

$$p_f = \mathrm{P}\left[P - \sum S_i < 0\right] = \Phi(-\beta)$$

where $$\beta = \frac{\mu_P - \sum \mu_{Si}}{\sqrt{(\sigma_P)^2 + \sum (\sigma_{Si})^2}}$$

P[ ] = probability of occurrence of an event (described in brackets)

$\Phi(\ )$ = standard normal distribution function

$\sum S_i$ = sum of structural loads acting on the connection

μ_P = mean of normally distributed connection resistance capacities

σ_P = standard deviation of normally distributed connection resistance capacities

μ_{Si} = mean of i^{th} normally distributed structural load

σ_{Si} = standard deviation of i^{th} normally distributed structural load

Thus, a large reliability index (β) is associated with small probability of failure (p_f).

When basic random variables are not normally distributed (a common occurrence for structural materials and loads), the reliability index can be determined using the Rackwitz-Fiessler algorithm to transform non-normal random variables into normally distributed random variables which exhibit equivalent values for their probability density functions and cumulative distribution functions at a particular point in the design space (frequently referred to as the "design point" or the "failure point"). This iterative process for locating the design point and calculating an associated reliability index is described in detail by Ang and Tang (1984) and Thoft-Christensen and Baker (1982). The reliability index for independent, non-normal random variables is:

$$\beta = \frac{\mu_P^N - \sum \mu_{Si}^N}{\sqrt{(\sigma_P^N)^2 + \sum (\sigma_{Si}^N)^2}}$$

where μ_P^N = mean of equivalent normal distribution for connection resistance
σ_P^N = standard deviation of equivalent normal distribution for connection resistance
μ_{Si}^N = mean of equivalent normal distribution for i^{th} structural load
σ_{Si}^N = standard deviation of equivalent normal distribution for i^{th} structural load

Since connection data sets were limited in size, Zahn simply assumed that connection resistance capacities were normally distributed with coefficients of variation (CV) estimated by pooling historical connection test data from various researchers on a standardized basis. Reliability analyses were performed for bolted connections assuming a live-to-dead load ratio of 4:1, with dead loads following a normal distribution and live loads characterized by a Type I asymptotic (Gumbel) distribution. Since load duration adjustments had not been finalized for draft LRFD procedures, Zahn simply calculated reliability indices based on comparisons of short duration test data with longer duration live and dead load combinations. However, he suggested that reliability indices would be lower for comparisons of test data and structural loads on the same load duration basis. Zahn concluded that bolted timber connections designed according to draft LRFD procedures had reliability indices in the range of $3.3 \leq \beta \leq 4.4$ on an offset yield load basis, and reliability indices of $4.4 \leq \beta \leq 5.5$ on the basis of ultimate connection capacities. Reliability indices for connections designed according to current allowable stress design (ASD) procedures were slightly higher, with $3.8 \leq \beta \leq 4.7$ on an offset yield load basis and $4.8 \leq \beta \leq 5.7$ on an ultimate strength basis. Zahn also noted that final reliability indices could vary somewhat, pending the availability of sufficiently large data sets for characterizing underlying probability distributions for connection resistance.

Since the publication of Zahn's connection reliability estimates in 1992, various researchers have conducted a variety of bolted and nailed connection tests with sufficiently large sample sizes to permit statistical distribution fits to connection strength (capacity) data. All of the connection tests were conducted in accordance with ASTM Standards D1761 ("Standard" 1998c) and D5652 ("Standard" 1998b). These tests included bolted double shear connections in Southern pine and Ponderosa pine lumber (Pollock 1997; Galloway 2000), nailed single shear connections in Southern pine lumber (Theilen et al 1998), and nails loaded in withdrawal from Southern pine lumber (Skulteti et al 1997; Rammer et al 2001). Summary descriptions of the various connection tests are provided in Table 1 (for fasteners loaded in shear) and Table 2 (for nails loaded in withdrawal). In each of these studies, connection ultimate capacity data were used to fit probability distributions. The method of maximum likelihood estimation was employed to fit distribution parameters for normal, lognormal, two-parameter Weibull and three-parameter Weibull distributions, as described in Worley et al. (1990). Best fitting distributions were identified based on visual appraisal in conjunction with chi-square (χ^2) and Kolmogorov-Smirnov (K-S) goodness-of-fit tests. Fitted distribution parameters are provided in Tables 3 and 4 for fasteners loaded in shear and withdrawal, respectively.

Determination of Reliability Indices

Bolted and nailed connections in this study were assessed to determine reliability indices on the basis of ultimate capacities. To facilitate direct comparisons with previous research, the same load combination and load distributions evaluated by Zahn (1992) and described in ASCE Standard 7-95 (1995) were considered. Thus, the dead load plus live load (D + L) combination was assumed to represent the governing design limit state, with live loads characterized by a Type I asymptotic (Gumbel) distribution (CV = 0.25) and dead loads characterized by a normal distribution (CV = 0.1). Reliability indices (β) were calculated for both a 4:1 live-to-dead load ratio and a 3:1 live-to-dead load ratio. As described by Zahn (1992), mean values for the Gumbel-distributed live load and the Normal-distributed dead load were assumed to be fractional portions of the published allowable design values (*National* 1997) for each connection configuration. (e.g.- For the 4:1 live-to-dead load ratio, the mean value for the live load was assumed to be 80% of the allowable connection capacity, and the mean value for the dead load was assumed to be 20% of the allowable connection capacity.) A ratio of mean dead load to nominal dead load of 1.05 was also incorporated in the reliability calculations, in accordance with the provisions of ASCE 7-95 (1995). It should be noted that allowable design values for laterally loaded connections in this study were based on nominal values for fastener bending yield strength (F_{yb}) provided in the National Design Specification for Wood Construction (NDS 1997). Furthermore, since the bolted and nailed connection test data was based on short-term loads (ASTM-specified time to failure of approximately 5-10 minutes), the allowable connection capacities from the NDS were multiplied by a load duration factor of 1.6 to provide a consistent load duration basis for the reliability analysis.

Results and Discussion

Reliability indices were calculated on a spreadsheet using the Rackwitz-Fiessler FOSM algorithm, and are reported in Tables 3 and 4. The reliability indices (β) are generally lower than those reported by Zahn for ultimate connection capacities. These differences in magnitude are primarily due to the fact that Zahn's analyses did not incorporate a consistent load duration basis for comparing connection test data with structural design loads.

Reliability indices ranged from 4.1 to 4.8 for Mode III and Mode IV bolted connections in this study. However, it should be noted that the actual F_{yb} values for the bolts were 54%-93% higher than the nominal F_{yb} of 310 MPa for A307 bolts. If the allowable design values had been increased to reflect the higher F_{yb} of the fasteners, then lower reliability indices would have been observed for these bolted connections. Reliability indices for Mode IV laterally loaded nailed connections ranged from 2.6 to 2.9 for 12d common nails (nominal F_{yb} = 621 MPa) and 20d ring-shank nails (nominal F_{yb} = 793 MPa) with F_{yb} values near or below the nominal F_{yb} values (data sets NL1 and NL3). However, reliability indices were close to 5.0 for 16d ring-shank nails with F_{yb} approximately 64% higher than the nominal F_{yb} of 793 MPa (data set NL2).

Reliability indices for threaded nails loaded in withdrawal from Southern pine lumber ranged from 2.9 to 3.2 for 16d ring-shank nails, 20d helically-threaded nails, and 60d ring-shank nails (data sets NW1, NW2, NW5 and NW6). The 20d ring-shank nails provided substantially higher reliability indices in the range of 4.2 to 4.8 (data sets NW3 and NW4).

Reliability indices for L:D = 3 were slightly higher than for L:D = 4. This should be expected since a higher percentage of the total load exhibits lower variability for L:D = 3 (D is 25% of total load) versus for L:D = 4 (D is 20% of total load). Finally, it should be noted that reliability indices for the bolted and nailed connections in this study were higher than the target reliability index (β = 2.4) for design of structural wood bending members ("Standard" 1995; "Standard" 1998a).

Conclusions and Recommendations

- Reliability indices (β) are generally higher for bolted and nailed connections than for wood members.

- Reliability indices are particularly high (in the range of 4.1 to 5.1) for laterally loaded fasteners with F_{yb} values substantially higher than the nominal F_{yb} in the NDS (1997).

- Future connection reliability analyses should focus on a wider range of bolt sizes, Mode I and Mode II laterally loaded connections, typical panel to framing nailed connections for shearwalls and diaphragms (e.g.- 8d and 10d box nails and common nails), and lag screw and wood screw connections.

- Structural reliability analyses for typical bolted and nailed connections can be combined with reliability analyses for wood members to investigate the overall reliability of structural wood systems.

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Table 1: Description of Laterally Loaded Bolt and Nail Connections

Data Set	Data Source	Connection Description	Fastener Diameter (mm)	Wood Species Grouping	Side Member Thickness (mm)	Fastener Length in Main Member (mm)	Sample Size
BL1	Pollock 1997	A307 Bolt, Mode III, Double Shear	12.7	Southern Pine	34.9	69.9	42
BL2	Galloway 2000	A307 Bolt, Mode III, Double Shear	12.7	Southern Pine	38.1	114.3	39
BL3	Galloway 2000	A307 Bolt, Mode IV, Double Shear	19.1	Ponderosa Pine	114.3	114.3	40
NL1	Theilen et al 1998	12d common nail, Mode IV, Single Shear	3.76	Southern Pine	38.1	44.5	40
NL2	Theilen et al 1998	16d ring-shank nail, Mode IV, Single Shear	3.76	Southern Pine	38.1	50.8	40
NL3	Theilen et al 1998	20d ring-shank nail, Mode IV, Single Shear	4.50	Southern Pine	38.1	63.5	40

Table 2: Description of Nail Connections Loaded in Withdrawal

Data Set	Data Source	Fastener Description	Fastener Diameter (mm)	Wood Species Grouping	Sample Size
NW1	Skulteti et al 1997	16d ring-shank nail, ungalvanized	3.76	Southern Pine	120
NW2	Skulteti et al 1997	16d ring-shank nail, galvanized	3.76	Southern Pine	120
NW3	Skulteti et al 1997	20d ring-shank nail, ungalvanized	4.50	Southern Pine	120
NW4	Skulteti et al 1997	20d ring-shank nail, galvanized	4.50	Southern Pine	120
NW5	Rammer et al 2001	20d helically-threaded nail, ungalvanized	4.50	Southern Pine	50
NW6	Skulteti et al 1997	60d ring-shank nail, ungalvanized	5.26	Southern Pine	60

Table 3: Distribution Parameters and Reliability Indices for Laterally Loaded Connections

Data Set	NDS Allowable Capacity (kN)	Actual F_{yb} (MPa)	Distribution Type	Shape Parameter	Scale Parameter	Reliability Index (β) for L:D=4	Reliability Index (β) for L:D=3
BL1	5.65	564	Lognormal (2 parameter)	0.140	3.47	4.7	4.8
BL2	5.87	476	Lognormal (2 parameter)	0.145	3.36	4.1	4.2
BL3	13.26	600	Lognormal (2 parameter)	0.124	4.17	4.2	4.4
NL1	0.565	639	Lognormal (2 parameter)	0.133	7.45	2.6	2.7
NL2	0.645	1300	Lognormal (2 parameter)	0.131	8.27	4.9	5.1
NL3	0.894	638	Normal	3.91 kN*	0.826 kN	2.8	2.9

* The mean value of the normally distributed data (3.91 kN) is actually a location parameter (rather than a shape parameter) for the Normal distribution.

Table 4: Distribution Parameters and Reliability Indices for Nails Loaded in Withdrawal

Data Set	NDS Allowable Capacity (N/mm)	Distribution Type	Shape Parameter	Scale Parameter	Reliability Index (β) for L:D=4	Reliability Index (β) for L:D=3
NW1	8.8	Weibull (2 parameter)	4.01	70.95	2.9	2.9
NW2	8.8	Weibull (2 parameter)	4.80	65.61	3.2	3.2
NW3	10.3	Lognormal (2 parameter)	0.226	4.30	4.7	4.8
NW4	10.3	Lognormal (2 parameter)	0.249	4.21	4.2	4.3
NW5	10.3	Weibull (2 parameter)	5.35	68.1	3.2	3.2
NW6	12.3	Weibull (2 parameter)	5.04	90.56	3.2	3.2