RELIABILITY OF WOOD SYSTEMS SUBJECTED TO STOCHASTIC LIVE LOADS

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ABSTRACT

Multiple-member wood structural systems are designed using the current National Design Specification with an increase in allowable bending stress of 15% to account for load sharing and partially composite action. Efforts are underway to develop Load and Resistance Factor Design (LRFD) procedures for engineered wood construction to enable design of wood structures to be performed in a similar fashion as design of steel or reinforced concrete structures. The proposed LRFD methodology includes a system factor derived by probabilistic analysis to account explicitly for load sharing among members in a wood structural system. Available statistical data on mechanical properties of individual pieces of lumber along with structural system and stochastic damage accumulation models can be utilized to evaluate system reliability and to develop LRFD design criteria that are consistent with a desired reliability.

Keywords: Buildings (codes), design (buildings), duration of load, limit states, load; probability theory, reliability, structural engineering, wood.

INTRODUCTION

The behavior of light-frame wood construction utilizing dimension lumber is affected by load sharing among members and partially composite action of framing and sheathing. The National Design Specification (NDS) permits a 15% increase in allowable stress for design calculations (NFPA 1986) involving bending members used repetitively in light-frame systems such as floors or roofs. This "repetitive use factor" accounts for load sharing and composite action within the system in a simple way. The 15% factor is subjective, but has been used in design for many years and results in safe structural performance in most instances.

Efforts now are underway to develop limit states design procedures for engineered wood construction (Murphy 1988). Denoted Load and Resistance Factor Design (LRFD) in the United States, these procedures eventually will supplant the Working Stress Design (WSD) procedures found in the NDS and other current design documents for wood products. Load and Resistance Factor Design has been made possible by recent advances in structural reliability analysis methods. The safety checks used in LRFD are based on the notion of a limit state probability or reliability index as a consistent measure of structural performance (Galambos et al. 1982). System reliability analysis can be used to obtain comparative measures of reliability and performance for systems and members, and to develop system factors for LRFD that serve a similar purpose as the 15% repetitive use factor in the NDS.

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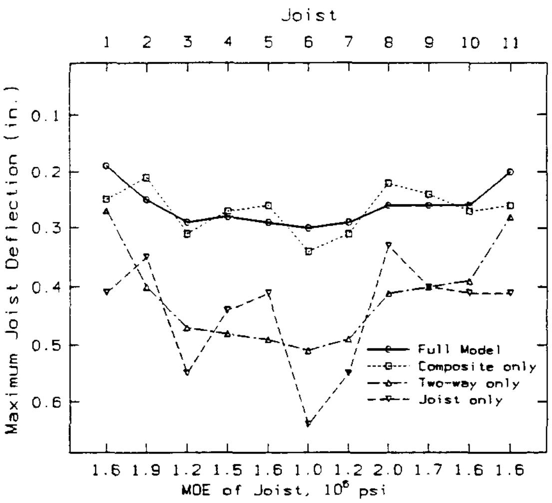

FIG. 1. Patterns of joist midspan deflections of a floor with variable joist stiffnesses, uniform load (from Criswell 1981).

LIMIT STATES FOR LIGHT FRAME WOOD SYSTEMS

Light frame wood systems, such as floor and roof systems, consist of a series of supporting joists or truss members interconnected by sheathing. The ultimate limit state (e.g., loss of load-carrying capacity) of a floor or roof system may not correspond to the failure of the first member in that system. Rather, the system limit state depends on the degree to which load redistribution following member failure is possible. Load sharing in a wood system is dependent on two-way action arising from the sheathing layer in the direction perpendicular to the joists. This structural action reduces the differences in joist deflections that otherwise might arise from unequal loading of the joists or from unequal joist stiffnesses (Criswell 1979, 1981; Vanderbilt et al. 1974). This smoothing effect increases as the sheathing layer becomes stiffer. Figure 1 illustrates this smoothing effect for a floor system fabricated with 2 × 8 joists spaced 16-in. (406 mm) o.c. and with ¾-in. (19 mm) plywood sheathing, subjected to a 50-psf (2.4 kPa) uniform load. The effect of composite T-beam action and two-way action is to produce approximately equal midspan deflections of the non-edge joists (Criswell 1981).

The focus of this study is on the load sharing aspects of system reliability. The system model used in the reliability analysis must be kept as simple as possible because of the computation involved in the time-dependent reliability analysis, described subsequently. In the simplified floor system models illustrated in Fig. 2, the sheathing layer serves simply to distribute the uniform load to the members, and the effects of partial composite action of joists, sheathing, and fasteners are not included. The members in the "flexible" deck model are assumed to take equal load initially. Failure of each member is characterized by its modulus of rupture. Subsequent to a member failure, its share of load is distributed to nearby members in accordance with one of the two load-shedding schemes shown in Fig. 2: (1) load shed only to adjacent members, and (2) load shed to all members, in inverse proportion to their distance from the failed member. Scheme 1 is an extreme case that may apply for large beam spacings. Scheme 2 is supported by recent studies (Cramer and Wolfe 1989) that suggest load shedding to be an approximately linear function of distance from the failed members. For purposes of comparison, reliability analyses also were performed using a "rigid" deck model, in which all joist members under load have the same curvature and midspan deflection, and there is no rigid body rotation of the floor section or twisting of the individual joists. Initially, the load is distributed to the joists in proportion to their individual bending stiffnesses. Following the failure of a member, its share of load is distributed to *all* of the remaining members in the system in proportion to their stiffnesses.

Studies of wood stud-wall behavior (Polensek 1976) and wood floor simulations (Criswell 1979; Vanderbilt et al. 1974) suggest that system capacity is usually reached or is imminent when failure of two adjacent members occurs. However, most previous reliability studies have equated system failure to first-member failure (Bulleit 1985; Folz and Foschi 1989;

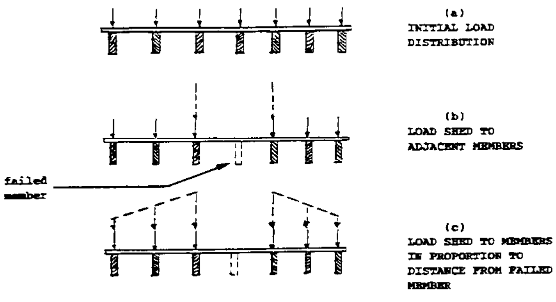

FIG. 2. Load redistribution schemes for system with flexible deck.

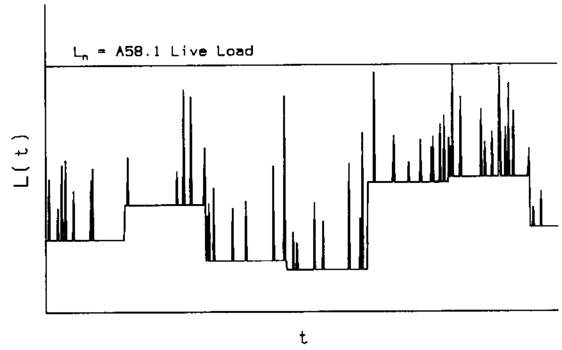

FIG. 3. Live load model.

Foschi 1982, 1984). Only in a few cases has the system limit state been defined in terms of multiple member failures (Bulleit 1986, 1987; Criswell 1979). In the present study, the limit state is defined as occurring when any two members fail in systems of fewer than eight members, and when two adjacent members fail in systems of eight or more members. This definition is consistent with previous experimental observations.

LIMIT STATE PROBABILITIES OF WOOD SYSTEMS

The effect of interaction of the load duration and load sharing on system limit state probabilities is evaluated by subjecting the simple models of light-frame floor systems to a combined dead plus live load stochastic process (Ellingwood and Rosowsky 1991). Live load is modeled as having a sustained component and a transient component, the latter of which is due to infrequent crowding, remodeling, and similar events that occur infrequently and have a relatively short duration. A sample function of the live load process is illustrated in Fig. 3, and typical statistics for the sustained and transient components are presented in Table 1 (Galambos et al. 1982); D_n and L_n are the nominal dead and live loads in ASCE Standard 7-88 (ASCE 1990). Note that the sustained live load averages only about 30% of the nominal live load. Thus, the full load process is required for reliability analysis because failure in wood systems may occur by accumulation of damage or creep-rupture (Barrett and Foschi 1978), primarily during the short-duration transient events, as well as by overload. An exponential damage rate model (Caulfield 1985; Gerhards and Link 1986) is used to model the damage accumulation process in an individual member of the system. This model is expressed in terms of a nondimensionalized state variable, $\alpha(t)$;

$$\frac{d\alpha}{dt} = \exp[-A + B\cdot\sigma(t)] \qquad (1)$$

in which $d\alpha$ is the increment of damage that accumulates during time increment dt, A and B are constants determined experimentally, and $\sigma(t)$ is the (stochastic) stress ratio at time t, defined as the load-induced stress divided by the stress that causes failure in a conventional short-term strength test (typically 5–10 min). For select structural Douglas-fir lumber, A = 39.99 (ln day) and B = 49.75 (Gerhards and Link 1986). Short-term strength data are described in the following section. With the stress ratio determined from the stochastic loads, Eq. (1) can be integrated to measure the accumulation of damage through the lifetime of the structure. At $t = 0$ in the undamaged state, the state variable $\alpha = 0$; the member is said to have failed when $\alpha = 1$. Thus, $\alpha(t)$ is a monotonically increasing stochastic process.

The limit state probability of a member for progressive accumulation of damage can be expressed as,

$$P_f = P[\alpha(t) > 1]; \qquad 0 \le t \le T \qquad (2)$$

TABLE 1. *Load process parameters.*

Load	Occurrence		Intensity		
	Mean rate/yr	Duration	Mean	c.o.v.	CDF
Dead	n/a	50 years	1.05 D_n	0.10	Normal
Light occupancy					
Sust. live	0.125	8 yr	0.3 L_n	0.60	Gamma
Trans. live	1 typ	1 wk	0.2 L_n	1.00	Gamma

where T is the reference period, typically taken to be 50 years in probability-based code studies in the United States (Galambos et al. 1982). Analysis of system reliability requires that damage accumulation in each member in the system be monitored using Eqs. (1) and (2). For comparison, an "overload" limit state probability is defined as the probability that the stress ratio exceeds unity at any time during 50 years; this probability depends on the intensity of the load but not on its duration. Equation (2) cannot be evaluated in closed form because of the difficulties in modeling stochastic damage accumulation over time and in the context of the multiple-member limit state. However, Monte-Carlo simulation methods can be used to include realistic load distributions and load histories, accurate statistical models for the member properties, and time-dependent damage accumulation models in the system reliability analysis. Simulation also is useful for investigating the time-dependent development of failures in multiple member systems. For limit state probabilities on the order of 10^{-3}, approximately 10^4 samples are required (Thoft-Christensen and Baker 1982).

A reliability index corresponding to the limit state probability for either overload or progressive accumulation of damage may be computed as (Thoft-Christensen and Baker 1982),

$$\beta = \Phi^{-1}(1 - P_f) \tag{3}$$

in which $\Phi^{-1}(\cdot)$ = inverse cumulative distribution function of the standard normal variate. These values of β are useful as a relative measure of reliability and for comparison with reliability studies involving steel and other construction materials (Galambos et al. 1982).

MEMBER STRENGTH AND STIFFNESS

Variability in strength and stiffness and correlation between mechanical properties may be attributed to wood species, grading, size, mill, and environmental conditions during storage and on-site. Statistics on the modulus of rupture (MOR) and the modulus of elasticity (MOE) for wood are available in the literature (Bodig and Jayne 1982; Ellingwood 1981; Forest Products Laboratory 1987; Gerhards 1979; Green and Evans 1987; Littleford 1978).

Correlation among member strengths and/or stiffnesses within a system may arise in a number of ways (Cramer and Wolfe 1989; Littleford 1978; Zahn 1970). For example, if a system is constructed from No. 2 or better hem-fir that is taken from the same source, originated at the same mill, and was graded by the same technique and personnel, the strengths of the pieces of lumber are likely to be correlated. Correlation may also arise from lumber being graded by the same personnel/apparatus, stored and transported in the same manner, and affected by the same environmental conditions.

Correlation between strength and stiffness may be a significant factor in determining the reliability of a system. Stiffer members carry a greater share of the load in statically indeterminate structures. Since stiffer wood members tend to be stronger, as evidenced by the positive correlation in MOR and MOE, the stronger members carry a larger share of the load. Bodig has suggested that the correlation coefficient between MOR and MOE ($\rho_{R\text{-}E}$) ranges from 0.65 to 0.91 (Bodig and Jayne 1982). Similar estimates have been obtained by other authors (Curry and Fewell 1977; El-

TABLE 2. *Summary of within-mill mean-to-nominal resistance values from IGTP.*

Data set	Mill	Species	Grade	Size (in.)	Sample size	m_{F_r} (psi)	V_{F_r}	F_b (psi)	m_{F_r}/F_b
WWPA	"A"	DF-L	No. 2	2 × 4	20	9,112	0.32	1,450	6.28
	"A"	DF-L	No. 2	2 × 8	20	4,566	0.41	1,250	3.65
	"A"	DF-L	No. 2	2 × 10	20	4,567	0.43	1,250	3.65
	"B"	H-F	No. 2	2 × 4	20	6,233	0.29	1,150	5.42
	"B"	H-F	No. 2	2 × 8	20	5,625	0.26	1,000	5.62
	"B"	H-F	No. 2	2 × 10	20	3,662	0.31	1,000	3.66
SPIB	"C"	SP	2-KD	2 × 10	20	5,709	0.20	1,300	4.39
	"D"	SP	2-KD	2 × 10	20	5,775	0.24	1,300	4.44
	"E"	SP	2-KD	2 × 10	20	6,033	0.26	1,300	4.64

lingwood 1981; Zahn 1970), citing values of ($\rho_{R\text{-}E}$) of 0.6 to 0.8. Most recently, the value of ($\rho_{R\text{-}E}$) = 0.7 has been used in system reliability studies (Folz and Foschi 1989).

Test data from the In-Grade Test Program (IGTP) were analyzed to select statistics of member properties for use in systems reliability analyses. The IGTP was carried out in the early 1980s as a joint effort by industry, government, and universities. The objective of the program was to determine the mechanical properties of visually graded dimension lumber nominally two inches in thickness. Members from over 30 species were tested in full scale, all with a range of sizes and grades. The results of the testing program (Green and Evans 1987) include information on MOR, MOE and ultimate tensile and compressive strengths. The data are presented by species, grade, and size, but no identification of mill origin is made. No effort was made in the course of the IGTP to collect large data sets from any *individual* mill, or to distinguish any within-mill properties from those associated with the collective samples.

In order to assess within-mill effects, test data used in the IGTP from individual mills were studied. Data sets for representative lumber types were obtained courtesy of the Western Wood Products Association (WWPA) and Southern Pine Inspection Bureau (SPIB). Individual mills were not identified. The test data analyzed are summarized in Table 2. A description of the data sets is presented below.

Data set 1 (WWPA)

This set contained test data on three sizes of No. 2 Douglas fir-larch (DF-L) and three sizes of No. 2 hem-fir (H-F). All of the DF-L specimens came from one mill, and the H-F specimens came from another mill. The nominal sizes are 2 × 4, 2 × 8, and 2 × 10 inches. Each set contained 20 pieces. Bending specimens were tested with third-point loading on edge, with a span-to-depth ratio of 17:1. The test data were adjusted to 73 F and 15% moisture content (FPRS 1989; ASTM 1989).

Data set 2 (SPIB)

This set contained data for 2 × 10 No. 2 kiln-dried southern pine (SP) from three different mills (20 pieces each). The members were tested with third-point loading on edge, with a span-to-depth radio of 15.6:1. The data were adjusted to the uniform temperature and moisture content conditions described above.

Table 2 presents the mean and coefficient of variation in the MOR, m_{F_r} and V_{F_r}, from the data sets. The nominal allowable stresses, F_b, are taken from the NDS (NFPA 1986). Figures 4 and 5 present the sample coefficients of variation in the MOR and in the MOE, and the strength-stiffness correlation for the six data sets from WWPA and the three data sets from SPIB. The dashed lines represent the previously published values for the c.o.v.'s for these quantities (Bodig and Jayne 1982; Doyle and Markwardt 1966; Ellingwood 1981; Green and Evans 1987; Littleford 1978). The nine data

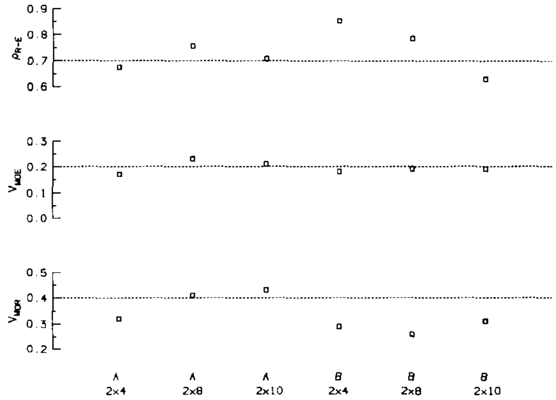

FIG. 4. Within-mill variability study, IGTP WWPA: Mill A—DFL, Mill B—HF.

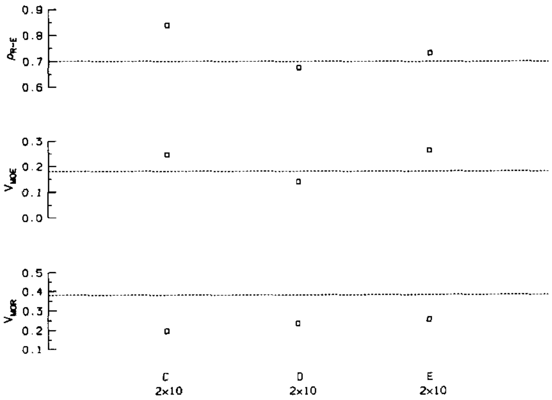

FIG. 5. Within-mill variability study, IGTP SPIB: Mills C, D, E—Southern Pine.

sets analyzed herein do not provide any evidence that there is a reduction in variability when only within-mill data are considered.

Statistics for MOR and MOE based on the collective mill data for the three lumber types considered in this study are presented in Table 3; m_E and V_e are the mean and coefficient of variation in the MOE, while the nominal MOE, E_n, is taken from the NDS. The MOR is modeled by a two-parameter Weibull distribution, and the MOE is modeled by a Lognormal distribution (Ellingwood 1981; Folz and Foschi 1989; Littleford 1978). A MOR-MOE correlation coefficient ($\rho_{R\text{-}E}$) = 0.7 was used in subsequent system reliability analyses.

RELIABILITY ANALYSIS OF FLOOR SYSTEMS DESIGNED BY WSD

Reliability analyses of systems designed using existing WSD criteria allow benchmark reliabilities to be established, and they permit a comparison of reliability-based system factors with the 15% repetitive use factor in the NDS. The WSD design equation for flexural members subjected to a combined dead plus live load has the form (NFPA 1986),

$$F_b S_x \geq D_n + L_n \tag{4}$$

in which F_b = allowable stress in bending, based on an assumed 10-year duration for full design live load, S_x = section modulus in bending, and D_n and L_n are the nominal load effects from ASCE Standard 7-88 (ASCE 1990). The individual joists in the system are designed to satisfy the safety check given by Eq. (4), with a 15% increase in F_b as permitted by the NDS for repetitively used members (NFPA 1986).

Figure 6 shows reliability indices, β, including duration-of-load effects, for systems ranging from 4 to 20 members using the three lumber types considered and the rigid deck model. System limit states defined by failure of "any two members" and "two-adjacent members" and the "combined" limit state all are considered. Figure 6 also shows the single-member reliability index for comparison with the system reliabilities; note the single-member reliability is obtained using Eq. 4 as the basis for

TABLE 3. *Flexural strength and stiffness statistics.*

Lumber	Sample size	m_F/F_b	V_F	m_E/E_n	V_E
Douglas fir-larch (DF-L), 2 × 10, No. 2	388	3.14	045	1.0	0.21
Southern pine (SP), 2 × 10, No. 2-KD	412	4.41	0.38	1.0	0.21
Hem-fir (H-F), 2 × 8, No. 2	372	5.72	0.39	1.0	0.20

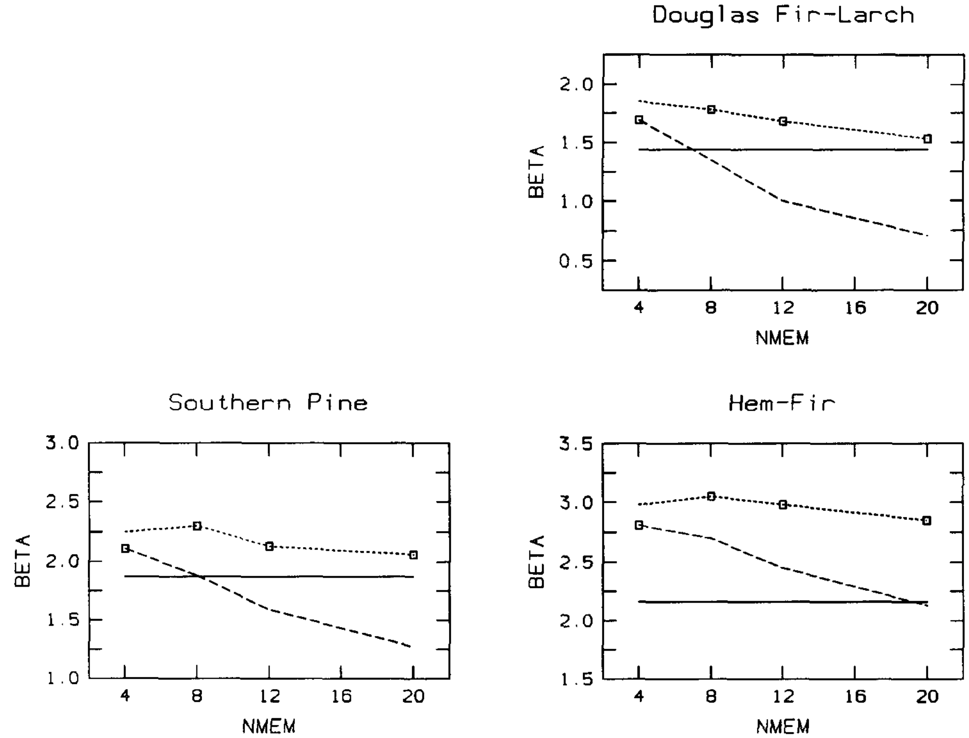

FIG. 6. Comparison of limit state definitions ····· 2 Adjacent – – – Any 2 □ Composite —— Single-member.

design without the 15% increase in F_b. The "two-adjacent" and "combined" system reliabilities appear to be relatively stable for systems of different sizes and are higher than those for the single members, a reflection of the effect of load sharing in a statically indeterminate system. In contrast, the use of "single member" or (for larger systems) "any two members" limit states as a basis for system reliability assessment would lead to a conservative appraisal of system reliability.

Table 4 compares reliabilities for 10-member systems modeled using both the rigid deck and the flexible deck (Fig. 2c) models. β_{dol} and β_{ovld} are the duration-of-load and overload reliabilities, respectively. These results illustrate the increase in reliability as the mean-to-allowable bending strength (m_{F_r}/F_b) increases. The β_{dol} values for the rigid deck and flexible deck systems are in general agreement. However, the β_{ovld} values are lower for the flexible deck, as a consequence of the load-redistribution schemes. That is, the redistribution of load to members as a function of distance of the member from the failed member (Fig. 2c) rather than in proportion to the member stiff-

TABLE 4. *Comparison of reliabilities for 10-member systems.*

Lumber	m_{F_r}/F_b	Rigid deck β_{dol}	Rigid deck β_{ovld}	Flexible deck β_{dol}	Flexible deck β_{ovld}
DF-L, 2 × 10, No. 2	3.14	1.55	2.22	1.54	1.85
SP, 2 × 10, 2-KD	4.41	2.23	2.97	2.21	2.50
H-F, 2 × 10, No. 2	5.72	2.80	3.29	2.72	3.06

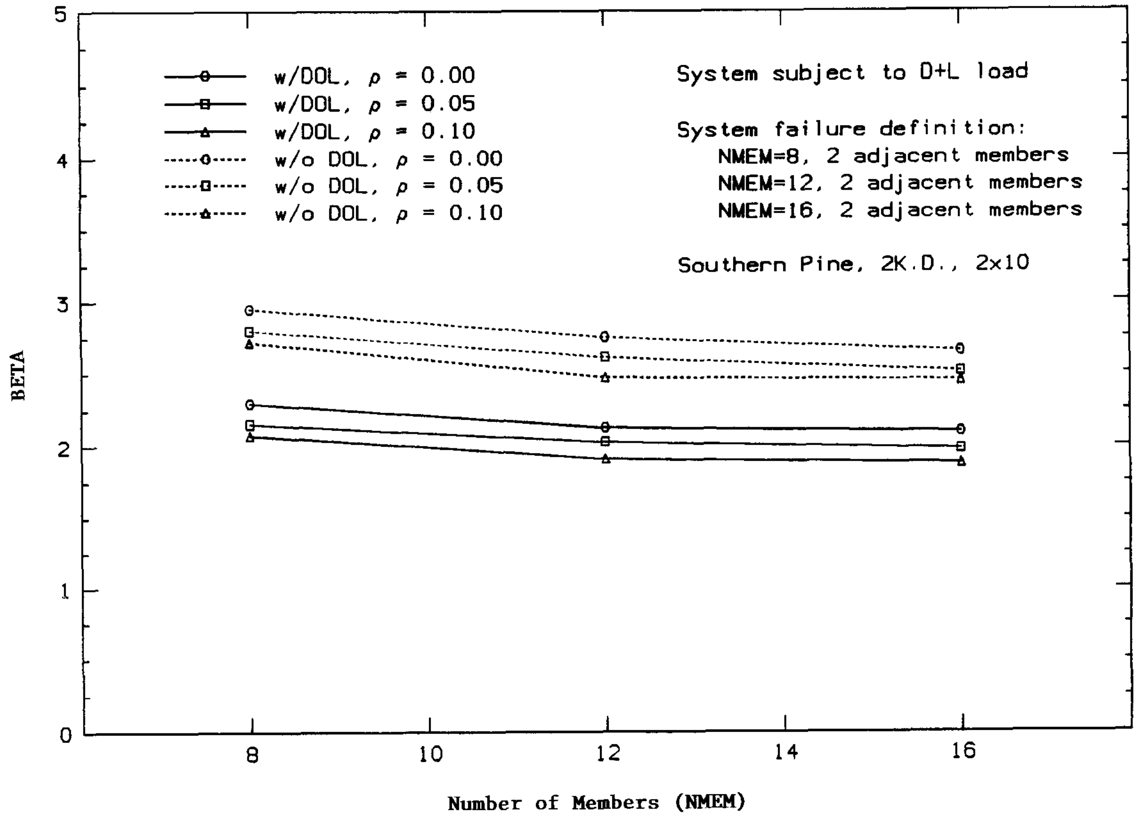

FIG. 7. Effect of increasing ($\rho_{R\text{-}R}$) on system reliability.

nesses (rigid deck assumption) results in a higher probability of system failure due to overload.

The effect of low values of strength-strength correlation on DOL reliability levels for rigid deck systems constructed of No. 2 (KD) 2 × 10 southern pine is illustrated in Fig. 7. Little effect on the system reliability index is evident. This finding, coupled with the inability to evaluate the correlation in strength of individual members explicitly based on the available mill data, suggests that this form of member property correlation might be neglected.

The β_{dol} values shown for SP and H-F in Table 4 and Figs. 6 and 7 are comparable to the reliability indices in the range of 2.3 to 2.7 that were obtained in recent work to develop LRFD for cold-formed steel construction (Hsiao et al. 1990).

SYSTEM FACTOR

For incorporation in existing WSD or proposed LRFD code formats, the system factor accounting for the effect of load sharing represents an equivalent increase in allowable stress, F_b (WSD), or nominal strength F_n (LRFD). The system factor is intended to make the system reliability equivalent to that of a single member where essentially no load sharing is possible in situations where the consequences of member and system failure are comparable. Denoting the system factor by ψ, the safety checking equations for flexure become,

$$\psi F_b S_x \geq D_n + L_n \tag{5}$$

for WSD and

$$\phi\lambda\psi F_n S_x \geq 1.2D_n + 1.6L_n \tag{6}$$

TABLE 5. *WSD system factors using rigid deck model.*

Limit state	Lumber	m_{F_r}/F_b	V_{F_r}	ψ_{dol}	ψ_{ovld}
Two adjacent	DF-L, 2 × 10, No. 2	3.14	0.45	1.11	1.37
Two adjacent	SP, 2 × 10, 2-KD	4.41	0.38	1.33	1.67
Two adjacent	H-F, 2 × 8, No. 2	5.72	0.39	1.53	1.88

for LRFD. It should be emphasized that the ψ-factors in Eqs. (5) and (6) may not be the same. The right-hand side of Eqs. (5) and (6) represents the structural action (forces and moments) due to the nominal loads, D_n and L_n. Factor ϕ is the resistance factor reflecting variability in short-term strength; λ is the duration-of-load factor reflecting effects of temporal characteristics of different structural loads on damage accumulation (Murphy 1988); and F_n is the nominal strength, typically taken as the 5% exclusion limit of the short-term strength adjusted for end use conditions. A sequence of reliability analyses of systems designed by Eqs. (5) and (6) was performed in order to determine that value of ψ such that the system has exactly the same reliability as that of a single member where no load sharing is possible.

WSD SYSTEM FACTORS

Table 5 presents system factors for WSD obtained from the reliability analysis of 10-member systems with the rigid deck model. These systems were subjected to the combined dead plus live load process discussed earlier. The system factors obtained from an analysis of failure due to overload are consistently higher than the system factors that take damage accumulation into account, indicating a coupling between the load sharing and duration-of-load effects. Table 6 compares system factors for WSD of a 10-member system of southern pine for the load-distributing/load-shedding (LD/LS) schemes described in Fig. 2. The values for ψ_{dol} for the rigid deck and the flexible deck shown in Fig. 2(c) are within about 6% of each other, and thus the sheathing stiffness does not have a significant impact on ψ_{dol}. In Table 7, WSD system factors for rigid deck model systems of No. 2 × 10 southern pine are presented as a function of the size of the system. The system factor is relatively stable across the various system sizes. The slight irregularity is due, in part, to sampling error and in part to the limit state definition (Fig. 6).

TABLE 6. *Comparison of system factors for rigid and flexible deck models.*

Lumber	m_{F_r}/F_b	V_{F_r}	Deck	ψ_{dol}	ψ_{ovld}
SP, 2 × 10, 2-KD	4.41	0.38	Rigid	1.33	1.67
			Fig 3(b)	1.00	1.40
			Fig 3(c)	1.25	1.42

The results for ψ presented in Tables 5–7 suggest that the current WSD adjustment for repetitive use (1.15) is conservative, and that a value of ψ approximately equal to 1.25 might be more appropriate in WSD.

LRFD SYSTEM FACTORS

The LRFD safety check given by Eq. 6, applied to members in flexure, uses a resistance factor $\phi = 0.85$ and a duration-of-load factor $\lambda = 0.8$ for the combination of dead plus live load (Ellingwood and Rosowsky 1991). The mean-to-allowable resistance values presented in Table 3 for WSD are converted to mean-to-nominal values for LRFD by

$$\frac{m_{F_r}}{F_{.05}} = \left(\frac{m_{F_r}}{F_b}\right) \Big/ C_f \tag{7}$$

TABLE 7. *Effect of system size on ψ_{dol}.*

Lumber	n	ψ_{dol}
SP, 2 × 10, 2-KD	4	1.30
SP, 2 × 10, 2-KD	6	1.21
SP, 2 × 10, 2-KD	8	1.37
SP, 2 × 10, 2-KD	10	1.33
SP, 2 × 10, 2-KD	16	1.28
SP, 2 × 10, 2-KD	20	1.25

TABLE 8. *Estimation of conversion factor, C_f, from IGTP results (F_b and $F_{0.05}$ in units of psi).*

Lumber	Sample size (IGTP)	$R_n = F_b$ (NDS)	$R_n = F_{0.05}$ (IGTP)	$F_{0.05}/F_b$ (C_f)	$m_{F_r}/F_{0.05}$
H-F, 2 × 8, No. 2	372	1,000	2,389	2.39	2.40
H-F, 2 × 10, No. 2	366	1,000	2,114	2.11	1.82
DF-L, 2 × 10, No. 2	388	1,250	2,215	1.77	1.77
DF-L, 2 × 10, Select	414	1,800	3,908	2.17	1.69
SP, 2 × 8, 2-KD	1,367	1,300	2,626	2.02	2.29
SP, 2 × 8, 1-KD	688	1,600	3,245	2.03	2.72
SP, 2 × 10, 2-KD	412	1,300	2,826	2.17	2.03

where C_f is the factor by which the purported 5% exclusion limit for short-term strength in the end-condition, $F_{.05}$, is divided to obtain the allowable stress in flexure, F_b (NFPA 1986). C_f is estimated using the nonparametric estimates of $F_{.05}$ from the published IGTP results (Green and Evans 1987) and the NDS (NFPA 1986), which are summarized in Table 8 for a number of lumber species and grades, all adjusted to 15% moisture content. The mean value of C_f across several species and grades in Table 8 is 2.09, which is close to the standard ASTM factor of 2.1 for flexure (Murphy 1988). Table 9 compares system factors for WSD and LRFD obtained from analyses that included DOL effects for the three dimension lumber types. The average values of ψ for WSD and LRFD are comparable, although the range of ψ^{LRFD} is smaller than that for ψ^{WSD}.

The LRFD safety check for members loaded by a combination of dead and live load in compression parallel to grain uses $\phi = 0.9$ and $\lambda = 0.8$ (Ellingwood and Rosowsky 1991) in an equation similar to Eq. 6, with S_x replaced by section area, A. System factors developed for the limit state of compression parallel to grain for a 10-member system provide a comparison with system factors obtained for the flexure limit state. It is assumed in performing the system reliability analysis that the axial strains in all compression members are the same. The statistics on strength in compression parallel to grain based on the nonparametric estimates for mean and 5th-percentile values taken from the collective mill In-Grade data (15% moisture content, adjusted) are summarized in Table 10. The mean-to-nominal compression strength, m_{F_c}/F_{c_n}, and the coefficient of variation, V_{F_c}, are insensitive to the lumber type considered, and values $m_{F_c}/F_{c_n} = 1.47$ and $V_{F_c} = 0.21$ were used, based on the average of these results. The correlation coefficient ($\rho_{R\text{-}E}$) was taken as 0.7 (Curry and Fewell 1977). The system reliability analysis leads to an LRFD system factor of $\psi_{dol} = 1.26$. In comparison, the system factor for flexure ranged from $\psi_{dol} = 1.25$ to 1.46 (Table 9).

TABLE 9. *Comparison of WSD and LRFD system factors.*

Lumber	ψ^{WSD}	ψ^{LRFD}
DF-L, 2 × 10, No. 2	1.11	1.25
SP, 2 × 10, 2-KD	1.33	1.35
H-F, 2 × 8, No. 2	1.53	1.46

If a single system factor were desired for code implementation, a factor of $\psi = 1.25$ would be required to encompass both the compression and flexure limit states based on this analysis. The variability in the tensile strength is on the same order as that in the MOR (Ellingwood 1981), so a system factor for the tension limit state would be comparable to that for flexure. It should be noted that the current NDS does not allow any increase in allowable stress for repetitively used members in tension or compression.

The fact that ψ decreased for the compression parallel to grain limit state, in which V_{F_c} was substantially less than for flexure, suggests a dependence of ψ on the coefficient of variation in strength. To investigate this dependence, three additional sets of statistics were considered: (1) glulam, flexure, $m_{F_r}/F_b = 3.17$, $V_{F_r} = 0.17$ (Ellingwood et al. 1988); (2) glulam,

TABLE 10. *Compression parallel to grain statistics.*

Lumber	Sample size	$F_{c_n} = F_{0.05}$ (psi)	m_{F_c} (psi)	m_{F_c}/F_{c_n}	V_{F_c}
No. 2-KD 2 × 10, SP	430	2,871	4,239	1.48	0.22
No. 2 2 × 10, DF-L	350	2,675	3,975	1.49	0.21
No. 2 2 × 8, HF	326	2,520	3,593	1.43	0.20

compression parallel to grain, $m_{F_c}/F_{c_n} = 2.62$, $V_{F_c} = 0.12$ (Knab and Moody 1978); and (3) an artificial data set constructed by assuming that $V_{F_r} = 0.10$ and developing the mean-to-nominal value from a two-parameter Weibull distribution function in which $F_{.05} = 2.1F_b$. This artificial data set yielded $m_{F_r}/F_b = 2.56$ with $V_{F_r} = 0.10$. System factors based on reliability analyses of 10-member systems designed by LRFD using Eq. (6) are shown on Fig. 8 along with those values obtained previously for dimension lumber. Lower system factors may be appropriate for systems constructed of members with low coefficients of variation in strength; such members may be associated with select structural lumber types or carefully controlled manufactured wood products. Based on these results, the system factors might be specified as $\psi = 1.25$ for $V_R \geq 0.20$ and $\psi = 1.10$ for $V_R < 0.20$.

COMPARISON WITH CANADIAN SYSTEM MODEL AND PROPOSED SYSTEM FACTORS

A study to develop system factors for wood design by the National Building Code of Canada (NBCC) has recently been completed (Fos-

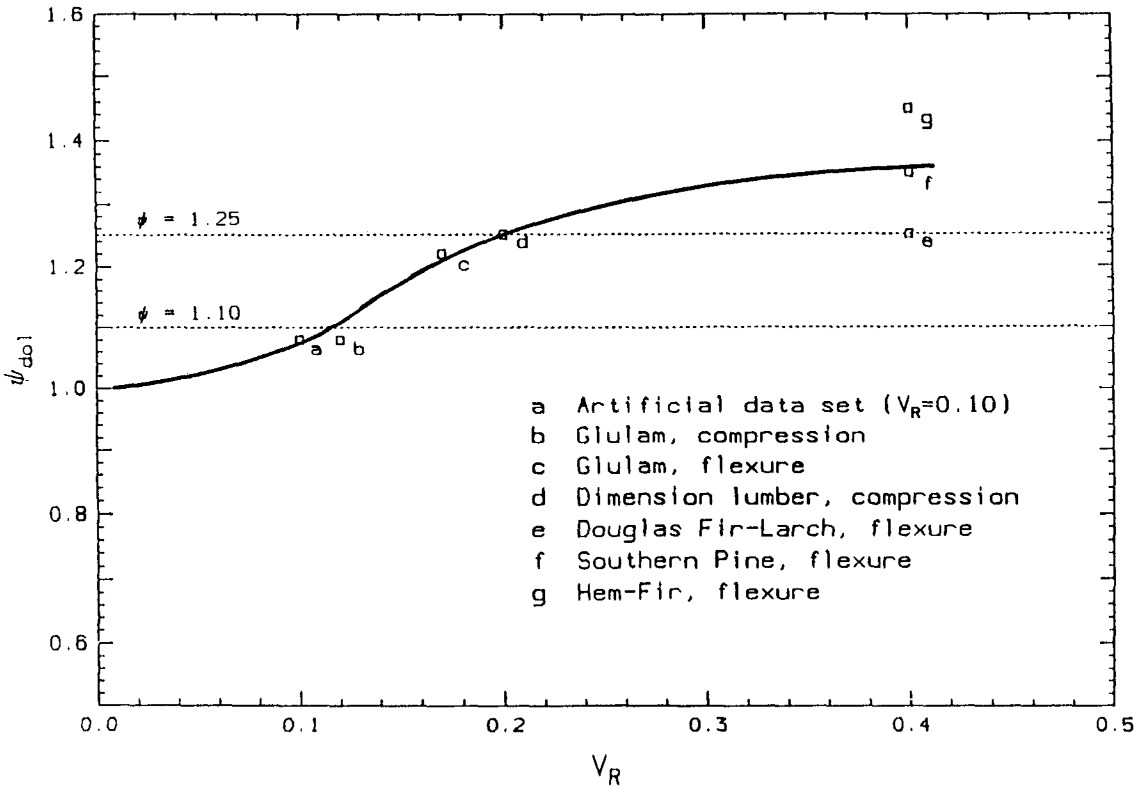

FIG. 8. Comparison of system factors for different lumber types and limit states.

chi et al. 1989). The system factors obtained in that study (designated K_s) varied from about 1.1 to 1.7. The system was analyzed using a finite element model of the complete deck system, which included effects of both load sharing among joists and composite action of joists and sheathing. However, system failure was defined as first- or weakest member failure and the time-dependent duration-of-load effects were not considered. General agreement between the reported NBCC values and those based on overload failures using the simple structural models herein can be seen from the last columns in Tables 5 and 6. However, the values of ψ accounting for the load-sharing effect are lower when the duration-of-load effect is included than when it is not. Therefore, estimation of the system factor should take duration-of-load effects into account. Furthermore, one should consider multiple member limit states in determining ψ.

CONCLUSIONS

System factors for LRFD of engineered wood construction can be developed from reliability analyses of simple structural models that take stochastic damage accumulation into account. The In-Grade Test Program provides the necessary statistical base on dimension lumber strength and stiffness. Load-sharing and duration-of-load effects in light-frame wood construction are coupled and must be considered together in analyzing system reliability. The stress increase currently allowed in WSD to account for multiple member system effects (15% increase for members in bending, none for members in tension or compression) is conservative in light of the limit states considered herein, especially since composite action, which would likely contribute further to the system effects, was not considered.

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