RELIABILITY-BASED SYSTEM FACTOR FOR SERVICEABILITY DESIGN OF WOOD FLOORS

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ABSTRACT

A structural analysis model for parallel-member wood joist floors is developed that includes the effect of component creep. Viscoelastic material models are calibrated using the data from a recently completed experimental program conducted as part of this overall study. Using this system model, deflection serviceability reliability analyses of parallel-member wood systems, including the effects of creep deformation, are conducted. Stochastic load models are used to simulate the time-varying nature of applied loads. Multiple limit state definitions for deflection serviceability of parallel-member wood floors are considered. Monte Carlo simulation is used to evaluate limit state probabilities. Reliability indices for current serviceability design provisions are also evaluated, and a serviceability system factor for Load and Resistance Factor Design (LRFD) is recommended.

Keywords: Creep, design, floor system, reliability, serviceability, wood.

INTRODUCTION

Design for creep in the National Design Specification (NDS) (AFPA 1991) is limited to a serviceability criterion with creep deflections calculated by multiplying deflections due to long-term loads (i.e., dead loads) by creep factors of 1.5 for seasoned sawn lumber (< 19% MC) and glued-laminated members and 2.0 for unseasoned sawn lumber. Thus, the total deflection is the sum of instantaneous deflection due to both long-term and short-term loads and creep deflections due to long-term loads. The current provision is based on the assumption that only long-term loads result in significant creep deflections; however, service loads are also known to cause considerable amounts of creep deflection even during relatively short durations (Fridley 1992). The proposed Load and Resistance Factor Design (LRFD) Specification for Engineered Wood Construction (ASCE 1994) specifies that dead load plus a portion of the live load must be considered when computing creep deflection. The creep factors in both the NDS and the LRFD specification are largely empirical and lack theoretical foundation. Further, no consideration is given to the interaction of creep and system effects.

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In this paper, the deflection serviceability reliability of wood joist floor systems, including the effects of creep deformation, is examined. A viscoelastic system model that accounts for the time-dependent material behavior of the components in the floor system is used. Time-dependent material behavior is modeled using mechanical analog models with parameters taken from a recently completed testing program to investigate service load behavior of wood joist floor systems. Time-dependent characteristics of loading must also be incorporated into the analysis since the response of a viscoelastic material depends on the current load level as well as the load history. Stochastic load models are used to simulate the time-varying nature of loads applied to the structural systems. Multiple limit state definitions for deflection serviceability of parallel-member wood systems are considered. Monte Carlo simulation is used to evaluate the system failure probabilities. Reliability indices for current serviceability design provisions are also evaluated, and a system factor for use in an LRFD serviceability design equation is recommended.

FLOOR SYSTEM MODEL

Background

In wood joist floor systems, load is applied to the sheathing or deck and distributed to the joists as a function of the flexural stiffness of the sheathing in the direction perpendicular to the joists. The sheathing forms a wide, shallow, continuous beam over the joists in the direction perpendicular to the joists. This continuous beam serves to distribute load. Two-way bending action contributes to a uniform deflection profile of the joists in the parallel-member system subjected to uniform load (McCutcheon 1984; Vanderbilt et al. 1974). This uniform deflection profile of joists implies that a stiffer joist carries more load than neighboring less-stiff joists.

The sheathing is attached to the joists by means of nails or a combination of nails and glue forcing a portion of sheathing to act with each joist to form a composite beam. Composite behavior is possible only if shear is developed between the two components. In other words, composite behavior will result if the horizontal shear at the interface of joist and sheathing is resisted by connection details used in the floor system. However, the connection details used in current design practice are usually not stiff enough to rigidly transfer the entire shear force between the sheathing and the joists, and partial composite action is developed. This partial composite action not only increases the effective flexural stiffness of the joist, but also decreases the flexural stresses in the joists.

Since sheathing materials commonly used in current practice are of finite size, gaps between sheets of sheathing will exist. The distribution, stiffness, number, and location of gaps can greatly affect the performance of parallel-member wood systems since gaps affect deflections, the magnitude and distribution of interlayer connector forces, and joist and sheathing stresses. Thus, gap distribution and stiffness must also be accounted for in the structural system model.

It is well known that wood exhibits continued, additional deflection under long-term load. This time-dependent phenomenon is termed *creep.* Differential creep behavior between joists, sheathing material, and connection details in a parallel-member wood system could affect the system performance of the parallel-member assembly over time.

Wood is a natural material, and variabilities exist in its elastic and viscoelastic properties according to species, origin, and grade. It is commonly recognized that variability in elastic material properties of the joists in a parallel-member wood system results in instantaneous load-distribution among joists upon loading. This elastic load-distribution can be substantial, depending on the flexural stiffness of the sheathing, loading type, and the relative stiffnesses of the joists. The National Design Specification for Wood Construction (AFPA 1991) empirically recognizes this beneficial system effect by increasing nominal allowable stresses by 15% for certain members that are used repetitively, for example, joists used in a floor system. It follows from this elastic load-distribution response that variability in viscoelastic properties of the joists of a parallel-member wood system will lead to load-redistribution over time. This behavior has not been taken into account in any recent system load-duration reliability analyses. It has been assumed in recent studies (e.g., Rosowsky and Ellingwood 1991) that load is apportioned to each joist by some elastic load-distribution mechanism and is maintained in that proportion until a joist in the system fails. Although the study reported herein relates to service-load behavior rather than ultimate behavior, the time-dependent load-redistribution can also be expected to have an effect on load-duration analyses of structural wood assemblies if the amount of the load-redistribution over time is found to be significant.

There have been a number of elastic analysis models developed in recent years for parallel-member wood systems that account for the partial composite action, two-way bending action, and the effect of gaps in sheathing material (e.g., Folz and Foschi 1989; Thompson et al. 1975). McCutcheon (1984) suggested a simple beam-spring analog model for the analysis of wood joist floor systems. This model has been found to reproduce experimental test results well and to be far simpler than other, more complex finite element models. In the beam-spring model, a floor system is idealized as a simple structure consisting of a beam, representing the sheathing, supported by a set of elastic springs, which model the midspan deflections of the joists.

Modified McCutcheon model

The McCutcheon beam-spring analog model was first modified to include the effects of creep response of component members in wood floor systems by Philpot et al. (1995). The modified model accounted for the creep behavior of joists in floor systems, and rigid body behavior of floor sheathing in the direction perpendicular to the joist was assumed causing extreme load-distribution between joists. Partial composite action between joists and sheathing was neglected by Philpot et al. (1995). This model is extended herein to relax the assumption of rigid body behavior of the floor sheathing beam. A brief summary of the model development is described below. Additional details may be found in Fridley et al. (1996b).

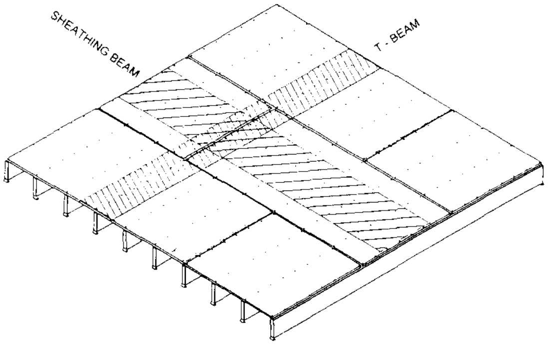


FIG. 1. Typical wood joist floor configuration.

A combination of T-beams and sheathing beams that are mutually perpendicular to each other can form the basic structural model for the analysis of parallel-member wood floor systems. Figure 1 shows a typical floor in which the T-beam and sheathing beam are shown by cross-hatched areas. The T-beam accounts for partial composite action, and the sheathing beam accounts for two-way bending action. Evaluation of the time-dependent stiffness characteristics of the partial composite action and two-way bending action is required in the development of the viscoelastic system model. The basis for this is the correspondence principle, which states that the stresses in the viscoelastic beam will be the same as in an elastic beam, but the strains and displacements will depend on time. The deformations can be evaluated from the solution of the elastic beam by replacing the modulus of elasticity by the modulus of relaxation, which is the reciprocal of the creep compliance. The modulus of relaxation can be viewed as a time-dependent modulus of elasticity in linear viscoelastic analyses. The relaxation modulus is defined by the time-dependent constitutive equations of

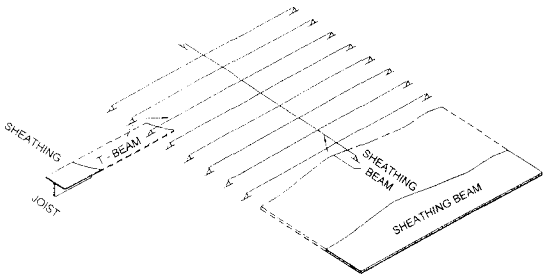


FIG. 2. Intermediate-level idealization of floor system.

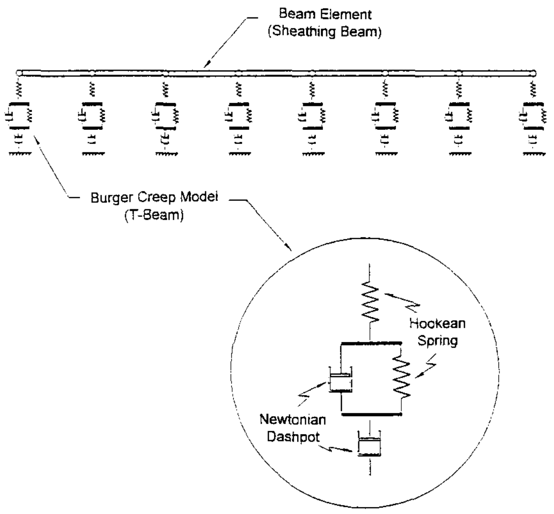


FIG. 3. Final idealization of floor system.

a material. Among the many constitutive equation models suggested to represent the viscoelastic material behavior of wood or wood-based materials, the four-element Burger model has been most widely used (Fridley et al. 1992). The Burger model is used to predict the creep behavior of components in this study without further discussion.

In the system model developed for this study, the viscoelastic midspan deflection of the joists is idealized using four-element creep models. The sheathing is considered to be a continuous beam supported by the Burger models at the locations of the intersections of the T-beams and the sheathing beam. Evaluation of the time-dependent flexural stiffness of the sheathing beam is straightforward since the bending stiffness of the sheathing beam is simply the stiffness of the sheathing in the direction perpendicular to the joist. Figure 2 illustrates an idealized floor system with the sheathing beam crossing the joists at midspan.

Before including the Burger elements to account for viscoelastic behavior, the beam-spring analog model was altered. The existing McCutcheon floor analysis model assumes uniform loading and uniform spacing of joists. In the case where the spacing of joists is not uniform, the average spacing is used (McCutcheon 1984). In the existing model, the entire sheathing beam is idealized as a single beam supported by a series of uniformly spaced elastic springs and subjected to a uniformly distributed load. To overcome this limitation, the bending behavior of sheathing spanning two adjacent joists was idealized by the simple beam finite element. A beam element that has two nodes with two degrees-of-freedom at each node, vertical translation and rotation, is used to represent the sheathing behavior in the direction perpendicular to the joists. The time-dependent flexural properties of the beam element can be found by evaluating the creep compliance of the sheathing materials. The final idealization of a typical floor system is illustrated in Fig. 3.

The data collected from three full-scale floor tests (see Fridley et al. 1996a) were used to verify the viscoelastic system model. The experimental results from the elastic and viscoelastic component tests were also used to evaluate the time-dependent material properties of the components in the system. Midspan deflections and support reactions of each joist in the floor systems were used to characterize the time-dependent system performance of the floor systems. Details of the model derivation and calibration to experimental test data can be found in Fridley et al. (1996a, b). The model developed was verified experimentally by comparing the predicted results with the observed system behavior. In general, excellent agreement was observed.

RELIABILITY EVALUATION PRINCIPLES

Structural reliability can be defined as the probability that a structure does not violate a given limit state during a specified time or reference period. In the simplest case, with the assumption that the resistance (R) and load effect (S) are independent and stationary with time, the probability that the structure will fail to perform any of its design requirements is given by

$$P_f = \mathrm{P}[M < 0] = \mathrm{P}[(R - S) < 0] = = \int_{-\infty}^{+\infty} F_R(x) f_S(x)\, dx \qquad (1)$$

in which M is the safety margin, $F_R(\cdot)$ is the cumulative distribution function for the resistance, and $f_S(\cdot)$ is the probability density function for the load effect. In the more general case, the failure probability can be expressed

$$P_f = \mathrm{P}[g(X) < 0] = = \int_D \cdots \int f_X(x_1, x_2, \ldots, x_n)\, dx_1 dx_2 \ldots dx_n \qquad (2)$$

where $g(X)$ is the limit state function expressed in terms of the basic variables x_i, $f_X(\bullet)$ is the joint probability density function, and D is the domain of integration corresponding to that region over which $g(X) < 0$. The integration shown in Eq. 2 can be evaluated in closed form only in very idealized (simplified) cases. However, these conditions are not often satisfied in real structural applications. Furthermore, in most structural design situations, some components of the loads applied to a structure (i.e., occupancy live load) are time-dependent, and the strength and stiffness of materials and components may also be time-dependent. For example, the stiffness of a structural member made of a viscoelastic material such as wood may decrease with time. In the reliability analysis of structures made of viscoelastic materials, the time-dependent material response and the continuous variations in loading must be properly taken into consideration.

In such time-dependent situations, conventional reliability analysis techniques such as first-order second-moment (FOSM) methods are not applicable. Monte Carlo simulation is considered to be the only tool currently available for evaluating problems involving both time-dependent loading and time-dependent material (system) response. Monte Carlo simulation is an alternative approach to performing the integration in Eq. 2 to compute the probability of failure. Using this method, the safety margin M in Eq. 1 is evaluated in each analysis using realizations of the basic variables generated according to assumed specific statistics and distributions. By repeating this procedure a large number of times, a complete distribution of the safety margin is obtained, and the probability of failure is easily calculated. The estimated probability of failure approaches the theoretical probability of failure as the number of simulations increases. The coefficient of variation in the estimated probability of failure can be estimated from the following equation:

$$\mathrm{COV}_{P_f} = \sqrt{\frac{1 - P_f}{n \cdot P_f}} \qquad (3)$$

in which P_f is the calculated probability of failure and n is the number of independent trials.

A complete reliability analysis of parallel-member wood systems is not the intent of this study, and has been reported elsewhere (see Philpot et al. 1993; Rosowsky and Ellingwood 1991). Rather, a procedure is suggested for a deflection serviceability reliability analysis in which the creep behavior of the constitutive materials is included. A deflection serviceability analysis for a single member of a viscoelastic material can be performed using a limit state function consisting of several random variables and deterministic quantities representing the creep factor, loads, material properties, and a resistance factor (Philpot et al. 1993; Fridley and Rosowsky 1994). However, the reliability analysis of complex structural systems such as parallel-member wood systems cannot be accomplished in the same fashion since the corresponding system limit state function cannot be expressed in closed form. In such cases, an appropriate structural analysis model is required for use in an analysis incorporating realizations of the basic random variables. This type of analysis also permits consideration of different failure modes. The probability of failure for a specific mode is calculated by dividing the number of analyses in which the particular limit state is exceeded by the total number of analyses. An FOSM reliability index can then be defined as:

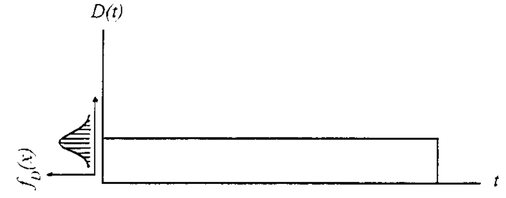
$$\beta = \Phi^{-1}(1 - P_f) \quad (4)$$

in which β is the reliability index and $\Phi^{-1}(\bullet)$ is the inverse standard normal cumulative distribution function (Melchers 1987).

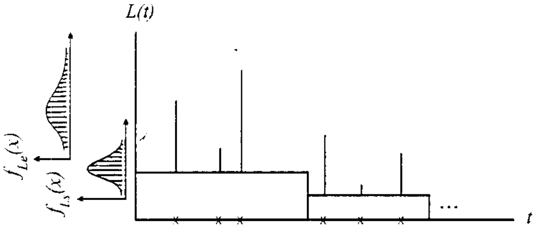
STOCHASTIC LOAD MODELING

Reliability analyses of structures made of materials whose properties are not time-dependent only require the distribution of the extreme values of the load. For reliability analyses of viscoelastic elements or systems, loads must be modeled as stochastic processes since structural responses of those structures are time-dependent. A stochastic process, $X(t)$, is a time-dependent random function such that for any point in time, t, there exists a random value X. The outcome or observation is governed by the probability density function $f_X(x, t)$. A complete set of the observed outcomes of $X(t)$ for each value of t is termed a stochastic process.

A number of statistical load models have been suggested based on the nature of the structural loading, load survey results, load scenario analyses, and engineering judgment (Ellingwood and Culver 1977; Chalk and Corotis 1980; Harris et al. 1981). Those models include descriptions of load intensity, duration, and frequency of occurrence. For a deflection serviceability analysis, the nature of the applied load to be considered is assumed static (dynamic effects of loading on deflection are usually neglected). Static structural loadings can be modeled as a series of relatively long duration constant loads. The changes of loads take place relatively quickly when compared with the periods of constant loading, and thus can be considered to occur instantly between consecutive constant loading intervals. For such a stepwise loading, a stochastic pulse process model, or sequence of constant intensity pulses, has been widely used. In such a model, the intensity, duration, and time between load pulses are represented by random variables with appropriate statistics and distributions.



(a) dead load



(b) Combined (sustained + extraordinary) occupancy live load

FIG. 4. Stochastic load process models.

The loads considered in this wood joist floor study are dead and occupancy live loads. The dead load is assumed to remain constant during the building's lifetime and thus is modeled by a single pulse. It has been shown that the intensity of the dead load follows a normal distribution (Ellingwood et al. 1980). Occupancy live load is modeled as having two parts: sustained components and extraordinary components (Chalk and Corotis 1980). The sustained component of the occupancy load accounts for the loads related to the initially designed purpose of the space and can be assumed to remain constant before interruption by an abrupt change in the intensity, such as a change in tenancy. Statistics for the sustained component of the occupancy live load are

TABLE 1. *Load process parameters (from Philpot and Rosowsky 1992)*

Load component	Intensity			Occurrence	
	Mean	COV	CDF	Mean Rate/yr	Duration
Dead	1.05 D_n^*	0.10	Normal	n/a	50 years
Sustained live					
18.6 m^2 (200 ft^2)	0.24 L_n^*	0.90	Gamma	0.125	8 years
74.3 m^2 (800 ft^2)	0.30 L_n^*	0.60	Gamma	0.125	8 years
Extraordinary live					
18.6 m^2 (200 ft^2)	0.16 L_n^*	0.84	Gamma	1.0	1 week
74.3 m^2 (800 ft^2)	0.19 L_n^*	0.66	Gamma	1.0	1 week

D_n^*, L_n^* are nominal dead and live load respectively.

summarized in Table 1. The extraordinary component of the live load is associated with unexpected events such as crowding of people in special circumstances or temporary changes of the usage of the space. The extraordinary live load statistics recommended by Philpot and Rosowsky (1992) are used in this study and are also presented in Table 1.

SERVICEABILITY RELIABILITY ANALYSIS OF WOOD FLOOR SYSTEMS

The performance of a structural member or system can be defined in terms of a limit state. Serviceability limit states refer to a disruption of the normal function of the structure, such as would be caused by excessive deflection or vibration. Although permanent damage may be caused in nonstructural elements such as ceilings and partition walls, no permanent damage is assumed to result from the violation of a serviceability limit state. Therefore, serviceability design is usually based on a reference period much shorter than the design life of the structure. A deflection serviceability limit state function can be written in the form:

$$M = \delta_{\text{allow}} - \delta_{\text{total}} \tag{5}$$

in which δ_{allow} is the code-specified allowable deflection and δ_{total} is the total deflection of a member or system including creep effects. In Eq. 5, M is termed the safety margin, and when the value of M is less than zero, the limit state is exceeded. Unlike exceeding a strength limit state after which the structure can no longer be used, exceeding a deflection serviceability limit state does not usually constitute a danger to the public and thus the structure may continue to serve its intended purpose, perhaps after minor rehabilitation.

For a system of flexural members subject to a uniformly distributed load, an LRFD checking equation for system deflection serviceability can be written as (Philpot et al. 1995):

$$\theta \cdot \phi_c \cdot Z_n \geq Z_u \tag{6}$$

in which

θ = serviceability system factor
ϕ_c = serviceability resistance factor which accounts for the effects of creep
Z_n = nominal (limiting) deflection
Z_u = ultimate deflection including creep

The nominal (limiting) deflection, Z_n, is usually specified as a fraction of the span length, l; for example $l/240$ where a load combination of dead and live load is considered. For a floor system designed according to existing design provisions, the maximum allowable span length can be determined for a given size, spacing, and stiffness of the flexural members. The ultimate deflection, Z_u, for a simply supported beam subjected to a uniformly distributed area load of $\gamma_D D_n + \gamma_L L_n$ is given by:

$$Z_u = \frac{5}{384} \frac{s(\gamma_D D_n + \gamma_n L_n) l^4}{E_n I} \tag{7}$$

in which

s = joist spacing
γ_D = dead load factor
γ_L = live load factor
D_n = nominal dead area load
L_n = nominal live area load
E_n = nominal modulus of elasticity
I = moment of inertia (assumed to be deterministic)

The allowable beam span can then be determined from:

$$\theta\phi_c \frac{l}{240} \geq \frac{5}{384} \frac{s(\gamma_D D_n + \gamma_n L_n) l^4}{EI} \tag{8}$$

or

$$l \leq \left[\frac{1}{3.125} \frac{\theta\phi_c E_n I}{s(\gamma_D D_n + \gamma_n L_n)}\right]^{1/3} \tag{9}$$

The maximum allowable span length is used in the reliability analysis to provide conservative reliability estimates. Considering the maximum joist deflection in a floor system subjected to a load combination of dead and live load, the limit state function can be written:

$$M_{sys}(X) = \frac{l}{240} - \max(\delta_{sys}) \tag{10}$$

in which $\max(\delta_{sys})$ is the maximum joist deflection occurring in the floor system subjected to the combination of random loads during the reference period.

If the maximum deflection along a joist exceeding the limiting criteria is considered to cause significant damage to the cladding or partitions, such as unsightly cracks, it may be reasonable to expect the same holds for deflections in the direction perpendicular to the joist for two-way bending systems such as floor systems. In certain practical situations, relative deflection between adjacent joists can create a critical curvature of the finishing material such that tensile stresses at the surface of the material exceed the ultimate tensile strength causing surface cracks. Differential deflection between any two adjacent joists can be checked with the following equation:

$$\frac{2 \cdot s}{240} \geq \delta_i - \delta_j \tag{11}$$

in which

δ_i, δ_j = deflections of any two adjacent joists in a floor system
s = joist spacing

In this limit state, any two adjacent joist spacings is analogous to the beam span, and thus Eq. 11 is analogous to the original serviceability checking equation, (7). In this case, the corresponding limit state function has the form:

$$M_{diff}(X) = \frac{2s}{240} - \max(\delta_{diff}) \tag{12}$$

in which $\max(\delta_{diff})$ = the maximum differential joist deflection occurring in the floor system during the reference period. Since the maximum differential joist deflection in a floor system can be assumed to occur at midspan, only the midspan deflection of each joist needs to be checked. Thus, the analysis program developed for this study did not have to be modified for this deflection limit state function.

In addition to overall deflection of a floor system and deflection of several consecutive joists, the average joist deflection in a floor system and the "soft-spot" deflection, defined as the maximum value of the average deflections of any three adjacent joists in a floor system, are also considered herein. If the same limiting (allowable) deflection applies, the average deflection of a floor system would be the most moderate design criterion among the four criteria considered. This limit state function can be written as:

$$M_{avg}(X) = \frac{l}{240} - \delta_{avg} \tag{13}$$

in which δ_{avg} = the average joist deflection in a floor system. The limit state function for the soft-spot deflection criterion can be written in a similar form:

$$M_{sft}(X) = \frac{l}{240} - \max(\delta_{sft}) \tag{14}$$

in which $\max(\delta_{sft})$ = the maximum soft-spot deflection in a floor system.

For the time-dependent simulation-based serviceability reliability analyses, the limit state function given by Eqs. 10 and 12–14 are checked, and reliability indices for each criterion are computed and compared. In order to include viscoelastic material behavior in the structural model used in this study, statistics and distributions of the four model parameters were obtained for each of the following: (1) joist creep, (2) sheathing flexural creep in the direction perpendicular to the joist, (3) sheathing compression creep in the direction parallel to the joist, and (4) creep behavior of connection details. Once this information was obtained from the experimental testing program (Fridley et al. 1996a), realizations of the random variables could be generated to describe the time-dependent behavior of the parallel-member wood system under stochastic load (see Table 1).

The analysis reported herein was limited to one species and joist size: No. 2 KD19 southern pine 50 mm × 200 mm (nominal 2 × 8 in.). The joist spacing was assumed to be 0.41 m (16 in.) on center. The maximum allowable span length for the given nominal MOE, dead and live loads, resistance and system factors is computed from Eq. 9. The statistics for the four model parameters for joist, plywood, and nailed connection creep were obtained from the experimental test results (Fridley et al. 1996a) as well as the results from previous studies. The model parameters were assumed to follow lognormal distributions as found by Fridley et al. (1992) for Select Structural Douglas-fir nominal 50 mm by 100 mm (nominal 2 by 4 in.) lumber at ambient conditions (22.8°C and 50% relative humidity). This assumption was made since sufficient information to determine the underlying probability distribution of the model parameters could not be obtained from the testing program. This assumption can also be justified by current design practice, as evidenced by the NDS (AFPA 1991) and the proposed LRFD Specification for Wood Construction (ASCE 1994), in which relative creep is assumed to be comparable across grades and species. The statistics for the four model parameters for the flexural creep of the No. 2, 50 mm by 200 mm (nominal 2 by 8 in.) southern pine joists are shown in Table 2. Details of the testing program and data analysis may be found in Fridley et al. (1996a).

TABLE 2. *Flexural creep properties of joist used in the reliability analysis.*

Parameter	K_e (GPa)	K_k (GPa)	μ_k (GPa-min.)	μ_v (GPa-min.)
Mean	11.02	102.79	4.90 (10^5)	1.38 (10^7)
COV	0.250	0.677	0.605	0.647

Note: 1 GPa = 0.1451 psi.

The statistics of the model parameters for the flexural behavior of the southern pine plywood in the direction parallel to its face grain were obtained from their corresponding component creep tests and are shown in Table 3. Although only nine specimens were tested (one less than the minimum number suggested to obtain distribution information from a creep test (Laufenberg 1987)), the COVs obtained from the tests for the plywood were comparable to those determined for oriented strandboard by Tang and Yeh (1987) and were therefore assumed to be reasonable.

For the compressive behavior of the southern pine plywood in the direction perpendicular to its face grain, the mean values of the model parameters were obtained from the compressive creep test results for the plywood. Since only a small number (3) of compressive creep tests for plywood were performed (and no additional statistical data on the compressive creep behavior of plywood were found in the literature), a good measure of variability was not available; therefore, the COV's for the

TABLE 3. *Flexural creep properties of plywood used in the reliability analysis.*

Parameter	K_e (GPa)	K_k (GPa)	μ_k (GPa-min.)	μ_v (GPa-min.)
Mean	8.81	58.39	3.06 (10^4)	2.89 (10^6)
COV	0.157	0.198	0.482	0.385

Note: 1 GPa = 0.1451 psi.

TABLE 4. *Compression creep properties of plywood used in the reliability analysis.*

Parameter	K_e (GPa)	K_k (GPa)	μ_k (GPa-min.)	μ_v (GPa-min.)
Mean	4.77	12.95	1.71 (10^4)	3.11 (10^6)
COV	0.222	0.198	0.482	0.385

Note: 1 GPa = 0.1451 psi.

model parameters were assumed to be the same as those for flexural behavior of the plywood. The statistics assumed for the model parameters for compressive behavior of the plywood are summarized in Table 4.

The statistics for the nailed connection creep behavior are presented in Table 5. The basis for these values, including a description of the relevant testing program, is presented in Fridley et al. (1996a).

The statistics for the Maxwell element spring constant, K_e, for all components except for the joist, were obtained from the corresponding static test results. For the joist MOE, the nominal value was taken from the NDS since the mean value obtained from the test was less than the nominal value and since the NDS value is derived from the In-Grade Test Program (Green and Evans 1987), which is assumed to provide more accurate estimates of the nominal values. The coefficient of variation in the MOE was based on values reported in the In-Grade Test Program (Green and Evans 1987). The experimental data obtained as part of this study should be considered to (1) augment current statistical data (i.e., Green and Evans 1987) where current data are lacking (e.g., creep properties), and (2) provide information to validate and calibrate the behavior model (see Fridley et al. 1996a, b).

A load combination of dead plus occupancy live loads, $D_n + L_n$, was considered. Consistent with current practice for serviceability design, γ_D and γ_L in Eqs. 8 and 9 are both set equal to 1.0. The serviceability creep resistance factor, ϕ_c, which accounts for the effects of creep is not included in any codes to date. Philpot et al. (1993) suggested a resistance factor of 0.45 for a single dimension lumber beam and that factor is adopted herein. The nominal live load was assumed to be 1.916 kN/m^2 (40 psf). The nominal dead load is defined as the calculated or estimated dead weight of the structure based (e.g.) on the minimum design loads for materials specified in the load standard ASCE 7-93 Minimum Design Loads for Buildings and Other Structures (1993). Ratios of the nominal live load to dead load are often used in reliability studies. Ratios of between 3 and 5 are generally appropriate for wood structures (Philpot et al. 1993). A ratio of $L_n/D_n = 4$ has been widely used in reliability analyses and was adopted herein. The final structural system model (see Figs. 1–3) used in the analysis had the following properties:

- 8 joists, 500 mm × 200 mm (nominal 2 × 8 in.) No. 2 KD19 southern pine, spaced 0.41 m (16 in.) o.c.
- no support along length of edge joists (one-way bending)
- 18 mm (23/32 in.) southern pine Sturd-I-Floor grade plywood
- Common 8d nails spaced 0.2 m (8 in.) on center
- designed for 1.916 kN/m^2 (40 psf) live load in accordance with APA and NDS, span = 3.91 m (12′-10″)

A total of 200,000 floor systems were analyzed. This provided approximately 95% confidence intervals on the estimates of probabilities of failure. A one-year serviceability reference period was considered.

TABLE 5. *Creep properties of nailed connection used in the reliability analysis.*

Parameter	K_e (GPa)	K_k (GPa)	μ_k (GPa-min.)	μ_v (GPa-min.)
Mean	0.080	0.795	3.79 (10^3)	6.69 (10^9)
COV	0.229	0.457	0.282	0.195

Note: 1 GPa = 0.1451 psi.

RESULTS AND DISCUSSION

The reliability index, including the effect of creep, for a design based on the current UBC requirements (no creep factor) and for a load combination $D_n + L_n$, was evaluated. The reliability indices for the four different limit states

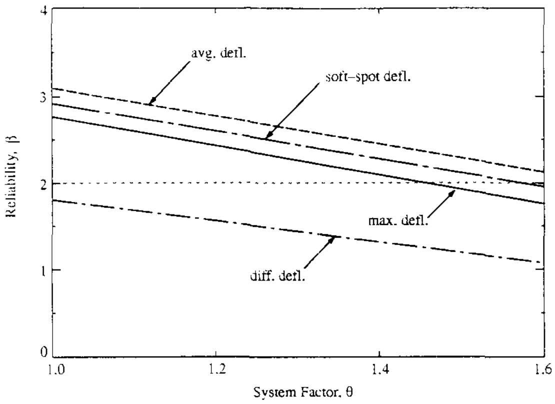


FIG. 5. Deflection Serviceability Reliability (β) vs. System Factor (θ).

were 1.06 (maximum deflection), 1.36 (average deflection), 0.07 (differential deflection), and 1.19 (soft-spot deflection); the corresponding failure probabilities were 0.146, 0.0876, 0.285, and 0.117, respectively. The reliability levels were considerably lower than a suggested target reliability level of $\beta = 2.0$ (e.g., Galambos and Ellingwood 1986). A target reliability index of $\beta = 2.0$ has been used in many recent serviceability reliability studies for wood (e.g., Foschi et al. 1989; Philpot et al. 1993). In their study, Philpot et al. (1993) also found the target reliability index for southern pine lumber to be slightly over 2.0. Thus, the target reliability of $\beta = 2.0$ adopted herein is considered to be appropriate. The results of the deflection serviceability reliability study (assuming a creep factor, $\phi_c = 0.45$) are presented in Fig. 5 which shows the relationship between the serviceability system factor θ and the reliability index β for the floor systems.

For design, the system factor should be selected such that the reliabilities of a single member and a system of members are comparable if failure consequences are comparable (Rosowsky and Ellingwood 1991). Thus, the optimal system factor is determined at the intersection of single member reliability level and the β-θ curves. System factors equal to or less than the optimal system factor will ensure that the floor system reliability will meet or exceed the single member target reliability.

Based on the results shown in Fig. 5, for the maximum deflection criterion, a system factor of $\theta = 1.4$ for a one-year reference period in combination with a resistance factor of $\phi_c = 0.45$ is recommended for the floor systems of grade No. 2 southern pine joists spaced 0.41 m (16 in.) on center. (Therefore, a combined resistance factor equal to the product of the single-member creep factor and the serviceability system factor, $1.4 \times 0.45 = 0.63$, is suggested). This recommended value for the system factor is expected to be applicable to floor systems made of joists of other species and/or grade since relative creep is assumed to be comparable across species and grade. As expected, the reliability index for the average deflection is the highest of the four limit states with that for the maximum soft-spot deflection being somewhat lower. The appropriate allowable deflection to be used for the two latter limit states has not been determined in this study. Figure 5 suggests that the reliability index for the differential deflection limit state is lower than the target reliability index for serviceability design, $\beta = 2.0$. Therefore, for special structures in which differential deflection may be considered critical in design, additional design criteria may be required.

SUMMARY AND CONCLUSIONS

Wood is a natural viscoelastic material and thus exhibits significant variability in material properties as well as creep behavior even under service load conditions. The ratio of the strength of wood to its modulus of elasticity is very high when compared to other building materials such as steel and concrete. Thus, the design of wood structures is often governed by serviceability issues. The effects of component creep (i.e., relaxation in stiffness of joist, sheathing, and connection between joist and sheathing) and variability in material properties of wood on the performance of parallel-member wood systems were experimentally and analytically investigated, and the results of a deflection serviceability reliability study were presented in this paper.

To quantitatively evaluate the effect of component creep on the time-dependent behavior of parallel-member wood systems, an experimental program was performed in the initial part of this study (Fridley et al. 1996a). The experimental program consisted of (1) component tests and (2) system tests. The component behavior tests included elastic and viscoelastic behavior of joist, sheathing, and connections between the joist and the sheathing. To obtain information required to relate the quantified component behavior to the time-dependent behavior of parallel-member wood systems, three replications of a complete, full-scale floor system were constructed and tested to determine their time-dependent behavior under a representative service loading. The floor systems were built in conformance with current design codes such as NDS (AFPA 1991) and APA (1986) specifications.

A widely used constitutive model, the Burger model, was used to represent the time-dependent behavior of the components. The component creep models were calibrated using the experimental data from the component tests and incorporated in a viscoelastic analytical model for parallel-member wood systems developed for the research. The data collected from the floor system tests were used to calibrate the overall system model. Generally, good agreement was observed between the experimental and analytical results (Fridley et al. 1996b). The system model was used in a deflection serviceability reliability analysis of wood joist floor systems. Multiple deflection serviceability limit states were considered, and the resulting reliability levels were compared for a floor system designed according to current practice.

The suggested viscoelastic model for parallel-member wood systems subjected to uniform loads accurately predicted the midspan creep deflections of the joists in the floor systems. The model could also be included in a simulation-based reliability analysis since the amount of computing time required was manageable (approximately 4 hours for 200,000 simulations on a 486-66 personal computer). According to the results of the deflection serviceability analysis of floor systems, a system factor for serviceability design of wood joist floors of $\theta = 1.4$ is recommended. This factor can be used in an LRFD checking equation for the deflection of parallel-member wood systems when used in combination with a creep resistance factor of $\phi_c = 0.45$.

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