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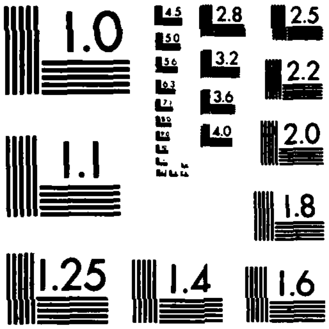

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Abstract

To implement more efficient design techniques for wood joist floor systems, existing systems with a history of satisfactory service must be characterized. Such a procedure, known as calibration, is necessary to ensure that new design techniques and construction materials do not change the overall acceptability of wood floor systems.

To characterize such performance, a structural analysis model and computer program for floors, FEAFLO, was used with data on numerous samples of lumber from sawmill inventory. Over 500 floor analyses yielded estimates of the distributions of floor stiffness and strength that will be useful to designers and code agencies in establishing or revising acceptance criteria for floors.

Acknowledgments

This report is based to a large extent upon the Master of Science thesis prepared by James T. Bufano while he was a graduate research assistant at Colorado State University *(5)*. The studies made using the complete data set were performed by Eugene Schaefer, Graduate Research Assistant, Colorado State University. The APA plywood data were furnished by Paul Post and Dr. Michael O'Halloran of the American Plywood Association.

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FPL 440

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Stiffness and Strength of Uniformly Loaded Floors with In-grade Lumber

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Introduction

Wood joist floors support loads in a complex manner involving interactions among sheathing, joists, and connectors. Whereas the existence of these interactions has been known for some time, lack of adequate analytical techniques has precluded their proper consideration in design. Consequently, the design methods still in use are based on the assumption that floor elements act independently.

Component interaction is recognized only through indirect procedures such as the National Design Specification's (NDS) increased allowable stresses for repetitive members *(15)*[2] and the American Plywood Association's (APA) glued floor design in which composite behavior is considered for stiffness but not for strength *(1)*. Hence current design techniques stifle innovation and hinder the utilization of new knowledge gained on the strength and stiffness distributions of material and connector properties.

The purposes of this study were to develop procedures for obtaining realistic estimates of the stiffness and strength at first joist rupture of floors constructed from material with variable mechanical properties and to use these procedures to develop definitive data on expected floor performance.

Definitive data on the stiffness and strength of wood joist floors are needed for two reasons. First, accurate information on the behavior of real floors built using in-grade lumber at both design loads and at failure loads is needed to quantify current floor performance. This information aids in the selection of limit states values for future design provisions, and may also have a role in the increasingly important area of product liability. Second, probability distributions of both strength and stiffness data and the resulting distributions of floor behavior are needed as input to the new generation of structural design procedures receiving worldwide attention. These new probability-based design methods have been developed and in some cases adopted for other materials and in other countries *(14,16,19)*. To ensure that the experience gained through many years of satisfactory floor service is carried into the new design techniques, the new design procedures must be calibrated against existing designs. Data on floor strength and deflection performance are vital components of the calibration procedure.

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[1] Maintained in cooperation with the University of Wisconsin.

[2] Italicized numbers in parentheses refer to literature cited at the end of this report.

Background

Colorado State University (CSU) and the Forest Products Laboratory (FPL) have engaged in a research project both individually and cooperatively, to develop analytical models that can form the basis for design procedures to produce acceptable, economical floors.

Researchers at CSU have developed a method for performing the structural analysis of wood joist floors using a finite element modeling of the floor. The method is presented in a computer program, FEAFLO (Finite Element Analysis of FLOors), which was verified by experimental tests of T-beams and floors *(6,8,9,20,21,22,23,25)*. The computer program, used in making parameter and simulation studies, forms the basis for proposed new design methodologies *(20)*.

Cooperative research by CSU and the Forest Products Laboratory (FPL) evaluated the behavior of baseline floors built using a pilot sample of in-grade lumber *(13)*.

For this report, in-grade lumber is defined as that sampled from sawmill production. Lumber data were collected by the West Coast Lumber Inspection Bureau, the Western Wood Products Association, and the Southern Pine Inspection Bureau as part of a cooperative research effort with the FPL *(7)*. A rather limited set of field data—consisting of modulus of elasticity (MOE), modulus of rupture (MOR), and cross-section dimensions for 60 lots of 10 joists each—that was available for the demonstration computer analyses is referred to as the sample data set. The more extensive data for over 550 lots that became available late in this study is denoted as the complete data set.

The scope of this research was limited to consideration of one typical floor configuration.

Research Methods

Many analyses of floors were performed to determine cumulative distributions of floor deflections and strengths. Joist strength and stiffness data were used both at the moisture content conditions at the time of test and adjusted using various moisture correction procedures. The adjustment for moisture was made for part of the data to determine the possible effects of seasoning on performance.

Analysis Program

The input to the FEAFLO program consists of a description of the floor geometry, the material MOE values, and the connector locations and stiffnesses. The MOE and connector stiffness values are constant along the length of each joist, deflections are assumed small, and the computed behavior is linear. As part of a previous study *(13)* the FEAFLO program was used either to input joist MOE values individually or to specify that the values be selected from a normal distribution. The process of selecting values from a distribution, instead of directly inputting values, is described as a simulation procedure. Because values are picked at random, the method is often described as Monte Carlo simulation *(11)*.

The FEAFLO program permits joist and sheathing properties to be input or simulated in seven different modes (table 1). The mechanics of inputting constant, variable, or simulation data are described by comment cards in the listing of the program. A statistical and plotting routine was used to arrange input and output data, to compute statistics such as means and standard deviations for such variables as joist MOE, midspan joist deflections, joist stresses, etc., and to plot cumulative distributions of input and output data. For this study, all floors were analyzed using Mode 6. Joist properties were input in 10-piece serial lots as they were obtained in the in-grade testing program *(7)*.

Floor Analyses

To simulate a complete distribution of performance, it was necessary to limit the number of floor configurations to be analyzed. This report contains the results of computer analyses of one typical floor construction (fig. 1). The floor contains 10 simply supported 2- × 8- inch (nominal) joists and two additional nondeflecting joists on the edges. The single layer of nominal 5/8-inch plywood sheathing is simply supported and spans perpendicular to the joists. Maximum allowable spans for the two species *(15)* considered in the in-grade testing program are shown in figure 1.

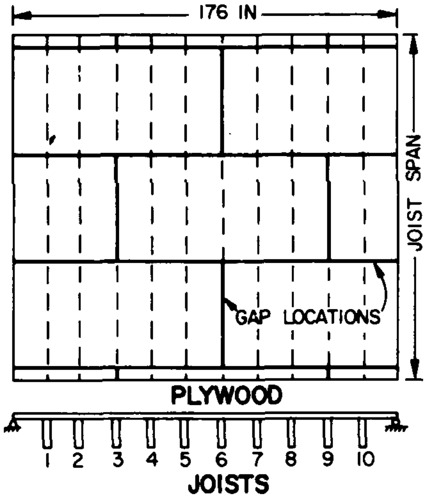

Figure 1.—Data for study floors from NDS (15) design values:
Douglas-fir:
MOE = 1,700,000 lb/in.^{2}
F_b(repetitive) = 1,450 lb/in.^{2}
Southern pine:
MOE = 1,600,000 lb/in.^{2}
F_b(repetitive) = 1,400 lb/in.^{2}
Joist span:
Douglas-fir = 157 in.
Southern pine = 154 in.
Nominal joist dimensions: 2 × 8
Sheathing thickness: 19/32 in., touchsanded
Nail size and spacing: 8d, 6.7 in.
Connecter stiffness: 30,000 lb/in.
Uniform load: 40 lb/ft^2
Tightly butted gaps

Table 1.—FEAFLO analysis modes

Mode	Number *of floors*	Joist *MOE*	Sheathing *MOE*
1	1	Assigned constant[1]	Assigned constant
2	1	Assigned variable[2]	Assigned variable
[3]3	n[4]	Simulated[5]	Assigned constant
[3]4	n	Simulated	Assigned variable
[3]5	n	Assigned variable per simulation run	Simulated
[6]6	n	Assigned variable per floor	Simulated
7	n	Simulated	Simulated

[1] All members given the same properties per layer.

[2] Properties manually assigned to individual members, thus may vary between members.

[3] In modes 3, 4, and 5, assigned constant or assigned variable properties remain constant for each floor in a simulation run.

[4] $n = \leq 100$.

[5] Material properties automatically assigned to members by Monte Carlo methods.

[6] Mode 6 presents strength—as well as stiffness—estimates using joist MOR values. Joist properties are manually assigned for each individual floor in a simulated run.

Previous studies have shown that the distributions of floor response are affected more by the variability of the joists than by any other component, particularly for uniformly loaded floors. Thus, the floors analyzed included an emphasis on the properties of the joists. Other floor component properties were modeled by constant values based upon best estimates of the mean property values. For selected studies, sheathing stiffnesses were varied from panel to panel using industry-provided estimates of plywood variability to determine the effects of varying this parameter.

One parameter that has a significant effect on floor performance is the stiffness of the short finite element used to model the contact surface between adjacent sheets of plywood. This contact region ("gap," fig. 1), has been studied at CSU, and recommended stiffness values have been developed. For the sheathing shown in figure 1, the recommended value of gap modulus of elasticity (E) is 500 lb/in.^{2}, which, when divided by the gap length (L) of 0.1 inch, gives a gap E/L value of 5,000 lb/in.^{2}/in. Because of an oversight, a value of 50,000 lb/in.^{2}/in. was used for the floors analyzed using the 60 lots of sample data. This value of gap stiffness does not affect the relative ranking of floor performances and thus the analyses were not repeated for these sensitivity studies using the sample data. The intended E/L value of 5,000 was used with the complete data group that included all of the sample data. Also with the complete group, a more flexible E/L value of 500 was used for the gaps parallel to the "along-joist" direction because these gaps are not tightly compressed as the floor deflects. The value of E/L used for these gaps along the joists has almost no effect on the behavior of uniformly loaded floors.

Joist Properties

The in-grade field testing program was conducted by testing joists in 10-piece serial lots from mill inventories of visually graded material using portable testing equipment *(7)*. The MOE obtained from the load-deflection behavior, the MOR obtained from the failure load, the moisture content (MC), the joist grade and species, and cross-sectional dimensions were recorded.

Most of the data were grouped in lots of 10 joists. The "sample data" included 30 lots of Douglas Fir-Larch[3] joist data and 30 lots of southern pine data. These data were used in studying effects of moisture adjustments, sheathing type, and sheathing variability on floor performances. The complete data became available late in the study and were not as extensively studied. The complete data included lots of 10 consecutive joists in two categories: (a) "as-graded," and (b) lots containing only joists verified by the grading agencies as being "on-grade." "As-graded" lots had a mixture of lumber stamped No. 2, No. 1, and Select Structural grade while all of the higher-grade material and that determined to be off-grade were eliminated in forming the "on-grade" lots. Thus, all joists in the "on-grade" lots were visually mill graded as No. 2 and verified to be that by a grading supervisor.

The data available and the analyses performed are described in table 2. Properties of the 10 joists in each lot were obtained from the field test data. A few of the lots in the complete data set contained 11 joists. The data for the 11th joist were ignored. Also, a few lots contained data for fewer than 10 joists. For these lots, the available joists were assigned starting at joist 1 and data for the first one or more joists were duplicated in a symmetrical fashion about the centerline of the floor as needed to define properties for all joists.

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[3] For the remainder of the report, the marketing group of Douglas Fir-Larch is referred to as Douglas-fir.

Moisture Adjustments for Joists

The thickness and width of a joist decrease as the MC decreases below the fiber saturation point. Most mechanical properties of clear wood, including MOE and MOR, increase as the MC decreases below the fiber saturation point. There is ample evidence, however, that seasoning has a variable effect on change in strength of structural lumber and might even result in strength reduction for some joists, especially for those having large knots *(12)*.

The MOE, MOR, thickness, and width of joists each vary at different rates as a function of MC. Meaningful comparisons of floor behavior as a function of joist stiffness and strength variability can best be made with all joists at a standard MC. The sample MOE and MOR data were adjusted to an assumed equilibrium MC of 12 percent using ASTM Standard D 2915 *(3)*. The adjusting equations are

$$MOE_2 = MOE_1 \left[\frac{1.44 - 0.02MC_2}{1.44 - 0.02MC_1}\right] \quad (1)$$

$$MOR_2 = MOR_1 \left[\frac{1.75 - 0.0333MC_2}{1.75 - 0.0333MC_1}\right] \quad (2)$$

where 1 and 2 refer to two MC's in percent. Equations based on the work of Wood and Soltis *(27)* were developed by FPL to adjust joist dimensions:

$$T_2 = T_1\,(1 - 0.01(MC_1 - MC_2)/5.53) \quad (3)$$

$$W_2 = W_1\,(1 - 0.01(MC_1 - MC_2)/4.64) \quad (4)$$

where T = thickness (approximately 1-1/2 in. for a 2 × 8), and
W = depth.

Table 2.—Data available and analyses performed

Joist type in floor	Number of 10-joist lots	Moisture condition and adjustment: Modulus of elasticity	Moisture condition and adjustment: Modulus of rupture[1]	Plywood properties
		SAMPLE DATA		
Douglas-fir	30	Green	Green	CSU
		Dry, ASTM[2]	Dry, ASTM	CSU
		Dry, ASTM	Dry, EVSF[3]	CSU
		Dry, ASTM	Dry, ASTM	APA
		Dry, ASTM	Dry, ASTM	APA[4]
Southern pine	30	As received	As received	CSU
		Dry, ASTM	Dry, ASTM	CSU
		COMPLETE DATA[5]		
Douglas-fir, as-graded	[6]138	As received	As received	APA
	108	green	green	APA
	30	dry	dry	APA
Douglas-fir, on-grade	[6]177	As received	As received	APA
	138	green	green	APA
	39	dry	dry	APA
Southern pine, as-graded	107	As received	As received	APA
Southern pine, on-grade	137	As received	As received	APA

[1] All capacities computed using linear FEAFLO were multiplied by 0.90 to approximately compensate for linear-nonlinear difference of fig. 10.

[2] Material properties adjusted using eqs. (1) and (2); dimensions adjusted using eqs. (3) and (4).

[3] MOR adjusted using empirical variable seasoning factor (fig. 2); all other adjustments made as above.

[4] Coefficient of variation = 0.26 for all EI and EA values for this floor.

[5] The complete data set includes the sample data; no moisture correction applied.

[6] 138 lots as-graded included 108 green and 30 dry lots; 177 lots on-grade = 138 green + 39 dry.

In equations (1) through (4), MC_2 was 12 percent and MC_1 was the as-tested value. The southern pine as-tested values ranged from 9 to 30 percent with a mean of about 15 percent for the 30-lot sample of table 2. The 30-lot sample of Douglas-fir joists was reported as green and these MOE and MOR values were corrected from a green MC of 24 percent to the seasoned value of 12 percent. The 24 percent value was reported as the point at which material properties begin to change with drying *(24)* and was the maximum value used in equations (1) and (2). Shrinkage computations were made using MC_1 as not more than 28 percent.

A second procedure was also used in modifying MOR. Termed the empirical variable seasoning factor (EVSF), this factor was based on work by Madsen *(12)* with some additional modifications. In drying from green conditions to 12 percent moisture content, the EVSF is assumed to vary between 1.0 and 2.0 (fig. 2) depending upon a joist's percentile ranking within the green MOR distribution. Lots within the same grade and species were all combined to form the MOR distribution. This second procedure was selected for demonstration purposes only and is not recommended as a universal procedure. The EVSF modifications of joist MOR values were accompanied by adjustments of the joist MOE and sizes using equations (1), (3), and (4).

Plywood Properties

The FEAFLO program models a floor as a set of crossing beams. One set comprises the joists and sheathing acting as T-beams in the floor span direction. The second is obtained by dividing the sheathing into strips spanning perpendicular to the T-beams. Two properties of the sheathing are required in each direction. These are the EA and EI values where E = modulus of elasticity, A = area, and I = moment of inertia. The plywood is assumed to be placed with the face grain perpendicular to the joists and it is convenient to describe the EA and EI values as parallel ($\parallel$) or perpendicular ($\perp$) to the face grain.

Two sets of values were used. The first was computed at CSU using a plywood layup having Group 2 face plies and Group 3 interior plies from the Plywood Design Specification (PDS) *(2)*. The second set was furnished by the APA as "best estimates" of these properties. The APA values are higher than the CSU values (table 3) primarily because of the conservative E values used in the CSU computations. According to APA, a high percentage of production uses stiffer Group 1 species in the layups instead of the Group 2 and 3 permitted and assumed for the CSU computation.

Table 3.—Plywood stiffness values

Rigidity[1]	Plywood[2] Design Specification	CSU[3] calculated values	APA average values[4,5]
$EI_{\parallel}$ (kip in.^{2}/ft)	184.5	220.8	287.5
$EI_{\perp}$ (kip in.^{2}/ft)	28.5	61.4	106.3
$EA_{\parallel}$ (kip/ft)	3,927	5,723	7,950
$EA_{\perp}$ (kip/ft)	2,415	3,640	6,525

[1] EA = axial rigidity per foot of width.
EI = flexural rigidity per foot of width.
$\parallel$, $\perp$ = properties parallel and perpendicular to face grain of panel.

[2] PDS values represent minimum values considering all available ply layups. Because minimum values for each direction occur for different layups, it is impossible to obtain a panel for which all the minima occur simultaneously; hence, these values are too conservative for use in floor analysis *(2)*.

[3] Computed using Group 2 faces and Group 3 interior plies *(2)*.

[4] Actual test data for EI and calculated for EA. These values represent industry production, which typically utilizes 90 pct or more of Group 1 woods *(2)*.

[5] COV for APA values = 0.26. Limited data indicate the COV for EA is larger than the COV's for the other rigidities. The COV for EA was assumed to apply to the other values in the study reported herein.

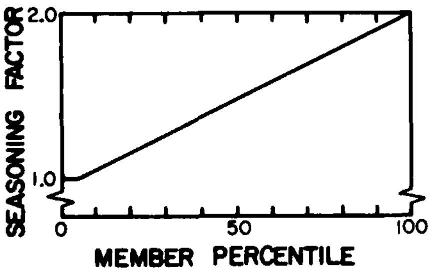

Figure 2.—Description of empirical variable seasoning factor (EVSF). (ML83 5170)

Connector Properties

Methods of determining the nonlinear load-slip curve for nails is a subject of current research. For this study, a 30,000-lb/in. connector stiffness value was chosen based on previous research *(25)* to best represent the conditions at the service load level for an 8d common nail connecting Douglas-fir plywood to a joist with a density near that of southern pine or Douglas-fir. A constant 6.7-inch nail spacing was specified to approximate the correct number of nails in the floor, considering that nail spacing is closer on sheathing edges than in the interior of the sheet.

Because connector stiffness is nonlinear and decreases with additional nail slip, the connector stiffness at overload and failure load levels is less than at service load level. This nonlinearity can be included in a nonlinear analysis *(26)* or it can be approximated by specifying a reduced connector stiffness. In this study, with a single connector stiffness of 30,000 lb/in. the resulting overestimation of the connector stiffness at overloads and its contribution to floor strength can be reasonably accounted for by a correction factor. A factor has been estimated based on analyses of three selected floors using both the linear model and the nonlinear analysis described by Wheat et al. *(26)*.

Service Load Response

Measures of Deflection Performance

Three measures of deflection response were obtained for each floor: The average deflection of the eight interior joists, the largest average of any three adjacent joists, and the largest individual joist deflection. Deflections in all cases were at midspan. The average deflection of the interior eight joists is a measure of mean floor performance and is hereafter referred to as the "mean" deflection. The deflections of joists 1 and 10 in (fig. 1) were excluded from this average because they are reduced by the parallel supports. The largest average of any three adjacent joists is a measure of the "soft-spot" performance. The third measure, maximum single joist deflection, typically, but not always, occurs for the joist with the lowest MOE.

In a hypothetical floor constructed with materials of uniform stiffness and having edges that are free to deflect, the three deflection measures will be identical. In real floors with variable properties, the mean deflections will be the smallest and will show the least variability; the soft-spot deflection values will be intermediate both numerically and in their variability; and the maximum single joist deflections will be the largest and the most variable. All three measures are influenced by floor size. Thus, all three are reasonable measures of the relative performance of floors all having the same number of joists.

Douglas-fir Floors, Sample Data

Effects of MC on Deflection Performance

The MC adjustment made using equations (1), (3), and (4) resulted in increasing joist MOE by 25 percent and decreasing the moment of inertia (MOI) by 12.6 percent. The final change in joist EI due to this assumed seasoning was (1.25 × 0.874) × 100 percent = 109 percent. This 9 percent increase agrees fairly well with limited test results *(27)*. To provide further demonstrations of the effects of joist EI on floor performance, analyses were also made using an arbitrary joist EI increase of 22 percent, which is believed to be greater than any possible increase.

Cumulative distribution functions (CDF) of mean deflections are shown (fig. 3, upper) for three MC conditions. Thirty points were used to draw each curve; each point was obtained using the joist data for one lot with the individual joist values assigned in the order given in the lot. Each point represents a separate floor analysis made holding all material properties constant (fig. 1, table 3 (CSU calculated plywood values)) except joist properties. Each distribution curve (fig. 3, upper) has the same general shape, as all joists underwent the same seasoning correction. The average decrease in mean deflection from green to 12 percent MC is 4 percent when EI is increased by 9 percent. Increasing EI by 22 percent decreased the average deflection by 12 percent. The changes in deflections are smaller than the changes in EI because the floor acts as a complex system in which the joist plays a major but not exclusive role. The larger the increase in EI, the larger is the corresponding change in deflection because the greater the EI, the greater is its influence on the system.

The span over 360 deflection value is noted in each distribution of joist deflections. This span/360 quantity is a customary deflection limitation value widely used in the simplified bare joist design of floors. As currently used in design, it implies that this value is at the 50th percentile of a distribution of floor deflections. It is cited here primarily because it is familiar to most designers and researchers of wood floors. Actual floors with composite behavior, designed according to the current simplified procedures with average-quality material, should deflect less than this customary design value. The correct service load deflection limit state for use with both improved analysis and design procedures and actual material properties remains to be defined. Its selection is complicated by the subjective and variable judgments of occupants of wood joist floor structures on what are acceptable floor deflection and vibrational properties *(17,18)*.

In addition to mean floor deflection, figure 3 includes cumulative distribution plots for soft-spot and maximum single joist deflections.

Sheathing Stiffness Effects on Deflections

Effects of varying sheathing stiffness were studied by analyzing 30 floors using the 30 lots of Douglas-fir data adjusted to 12 percent MC and 3 sets of plywood values (table 3): The CSU values, the APA values without variability, and the APA values with a coefficient of variation (COV) of 26 percent (fig.4). In the study of the floor response for a COV of 26 percent, the plywood EI and EA values for each sheet were randomly selected from a normal distribution that was truncated three standard deviations above and below the mean.

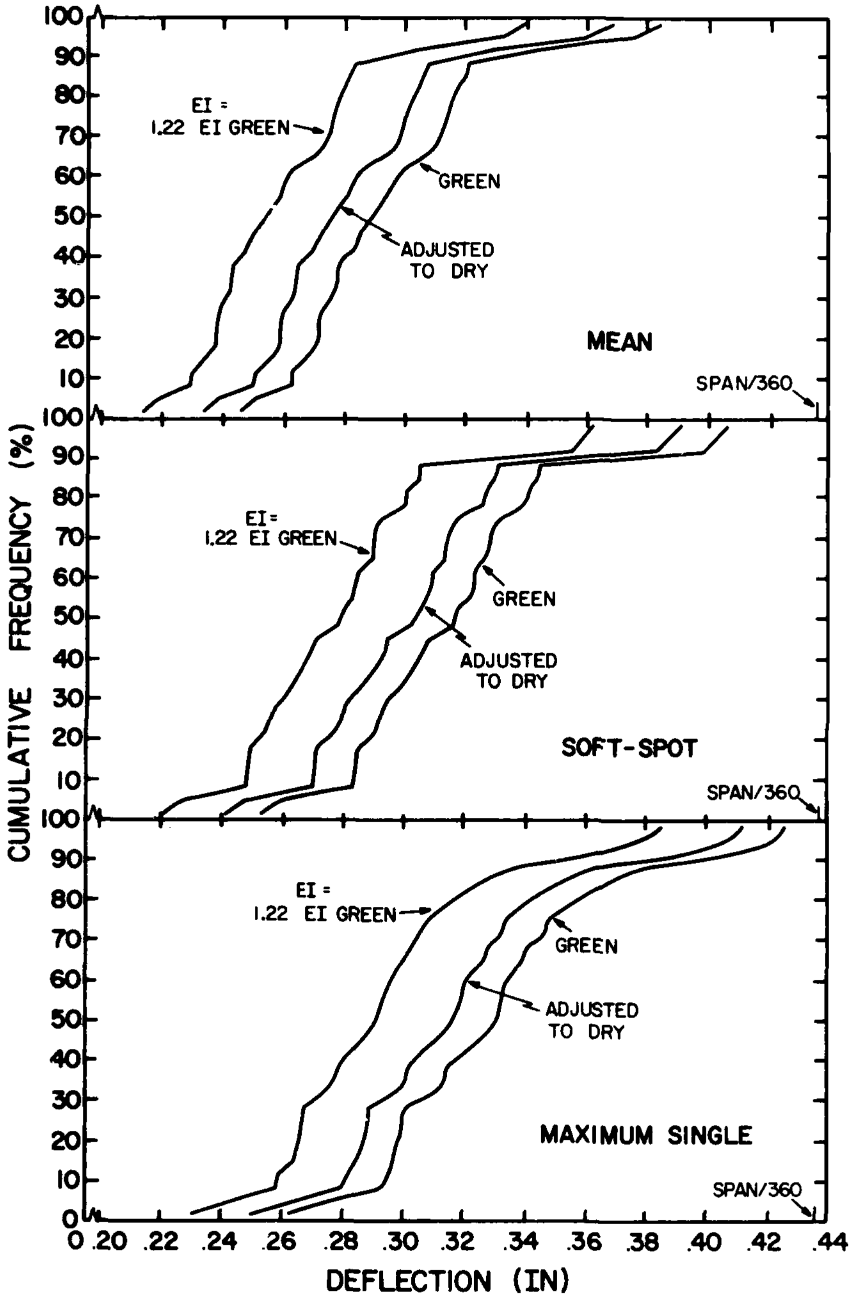

Figure 3.—Cumulative mean (upper), soft-spot (center), and maximum single (lower) joist deflections, Douglas-fir sample data. (ML83 5169)

Cumulative distributions for mean floor deflections and for maximum single joist deflections are plotted in figure 4; soft-spot distributions fell about halfway between the other values, allowing several observations. First, the values for the APA plywood with and without variation are so close that, for all practical purposes, variability of plywood can be omitted from consideration in the design of uniformly loaded floors. However, it is expected that point (concentrated) loaded floors will be more sensitive to plywood variations. Second, the APA deflections are about 8 percent less than the CSU deflections largely because the APA $EA_{\perp}$ value is 80 percent greater than the CSU values. Of the four EA and EI values, the $EA_{\perp}$ value has the greatest influence on the behavior of uniformly loaded floors because it controls the stiffnesses of the compression flanges of the T-beams. (Note that the plywood perpendicular to the face grain direction is parallel to the joists.)

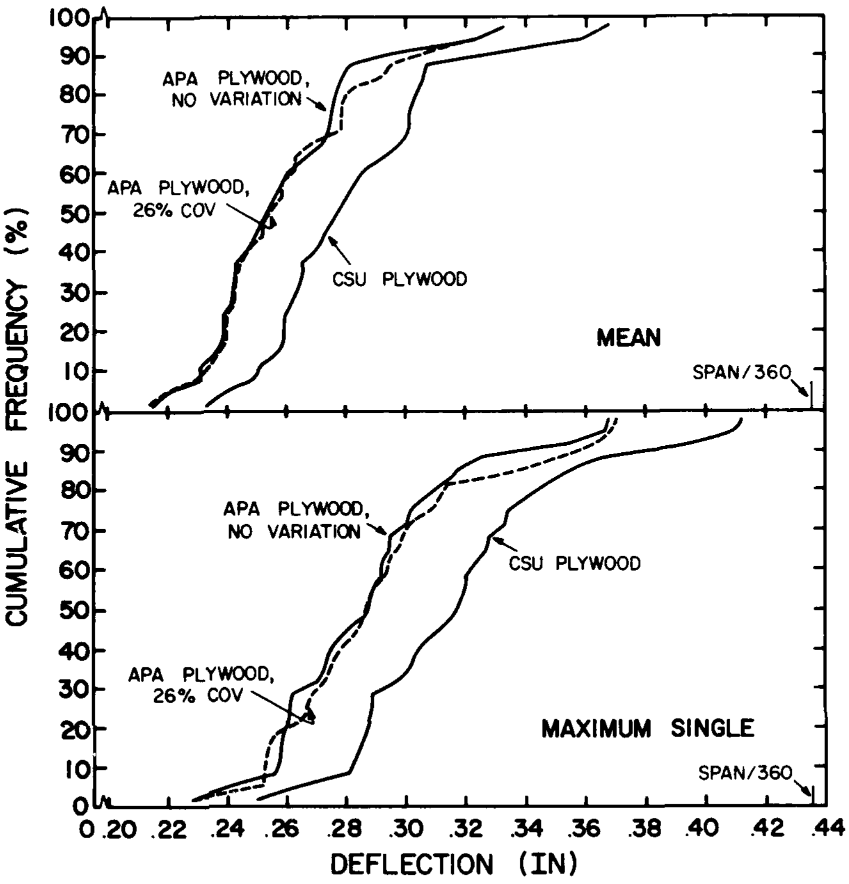

Figure 4.—Mean (upper) and maximum single (lower) joist deflections, Douglas-fir sample data, dry, with CSU and APA plywood data (see table 3). (ML83 5171)

Comparisons of Deflection Performance Criteria

Distributions of floor deflection as measured by the three deflection criteria are shown for green joists and CSU plywood (fig. 5, upper) and for seasoned (12 pct MC) joists and APA plywood (fig. 5, lower). Values for seasoned joists and CSU plywood lie between those values and are not shown. Deflection statistics are summarized in table 4. The plots and table show two results of interest. First, the ratio of mean interior deflection to mean maximum single joist deflection is about 0.89 for each of the moisture conditions listed in table 4. The ratio of mean soft-spot to maximum single joist deflection is about 0.95. These differences are not very great for the uniform loading condition, the shapes of the distributions are similar, and any one of the criteria appears satisfactory for use in calibrating future design. Second, all floors were considerably stiffer (i.e., deflected less) than the span/360 value shown in each figure. In fact, the maximum single joist deflection of all 60 floors was less than span/360.

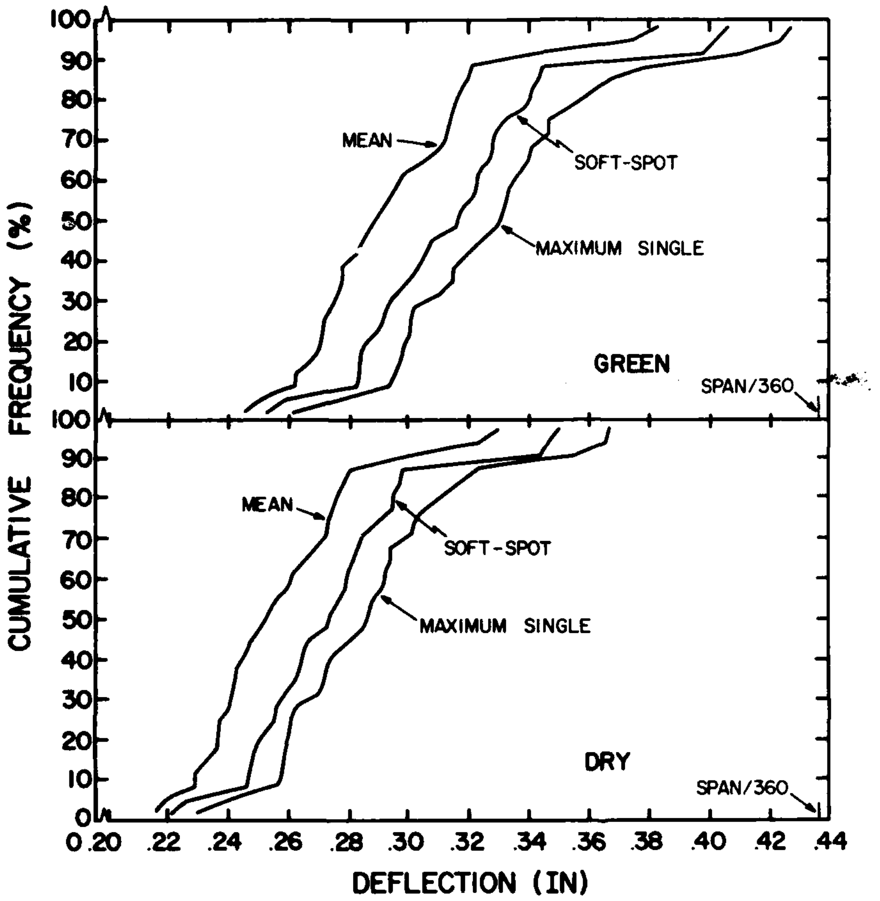

Figure 5.—Deflection performance criteria for Douglas-fir sample data, green (upper) and dry (lower), with APA plywood values and no plywood variation. (ML83 5172)

Table 4.—Summary of deflection statistics, Douglas-fir sample data

Moisture condition	Deflection performance criteria	Deflection statistics				
		Range		Mean	COV	Mean ÷ L/360
		Low	High			
		------In.	-------			
Green, CSU plywood data	Mean	0.246	0.383	0.296	0.109	0.679
	Soft-spot	.253	.406	.318	.116	.729
	Maximum single	.262	.427	.333	.120	.763
Adjusted to dry, CSU plywood data	Mean	.234	.368	.283	.111	.649
	Soft-spot	.241	.391	.304	.119	.697
	Maximum single	.250	.412	.319	.122	.731
Adjusted to dry, APA plywood data, no variability	Mean	.216	.332	.258	.106	.592
	Soft-spot	.222	.352	.277	.114	.635
	Maximum single	.229	.368	.289	.117	.662
Adjusted to dry, APA plywood data, 0.26 COV	Mean	.215	.332	.260	.110	.596
	Soft-spot	.221	.358	.280	.106	.642
	Maximum single	.228	.370	.292	.124	.670

Douglas-fir Floors, Complete Data

Cumulative distributions of floor deflections for the complete set of data are shown in figures 6 and 7 in the form of span/deflection ratios. Statistics are given in table 5. An estimate of the 5th and 50th percentiles (by count) along with the 360 value of the span/deflection ratio are identified on each plot for purposes of comparison only. The 5 percent and 50 percent values (by count) for maximum single joist deflections correspond to a span/deflection ratio of about 330 and 420, respectively. Similar values for mean joist deflection are 380 and 460, respectively. The soft-spot data fall about midway between the individual and mean joist data. The deflections observed are somewhat different from the sample data because, as previously noted, a lower, more realistic gap stiffness value was used with the complete joist data.

The as-graded lots that were reported in the green condition were used in computing the CDF of figure 6, center, and the reported dry data were used for figure 6, lower. The performance of the dry floors appears to be poorer than the performance of the total sample (fig. 6, upper). However, the sample size of 30 is small and the more meaningful CDF's are those in the total sample.

The CDF's for the on-grade data are shown in figure 7.

Southern Pine Floors, Sample Data

In cumulative plots for mean deflections (fig. 8, upper) and maximum joist deflections (fig. 8, lower) for the southern pine floors, the curves for the two moisture conditions do not display the similarity of shapes shown by the Douglas-fir floors because of the variable moisture adjustments applied to the southern pine. The average MC adjustment was small and hence the two curves on each figure are close together. For example, the mean deflection for the as-received condition was 0.289 inch, which is only 1.7 percent greater than the 0.284-inch value for the dry case. Deflection data are summarized in table 6.

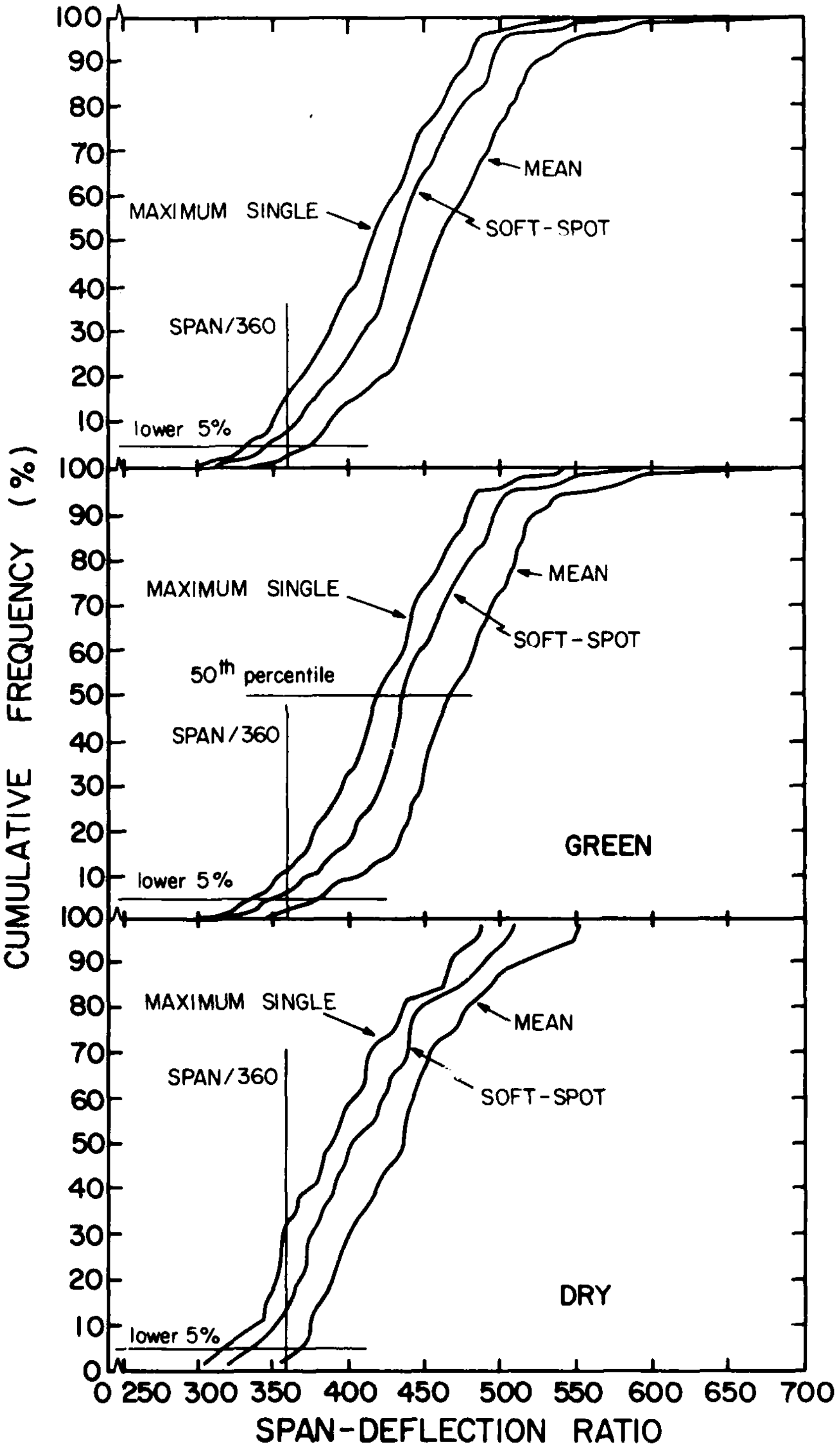

Figure 6.—Cumulative span-deflection ratios, Douglas-fir as-graded, 138 lots (upper), of which 108 were green (center) and 30 were dry (lower). (ML83 5173)

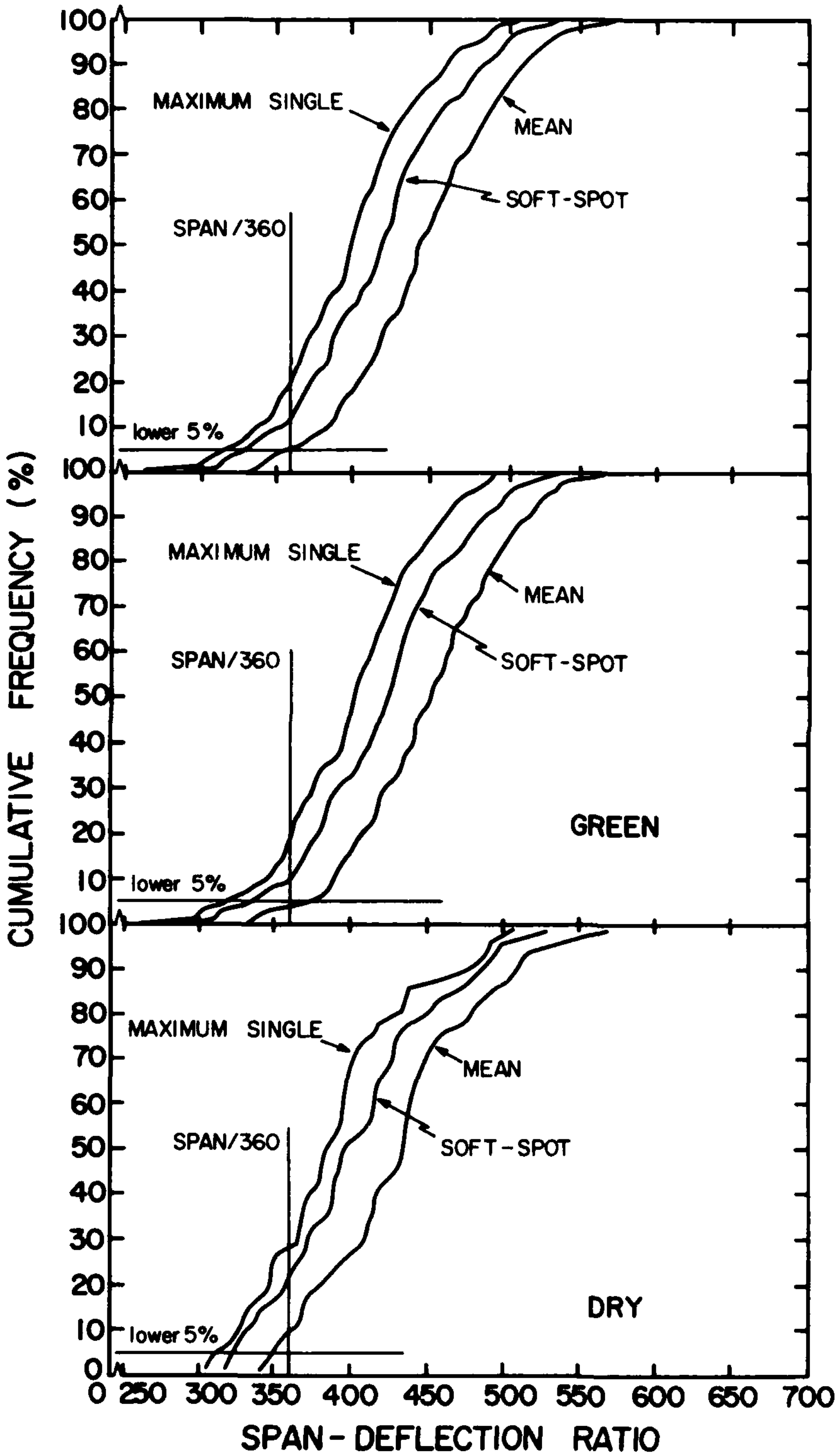

Figure 7.—Cumulative span-deflection ratios, Douglas-fir on-grade, 177 lots (upper), of which 138 were green (center) and 39 were dry (lower). (ML83 5174)

Table 5.—Summary of span-deflection statistics, complete data

Number of floors	Joist type in floor	Deflection performance criteria	Distributions shown in	Span-deflection ratio statistics		
				Range	Mean	COV
107	Southern pine, as-graded	Mean	Figure 9, upper	343-691	478	0.133
		Soft-spot		305-651	443	.145
		Maximum single		295-605	417	.142
137	Southern pine, on-grade	Mean	Figure 9, lower	352-681	474	.134
		Soft-spot		316-647	438	.143
		Maximum single		306-580	415	.143
138	Douglas-fir, as-graded	Mean	Figure 6, upper	342-678	464	.118
		Soft-spot		315-587	434	.116
		Maximum single		303-542	416	.119
108	green	Mean	Figure 6, center	342-678	472	.113
		Soft-spot		315-587	441	.111
		Maximum single		303-542	422	.114
30	dry	Mean	Figure 6, lower	357-552	437	.119
		Soft-spot		322-509	412	.121
		Maximum single		306-488	394	.123
177	Douglas-fir, on-grade	Mean	Figure 7, upper	334-570	446	.112
		Soft-spot		290-533	416	.121
		Maximum single		264-508	398	.118
138	green	Mean	Figure 7, center	334-566	450	.107
		Soft-spot		290-533	420	.117
		Maximum single		264-493	400	.114
39	dry	Mean	Figure 7, lower	342-570	433	.126
		Soft-spot		318-530	405	.132
		Maximum single		306-508	390	.131

Table 6.—Summary of deflection statistics, southern pine sample data[1]

Moisture condition	Deflection performance criteria	Deflection statistics				
		Range		Mean	COV	Mean ÷ L/360
		Low	High			
		------- In. -------				
As-received	Mean	0.223	0.394	0.289	0.129	0.676
	Soft-spot	.233	.425	.313	.138	.732
	Maximum single	.249	.431	.333	.134	.778
Adjusted to dry	Mean	.220	.387	.284	.129	.664
	Soft-spot	.231	.418	.308	.137	.720
	Maximum single	.248	.423	.328	.136	.767

[1] Plywood stiffness based on CSU calculations.

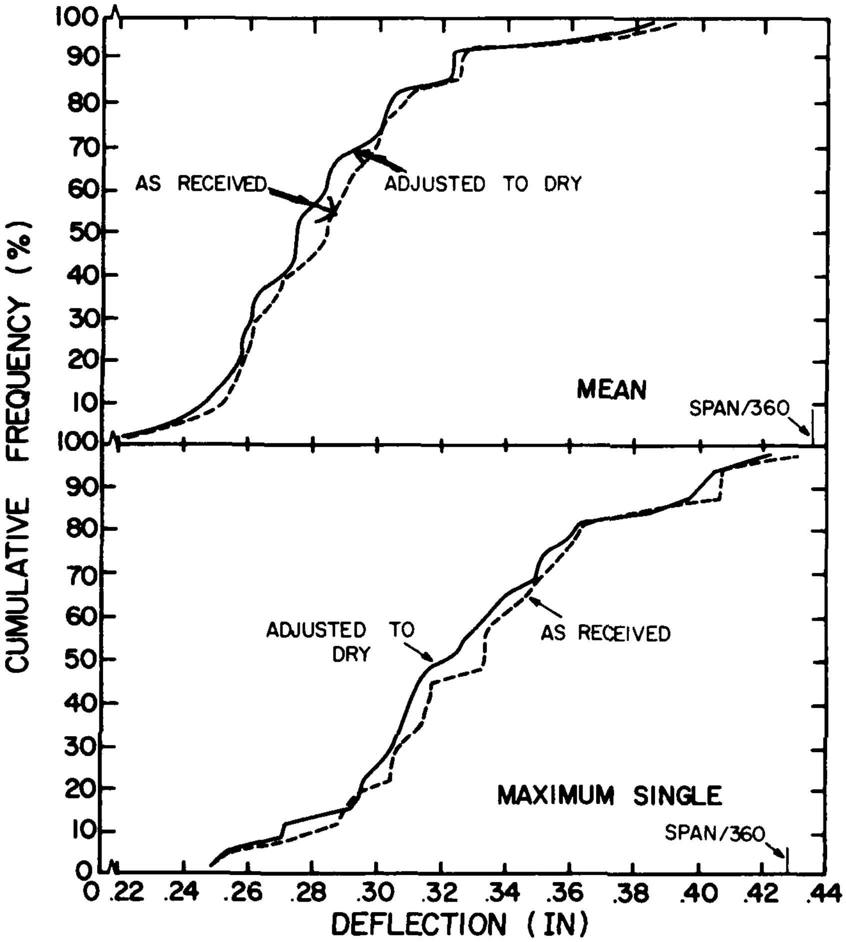

Figure 8.—Cumulative mean (upper) and maximum single (lower) joist deflections, southern pine sample data. (ML83 5175)

Southern Pine Floors, Complete Data

The deflection data for the southern pine as-graded (fig. 9, upper) and on-grade (fig. 9, lower) MOE values are quite close to the results for the Douglas-fir. Again, the lower sheathing gap stiffness value used with the complete joist data is responsible for at least part of the difference between the sample and the complete data results. Various statistics are given in table 5.

Discussion of Performance Criteria

Each of figures 6, 7, and 9 shows several possible ways of defining acceptable performance. Deflections are reported for three cases: the average of the eight interior joists (mean), the softest of the eight sets of contiguous three joists in a floor (soft-spot), and the joist in each floor exhibiting the maximum deflection. These are compared with two criteria: The lower 5th percentile usually associated with allowable stresses in engineered wood products and the 50th percentile often associated with stiffness criteria. The percentile corresponding to the historic L/360 value is a third possible criterion (table 7).

If the acceptance criterion is chosen to be the L/360 limit, then from 5 to 21 percent of the floors deflect more than this limit depending upon the measure of performance chosen. The applicability of the L/360 limit for actual floor performance, as opposed to calculations using bare joists and mean MOE, has not been yet resolved. This limit certainly cannot be expected to apply equally to these three different deflection measures.

One important source of evidence on which deflection performance is now judged to be adequate is to examine a reasonably lower bound of values now being provided. If it is assumed that 95 percent of the floors built using on-grade Douglas-fir and APA plywood are satisfactory, then the corresponding span/deflection ratios range from 320 to 360, depending upon the performance measure selected. An infinite number of other values could be obtained by choosing other exclusion limits and span/deflection criteria.

Design values of MOE have historically been selected to represent the population mean for the species and grade considered. Thus, it is interesting to compare mean floor performance to the commonly used L/360 limit. The mean ratios (table 5) range from 8 to 33 percent greater than the L/360 value, showing that the mean floor behaviors were better than the bare-joist design limit. This would certainly be expected due to the consideration of composite action.

There is no consensus on what constitutes the best measure of acceptable floor performance. A generally accepted definition is required for use in calibrating probability-based procedures for floor design, especially if both concentrated and uniform loads are to be considered.

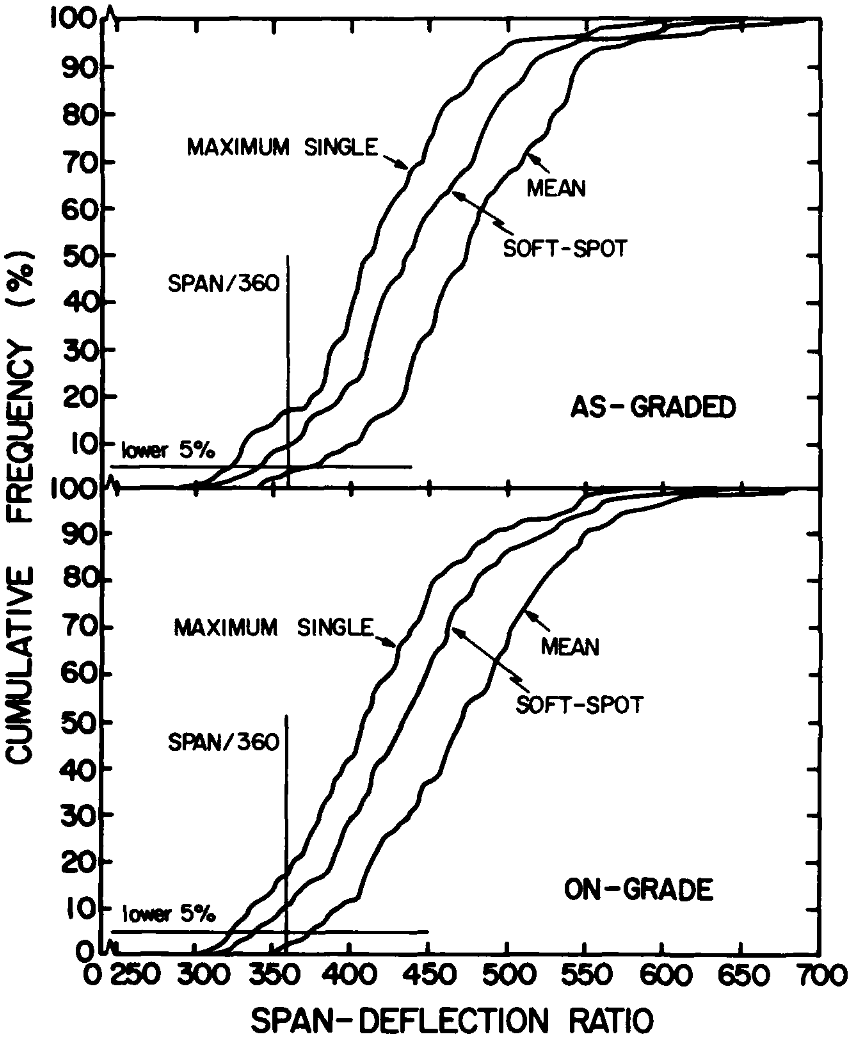

Figure 9.—Cumulative span-deflection ratios, southern pine as-graded, 107 lots (upper) and on-grade, 137 lots (lower). (ML83 5176)

Table 7.—Three criteria for judging acceptability of floors with on-grade Douglas-fir joists.

Measure of performance	Span/deflection ratio at lower 5th percentile	Span/deflection ratio at 50th percentile	Percentile corresponding to L/360
Mean	360	440	5
Soft-spot	330	420	13
Maximum single	320	400	21

Failure Load Response

Linear Prediction Technique

Although floor strength is a function of all the factors affecting deflections, it is most greatly influenced by joist MOR. As shown by Wheat et al. *(26)*, floor strength at first joist failure can be predicted accurately only if paired MOE-MOR data for each joist are used with a nonlinear analysis program. An approximate nonconservative estimate can be made using paired data with the linear FEAFLO program. The linear prediction technique used in obtaining the strength data presented in this paper consists of determining the uniform load at first joist rupture by linearly extrapolating joist stresses at design load using the expression

$$W_f = W_s\,(MOR_l/\sigma_l) \qquad (5)$$

where W_f = failure load, lb/ft²,
W_s = service load of 40 lb/ft²,
MOR_l = MOR of controlling joist, and
σ_l = stress in controlling joist at 40-lb/ft² loads, lb/in.².

The controlling joist for a given floor is the joist that gives the lowest predicted failure load.

Equation (5) results in overestimating floor strength at first joist failure because it is based on the assumption of linear behavior to failure and on a connector stiffness chosen to be most valid in the service load range. In reality there are several sources of nonlinear material behavior with increasing floor load. These include nonlinear load-deflection behavior of joists, sheathing, gaps, and connectors.

In the floor-strength model, connector nonlinearity was assumed to be the dominant nonlinear effect. Thus, the stiffnesses of the joists, sheathing, and gaps were assumed to be linear. Strengths predicted by linear and nonlinear analyses (for connectors only) for three floors were compared (fig. 10) with the linear analysis from FEAFLO and the use of equation (5), and the nonlinear analysis from the techniques described by Wheat et al. *(26)*. The three floors consisted of green Douglas-fir joists and were chosen to represent low, average, and high strengths with respect to the sample

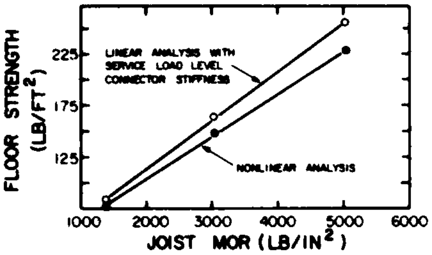

Figure 10.—Controlling joist MOR versus floor strength, linear and nonlinear analyses. (ML83 5178)

population. The linear model with the service load connector stiffness value overestimated capacities by 8 percent (low MOR) to 12 percent (high MOR).

Whereas the linear model overpredicts strength, it apparently can provide a reasonable estimate of strength at virtually no additional cost after the service performance analysis has been made. The linear model also provides a useful way to study the effects of the MC adjustment technique and other behaviors.

Effects of MC Adjustment on MOR

Determining the effects of MC changes on MOR is complicated by the necessity of performing destructive tests to measure MOR. Hence defining effects of MC change on MOR must be made by testing many similar specimens at various MC levels. Because of the uncertainty in describing MOR adjustments due to MC changes, two techniques were studied using the sample data, the ASTM method of equation (2) and the empirical variable seasoning factor (EVSF) (fig. 2).

The ASTM adjustment was applied to the 30 lots of both Douglas-fir and southern pine joists to adjust their MOR values to a 12 percent MC. Because all the Douglas-fir joists were adjusted from the assumed green or "intersection" MC of 24 percent to the seasoned value of 12 percent using equation (2), each MOR value for Douglas-fir was given by the expression

$$MOR_{dry} = 1.42\ MOR_{green} \qquad (6)$$

This adjustment differs from the 35 percent increase in MOR given by ASTM D 245 *(4)* for drying from green to 15 percent maximum MC, because of the assumed value of the "intersection" moisture content (MC_i) in equation (6). To obtain an adjustment of 35 percent, a value of MC_i of 22.5 percent must be used *(10)*. The MOR adjustment for southern pine differed for each piece as reported MC values ranged from 8 to 30 percent. The average adjustment was an increase of 8 percent.

The EVSF procedure is based on the theory that weaker joists do not improve with seasoning as much as do stronger joists. Lower strength joists may more often develop seasoning defects such as checks and shakes that can further reduce their strength. The EVSF was assumed to be 1.0 for the joists in the lower 5th percentile although there is some evidence that lower strength joists can lose strength with seasoning *(12)*. The EVSF method was used only with the Douglas-fir data. It was assumed that the southern pine data reflected the effects of seasoning defects as these data were reported for an average MC of 15 percent.

In all of the floor strength analyses in which moisture corrections were made, the joist width and thickness were adjusted in computing the MOI (and section modulus), and the MOE and MOR were adjusted as previously described. Hence the deflection calculations consider these dimensional changes. However, because of a programming oversight, the flexural strains were computed using the nominal depth of 7.25 inches rather than the actual depth. For the Douglas-fir joists, the actual depth using equation (4) should have been 7.25 × (1 — 0.0345) = 7.00 inches. Hence the flexural component of the total strain for the Douglas-fir floors was 3.5 percent too high. The corresponding average error for the southern pine floors was 0.7 percent too high. The capacities reported in the following section and in figures 11 through 13 are thus slightly in error but the relative rankings are still correct.

The nominal depth error and gap E/L = 50,000 error do not occur in figure 10.

Effects of MC Adjustment on Failure Loads

The cumulative distributions of failure loads, based on predicted first joist failure, for floors of southern pine joists and CSU plywood are nearly the same for the two conditions, with and without the moisture content adjustments (fig. 11, upper). This similarity is due to the small average ASTM seasoning adjustment for MOR of only 8 percent for the 30 lots of sample data. The mean failure load for the as-received floors (no MC adjustment) was 190 lb/ft^2, and for the assumed-dry condition (12 pct MC) was 6 percent higher, 201 lb/ft^2.

Mean failure loads of the Douglas-fir floors adjusted to dry using the ASTM procedure are about 22 percent greater than the mean for floors with green lumber and CSU plywood (fig. 11, lower). The effect of using APA plywood with its 80 percent greater EA value, compared to the CSU plywood, is to increase the mean strength by 5.4 percent. This shows, as expected, that increasing sheathing stiffness has little influence on increasing strength. Statistics are summarized in table 8.

The combination of increasing MOE by 25 percent using equation (1), reducing MOI by 16 percent using equations (3) and (4), and increasing MOR by 0 to 100 percent using figure 2 results in a net decrease in strength except for the strongest floors (EVSF curve, fig.11, lower) . The reason is that the seasoning correction increases the stiffness of the joist layer with respect to the sheathing layer, thus increasing the proportion of the total strain energy carried by the joists, but the EVSF does not provide a commensurate increase in strength for the low-strength joists most likely to control the floor strength. Stiffness attracts stress, and this results in lower floor strength when these stiffer joists do not have at least a corresponding increase in strength.

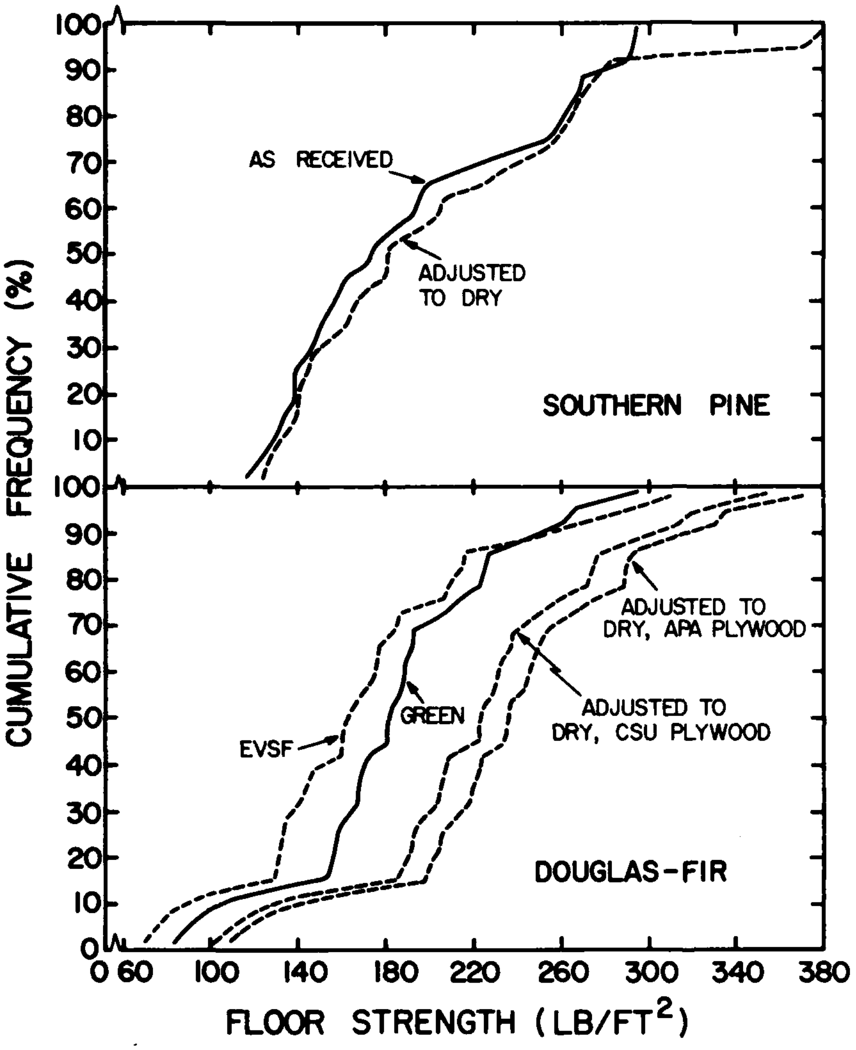

Figure 11.—Cumulative floor strength, southern pine sample data (upper) and Douglas-fir sample data (lower). (ML83 5177)

Table 8.—Floor strength, Douglas-fir sample data[1]

Moisture condition or adjustment type	Plywood values	Lowest floor strength	Mean floor strength	COV
		Lb/ft²		
Empirical variable seasoning factor	CSU	72	170	0.34
Green	CSU	84	182	.26
Dry, ASTM adjustment	CSU	103	222	.26
Dry, ASTM adjustment	APA	108	234	.26

[1] Floor strength values (at first joist failure) computed using nominal joist depth of 7.25 in.

The high-strength floors contained no low-MOR joists. The controlling joists in these floors were in the mid- to high-MOR range and were assigned significant seasoning increases by the EVSF curve, which more than compensated for the additional stress attracted by these joists by the increased joist EI. Consequently, these strong floors became even stronger. This is why the EVSF curve (fig. 11, lower) crosses the green curve near the top of the distributions.

These analyses have been limited to the case in which only the joists change in moisture content. For an entire system that undergoes a change in moisture content, changes in both connector and sheathing stiffness must be considered.

Floor Failure Loads

Failure loads for the complete data sets for southern pine as-graded and on-grade, and for Douglas-fir as-graded and on-grade (fig. 12) were computed with no moisture adjustment factors and using the APA-provided plywood properties. The strengths computed using the linear model were all reduced by 10 percent to compensate approximately for the differences between linear and nonlinear analyses shown in figure 10. Strength statistics are summarized in table 9.

The failure loads at the lower 5 percent level (shown on each figure) and ratios of these loads to the 50 lb/ft² (40 lb/ft² live load plus 10 lb/ft² dead load) design load are shown in table 10. The ratios of load/50 are not directly comparable to factors of safety associated with published values of allowable stresses as these MOR data are unadjusted for either MC or duration of loading. Also, these are measures of loads at first joist failure and likely underestimate the actual collapse load.

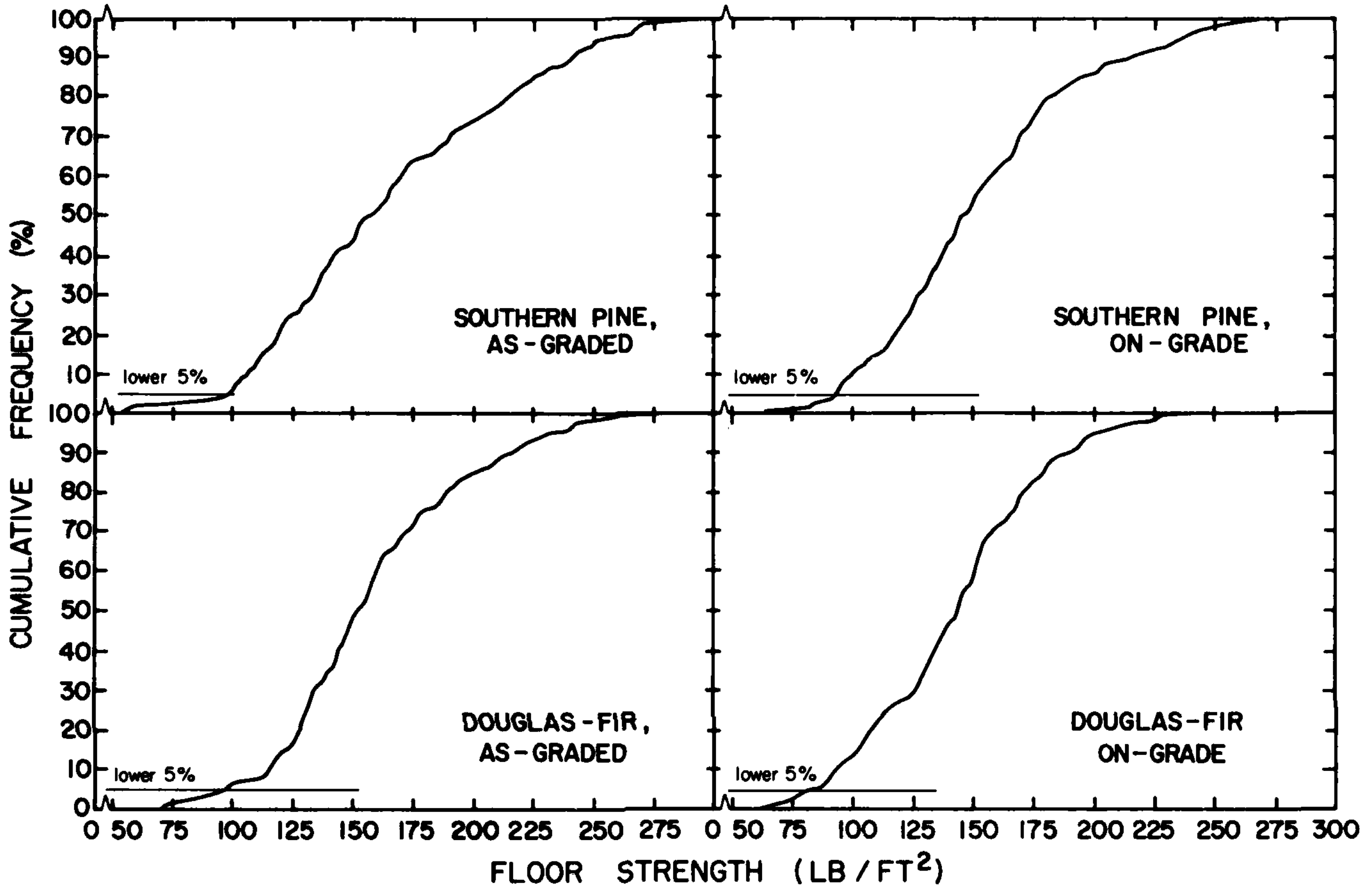

Figure 12.—Cumulative floor strength, southern pine as-graded, 107 lots (upper left) and on-grade, 137 lots (upper right), Douglas-fir as-graded, 138 lots (lower left) and on-grade, 177 lots (lower right). (ML83 5179)

Table 9.—Summary of floor strength capacity statistics, complete data

Number of floors	Joist type in floor	Floor strength statistics[1]			
		Range		Mean	COV
		Low	High		
		---------Lb/ft²---------			
107	Southern pine, as-graded	64	338	168	0.32
137	Southern pine, on-grade	64	277	153	.29
138	Douglas-fir, as-graded	71	277	158	.25
108	green	71	277	161	.23
30	dry	72	249	148	.32
177	Douglas-fir, on-grade	62	249	143	.26
138	green	62	249	147	.25
39	dry	67	228	127	.29

[1] Floor strength values (at first joist failure) computed using nominal joist depth of 7.25 in., and linear FEAFLO with a reduction factor of 0.90.

Correlation of Joist Characteristics with Floor Strength

Possible correlation between joist properties MOE, MOR, and joist deflection capacity index (DCI) and the floor strength were studied using the sample data. MOE, MOR, and DCI were each plotted against floor strength for floors with green Douglas-fir joists (sample data) and CSU plywood. The DCI is defined as the ratio of joist MOR to MOE and is a combined measure of both strength and stiffness. This index assumes that the joists deflect linearly to failure.

In a plot of MOE of the controlling joist versus floor strength, the correlation coefficient (r) is 0.27 and the standard error of the estimate (SEE) is 45.5 lb/ft² (fig. 13, upper). Clearly, attempting to compute floor strength based on MOE is unsatisfactory.

The DCI was developed in an attempt to relate floor strength to both strength and stiffness of the joists (fig. 13, center; r = 0.87, SEE = 23.1 lb/ft²), but it does not provide any improvement over considering MOR (fig. 13, lower; r = 0.92, SEE = 18.1 lb/ft²) alone and hence may be discarded. Thus, accurate knowledge of joist MOR leads to acceptable definition of floor strength as predicted by the linear model.

Table 10.—Calculated near-minimum floor failure loads, complete data sets

Species	Grade	Failure load, lower 5 percent	Load/50
		Lb/ft²	
Southern pine	As-graded	102	2.04
	On-grade	93	1.86
Douglas-fir	As-graded	99	1.98
	On-grade	83	1.66

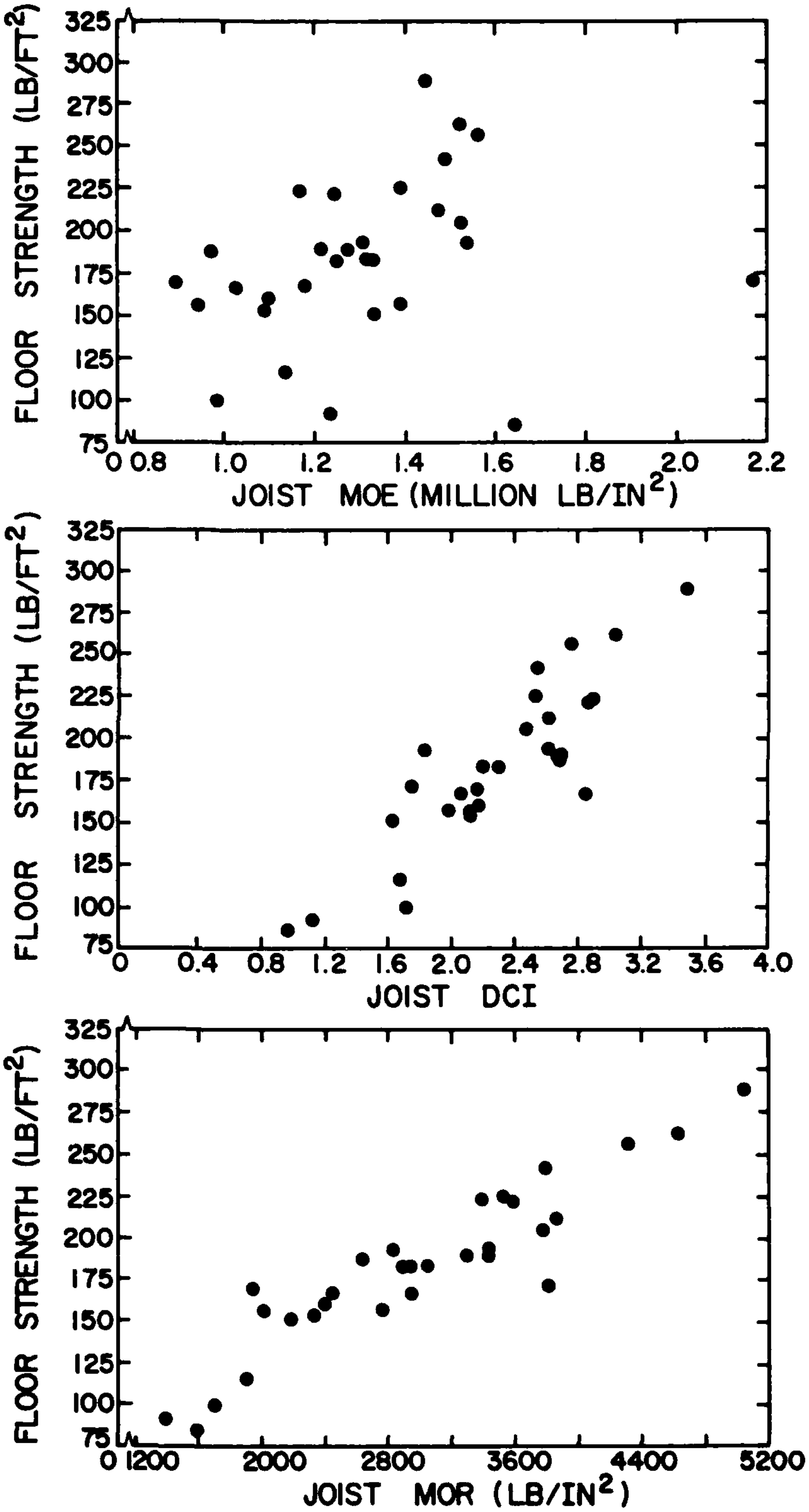

Figure 13.—Controlling joist MOE (upper), controlling joist DCI (center), and controlling joist MOR (lower) versus floor strength, Douglas-fir sample data. (ML83 5180)

Summary

Data from in-grade lumber tests were used to predict the stiffness and strength of one configuration of uniformly loaded floors. Over 500 floors, each consisting of ten 2 × 8's, were analyzed using an expanded version of FEAFLO. Distributions of performance were generated and compared to current design requirements.

In addition to average floor deflection, two new (other) measures of floor stiffness are examined. Estimates of floor strength distributions, generated by a linear analysis and modified by a nonlinearity scaling factor, are also presented.

Stiffness

The deflection data shown as cumulative distributions (CD's) for the sample data and for the complete data set identify the following trends:

1. System filtering effect. The interactions among the joists, sheathing, and connectors in a floor act to filter out part of the variability of the input data.

2. Stiffening of sheathing layer. Two different estimates of plywood properties were used. The APA plywood data provided an EA value 80 percent greater than did the CSU data. This stiffened the sheathing layer and provided a more effective T-beam flange, but this 80 percent increase reduced mean deflections by only 8 percent.

3. Variability of sheathing properties. Analyses made assuming that sheathing MOE values vary following a normal distribution with a coefficient of variation of 26 percent showed that this variability has no significant effect on the deflection performance of uniformly loaded floors. However, the effect of sheathing variability may be important for floors subjected to concentrated loads.

4. Moisture adjustments. As MC decreases, MOE increases but the moment of inertia decreases. The product, EI, is inversely related to deflections. Even an extreme increase in EI of 22 percent for the Douglas-fir floor resulted in only a 12 percent decrease in deflections compared to the green condition. This suggests that uncertainties in the moisture adjustment factors will be reduced by about one-half in determining uncertainties in deflections of the uniformly loaded floors studied.

5. Calibration data. Data are presented for one floor configuration. A major use of the computed performance data will be in the calibration of probability-based design procedures for wood joist floors. The plots for the complete data set can be used for this purpose after decisions have been made concerning which measures of acceptable deflection performance are best suited for calibration purposes.

Strength

A number of trends relative to strength computations were discerned.

1. Single analysis estimations. The linear FEAFLO program using a scaling factor provides a way to estimate both deflection performance and strength data for a floor using a single analysis. The strength data will be nonconservative but refinement of a correction factor accounts for nonlinearities should provide adequate estimates. In this study the correction factor of 0.90 provided a useful way to examine effects of various seasoning adjustment factors on strength.

2. Effect of plywood stiffness. Increasing plywood stiffness causes the plywood to carry more of the total strain energy in the system, thus relieving the joists of load and producing a slightly stronger floor. However, increasing floor capacity by increasing sheathing stiffness does not appear to be an efficient approach.

3. ASTM seasoning. Increasing both joist MOE and MOR using the ASTM seasoning adjustment while decreasing dimensions results in a net increase in strength. The relatively stiffer joists attract more stress but the increase in strength more than compensates for this increase.

4. EVSF seasoning. The EVSF adjustment procedure leaves MOR values near the bottom of the distribution unchanged. These joists, which usually control the floor failure load, undergo a stiffness increase because of seasoning and hence attract more stress. Because the joist strength is unchanged, use of the EVSF results in a net decrease in strength except for floors with all joists from the average or high-strength ranges of the distribution.

5. Joist parameters as failure load predictors. MOE, MOR, and DCI were studied to determine their utility as predictors of floor strength. Both MOR and DCI showed good correlation with strength but they cannot be defined except through destructive testing. While MOE can be obtained by nondestructive means, it correlates poorly with predicted failure loads. Hence it is not feasible to predict the true capacity of a given floor using MOE information alone.

Conclusion

A computer model, FEAFLO, can be used to estimate the stiffness and strength distributions of wood joist floor systems. By using lumber samples collected at sawmills, estimates of the distributions of actual in-place performance of such floors were made. Data on the stiffness and strength performance of one floor configuration will be helpful in establishing acceptance criteria for probabilistic based design of wood joist floor systems.

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Stiffness and Strength of Uniformly Loaded Floors with In-grade Lumber, by M. D. Vanderbilt, M. E. Criswell, J. Bodig, R. C. Moody, and D. S. Gromala, Madison, Wis., FPL, 1983.

20 pp. (USDA For. Serv. Res. Pap. FPL 440).

To ensure that new design techniques and construction materials do not change the overall acceptability of wood floor systems, it is necessary to characterize existing systems with a history of satisfactory performance. A structural analysis model and computer program for floors, FEAFLO, was used with data on lumber samples from sawmill inventory. Over 500 floor analyses yielded estimates of floor stiffness and strength distributions that will be useful to designers or code agencies.

Keywords: floors, strength, stiffness, joists, analysis, calibration, light-frame construction, structural.

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