FIRE ENDURANCE MODEL VALIDATION BY UNPROTECTED JOIST FLOOR FIRE TESTING

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Abstract

Previous publications presented the generation of a model for predicting the fire performance of unprotected joist floor assemblies and reported replicate experimental validation tests of the fire endurance of such assemblies. Parameters for the model had been estimated from experiments other than the validation experiments. The study reported here found that predicted times-to-failure using previously estimated parameters fell within the standard deviation of tested floor assemblies. As a result the model is validated. We suggest, however, that a given parameter, fire performance factor γ, be changed to 0.20 to reflect improved confidence in the control of the materials used and testing conducted in this study. The sensitivity of the model to variations in load, estimated mean modulus of rupture (MOR), material density, char rate, and joist dimensions were evaluated. The model predicts the following:

- An exponentially decreasing effect on time to failure of increasing load
- High sensitivity to char rate when floors are under low load, but insensitivity at high loads
- High sensitivity of time to failure to the strength of the joists (MOR) (that is, the higher the actual joist strengths are compared to design strengths, the longer the time to failure)
- Insensitivity of time to failure to joist depth, but increase of time to failure with increase in width

Introduction

The fire endurance of structural components or assemblies refers to the fire exposure duration for which these components or assemblies will act as a barrier to fire or retain their structural integrity. In North America, the fire endurance of structural components and assemblies is evaluated according to the procedures in ASTM Standard E 119 (1). The standard requires that an assembly or component (like that used in construction) be exposed to severe fire while subjected to design load levels. The successful testing of one assembly is normally sufficient to satisfy the code requirements for the construction design. Thus, variability in fire endurance performance is not measured.

In contrast to this single comparative test approach, studies worldwide are investigating a more objective procedure, which computes the fire safety of structural assemblies based on the degree of risk (e.g., references 2,7,10). A risk-based safety approach provides a more solid basis for establishing building code requirements that insure sufficient fire endurance for life and property protection while encouraging new construction technologies. Risk-based safety design and analysis, however, depend upon the availability of estimates of at least the mean and variance of the fire endurance behavior of assemblies. Information on the variability of fire exposure, applied load, and properties of the test assembly or component is required.

The purpose of this research program was to generate a model for the fire endurance of a conventional light-frame unprotected joist floor compatible with probability-based analyses and to validate the predictive capability of the model through a series of studies. The model has been discussed in previous papers (14,15). The results of experiments for validating the model were recently described by White et al. (13). This study compares the experimental results with model predictions and indicates the sensitivity of model predictions to various floor properties.

Background

Joist Floor Strength and Stiffness

The design of joist floors assumes that the total load-carrying capacity is borne by the joists alone. The load-carrying contribution of the connection of floor sheathing and subsequent generation of T-beam action is neglected, as is the effect of load sharing between adjacent joists. In non-fire-exposed joist floors, load sharing increases the observed strength 20 percent and stiffness about 36 percent at a 5 percent exclusion limit level compared to that where no load sharing is assumed (6,11). No contribution to bending resistance is assumed for the decking. If the contribution of the decking and its rigidity of connection to the joists for well-connected sheathing-decking assemblies is included, these load-sharing factors can be increased. Substantial increases in floor stiffness in the transition from a nonconnected to fully connected floor sheathing is reported by Criswell (3). Load sharing can be expected to enhance floor strength under fire exposure.

Fire Endurance Model

Woeste and Schaffer (14,15) presented an analytical model for assessing the fire endurance of two unprotected light-frame floor assemblies--a conventional joist assembly and a floor-truss assembly. Based upon available test results in the literature, the following Moment-residual cross-section modulus model was selected as the best predictor of structural failure time t_f for fire-exposed floor joists:

$$\frac{M(d - Ct_f)/2}{(b - 2\,Ct_f)(d - Ct_f)^3/12} = \frac{B}{1 + \frac{b + 2d}{bd}\gamma t_f} \qquad [1]$$

where
- M = applied moment due to both dead and live loads (in-lb)
- d = initial joist depth (in)
- C = char rate (in/min)
- t_f = time to failure (min)
- b = initial joist width (in)
- γ = fire-exposed joist performance factor
- B = joist MOR at room temperature (psi)

For this analysis, Equation [1] was converted to a cubic equation in t_f. This was then solved for t_f with various input parameters (γ, c, b, d, B) using the Newton-Raphson iterative procedure described previously (14).

It was assumed that the failure is due to charring of the three fire-exposed sides of the joist, and this loss of section, coupled with elevated temperature of the wood, causes rupture of the joist. The fire-exposed joist performance factor γ includes the effect of load sharing between joists, the load-carrying contribution of floor sheathing, the loss of strength due to temperature rise of the uncharred section, and other nonaccountable effects.

Previous estimates of γ, as based upon calibration to limited fire endurance tests of unprotected joist floor assemblies (14,15), indicated an expected value of 0.170. Residual t_f standard deviations of the model predictions to experimental results was 2.57 min. An improved estimate for γ was one of the objectives of the series of validation tests reported previously (13).

Experimental Results

A total of 10 ASTM E 119 tests were conducted on an unprotected wood joist floor system with joists drawn from a population of 2- by 10-in Douglas-fir joists with known structural properties (13). The results are given in Table 1.

The joist population used in the floors had a mean MOR of 5,280 psi and mean modulus of elasticity (MOE) of 1.530 x 10^6 psi. For the five floors loaded to 11.35 psf, the mean time for initial joist failure was 17.9 min with a coefficient of variation (COV) of 3.7 percent. For the five floors loaded to 79.2 psf, the mean time for initial joist failure was 6.5 min with a COV of 11.6 percent.

Table 1.--OBSERVED TIMES TO FAILURE OF WOOD JOISTS IN UNPROTECTED JOIST FLOOR ASSEMBLY FIRE ENDURANCE TESTS (13).

Live load[1] level, Floor No.	First joist		Second joist		Third joist	
	Joist No.	Time	Joist No.	Time	Joist No.	Time
		Min		Min		Min
11.35 psf						
No. 1	5	17.8	7	18.0	3	18.5
2	5	16.8	4	17.2	3	17.4
3	4/5	18.0	4/5	18.0	2	18.5
4	6	18.4	7/9	18.8	7/9	18.8
5	6/7	18.5	6/7	18.5	8	18.9
Mean		17.9		18.1		18.4
COV		3.7%		3.2%		3.2%
79.2 psf						
No. 6	5/6	6.2	5/6	6.2	--	--
7	12	6.8	8/9	7.6	8/9	7.6
8	3/5	7.5	3/5	7.5	7	7.7
9	6	5.5	7	5.6	9	6.3
10	6	6.3	7	6.7	9	6.8
Mean		6.5		6.7		7.1
COV		11.6%		12.4%		9.4%

[1]The dead load of the floor assembly was 4.3 psf.

Visual observations and the noise associated with joist failures were generally consistent with deflection measurements. Contributions to load-carrying capacity by the floor sheathing itself and by load sharing between joists were evidenced in the data and by visual observations.

Model Validation

The time-dependent strength model described in Equation [1] can be used to estimate the t_f of a joist exposed to fire on three sides (two sides and bottom). The joist performance factor γ is the only parameter that is not fixed in Equation [1] by material properties. It compensates for strength loss of the residual uncharred joist cross section due to heating, load sharing between joists, and load-carrying contribution by the floor sheathing. As previously stated, Woeste and Schaffer (15) calculated γ to be 0.170 in/min based upon calibration to previous tests (5). The model could predict overall t_f for those tests with a residual standard deviation of 2.57 min.

In the independent experiments recently conducted, t_f for the first, second, and third joist was noted (13). Overall failure was dictated by inability to maintain the total hydraulically applied load. Although first joist failure has been used by Vanderbilt et al. (12) to characterize joist floor strength, inability to support total load is consistent with the ASTM E 119 fire test procedure. The time difference between first through third joist failure and overall inability to sustain total load was small in the experiments conducted. Normally the difference was a fraction of a minute.

The joists selected for the validation fire endurance tests were nominal 2 by 10 (1.5 by 9.25 in, per National Design Specifications (8)) coast Douglas-fir assumed to have a population representative mean B = 4,308 psi (4). The mean specific gravity for Douglas-fir of 0.45 gave an assumed C = 0.025 in/min and moisture content of 10 percent (9). Based upon these parameters and γ = 0.17 previously determined, the results of the independent fire endurance tests were predicted for validation purposes. The predicted and actual results for each load level were as follows:

Live load level (psf)	Times to failure[1] (min)		
	Predicted	Actual	
	Mean	Mean	Standard deviation
11.35	19.12	18.4	0.59
79.20	6.16	7.1	0.67

[1]Failure of third joist; equivalent to collapse of assembly.

The actual results of failure of the floor assemblies fell well-within one standard deviation of those predicted.

The actual joist dimensions used in the experiments were recorded as mean width and depth of 1.47 in and 9.02 in. Predicted failure times in comparison to the actual results for these dimensions when used in the model were as follows:

Live load level (psf)	Times to failure[1] (min)		
	Predicted	Actual	
	Mean	Mean	Standard deviation
11.35	18.23	18.4	0.59
79.20	5.56	7.1	0.67

In this case, the predictions were improved at the low load level but not at the higher level.

We conclude that the previously developed model, which incorporated a factor γ = 0.17 and mean dimensions and strength of a given population of structural lumber, was a good predictor of unprotected joist floor fire endurance.

Model Parameter Reassessment

The independent set of results for the fire performance of unprotected joist floor assemblies allowed us to 1) improve the estimate of the factor γ for structural lumber for a population described by a Weibull strength distribution and 2) assess model sensitivity to parameter variation.

Experimental Joist Performance Factor

Nonlinear regression estimates of γ were derived for the model equation using the data given in Table 1. The technique is based upon minimizing the sum of squares of residuals. Separate analyses were performed for failure times as a function of first, second, or third joist failure. The dead load for each assembly was 4.3 psf, which was added to the live load applied for the analysis.

The properties of the joists assumed in the analysis were as follows:

C = 0.025 in/min
b = 1.47 in
d = 9.02 in
B = 5,280 psi

The joists were spaced 16 in on center and spanned 13.0 ft. The MOR is the mean for 20 randomly selected joists tested in bending under one-third-point loading. The estimates of γ using this mean MOR and mean dimensions and char rate for Douglas-fir are given in Table 2, with $\gamma \cong 0.20$.

Table 2.--RESULTS OF NONLINEAR REGRESSION ANALYSIS OF 2 BY 10 JOISTS.[1]

Load	Joist	Estimate of γ	Root mean square	Predicted t_f
Psf				Min
15.6	1	0.2314	0.678	17.90
	2	0.2239	0.608	18.10
	3	0.2122	0.597	18.42
83.5	1	0.1920	0.744	6.46
	2	0.1809	0.853	6.72
	3	0.1662	0.668	7.10
Both[2]	1	0.2178	0.826	5.93 & 18.26
	2	0.2084	0.892	6.11 & 18.53
	3	0.1983	0.866	6.32 & 18.82
Average		0.2035		

[1]Average MOR was 5,280 psi. Analyses were repeated for first, second, and third joist failure estimates.

[2]Both load levels--15.6 and 83.5 psf.

Simulations

To improve the estimate of γ based on the failing joist rather than on mean properties for the population of joists used, we used the Monte Carlo Simulation Method to simulate the fire endurance of floors. The properties that were represented by their distributions were MOR, density, and char rate. Individual values were randomly selected for each simulation.

Modulus of Rupture. Bending tests of 20 randomly selected joists from the population of joists used in the fire endurance experimental floors (Table 3) allowed an estimate of the MOR distribution. The Weibull equation for the distribution is

$$f(B) = \left(\frac{2.20}{5630}\right)\left(\frac{B-270}{5630}\right)^{1.20} \times \exp\left\{-\left(\frac{B-270}{5630}\right)^{2.20}\right\} \qquad [2]$$

where B = MOR. This distribution fits the upper 75 percent of the MOR data well, but not the bottom 25 percent.

Table 3.--DIMENSIONS AND PROPERTIES OF EXPERIMENTAL 2 BY 10 DOUGLAS-FIR JOISTS.

Depth	Width	Moisture content	Density	Modulus of rupture
In	In	%	Pcf	Psi
8.98	1.48	8.9	26.27	7,990
8.92	1.44	8.9	26.27	5,600
9.10	1.48	9.2	24.90	3,060
8.96	1.44	9.3	28.33	9,990
9.00	1.46	9.2	27.71	6,130
8.94	1.48	9.9	22.65	6,710
8.96	1.46	9.9	24.52	5,430
9.12	1.46	10.3	29.83	8,140
9.06	1.50	9.4	23.15	4,740
8.96	1.47	10.0	25.83	6,480
9.00	1.47	9.9	29.08	5,440
8.95	1.47	9.4	27.14	3,810
8.92	1.47	9.9	24.21	1,930
9.08	1.46	10.0	29.27	4,090
9.04	1.47	9.9	28.45	1,760
9.00	1.48	9.9	33.95	8,650
9.08	1.46	9.9	28.83	4,850
9.12	1.46	9.8	26.89	2,270
9.10	1.46	9.3	25.27	7,260
9.13	1.49	9.8	23.52	1,200

Density. The density ρ and MOR data for the same population of joists (Table 3) were used to estimate density as a linear regression function of joist MOR.

$$\rho = 24.668 + 0.0004049B + \varepsilon \qquad [3]$$

For the expression, the standard deviation $S = 2.617$ ($\sqrt{ss/df}$ of the residual) and the correlation coefficient R = 0.365.

Char Rate. From each of 10 joists tested destructively for MOR, sections from each end were fire exposed (ASTM E 119 conditions) for 6.5 and 17.9 min. Char depth after exposure was assessed using three techniques: visual measurement of uncharred dimension, specimen weight loss, and residual cross-sectional area. These data are provided in Table 4. The average char rate was computed by taking the mean of the char rates obtained using the three techniques.

The char rate was correlated to density and moisture content using linear regression analysis. For density alone, the expression is

$$C = 2.3898 - 0.03189\rho + \varepsilon \text{ (in/min)} \qquad [4]$$

with S = 0.1015 in/min and $R^2 = 0.214$.

For both density and moisture content, the expression is

$$C = 3.674 - 0.0295\rho - 0.1404u + \varepsilon \text{ (in/min)} \qquad [5]$$

where u is moisture content. The standard deviation is nearly the same as with density alone at 0.0998, but R^2 improves to 0.282.

Procedure. Monte Carlo simulation was done for a given load level in sets of 475 floors. The procedure for a given floor was as follows:

1. The Weibull distribution was used to randomly select MOR for 1 joist going into a 12-joist floor assembly.
2. Density for the joist was calculated from Equation [3] relating ρ to a given MOR level plus a random normal deviate based upon the residual standard deviation.
3. The char rate for the joist was calculated from Equation [4] relating char rate to density alone plus the random normal deviate around the regression as based upon the char rate residual standard deviation.
4. The procedure was repeated for another joist until properties for 12 joists were generated.
5. Based upon the simulated properties of the 12 joists, the failure time under load and fire exposure was calculated for each joist.
6. The first three joist failures were recorded.

Based on simulations of 475 floor assemblies at two load levels, the average MOR and char rate for the first, second, and third failing joists were as follows:

MOR and char rate		1st joist	2d joist	3d joist
MOR	(psi)	1,917	2,688	3,374
C	(in/min)	0.0267	0.0267	0.0268

Nonlinear regression was then performed to obtain estimates of γ for each joist using the above char rates and MOR. These results (Table 5) reflect the γ for the joist that failed. The change of γ with the sequence of joist failure probably reflects the number of joists used in the assembly, the effect of load

Table 4.--EXPERIMENTAL CHAR RATE DATA.

Joist No.[1]	Time exposed to fire	Moisture content	Specimen density	Char rate			
				Thickness	Weight	Area	Average
	Min	%	Pcf	- - - - - - - - In/hr	- - - - - - - - - -		
65	17.9	9.6	28.7	1.43	1.49	1.54	1.49
	6.5	9.6	29.7	1.54	1.68	1.62	1.61
38	17.9	9.5	25.7	1.50	1.60	1.60	1.57
	6.5	9.5	25.7	1.48	1.62	1.33	1.48
43	17.9	9.6	26.2	1.48	1.58	1.54	1.53
	6.5	9.6	26.5	1.33	1.48	1.36	1.39
95	17.9	9.8	30.9	1.29	1.41	1.37	1.36
	6.5	9.8	30.4	1.33	1.38	1.27	1.33
121	17.9	9.6	26.7	1.62	1.66	1.67	1.65
	6.5	9.6	25.3	1.57	1.71	1.79	1.69
143	17.9	9.8	27.3	1.54	1.67	1.73	1.65
	6.5	9.8	29.4	1.24	1.39	1.54	1.39
160	17.9	9.4	28.1	1.48	1.63	1.42	1.51
	6.5	9.4	29.6	1.34	1.61	1.35	1.43
172	17.9	9.8	27.9	1.48	1.54	1.62	1.55
	6.5	9.8	28.3	1.42	1.38	1.42	1.41
193	17.9	9.9	27.1	1.50	1.54	1.56	1.53
	6.5	9.9	27.1	1.40	1.57	1.26	1.41
200	17.9	9.2	28.7	1.48	1.56	--	1.52
	6.5	9.2	27.4	1.70	1.75	1.50	1.65
Average		9.6	27.8	1.46	1.56	1.50	1.51
SD[2]				0.111	--	--	0.105
COV				7.6%	--	--	6.95%

[1]Two specimens per joist.

[2]SD = standard deviation.

sharing between the joists, and T-beam action. The determination of g for the first joist failure is also sensitive to the mean MOR ($\overline{MOR}$) selected for the joist population. This linear relationship is shown in Figure 1 and is given by

$$\gamma = -0.060 + (5.25 \times 10^{-5})\,\overline{B} \qquad [6]$$

Table 5.--ESTIMATE OF g FOR SIMULATED JOISTS.

Joist	Modulus of rupture	γ		
		Low load	High load	Both loads
	Psi			
1	1,917	0.04884	0.00036	0.03208
2	2,688	0.08019	0.03919	0.06578
3	3,374	0.10199	0.06732	0.08890

Table 6.--PREDICTED FAILURE TIMES[1] FOR COMBINATIONS OF γ AND MODULUS OF RUPTURE.[2]

γ	Failure time for various joist MOR values		
	1,917	2,688	3,373
	- - - - - -	Min	- - - - - -
0.04884	17.90	20.09	21.27
0.08019	15.69	18.10	19.48
0.10199	14.47	16.95	18.42

[1]Mean experimental failure times for the first three joist failures were 17.9, 18.1, and 18.4 min, respectively (Table 1).

[2]Load of 15.6 psf.

Table 7.--PREDICTED FAILURE TIMES[1] FOR COMBINATIONS OF γ AND MODULUS OF RUPTURE.[2]

γ	Failure time for various joist MOR values		
	1,917	2,688	3,373
	- - - - - - - - - Min - - - - - -		
0.00036	<u>6.46</u>	11.95	14.82
0.03919	3.17	<u>6.72</u>	9.05
0.06732	2.33	5.13	<u>7.10</u>

[1]Mean experimental failure times for the first three joist failures were 6.5, 6.7, and 7.1 min, respectively (Table 1).

[2]Load of 83.5 psf.

To better illustrate the effect of joist MOR, the failure times for combinations of γ and MOR were calculated (Tables 6,7). For a given γ, the range of failure times for the three joists was greater than the range of experimental results for the three joists.

As a result of using the nonlinear regression estimates of γ, the underlined predicted times in Tables 6 and 7 were precisely the same as the mean experimental failure times of each of the first three joists (Table 1). However, a γ factor as a function of the expected mean strength of each joist and the load level are needed to achieve this level of accuracy.

Model Sensitivity

The effect of variation in model parameters on the predicted t_f can be assessed under fire exposure. For this purpose, we selected the following base parameter values:

γ = 0.20
C = 0.025 in/min
MOR = 5,280 psi
b = 1.47 in
d = 9.02 in

Load

The influence of variation in load (psf) on t_f for a constant γ = 0.2 is illustrated in Figure 2. Joists are spaced 16 in on center and span 13 ft. For systems carrying no live load (dead load only), it is expected that $t_f > 20$ min. At 40 psf live load, t_f is just over 10 min.

Experimental Joist Performance Factor

The influence of γ on t_f was examined. Figure 3 shows the change in estimated t_f with increasing γ at three initial joist bending-stress levels (250, 745, and 1,500 psi). The 745 psi stress level indicates a live load of 40 psf plus dead load of the floor consisting of 2 by 10 joists on 16-in centers and spanning 13 ft.

The error in estimating t_f by a $\pm$ 0.03 change in γ, with 0.20 as a base, is 0.7 min.

Char Rate

The influence of assumed rate of charring (in/min) on predicted t_f is illustrated in Figure 4. Three initial joist bending-stress levels are assumed. Char rate level has a lesser influence on t_f as stress level increases, as one would reasonably expect.

Joist Strength

Joist bending strength varies as the quality of the lumber varies. The t_f of an assembly can be influenced by the lower strength joists from a population going into the floor assembly. This effect is seen in Figure 5 by the variation in t_f with initial joist bending strength (MOR) at stress levels of 250, 745, or 1,500 psi in the fire-exposed assembly. The best t_f levels are obtained using the highest quality structural joists for all initial stress levels.

Joist Dimensions

The t_f for a joist floor assembly with variation in joist width and depth is shown in Figures 6 and 7. Two initial stress levels of 250 and 1,500 psi and a stress level of 745 psi consistent with a constant load condition of 40 psf are again used to illustrate how dimensions influence t_f with stress level. Failure time is relatively insensitive to the actual joist depth, but increases as actual joist width increases. The change is less at high initial stress levels.

Discussion

The prediction of results for an independent set of experiments using γ of 0.17 in/min showed the model to be sufficiently accurate and thereby validated.

The value for γ given in previous work (9,13) was 0.17 as calibrated to tests conducted by Lawson (5). The calibration was done with weaker estimates for the model parameters than the estimates used in our controlled study.

Using t_f for each of three joists of floors fire tested at two applied load levels, mean γ was reassessed as 0.20. The mean strength of the joists, 5,280 psi, was considered the characteristic strength value. For first joist failure estimates the sensitivity of γ to selected MOR is linear (Fig. 1). The factor γ is very sensitive to the selected mean bending strength, MOR, of the joists. A change of 500 psi in mean MOR can result in a 0.025 change in γ. Similarly, a 0.025 change in γ at a 1,500 psi initial stress level (with 0.20 as a reference γ) results in a change of about 0.5 min in t_f. A 0.5-min difference in experimental test results is seen in Table 1; a good estimate of mean MOR was obtained.

The t_f prediction sensitivity of the model to variation in model input parameters indicates the following:

--The model has nonlinear sensitivity to applied load (Fig. 2). An increase in load generally results in more than a proportionate decrease in t_f

--A change of 0.03 in γ changes t_f by about 0.7 min (when γ is near 0.20) (Fig. 3).

--A change in charring rate is highly significant for low initial joist stress, but not for stress levels as high as 1,500 psi (Fig. 4).

--The room temperature bending strength (MOR) of joists has a strong effect on t_f (Fig. 5). A change in 1,000 psi (from a base level of 6,000 psi) can result in a change in t_f between 1.2 to 1.5 min.

--A change in joist width of 0.2 in has a substantial effect on t_f (Fig. 6), whereas depth does not (Fig. 7).

If the mean MOR for the lowest joists in the population is used instead of a mean MOR for a population of joists, the value for γ decreases accordingly (Tables 5-7 and Fig. 1). The result of using the factor γ associated with the expected lower strength of the first, second, or third joist to fail allows good prediction of the experimental results. This will not be pursued further here, but it does indicate a means of using expected lower exclusion limit levels of strength for a population of joists to estimate near minimum fire endurance times for unprotected joist floors.

Conclusions

The t_f model given in Equation [1] can accurately predict the fire endurance of unprotected joist floor assemblies. A fire performance factor γ can be specified from correlation of parameters for a small population of Douglas-fir joists used in 10 fire-tested floor assemblies and from simulations based upon these parameters. Depending upon the γ specified, the estimated MOR may be the mean, or some other level, that reflects the population of joists used.

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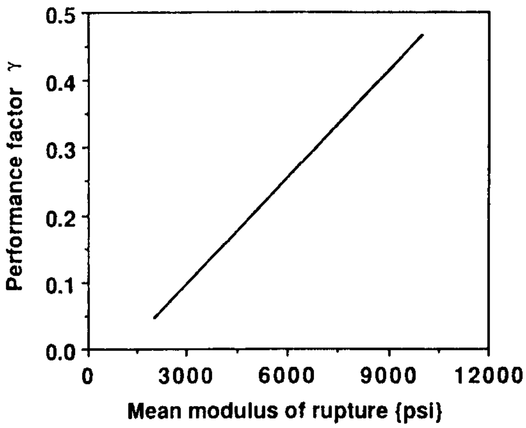
Figure 1. Variation in performance factor γ with mean modulus of rupture (psi) of joists.



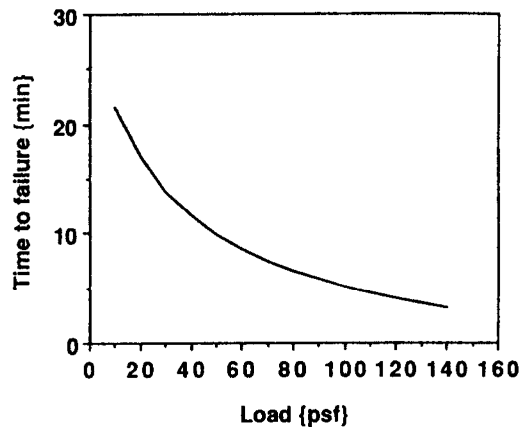
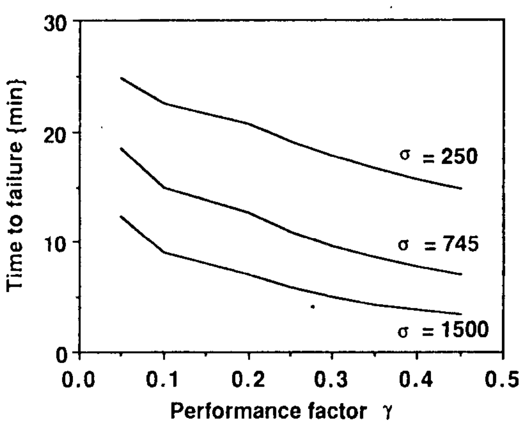


Figure 2. Failure time as a function of load for floor joist assembly. Joists 16 in on center and span 13 ft.

Figure 3. Variation in failure time with performance factor γ for two initial levels (250 and 1,500 psi) and constant load level of 44.3 psf ($\approx$ 745 psi) of bending stress σ.



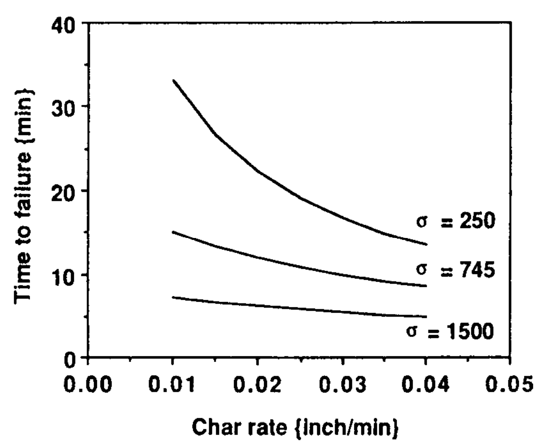


Figure 4. Failure time as a function of char rate for two initial levels (250 and 1,500 psi) and constant load level of 44.3 psf ($\approx$ 745 psi) of bending stress σ.

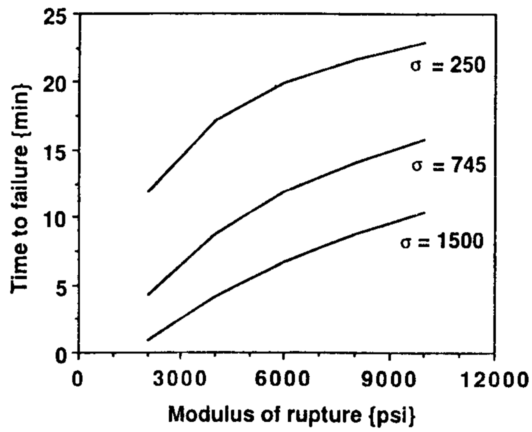


Figure 5. Failure time as a function of joist strength for two initial levels (250 and 1,500 psi) and constant load level of 44.3 psf ($\approx$ 745 psi) of bending stress σ.

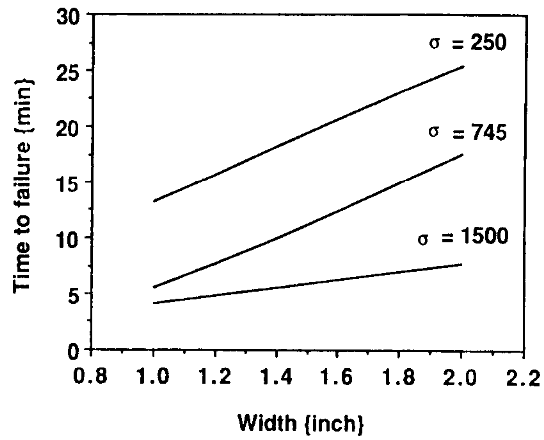


Figure 6. Failure time as a function of joist width for two initial levels (250 and 1,500 psi) and constant load level of 44.3 psf ($\approx$ 745 psi) of bending stress σ.

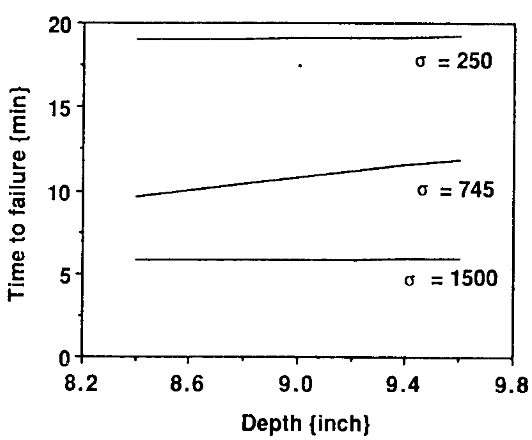


Figure 7. Failure time as a function of joist depth for two initial levels of 250 and 1,500 psi and a constant load level of 44.3 psf ($\approx$ 745 psi) of bending stress σ.

Proceedings of the

1988 INTERNATIONAL CONFERENCE ON TIMBER ENGINEERING

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Westin Hotel
Seattle, Washington
U.S.A.

September 19-22, 1988

VOLUME 1

1988 INTERNATIONAL CONFERENCE ON TIMBER ENGINEERING

This proceedings includes papers presented at the 1988 International Conference on Timber Engineering which was held September 19-22, 1988 in Seattle, Washington, U.S.A. These papers are printed directly from camera ready manuscripts prepared by the authors. Views presented in the various papers are those of the respective authors and do not necessarily reflect those of the sponsors.

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