FAILURE TIME OF LOADED WOODEN BEAMS DURING FIRE

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(Received May 31, 1983)
(Revised September 26, 1983)

ABSTRACT

A model is presented for predicting the failure time of loaded wooden beams of rectangular cross-section exposed to elevated temperatures or to fire. Failure times calculated by the model were compared to failure times measured in this study using 19.05 mm × 19.05 mm simply supported southern pine beams, and to failure times measured by the National Bureau of Standards during the fire of a full scale room. Reasonable agreements were found between the calculated failure times and the data.

INTRODUCTION

THE STRENGTH OF STRUCTURAL TIMBER DECREASES WHEN THE wood is exposed to high temperatures, such as arise during fire. The decrease in strength may, in turn, lead to the failure of load bearing wooden structures. For reasons of safety, it is important to know the time required for failure to occur under given conditions. Therefore, the objective of this investigation was to develop a method that can be used to predict the failure time of loaded wooden beams during exposure to elevated temperatures or to fire.

METHOD

The flexure formula is frequently used to determine the safe load that a beam of given cross section and span will support [1,2]. Accord-

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0734-9041/83/04 0297—07 $04.50/0

ing to this formula the beam is safe when the following inequality is satisfied

$$M \leqslant S_b C \tag{1}$$

where M is the maximum applied bending moment, S_b is the maximum allowable extreme fiber stress in bending, and C is the section modulus. For a rectangular beam of height d and width b the section modulus is $C = bd^2/6$.

The following dimensionless ratio is now introduced

$$R \equiv \frac{S_b}{M/C} \tag{2}$$

R is the ratio of the allowed stress (S_b) to applied stress (M/C). Thus, the strength ratio R is a measure of the margin of safety and may have a value from one to infinity

R = ∞ when the applied stress is zero
R > 1 when the applied stress is safe
R = 1 when the allowable ultimate stress is reached

During exposure to elevated temperatures the strength of the wood and, consequently, the value of S_b decrease. This results in a decrease in the value of R with exposure time. The beam will fail at the time t_f at which the value of R reaches unity. The variation of R with exposure time is illustrated in Figure 1. S_b is now expressed as

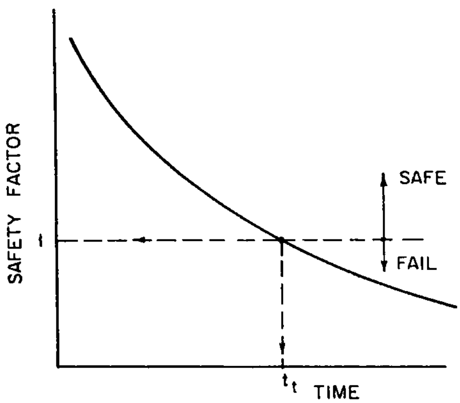

Figure 1. The variation of the safety factor R with exposure time.

$$S_b = S_b{}^{\circ} \frac{S_b}{S_b{}^{\circ}} \qquad (3)$$

where $S_b{}^{\circ}$ is the maximum allowable extreme fiber stress in bending of the unburned wood, i.e. of wood unexposed to elevated temperature. Equations (2) and (3) may be combined to yield

$$R = \frac{(S_b/S_b{}^{\circ})}{[M/(C \times S_b{}^{\circ})]} \qquad (4)$$

The above form of R is convenient because strength loss $S_b/S_b{}^{\circ}$ can be calculated, as described in ref. [3].

The strength ratio R (which may be construed as a factor of safety) as a function of exposure time and the time to failure t_f is thus determined by the following steps:

1. The maximum bending moment M and the section modulus C are calculated. Both M and C depend on the geometry. For the purpose of the calculations, they may be taken to be constant.
2. The loss of strength $S_b/S_b{}^{\circ}$ is calculated as a function of exposure time according to the method given in ref. [3]. The strength loss depends on the material, the geometry, and the ambient temperature.
3. The strength ratio R is calculated as a function of exposure time, and the failure time is determined.

Step 2 of the above procedure requires the calculation of the strength loss. The loss in strength with exposure time may be obtained from the expression [3]

$$\frac{S}{S^{\circ}} = \frac{1}{A} \iint_A [1 - \left(\frac{\Delta m_{xy}}{\Delta m_m}\right)^e] \, dA \qquad (5)$$

In this equation $\Delta m_{xy}/\Delta m_m$ is the mass loss which can be calculated by the method described in detail in ref. [4]. The exponent e is a constant. When the constant for fiber stress in bending e_b is unknown, it may be approximated by the constant for fiber stress in tension, e_t. For southern pine e_t was found to be 0.1 [3].

Calculations of the mass loss $\Delta m_{xy}/\Delta m_m$, the strength loss, S/S_o, and the strength ratio R as functions of exposure time, and the calculation of the failure time t_f require numerical procedures. A "user friendly" computer code was developed for performing these calculations. This computer code (designated as FIRE) may be obtained from the Department of Aeronautics and Astronautics, Stanford University.

RESULTS

In order to assess the accuracy of the method, failure times calculated by the method proposed here were compared to experimentally determined failure times. To generate data suitable for such comparisons, tests were performed with nominal 19.05 × 19.05 mm (3/4 × 3/4 in.) and 1.2 m (47 in.) long southern pine beams. Each beam was simply supported at its two ends and was loaded at the center (Figure 2). A burner was placed under the beam. The flame temperature at the location of the beam was measured by a shielded thermocouple. The flame temperature was adjusted to the required value, and the time it took the beam to collapse was recorded. The tests were performed with different loads and at different temperatures. The measured failure times are shown in Figure 2. In this figure, the failure times calculated by the model are also included. Each calculation was performed using a uniform and constant temperature corresponding to the average thermocouple reading. In the tests the temperature fluctuated, and was not uniform around the entire surface. It is noteworthy, that even under these conditions the calculated results agree reasonably well with the data. This lends support to the validity of the model, at least

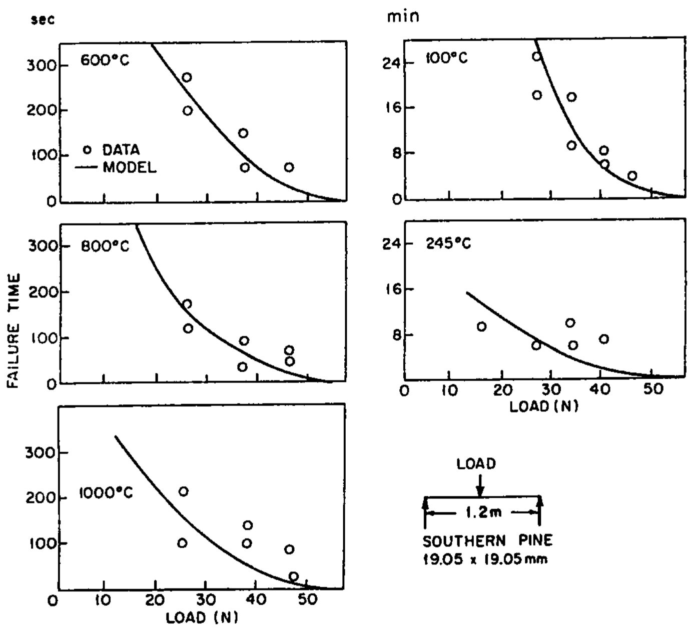

Figure 2. Failure times of simply supported southern pine beams ($S_b°$ = 13.8 MPa) o data ____ Model.

when applied to "small" beams (less than 1 × 1 in., say) exposed to fairly uniform heating.

It remains to evaluate the usefulness of the model in predicting failure times of larger beams during actual fire exposure conditions. To accomplish this, failure times calculated by the method were compared to data generated during large scale burn tests by the Center for Fire Research, National Bureau of Standards [5,6]. These tests were performed in a 3.3 × 3.3 m (10.7 × 10.7 ft.) burn room with a ceiling height of 2.3 m (7.4 ft.) [5]. A 3.7 × 3.7 m (12 ft.) floor—ceiling assembly was built over the concrete block walls of the burn room. The assembly was supported by nominal 51 × 203 mm (2 × 8 in.) southern pine, construction grade No. 2, medium grain wood joists spaced 0.61 m (24 in.) apart. The span of every joist was 3.25 m (10.67 ft.). A single layer of 18 mm (23/32 in.) thick underlayment grade douglas fir plywood subfloor was laid perpendicular to the joists. The floor ceiling assembly was loaded with steel blocks providing a nearly uniform load of 1900 N/m^2 (40 lb$_f$/ft.^{2}).

The burn room contained furnishings common in a recreation room. Paper was added to increase the fire load. A doorway provided a simple source of ventilation.

The temperatures were measured by thermocouples at various locations in the room as well as on the unexposed sides of the assembly. The average upper room gas temperature is shown in Figure 3.

For the conditions of the test the floor support joists collapsed in approximately 12 minutes. The tests were repeated by placing the assembly into a furnace in which both the temperature and the oxygen concentration were controlled [6]. Failure times in this furnace ranged from 9 to 17 minutes. Readers interested in further details of these

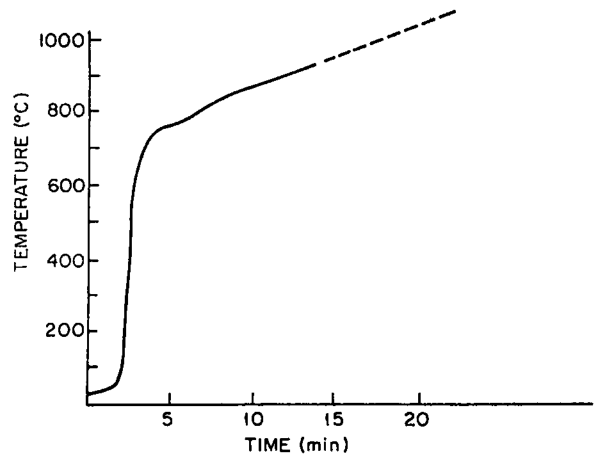

Figure 3. Upper room gas temperature measured in the NBS room test.

Table 1. Failure times of wooden floor assemblies measured by NBS in a test room and in a fire endurance furance, and calculated by the present model. For details of the test conditions see refs. [5,6].

	Failure Time
Room fire test	12 min
Furnace test	6-17 min
Calculated (present study)	19-22 min

tests are referred to refs. [5] and [6]. The data are summarized in Table 1.

The failure times of nominal 51 × 203 mm (2 × 8 in.) and 51 × 101 mm (2 × 4 in.) southern pine beams were calculated by the present method for different maximum bending moments and for different constant surface temperatures. The value of $F_b^{\circ} = 8.27$ MPa (1200 psi), specified for the southern pine beams used in the NBS burn tests [5,6] was used in these calculations. The results of the calculations are shown in Figure 4 and 5.

The calculated failure times in Figure 4 can now be compared to the NBS burn test data. The maximum bending moment in the tests was 1690 Nm. The temperature in the tests ranged from about 750 °C at 3

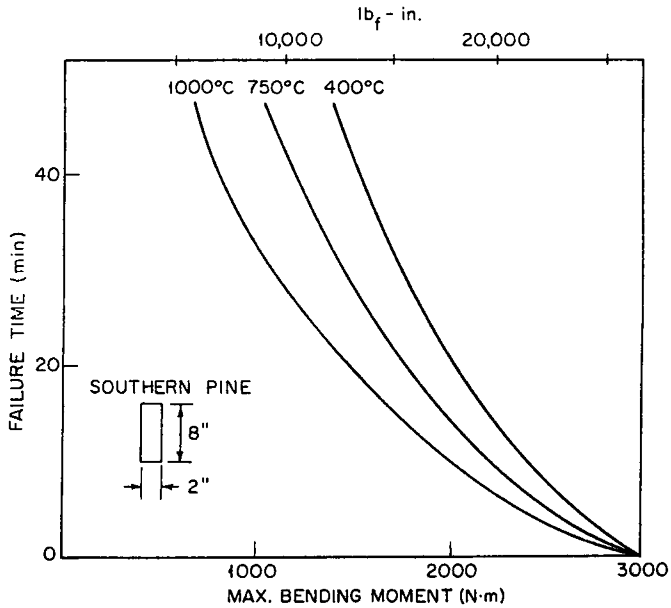

Figure 4. Failure times versus maximum bending moment of loaded southern pine beams exposed to constant temperatures (S_b° = 8.27 MPa).

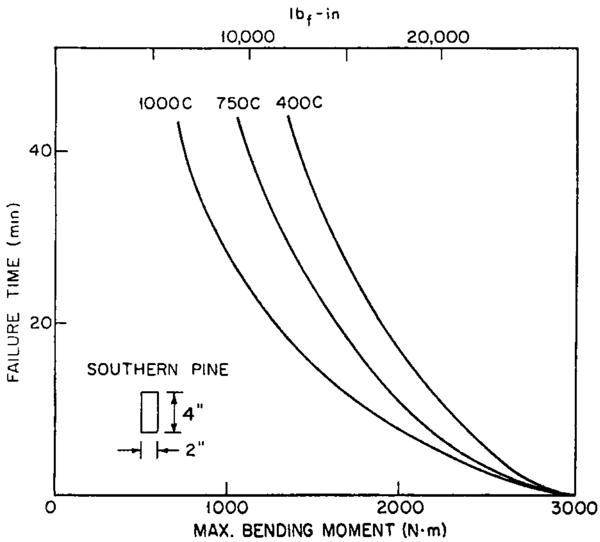

Figure 5. Failure times versus maximum bending moment of loaded Southern Pine beams exposed to constant temperatures ($S_b°$ = 8.27 MPa).

minutes to about 900 °C at 12 minutes (Figure 4). For a bending moment of 1690 Nm the calculated results in Figure 5 give failure times of 22 min. at 750 °C and 19 min. at 900 °C. The measured failure times are given in Table 1. It appears that the model is a useful tool for calculating failure times of loaded wooden beams exposed to elevated temperatures and to fire.

ACKNOWLEDGEMENTS

This work was supported by the Center for Fire Research, National Bureau of Standards under Grant Number NB80 NADA 1054.

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