MODEL FOR PREDICTING CHANGES IN THE STRENGTHS AND MODULI OF TIMBER EXPOSED TO ELEVATED TEMPERATURES

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ABSTRACT

A model is presented for predicting changes in the tensile, compressive, and shear strengths and moduli of timber exposed to high temperature. The strengths and moduli of southern pine exposed for predetermined lengths of time to either 100, 160, 245, 400, 600 or 800 °C were measured. The accuracy of the model was assessed by comparing the strengths and the moduli predicted by the model to the data.

INTRODUCTION

IN ORDER TO UTILIZE THE FULL POTENTIAL OF WOOD AS BUILDING material, the changes in the mechanical properties of wood during exposure to elevated temperature must be known. For reasons of safety, it is especially important to know the strengths of load bearing timber structures under fire exposure conditions. However, analytical methods are as yet unavailable which would predict the performance of loaded structural timber members during fire. Therefore, the objective of this investitation was to develop a model which can be used to predict changes in the tensile, compressive, and shear properties of wood during elevated temperature exposure.

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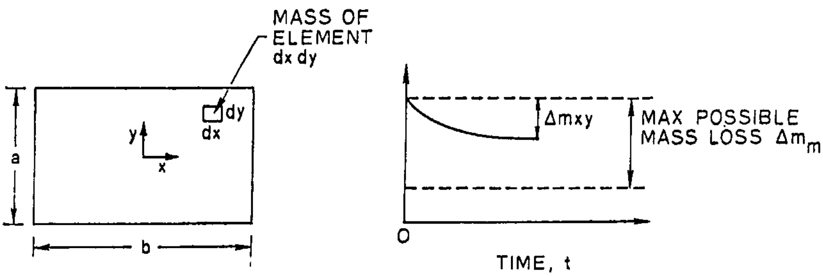
THE MODEL

A model is presented here for predicting changes in the tensile, compressive, and shear strengths and moduli of wood when the wood is exposed to high temperatures. In this paper, the hypothesis is made that degradation in the mechanical properties is related to the mass loss. Accordingly, the strength and the modulus at any point (designated by the coordinates x, y, Figure 1) are expressed as

$$\frac{S_{xy}}{S^{\circ}} = 1 - \left(\frac{\Delta m_{xy}}{\Delta m_{m}}\right)^{e} \tag{1}$$

$$\frac{E_{xy}}{E^{\circ}} = 1 - \left(\frac{\Delta m_{xy}}{\Delta m_{m}}\right)^{g} \tag{2}$$

S_{xy} and E_{xy} are the strength and the modulus at time t at the x,y position. S° and E° are the strength and modulus at a reference temperature (room temperature, say). Δm_{xy} is the mass loss of the wood at position x,y at time t. Δm_{m} is the maximum mass loss the wood can experience. Δm_{xy} and Δm_{m} are mass losses resulting from volatilization only, and do not include mass losses due to water vaporization. In eqs.



INITIAL STRENGTH (t = 0): S_0

STRENGTH OF ELEMENT dxdy AT TIME t : $S_{xy} = S_0[1-(\Delta m_{xy}/\Delta m_m)^e]$

STRENGTH OF TOTAL CROSS SECTION AT TIME t : $S = \frac{1}{A}\iint_A S_{xy}\,dA = \frac{1}{(a)(b)}\int_0^a\int_0^b S_0[1-(\Delta m_{xy}/\Delta m_m)^e]\,dx\,dy$

Figure 1. Description of the geometry and the model.

(1) and (2) the exponents e and g are constants which depend on the material but which, by definition, are independent of geometry and temperature. The values of these constants must be determined experimentally, as will be discussed subsequently.

By assuming that the strain ε is constant across the cross section A, the maximum load that the wood can carry is

$$F = \iint_A S_{xy} dA \tag{3}$$

where F is the load at which failure occurs. The total ("overall") strength of the wood at time t is

$$S = \frac{F}{A} = \frac{1}{A} \iint_A S_{xy} dA \tag{4}$$

The modulus of elasticity can be determined by similar reasoning. It is assumed that up to the point of failure the relationship between the strength and the modulus is linear and can be represented by Hooke's law

$$S_{xv} = E_{xy}\, \varepsilon \tag{5}$$

where the strain ε is taken to be uniform across the cross section. Equations (3) and (5) yield

$$F = \iint_A E_{xv} \varepsilon dA = \varepsilon \iint_A E_{xy} dA \tag{6}$$

Equation (6) can be written as

$$\frac{F}{(A)(\varepsilon)} = \frac{1}{A} \iint_A E_{xy} dA \tag{7}$$

The "overall" modulus of elasticity at time t is

$$E = \frac{S}{\varepsilon} = \frac{1}{A} \iint_A E_{xy} dA \tag{8}$$

Equations (4) and (8) provide the strength and the modulus as a function of exposure time. It is noted that these equations apply to tensile, compressive, and shear properties. The values of the constants e and g are different for the different types of properties as will be discussed in the Results section. However, as noted before these constants are taken to be independent of geometry and temperature.

CALCULATION PROCEDURE

The strength S and the modulus E can be calculated by the following steps:

1. The mass loss at every point $\Delta m_{xy}/\Delta m_m$ is calculated as a function of time. Equations appropriate for calculating the mass loss are given, for example, by Do and Springer [1].
2. The strength S_{xy} and the modulus E_{xy} at every point are calculated as a function of time using eqs. (1) and (2).
3. The "overall" strength S and modulus E as a function of time are calculated by eqs. (4) and (8).

Once the surface temperature or the heat flux to the surface is specified (both of these parameters may vary with position and time) the strength and the modulus can readily be calculated by the procedure outlined above. The calculations must be performed by numerical methods. A "user friendly" computer code for two dimensional slabs (rectangular cross section) is available from the authors.

RESULTS

In order to assess the validity of the model and to determine the values of the constants (e and g) the results of the model must be compared to data. Here the model was compared to the measured strengths and moduli of construction grade, kiln dried southern pine. Details of the tests were reported elsewhere [2] and will not be repeated here. Essentially, test specimens were heated in a muffler oven at either 100 °C, 160 °C, 245 °C, 400 °C, 600 °C or 800 °C for a predetermined length of time. The strengths and the moduli were then measured at room temperature. The longitudinal (i.e., in the direction along the grain) and the transverse (in the direction perpendicular to the grain) tensile strengths and moduli of southern pine were measured as functions of exposure time at all six of these temperatures. In addition, the longitudinal and transverse compression, and the longitudinal shear strengths and moduli were measured at 400, 600 and 800 °C. The data are shown in Figures 2-15. In these figures the cross sectional areas of the specimen are also indicated.

The strengths and the moduli were also calculated by the model described previously. The values of the constants e and g were adjusted to provide a best fit between the model and the data. The e and g values thus obtained are listed in Table 1. The results of the model are represented by solid lines in Figures 2-15. The results of the model and the data agree well, creating confidence in the validity of the model.

With e and g values given in Table 1 the model may now be used to estimate the degradation in the strengths and moduli of southern pine

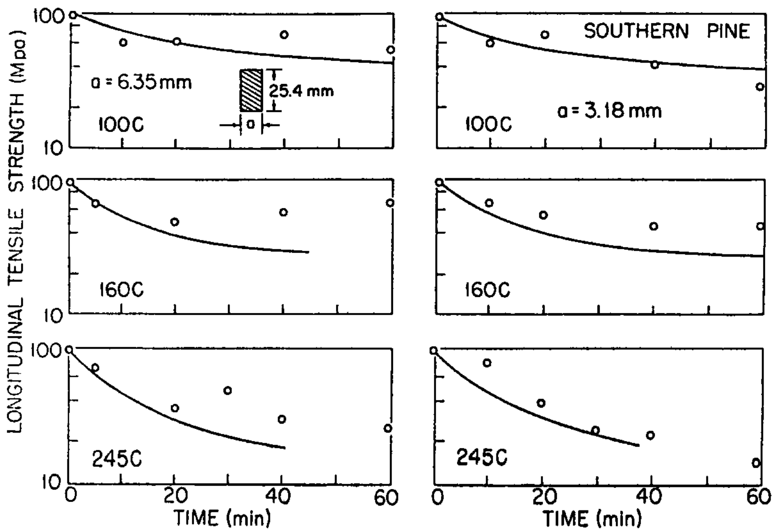


Figure 2. Longitudinal tensile strength as a function of exposure time. Southern Pine at 100, 160 and 245°C. o Data, _____ model.

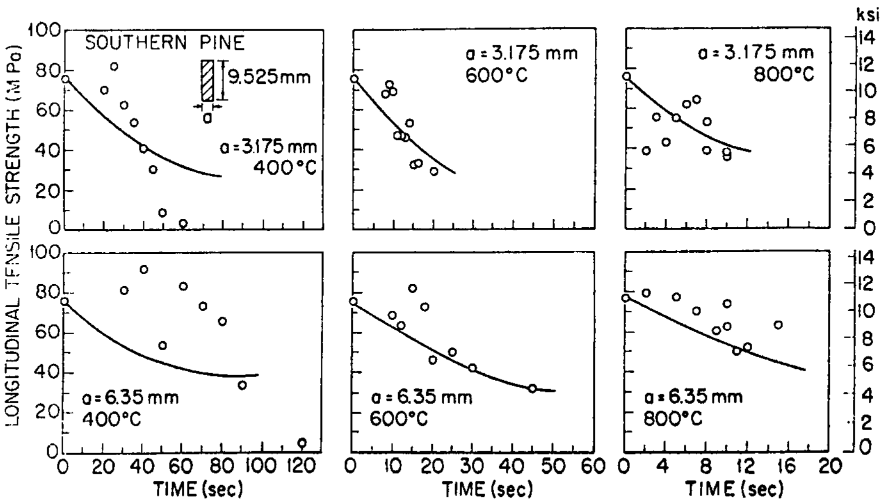


Figure 3. Longitudinal tensile strength as a function of exposure time. Southern Pine at 400, 600 and 800°C. o Data, _____ model.

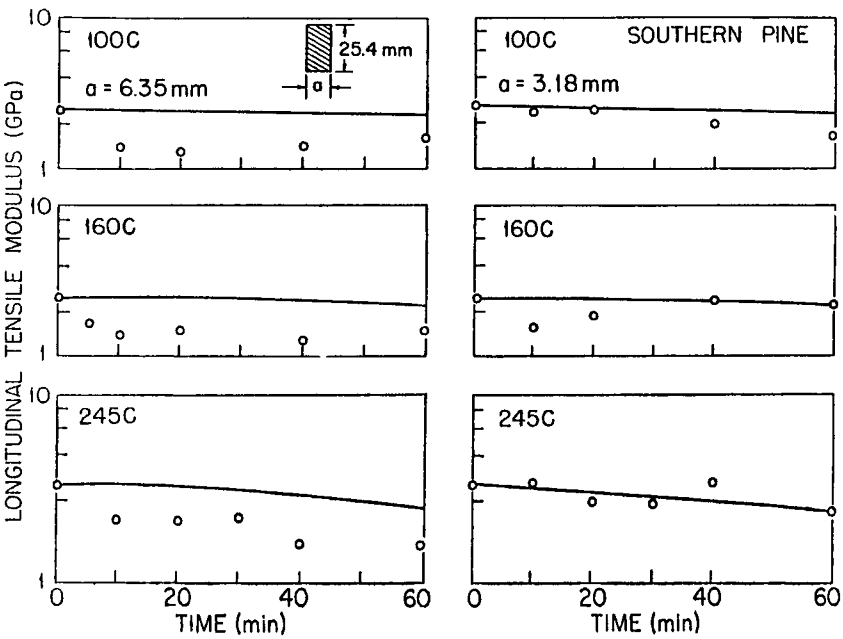


Figure 4. Longitudinal tensile modulus as a function of exposure time. Southern Pine at 100, 160 and 245°C. o Data, _____ model.

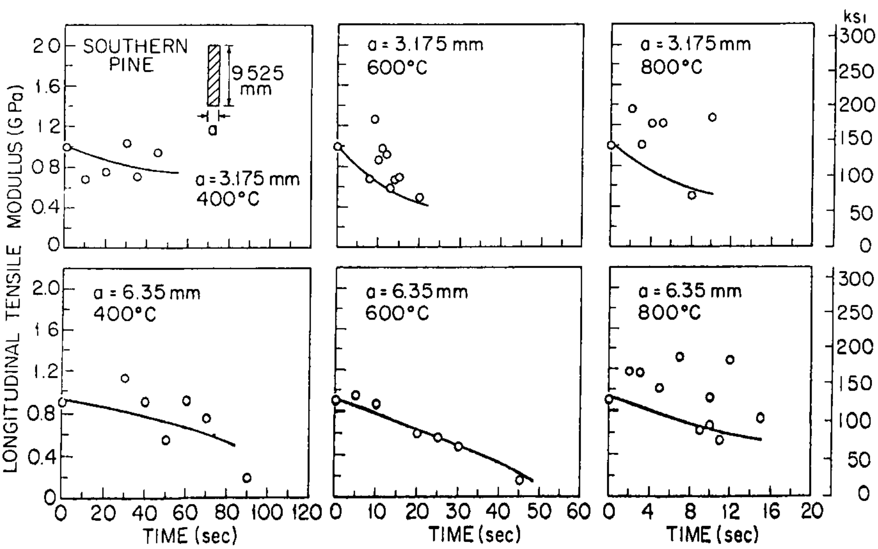


Figure 5. Longitudinal tensile modulus as a function of exposure time. Southern Pine at 400, 600 and 800°C. o Data, _____ model.

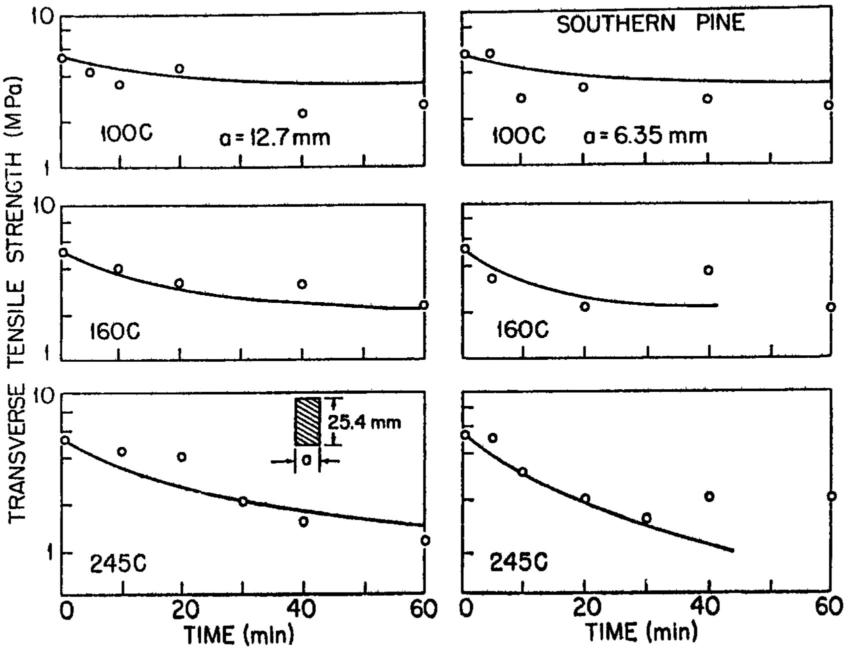


Figure 6. Transverse tensile strength as a function of exposure time. Southern Pine at 100, 160 and 245°C. o Data, _____ model.

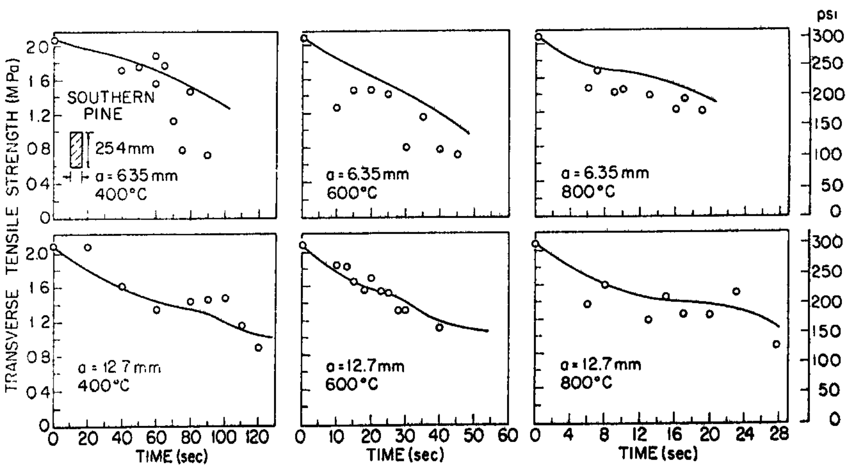


Figure 7. Transverse tensile strength as a function of exposure time. Southern Pine at 400, 600 and 800°C. o Data, _____ model.

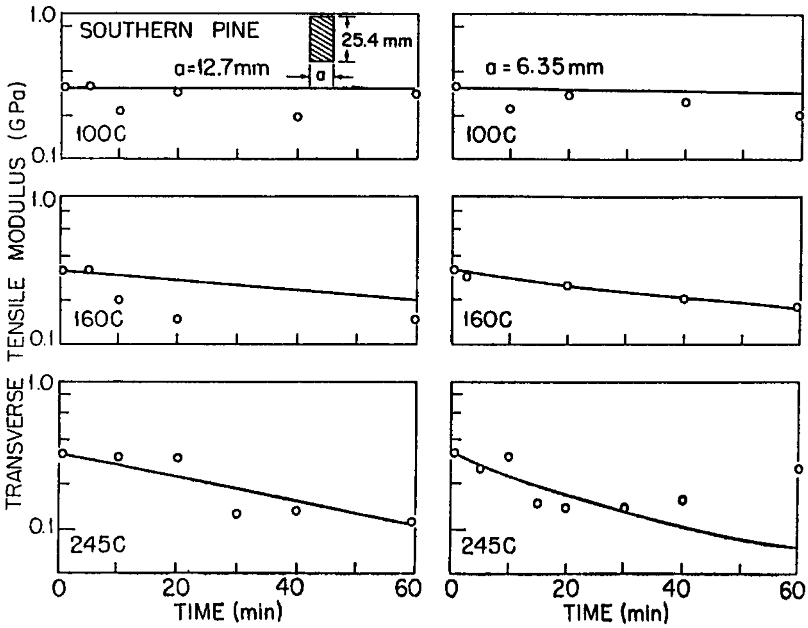


Figure 8. Transverse tensile modulus as a function of exposure time. Southern Pine at 100, 160 and 245°C. o Data, _____ model.

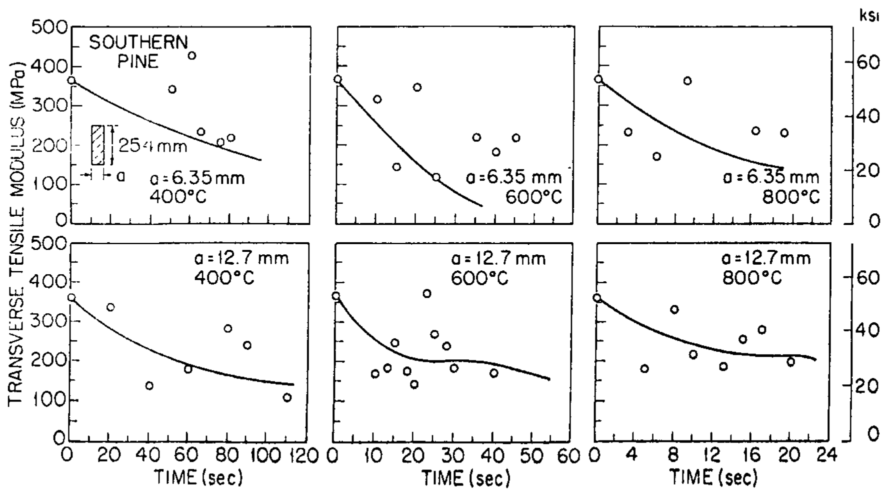


Figure 9. Transverse tensile modulus as a function of exposure time. Southern Pine at 400, 600 and 800°C. o Data, _____ model.

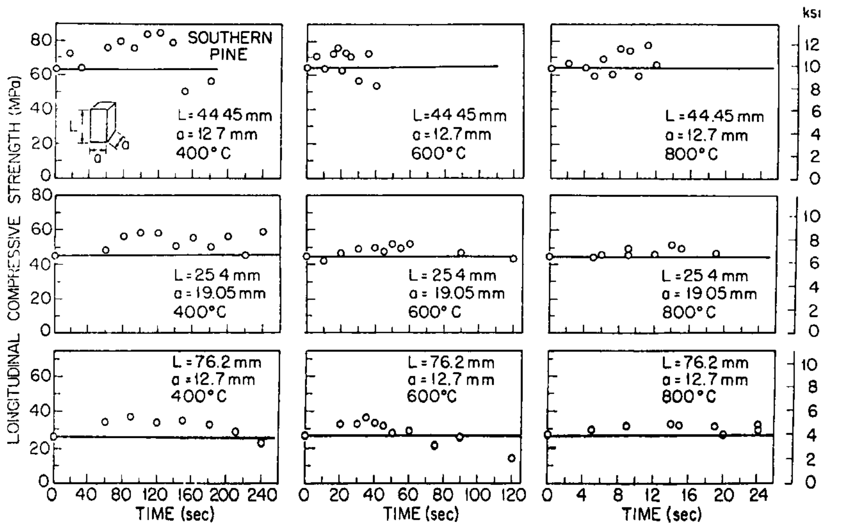


Figure 10. Longitudinal compressive strength as a function of exposure time. Southern Pine at 400, 600 and 800°C. o Data, _____ model.

in the temperature range 100 to 800 °C. The model is not restricted, of course, the southern pine or to this temperature range. However, the values of *e* and *g* may be different for different types of wood. The values of *e* and *g* may even be different for different species within the southern pine group. Nonetheless, the data presented here indicate the usefulness of the model for estimating changes in the mechanical properties of wood exposed to elevated temperatures. Specifically, the

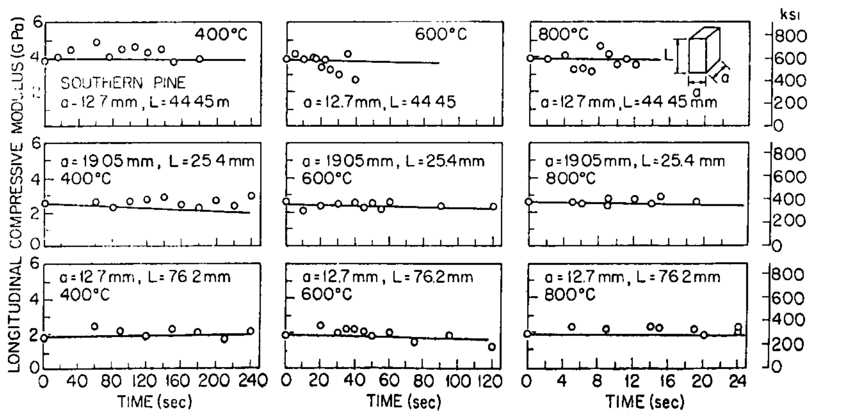


Figure 11. Longitudinal compressive modulus as a function of exposure time. Southern Pine at 400, 600 and 800°C. o Data, _____ model.

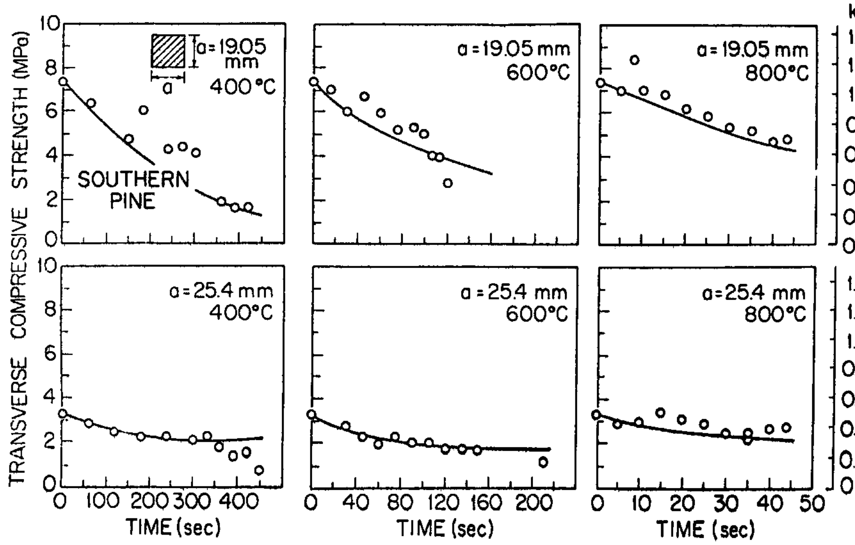


Figure 12. Transverse compressive strength as a function of exposure time. Southern Pine at 400, 600 and 800°C. o Data, _____ model.

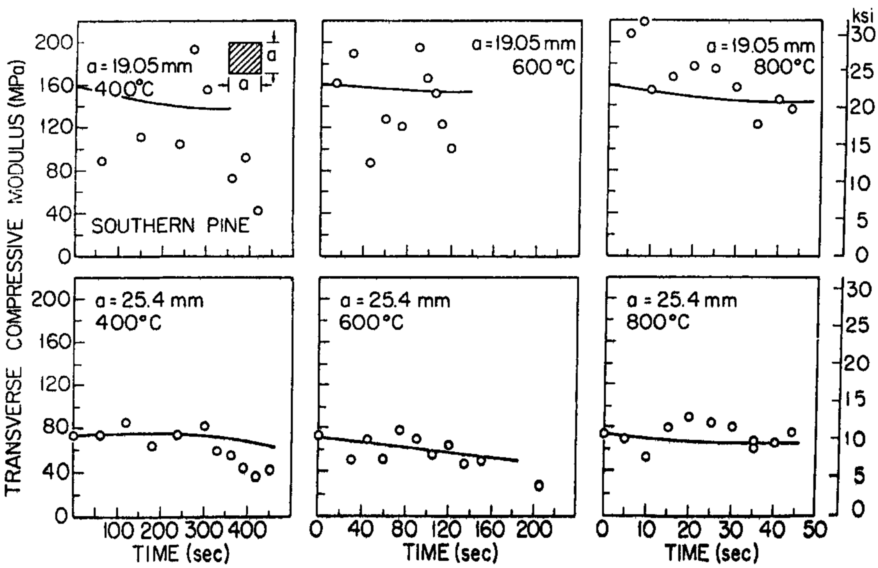


Figure 13. Transverse compressive modulus as a function of exposure time. Southern Pine at 400, 600 and 800°C. o Data, _____ model.

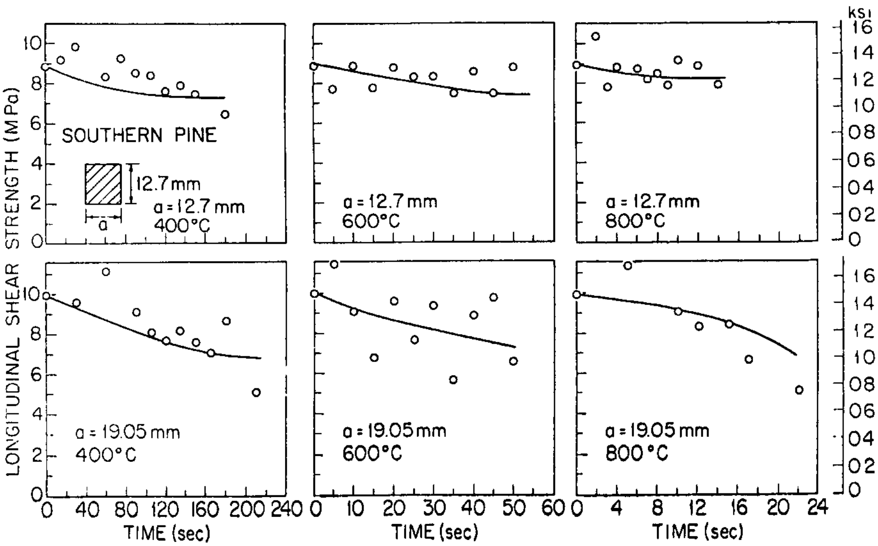


Figure 14. Longitudinal shear strength as a function of exposure time. Southern Pine at 400, 600 and 800°C. o Data, _____ model.

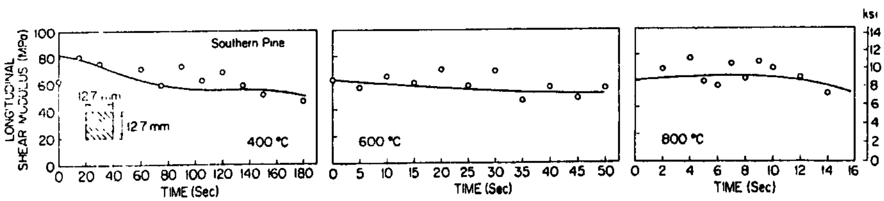


Figure 15. Longitudinal shear modulus as a function of exposure time. Southern Pine at 400, 600 and 800°C. o Data, _____ model.

Table 1. The constants e and g used in equations 1 and 2.

	Southern Pine	
	e	g
Longitudinal Tensile Strength	0.1	1.0
Longitudinal Compressive Strength	1×10^{-5}	1×10^{-2}
Transverse Tensile Strength	0.2	0.35
Transverse Compressive Strength	2×10^{-3}	4×10^{-2}
Longitudinal Shear Strength	6×10^{-3}	6×10^{-2}

model provides a suitable means for predicting failure times of wooden structures during fire exposure, a problem which is discussed in a companion article [3].

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