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Modeling of the thermal degradation of structural wood members exposed to fire

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SUMMARY

To accurately predict the structural performance of a wood member, knowledge is required of the rate at which it chars and the temperature distribution in the residual load-bearing section. The charring rate and temperature distribution can be calculated with a model that predicts the thermal degradation or pyrolysis of wood exposed to a high-temperature environment. More than 50 wood pyrolysis models have been developed since World War II. They range from simple analytical expressions to complex systems of coupled partial differential equations that describe the heat and mass transfer through wood and char.

This paper presents a brief overview of the aforementioned models and provides a more detailed description of a new model. This model is referred to by the acronym CROW (Charring Rate Of Wood). Although the intent was to keep CROW as simple as possible, the model accounts for the four major factors that affect the thermal degradation of wood: dry density of the wood; moisture content of the wood; lignin content of the wood; char contraction.

The predictive capability of CROW was evaluated on the basis of ASTM E 119 furnace data obtained for a Douglas fir glulam beam tested under different loads. CROW predictions, with some adjustment for moisture effects, are in reasonable agreement with the measurements. The model will be most useful to predict performance of wood members exposed under thermal conditions that deviate from the standard fire (natural or parametric fires) and/or members that are protected by a membrane. Copyright © 2004 John Wiley & Sons, Ltd.

KEY WORDS: charring rate; fire resistance; fire model; fire test; pyrolysis; wood

INTRODUCTION

The charring rate, β, is an important factor in the fire design of exposed structural timbers, because it determines how quickly the size of the load-bearing section decreases to a critical level. Design procedures for fire-resistant wood members in the U.S. model building codes [1]

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are based on work done by Lie in the early 1970s [2]. Lie assumed a constant charring rate of 0.6 mm/min, regardless of species and moisture content.

White performed extensive measurements of the charring rate of eight wood species exposed according to ASTM E 119 [3]. He found that the data could be correlated according to the following equation:

$$t = mx_c^{1.23} \tag{1}$$

where t is the time (min), m is the char rate coefficient (min/mm$^{1.23}$) and x_c is the char depth (mm).

Based on the experimental data, an empirical model was developed that expresses m as a function of density, moisture content and a char contraction factor. The latter is the ratio of the thickness of the char layer at the end of the fire exposure divided by the original thickness of the wood layer that charred. The char contraction is primarily a function of the lignin content in the wood. Permeability was identified in a more recent publication as an important missing factor in this correlation [4].

By using White's time-location model it is possible to refine Lie's method and account for the effects of species and moisture content [5]. Moreover, application of Equation (1) results in a more economical design if the desired fire endurance is greater than 60 min as the charring rate decreases with time.

White's model is not applicable if exposure conditions deviate from the standard fire. A limited amount of charring rate data is available for natural fire conditions and wood members covered by a protective membrane. A more universal approach to determine the charring rate of wood members involves the use of a pyrolysis model that predicts the thermal degradation under specified thermal exposure conditions.

White's data and correlation provide guidance as to the physical and chemical phenomena that need to be addressed by the pyrolysis model. A conceptual description of these phenomena is provided in the next section. A literature survey was conducted to determine whether a suitable model with the necessary features is not already available. Since the search was unsuccessful, it was decided to develop a new model. The development and experimental validation of the new pyrolysis model form the main subject of this paper.

CONCEPTUAL DESCRIPTION OF WOOD PYROLYSIS

Pyrolysis of porous char-forming solids, such as wood, exposed to fire is a very complex process. Figure 1 identifies the major physical and chemical phenomena involved in the pyrolysis of an exposed slab of wood.

Under practical conditions of use, wood products always contain a certain percentage of moisture. When exposed to fire, the temperature of the wood will rise to a point when the moisture starts to evaporate. Since the water is adsorbed to the cell walls (at least if the moisture content is below the fiber saturation point, which is approximately 30% by mass), evaporation requires more energy than needed to boil free water and may occur at temperatures exceeding 100°C. The water vapor partly migrates toward, and escapes through, the exposed surface. A fraction also migrates in the opposite direction, and re-condenses at a location where the temperature is below 100°C.

The dry wood (zone 3) further increases in temperature until the fibers begin to degrade. The thermal degradation starts around 200°–250°C. The volatiles that are generated again travel

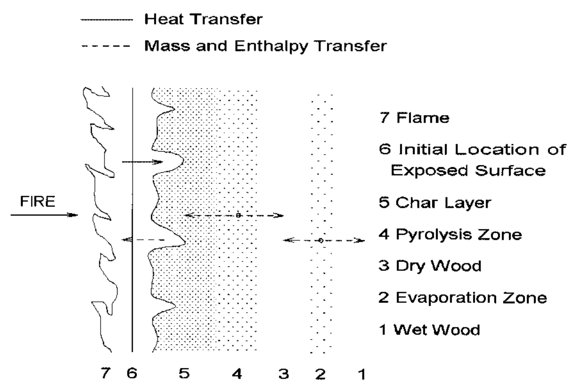

Figure 1. Heat and mass transfer in a pyrolysing slab of wood.

primarily toward the exposed side, but also partly in the opposite direction. They consist of a combustible mixture of gases, vapors and tars. A solid carbon char matrix remains. The volume of the char is smaller than the original volume of the wood. This results in the formation of cracks and fissures which greatly affect the heat and mass transfer between the flame and the solid. The combustible volatiles that emerge from the exposed surface mix with ambient air and burn in a luminous flame.

Under certain conditions, oxygen may diffuse to the surface and lead to char oxidation. The exposed surface recedes as combustion progresses due to the char contraction and possible char oxidation.

MATHEMATICAL MODELS FOR WOOD PYROLYSIS

More than 50 different mathematical models for the pyrolysis of wood have been developed since WW II [6–56]. These models range from simple approximate analytical equations to very complex numerical solutions of the conservation equations. They vary widely in complexity depending on the physical and chemical phenomena that are included and the simplifying assumptions that are made. Some address both heat and mass transfer, while others completely ignore migration of water and/or fuel vapors. There are two main application areas for such models:

- Use of wood fuel for energy generation
- Fire performance of wood

Ten of the models in the second category were specifically developed for structural applications [14,18,21,23,31,41,44,45,49,51]. The remaining models in the second category were developed to predict the flammability of wood in building fires or the burning behavior of forest fuels.

It is relatively easy to write down a comprehensive set of model equations [57]. The main equation expresses the conservation of energy as follows:

$$\rho c_{\mathrm{p}}\frac{\partial T}{\partial t} + \nabla(\rho_{\mathrm{g}}\bar{v}_{\mathrm{g}}c_{\mathrm{g}}T) = \nabla(k\nabla T) - \dot{r}_{\mathrm{v}}(\Delta h_{\mathrm{v}} + \Delta h_{\mathrm{w}}) - \dot{r}_{\mathrm{p}}\Delta h_{\mathrm{p}} \quad (2)$$

where ρ is the density of wood, partially charred wood, or char (kg/m^3), c_{p} is the specific heat of wood, partially charred wood, or char (J/kg-K), T is the temperature (K), t is the time (s), ρ_{g} is the density of volatiles (kg/m^3), $\bar{v}_g$ is the velocity vector of the volatiles (m/s), c_g is the specific heat of volatiles (J/kg-K), k is the thermal conductivity of wood, partially charred wood, or char (W/m-K), $\dot{r}_v$ is the vaporization rate of water (kg/s), Δh_v is the heat of vaporization of water (J/kg), Δh_w is the heat of wetting (J/kg), $\dot{r}_p$ is the generation rate of pyrolysates (kg/s) and Δh_p is the heat of pyrolysis (J/kg).

Solving the equations is not so easy. Moreover, obtaining material properties can be a monumental task. For example, the thermal conductivity of wood is a function of temperature, density and moisture content. It is hard to obtain experimental data at elevated temperature, and some models simplify this problem by using a constant that is representative for a certain density of the wood, moisture content and temperature range. A similar challenge exists in selecting suitable values for the thermal conductivity of partially charred wood and char.

NEW ENGINEERING WOOD PYROLYSIS MODEL

It is clear from the information provided in the previous section that a tremendous amount of work has been done in the area of pyrolysis modeling of wood. Unfortunately, none of the models that have been developed include all the important features that need to be addressed. For example, one of the most complete models was developed by Fredlund [41]. This model includes unique mass transfer and char oxidation algorithms, but it does not address char contraction.

In addition, there are many inconsistencies and contradictions between the different models. For example, different thermal properties are being used for similar wood species. The thermal conductivity of char varies by two orders of magnitude. Janssens developed a procedure to generate thermal properties for wood, partially charred wood and char, but to date this procedure has not been used in any published pyrolysis model [58]. The new model incorporates properties that are calculated according to this procedure. The model is one-dimensional, and consists of the following energy conservation equation

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial}\left(k \frac{\partial T}{\partial x}\right) - (\Delta h_v + \Delta h_w)\rho_0 \frac{\partial u}{\partial t} \tag{3}$$

where x is the length coordinate (m), ρ_0 is the density of oven dry wood (kg/m^3) and u is the moisture content by mass.

The primary model assumptions are as follows:

- Wood properties are used when $T \leqslant 200°C$
- Char properties are used when $T \geqslant 800°C$
- Mass weighted averages are used at $200°C < T < 800°C$
- Water evaporates at $T = 100°C$
- The heat of pyrolysis is equal to 0
- Char contraction is taken into account
- The equation is solved via a finite difference method

Moisture migration to the cold side is not directly accounted for, but is addressed as discussed in the next section. To simulate the behavior under standard fire exposure conditions, Equation (3) is coupled with a surface boundary condition that accounts for the heat transfer from the furnace and its own flame as described by Hadvig [23]. The furnace is modeled in the same way as done by Mehaffey *et al*. [44].

EVALUATION OF THE PREDICTIVE CAPABILITY OF CROW

Experiments

In 1997, the American Forest & Paper Association (AF&PA) conducted a series of four experimental glued laminated (glulam) beam tests according to ASTM E 119 at Southwest Research Institute (SwRI) in San Antonio, Texas. The primary objective of the tests was to evaluate the effect of load on the fire resistance of glulam beams. Four 2400F-V4 Douglas fir beams, with an actual section of 222×419 mm, were tested under different load conditions. The clear span of the beams was 4.57 m, of which the central 3.76 m section was exposed in the furnace. Times to structural failure, measurements of beam temperature and post-test char measurements were recorded.

The first of the four tests was conducted without external load, but with an extensive number of thermocouples distributed across the section to determine charring rates in different directions as a function of time.

In the remaining three tests, the beams were loaded at 27%, 44% and 91% of the design load. The reported allowable stresses and stiffness were $F_b = 16.55$ MPa and $E = 11$ GPa, respectively. Each beam was braced against lateral translation and rotation at the supports and was loaded at two evenly spaced load points. The resisting moment was estimated to be 302 kN m compared with induced moments of 25.7 kN m, 41.6 kN m and 88.2 kN m for the 27%, 44% and 91% design load cases, respectively. The corresponding failure times were 147 min, 114 min and 85 min, respectively.

Calculations

The effects of moisture migration toward the cold side are indirectly accounted for by the CROW model. It is assumed that only part of the moisture evaporates and escapes through the exposed surface. The remaining part evaporates, moves toward the cold side where it condenses, evaporates again at a later time, etc. The energy required to initially evaporate the second fraction of the moisture is never lost from the system.

The fraction of the moisture content that evaporates and escapes in the form of steam is determined by matching CROW charring rate predictions with White's time-location model. The Douglas fir beams tested at SwRI had a density of 460 kg/m^3 and an average moisture content of approximately 9% by mass. The corresponding values for m in White's model are 0.47 and 0.58 for a moisture content of 0% and 9%, respectively. Figure 2 shows that the times to reach char depths of 12.7, 25.4, 38.1, 50.8 and 63.5 mm in dry wood according to the CROW model are in good agreement with White's time–location model. Best agreement between CROW model predictions and Equation (1) for a moisture content of 9%, was obtained by assuming that half of the moisture is conserved.

The section modulus at failure was determined for each of the three loaded beam tests conducted at SwRI based on the following equation

$$S_f = \frac{M}{k_f k_{mean} F_b} \tag{4}$$

where S_f is the section modulus at failure (m^3), M is the maximum load-induced moment (kN m), k_f is the strength reduction factor to account for partial heating of the section, k_{mean} the

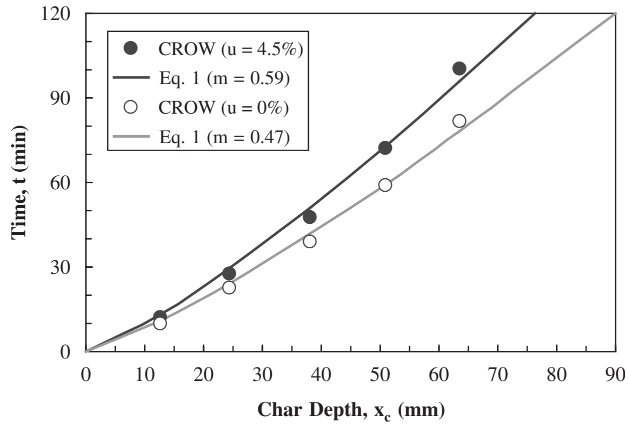

Figure 2. Comparison between CROW predictions and White's time-location model.

Table I. Calculated char depths at failure for the Douglas fir beam tests at SwRI.

M (kN m)	k_f	S_f (m^3)	x_c (mm)
25.7	0.819	0.000666	81.1
41.6	0.849	0.001039	74.5
88.2	0.893	0.002093	57.3

factor to convert from allowable stress to mean failure stress (2.85) and F_b is the allowable stress (16 550 kPa).

The strength reduction factor was calculated as a function of the beam perimeter P (m) and area A (m^2) according to Eurocode 5 [59]

$$k_f = 1 - \frac{P}{200A} \tag{5}$$

The corresponding char depth was then obtained by solving the following equation, which accounts for corner rounding.

$$S_f = \frac{(b - 2x_c)(d - x_c)^2}{6} - 0.215x_c^2(d - x_c) \tag{6}$$

where b is the initial width of the beam section (m), x_c is the char depth (m) and d is the initial depth of the beam section (m).

The results of these calculations are given in Table I. Figure 3 compares CROW char depth predictions with the calculated char depth values in Table I. It can be concluded from Figure 3 that the 'calibrated' CROW model predicts charring rates that are consistent with the results of two of the three beam tests. The CROW model slightly underestimates the char depth for the beam loaded at 44% of the design load.

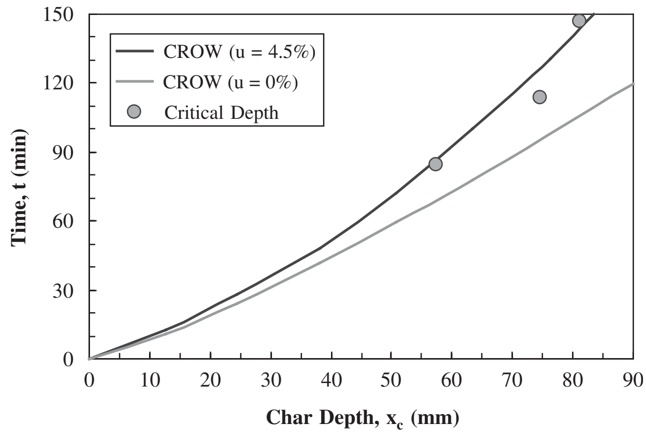

Figure 3. CROW char depth predictions vs. estimated char depths at failure.

CONCLUSIONS

A new pyrolysis model was developed to predict the charring rate of and temperature distribution in wood members exposed to specified fire conditions. The model is calibrated on the basis of White's correlations for the charring rate of wood members exposed to the standard ASTM E 119 fire. Model predictions are consistent with char depth estimates from Douglas fir beam tests conducted at SwRI. Additional comparisons with experimental data are needed to extend the validity of the pyrolysis model.

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