Charring rate determination of wood pine profiles submitted to high temperatures

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Abstract

The wood material presents an increasing use for structural engineering applications in buildings and other specials engineering production. To assess safety rules, this type of elements should have sufficient mechanical resistance to guarantee the design loads. Wood is a natural material and is submitted to many constantly changing influences. The high wood vulnerability, due accidental conditions, requires rigorous thermal and mechanical assessment. The combustion and the chemical phenomena occurred in wood during an accidental situation of elevated temperature is a complex study issue. When wood structures are exposed to high temperatures, the burned wood becomes a char layer which loses all strength but insulating temperature rise in the core of material. The charring rate is more or less constant and mainly depends on the density and moisture content wood properties. Safety rules and guidelines should be useful for different wood applications. The fire safety of this type of material involves prevention, inhibition, detection and evacuation. This involves appropriate design rules, installation, construction and maintenance of the wood material applications. This paper proposes an experimental and a numerical method for charring rate determination in pine wood. Different pine sections will be tested and submitted to high temperatures using a heating power unit based on electrical resistances. The temperature results will be measured through wood profile during time heating exposure. Using appropriated material properties and boundary conditions, reasonable predictions of charring layer with a finite element analysis method, can be provided. The thermal response obtained with the finite element formulation will be compared with experimental results, in several series of wood pine profiles. Char layer thickness will be determined.

Keywords: charring rate, wood, high temperatures, safety.

1 Introduction

The use of timber material include several interior and exterior applications: piles, barriers, railings, boardwalks, decks, fender systems, privacy fences, landscaping, railroad ties, residential construction, wall and ceiling linings, bridges and retaining walls. The main advantages of timber constructions relatively to the use of other materials are: ease of construction and maintenance, pleasant appearance, renewable resource, lightweight and construction is not weather-dependent, [1]. When wood materials are used, fire protective finishes are typically required and the protection needed can be determined using building codes. The fire resistance rating calculation is based on standard fire test procedure and allows identifying the amount of time for which the structure must sufficiently carry load. Because wood is combustible, designers have major concerns about fire safety in timber construction. But the wood combustion is slowly and regular, and their behaviour is predictable. If wood is submitted to a sufficient heat, a degradation thermal process (pyrolysis) occurs, producing gases accompanied by loss in weight and serviceable cross-section. The burning behaviour can be described through the following processes: pyrolysis, ignition, reradiation, char formation. Figure 1 represents the different degradation zones in a wood section.

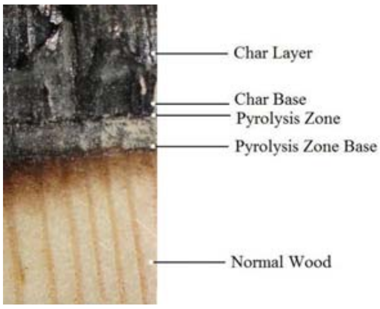

Figure 1: Degradation zones in a wood section.

The factors which affect the burning behaviour of wood will determine the charring rate. These types of factors are considered the following: level of radiant heat exposure, formation of char, moisture content, species of timber and dimensions of the timber, [2]. Design models of timber structures submitted to high temperatures take into account the loss in cross section due to charring layer and the temperature dependent reduction of strength and stiffness of the uncharred residual cross section [3]. The stiffness and strength of wood significantly decrease with increasing temperature [4]. The interface between charred and noncharred wood is the demarcation plane between black and brown material, characterized by a temperature of 300ºC [5]. The charring rate for different types of species exposed to the standard time-temperature curve has been studied in different countries for many researchers, [6-8]. The objective of this work is to present a numerical and an experimental method, which could be used to assess the performance time of pine wood profiles, during high temperatures exposure. With this study the charring rate is calculated for pine profiles. This factor is important in fire safety design because it determines how quickly the size of the load-bearing section decrease to a critical level.

2 The study of pine wood

The wood specie in study is pine, representing 40% of the forest area in Portugal. It constitutes one of the most typical Portuguese natural scenery. Its economical importance is raised, since the pine wood has been widely used for construction, for paper industry and for resin production. For this work, the physical characteristics adapted are referred by [4], where different wood sections tests are presented due fire conditions, according to the normalized fire curve ASTME119, with initial water moisture between 8% and 9%, table 1.

Table 1: Physical characteristics of pine wood.

Specie	ρ kg/m^3	Linear charring rate β' min/mm	Non-linear charring rate β'' min/mm$^{1.23}$
Pine	509	1.24	0.56

2.1 Analytical models for charring layer determination

When a wood section burns, at a constant rate of heat release per unit area, the boundary between the pyrolysed material and the core wood (designated by pyrolysis front) proceeds to the wood in depth direction. Since all pyrolysing wood can be considered to char, the charring rate β corresponds to the propagation rate of the pyrolysis front. This parameter is an essential quantity for fire safety, because the wood under the char layer preserves its original properties. Important factors for the charring rate of wood are the density, the external heat flux and the moisture content. Charring rate decreases with increasing density and increases linearly with the external heat flux, [7]. There are typical values for charring rate of wood between 0.5-1.0mm/min. EC5 [5] for wood design suggests a charring rate of 0.64mm/min for softwoods and 54mm/min for hardwoods. Following EC5 [5], the design equation proposed for on direction charring layer determination, function of the charring rate for non protected surfaces to normalized fire conditions is presented in equation 1.

$$d_{char,0} = \beta_o\, t \qquad (1)$$

When the propagation of fire conditions is more than in one direction the equation 2 should be used.

$$d_{char,n} = \beta_n\, t \qquad (2)$$

Table 2 represents design values of the charring rate, for softwood according the EC5 [5].

White, [4] proposed different analytical equations for charring rate determination. White performed extensive measurements in wood species and proposed the following equations:

$$t = \beta^{'} d_c \tag{3}$$

$$t = \beta^{''} d_c^{1.23} \tag{4}$$

where t is the time in mim; $\beta^{'}, \beta^{''}$ are the charring rate coefficient according table 1 and d_c is the char depth in mm.

Table 2: Charring rate of softwood for simple models.

Material	β_0 mm/min	β_n mm/min
Glued laminated timber with $\rho \geq 290 Kg/m^3$	0,65	0,7
Solid timber with $\rho \geq 290 Kg/m^3$	0,65	0,8
β_0 – design charring rate for one-dimensional charring under fire exposure;		
β_n – design notional charring rate under standard fire exposure.		

2.2 Thermal proprieties

The thermal properties of wood vary considerably with temperature. For pine wood the physical characteristics used are referenced by [4] through table 1. Annex B of Eurocode 5, EC5 [5], provides the design values for density, thermal conductivity and specific heat of wood. The values below about 350ºC represent the properties of wood and above 350ºC represent the properties of char layer.
The following tables summarize the values of the thermal conductivity, the specific heat and the density of wood, assuming initial moisture of 12%.
In table 3 the values of the wood thermal conductivity are presented as temperature dependent.

Table 3: Thermal conductivity, *k*.

Temperature ºC	k W/mK
20	0.12
200	0.15
350	0.07
500	0.09
800	0.35
1200	1.50

The specific heat for wood and for carbonized layer is temperature dependent, according table 4. The peak verified for a value equal to 100 ºC is related to moisture wood evaporation.
Moisture in wood affects mass and volume. Density is presented in kg/m^3 for each specified condition. The strength of wood has direct correlation with density. The design values for the ratio of density to dry density of softwood for standard fire exposure are given in table 5.

Table 4: Specific heat, C_p.

Temperature ºC	C_p kJ/kgK
20	1.53
99	1.77
99	13.60
120	13.50
120	2.12
200	2.00
250	1.62
300	0.71
350	0.85
400	1.00
600	1.40
800	1.65
1200	1.65

Table 5: Density ratio*, ρ.

Temperature ºC	ρ
20	1+w
99	1+w
120	1.00
250	0.93
300	0.76
350	0.52
400	0.38
600	0.28
800	0.26
1200	0

*w is the initial moisture content.

3 Numerical and experimental methods

For char layer determination in wood profiles submitted to high temperatures, two alternative methods will be presented in this work.
Differential equations are commonly approximated by the finite element method. The method can be used for a wide of different analyses and structural applications. The finite element program *Ansys* was used to model and analyse the thermal behaviour of pine wood profiles exposed to high temperatures. A finite plane element (Plane 77), with 2 degrees of freedom per node, is used for thermal and nonlinear transient analysis. The non-linearity due to the material properties thermal dependence will be taken into account in the numerical model. Temperatures will be determined during transient thermal analysis. Thermal analysis will be performed over specimens with 500x180x80mm dimensions, as represented in figure 2.

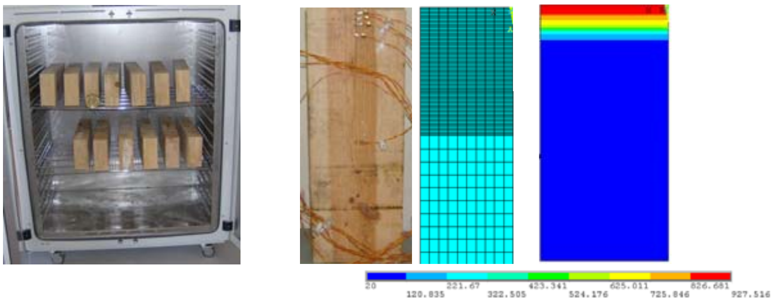

Figure 2: Experimental and numerical model.

An experimental method was also defined, for measuring temperatures and charring layer in wood pine profiles. An electro-ceramic heating system will be used with a thermal power unit of 70kVA. A typical heating curve was used and a programmable controller verifies the temperature during each experimental test.

Figure 3 shows the experimental test setup used in laboratory. In the present work different profiles were submitted to high temperatures for one exposure side. Nine samples of pine wood were tested (T1, T2, ... T9). The charring layer was measured in five different points using K thermocouples through an MGCPlus data acquisition system. The temperature was measured at different positions 1, 2, 3, 5 and 25cm, from the heating exposure surface.

a)Pine b)Ceramic resistances c)Thermal unit d)Timber insulation e)Final test

Figure 3: Experimental setup.

The final stage of each test is represented in figure 4, after one hour high temperature exposure.

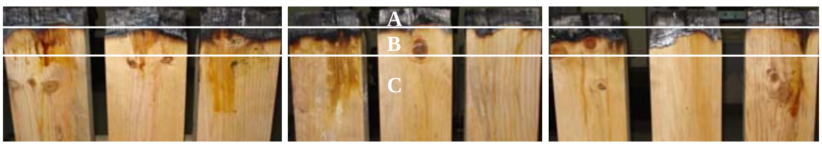

Figure 4: Charring layer in tested profiles wood.

As can seem there are three different zones in all tested profiles: *A* which corresponds to charcoal zone, *B* corresponds to pyrolyse zone and *C* the intact core wood.

Figures 5, 6 and 7 represent the temperature evolution obtained for different charring layer measured positions. The experimental results are compared with the numerical results. In all figures the time heating curve is also represented.

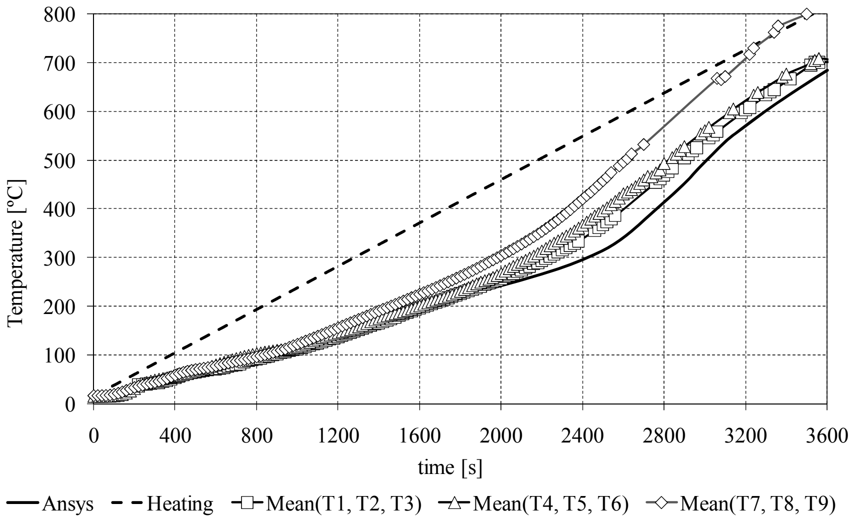

Figure 5: Temperature at 1cm from top surface.

After 2000s high temperature exposure and for 1cm position from top surface a wood charcoal is obtained. For this position and after one hour the temperature is between 700-800ºC for different experimental tests.

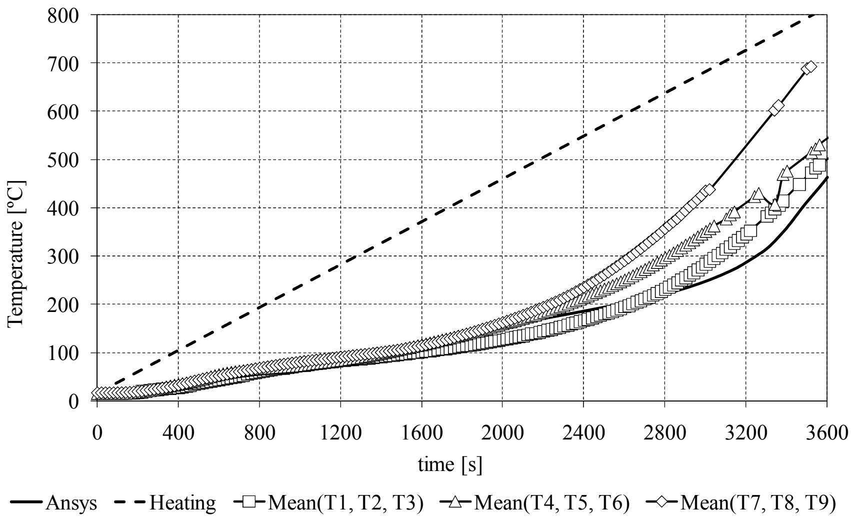

Figure 6: Temperature at 2cm from top surface.

For the position of 2cm from top surface, wood is charcoal after 2500s. At this measured point and after one hour, the temperature is between 400-600ºC.

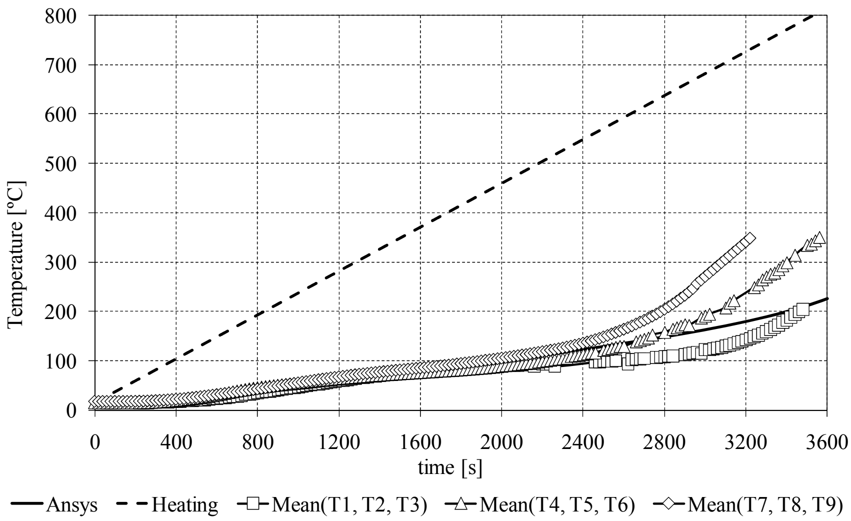

Figure 7: Temperature at 3cm from top surface.

At 3cm from top surface, and before one hour, temperature is still bellow 300ºC, see figure 7. For this point and for this time, the wood is noncharred. The measured points at 5 and 25cm had low temperatures during one hour of high heating exposure and the heat inside wood profile decrease. At 25cm from top surface, sections remain at normal temperature, 16ºC.

4 Conclusions

Wood exposed to high temperatures will decompose to provide an insulating layer char that retards further degradation. The load carrying capacity of a structural wood member depends upon its serviceable cross-sectional dimensions. The amount of the cross section charring is the major in the fire endurance of structural wood members [4]. The numerical model reveal of great importance for charring layer determination. The charring thickness layer was calculated with the numerical results obtained from *Ansys* program and compared with experimental tests. The pine wood has a greater resistance to high temperatures exposure when compared with other types of woods [8].

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