Behaviour of timber and wood-based materials in fire

STEP lecture A13
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Objective

To present information about the behaviour of timber and wood-based materials under the influence of fire.

Prerequisite

A4 Wood as a building material

Summary

Information is provided based on the knowledge of the essential components and natural properties of timber affecting its behaviour when exposed to fire, that is the chemical and physical changes under the influence of fire, are explained.

Introduction

There is no simple way of expressing the behaviour of a material with respect to fire. There are two distinct phases to a fire, the developing phase and the fully developed phase and a materials performance has to be categorised in respect of those two conditions. The developing phase incorporates a number of separate phenomena, the combustibility of the material, the ease of ignition, the speed of the spread of fire/flame across its surface and the rate at which heat is released.

The fully developed phase represents the post flash over conditions where all combustible materials become involved in the fire. The desirable properties are the ability to continue to carry load to contain the fire within the zone of origin without the escape of flames or hot gases and without conducting excessive heat to the unexposed face that may lead indirectly to fire being transmitted to adjacent areas. The ability to resist the fully developed fire is known universally as the fire resistance but in general terms this can only relate to an element of construction rather than to a material. The performance of even a simple element such as a column or a beam is dependent upon such factors as the end conditions and the magnitude and distribution of any loading.

Considering the behaviour of wood-based materials and solid timber when subjected to the developing fire, wood-based materials will burn and are therefore rated as combustible. Whilst the combustible nature may be modified by the use of coatings or impregnation with flame/fire retarding salts, none of these can render timber, or its related products, non-combustible, albeit higher levels of energy may be needed to cause it to burn. Solid timber is not readily ignited and there are very few recorded cases where timber will have been the first material to be ignited. Solid timber will require surface temperatures well in excess of 400 °C if the material is to ignite in the medium to short term without the pressure of a pilot flame. Even when a pilot flame is present the surface temperature will have to be in excess of 300 °C for significant time before ignition occurs. Timber tends to be used as the basis against which other materials are adjudged as timber is not considered to represent an unacceptable ignition risk in most environments. The actual values are related to the density, species, moisture content and shape/section factor.

Timber, being combustible will spread fire across its surface, the phenomena being a number of ignitions each triggering an adjacent ignition. As timber is not readily ignitable the speed at which flame will spread across its surface is also reasonable for a combustible material. Nearly all countries will permit the use of untreated timber for low risk applications. The rate at which timber releases heat is obviously very dependent upon the nature of the initial heating regime, the availabilitiy of oxygen and the density, shape and size the timber member being located. As with all of the above properties, European countries each developed their own bench scale tests for establishing the fundamental performance of materials against these categories and as such there is no pan-European way of expressing the performance of timber against these developing fire conditions. All countries allow the use of timber in many applications, indicating that its behaviour is not considered to be particularly hazardous.

When timber or wood-based materials are exposed to a fully developed fire they exhibit many desirable characteristics. Whilst the exposed surfaces will ignite when the heat flux becomes great enough, and initially burn fairly vigorously it soon builds up a layer of insulating charcoal, see Figure 1. As wood is a poor conductor of heat there is very little transmission of heat into remaining unburnt material. This has many benefits.

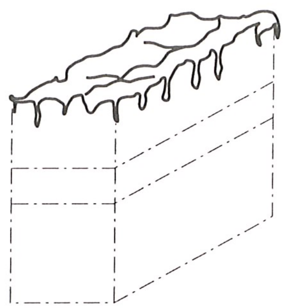


Figure 1 *The changes in timber under the influence of fire: (a) charred timber, (b) pyrolisis layer, (c) timber unaffected by fire.*

In the case of solid timber the core section remains cool only a short distance behind the burning zone. As a consequence the temperature of the residual section is cool and the construction does not have to accommodate damaging thermal expansions. Also, because the core remains cool, all of the cold state physical properties of the timber are retained and any loss of loadbearing capacity is as a result of reduced cross-section, rather than a change in the physical poperties. When wood-based sheet materials are used in the construction of seperating elements, both as structural members and linings, the low thermal conductivity prevents the heat from being easily transmitted from the hot to the cold face of the construction.

The fully developed fire is characterised in tests by the standard temperature-time curve given in ISO 834 (see Figure 2) or the equivalent national standard. The relevant criteria are given as:

- loadbearing capacity (separating and non-separating elements)
- integrity (separating elements)
- insulation (separating elements)

Critical deflection and rates of deflection are normally given as criteria for loadbearing capacity. The integrity is generally evaluated by means of the development of gaps of excessive size (set nationally) or the ignition of a cotton fibre pad. Insulation is deemed to be compromised if a mean temperature rise of 140 °C is experienced or a maximum rise of 180 °C is exceeded.

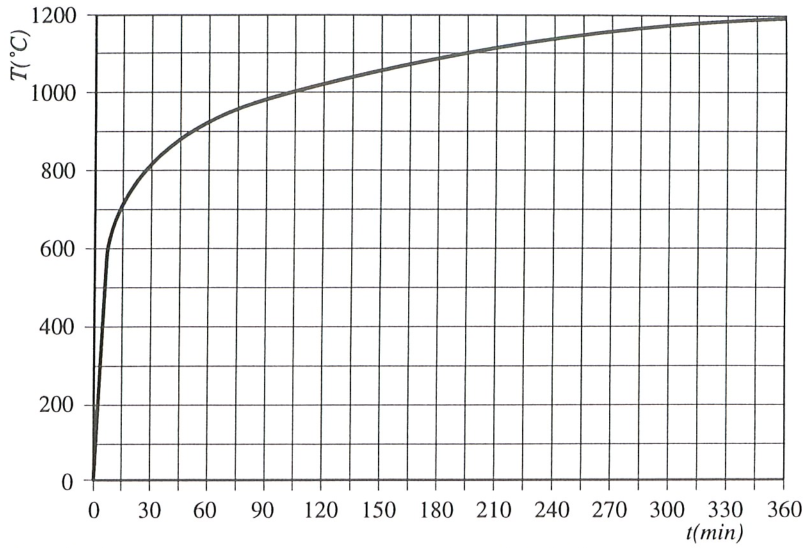


Figure 2 *Standard temperature-time curve according ISO 834.*

Timber will only lose loadbearing capacity when the cross-section of the non-fire damaged/residual section is reduced to the size where the stress in the section as a result of the applied load is in excess of the strength of the timber.

Timber-based materials will not fissure or shrink such that gaps may develop until the timber is so thin that burn-through is close and the rise in temperature will only exceed the criteria when the thin, heat affected zone reaches the outer face and again burn-through will soon follow. Timber is highly predictable when exposed to the fully developed fire conditions.

Fundamentals

Timber and wood-based materials consist mainly of cellulose and lignin, which themselves are formed from carbon, hydrogen and oxygen. They are therefore combustible and it is almost impossible to make them incombustible. But complete incombustibility is only necessary in very rare specific cases.

Influences on the fire behaviour

The form, surface, shape and the size of the cross-section of timber and wood-based elements are of great influence upon their fire behaviour.

Combustibility is dependent on the surface/volume-ratio. The greater this is the more easily ignition starts and the faster the flames spread. Many sharp corners and coarse surfaces enlarge this ratio and result in a less favourable fire behaviour. Cracks and shakes also increase the effects of fire. Thus the charring rate of glued laminated timber, which is mostly free of shakes and cracks, is lower than for solid timber.

The time taken for wood to ignite and for combustion to spread is dependent on the (oven dry) density. Thus different kinds of wood behave differently under the influence of fire. The relationship between density and the rate of combustion is shown in Figure 3.

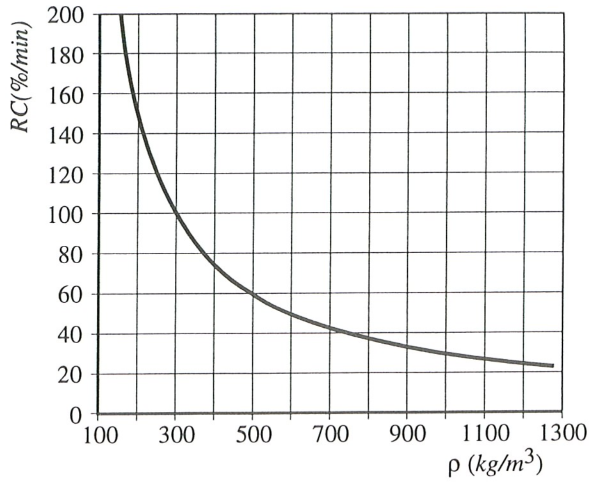


Figure 3 *Relationship between density* ρ *and rate of combustion RC (Kollmann and Coté, 1968).*

The relationship between density and ignition is similar: the higher the density the longer it will take for the wood to ignite.

The moisture content of timber is another important factor influencing the behaviour of timber when exposed to fire. In timber structures the moisture content is mostly between 8% and 15%. This means that for each tonne of wood about 80 to 150 *kg* of water have to evaporate before the wood will burn. The influence of the moisture content upon the charring rate need not be taken into account because of the low variation in the equilibrum moisture content.

Chemical and physical processes during the combustion of wood

When wood and wood-based materials burn, chemical decomposition starts with the resultant formation of charcoal and combustible gases. Spontaneous ignition of a thin strip of wood may occur within a range of temperature from 340 to 430 °C. But ignition is also possible at a much lower temperature (e.g. 150 °C) if the piece of wood has been subjected to heat for a long time. Temperatures under 100 °C but well above room temperature heat up the timber and bring about a drying process. A decrease of strength and modulus of elasticity takes place.

When the temperature of 100 °C is reached water begins to evaporate and steam takes the path of lowest resistance to escape through corners, arrises, joints, open pores and shakes. In these places the timber dries more quickly. The temperature does not increase until all of the water has evaporated. Figure 4 shows the temperature below the pyrolisis layer, when the timber is heated according to the ISO temperature-time curve and in relation to time. The figure shows that the temperature increases after the water has evaporated (100°C). The pyrolisis layer is the zone between the charred and natural timber where the wood has been affected chemically by the fire but has not fully decomposed.

Between 150 and 200 °C gases are generated which consist 70% incombustible carbon dioxide (CO_2) and 30% combustible carbonmonoxide (CO). Once the temperature reaches 200 °C, more and more combustible gases form and the proportion of CO_2 decreases. As soon as the gases ignite the temperature on the surface increases rapidly. Carbonization of the wood then continues. The decomposition occurs in a the pyrolisis layer which is about 5 *mm* thick. At temperatures above 500 °C the production of gas is very much reduced and the production of charcoal increases. This explains the appearance of timber after exposure to fire.

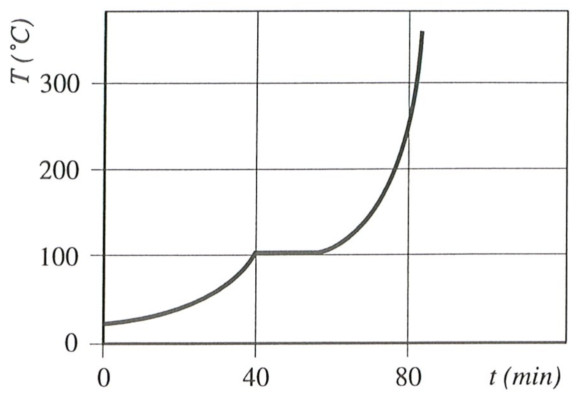


Figure 4 *Temperature in the heated timber below the pyrolisis layer (see Figure 1) according to the ISO temperature-time curve (Figure 2).*

The thermal conductivity of charcoal is only about one sixth that of pure solid timber. The layer of charcoal therefore acts as an insulant and the decomposition of the deeper internal zones of the remaining cross-section is thus greatly retarded. Due to this effect and because of the low heat conductivity of timber the temperature in the middle of the cross-section is much lower than on the surface. For this reason the fire resistance of timber is much higher than generally supposed. The following Figure 5 shows beams and columns exposed to fire from 3 and 4 sides.

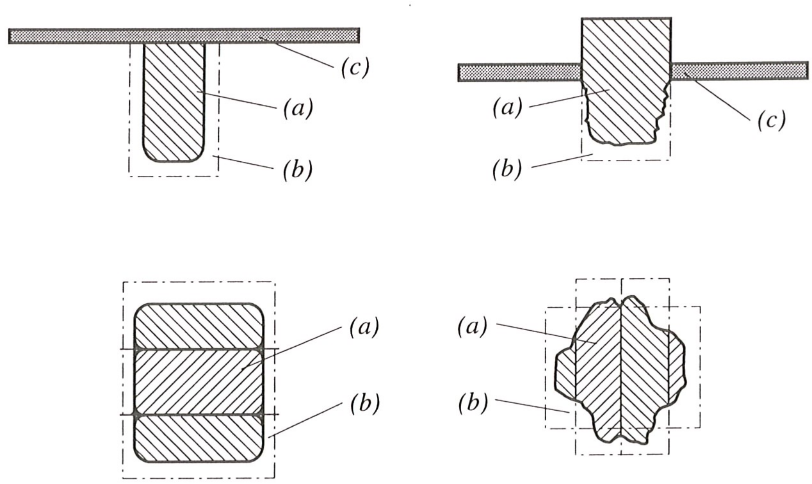


Figure 5 *Beams and columns before and after the exposure to fire. (a) remaining cross-section, (b) charred timber, (c) fire barriers.*

Charring rates

Many test results for wood and wood-based materials have shown a linear relationship between charring depth and time. A constant charring rate can therefore be assumed for calculation of the fire resistance of a section. The following charring rates β_0 in Table 1 can be used for simple methods of structural fire design (see STEP lecture B17) without the need to take special consideration of the rounding of edges. Thus the residual cross-section is considered to be rectangular in fire design calculations. The more accurate assessment of residual cross-section covering rounding of arrises allows a slower charring rate, β, in Table 2.

Material		β_0 in *mm/min*
Solid softwood	with $\rho_k \geq 290$ kg/m^3 and min $a \geq 35$ mm	0,8
Glued laminated softwood	with $\rho_k \geq 290$ kg/m^3	0,7
Wood panels	with $\rho_k = 450$ kg/m^3 and $t_p = 20$ mm	0,9
Solid hardwood	with $\rho_k \geq 450$ kg/m^3	0,5
Glued laminated hardwood	with $\rho_k \geq 450$ kg/m^3	0,5
Oak		0,5
Solid hardwood	with $\rho_k \geq 290$ kg/m^3	0,7
Glued laminated hardwood	with $\rho_k \geq 290$ kg/m^3	0,7
Plywood	with $\rho_k = 450$ kg/m^3 and $t_p = 20$ mm	1,0
Wood-based panels	with $\rho_k = 450$ kg/m^3 and $t_p = 20$ mm	0,9

EC5: Part 1-2: 3.1

Table 1 *Design charring rates β_0. t_p: thickness of wood and wood-based panels, a: width/depth of cross-section.*

For other densities and thicknesses of wood and wood-based panels the charring rate should be calculated as

$$\beta_{0,\rho,t} = \beta_{0,45,20}\; k_\rho\, k_t \qquad (1)$$

where

$$k_\rho = \sqrt{\frac{450}{\rho_k}} \qquad (2)$$

$$k_t = \min \begin{cases} \sqrt{\dfrac{20}{t_p}} \\ 1{,}0 \end{cases} \qquad (3)$$

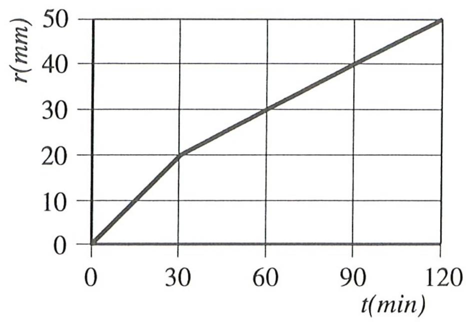
For closely packed multiple layers the charring rate may be calculated based on the total thickness.

Material		β in *mm/min*
Solid softwood	with $\rho_k \geq 290$ kg/m^3	0,67
Glued laminated softwood	with $\rho_k \geq 290$ kg/m^3	0,64
Solid hardwood	with $\rho_{mean} \geq 350$ kg/m^3	0,54
Glued laminated hardwood	with $\rho_{mean} \geq 350$ kg/m^3	0,54

EC5: Part 1-2: Table A.1

Table 2 *Design charring rates β. Rounding at arrises has to be fully considered.*

The shape of the char-line at arrises should be assumed as circular with a time-dependant radius according to Figure 6. For more complicated methods of structural fire design applicable for parametric fire exposure should be used the charring rate β_{par} according Annex D in EC5: Part 1-2.



EC5: Part 1-2: Figure A.1 *Figure 6* *Time-dependant radius of the char-line at arrises.*

Example

Calculation of residual section and second moment of area after 60 minute fire for a glulam beam (softwood, $\rho_k \geq 290$ *kg/m*^{3}, $b \times h = 200 \times 600$ *mm*).

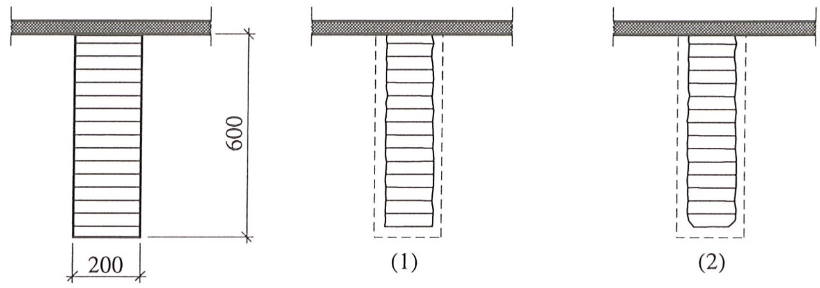


Figure 7 *Cross-section of glulam beam.*

Case 1

$\beta_0 = 0{,}7$ *mm/min*

Charring depth $d_{char} = 60 \cdot 0{,}7 = 42$ *mm*

Residual cross-section area

$A_f = (200 - 84)(600 - 42) = 64728$ *mm*^{2}

Second moment of area

$$I_f = \frac{116 \cdot 558^3}{12} = 1{,}68 \cdot 10^9 \ mm^4$$

Case 2

$\beta = 0{,}64$ *mm/min*

Charring depth $d_{char} = 60 \cdot 0{,}64 = 38{,}4$ *mm*

radius at arrises $r = 30{,}0$ *mm* (see Figure 6)

Residual cross-section area

$A_f = (200 - 76{,}8)(600 - 38{,}4) - 0{,}5 \cdot 30^2 (4 - \pi) = 68803$ *mm*^{2}

Second moment of area

$$I_f \approx \frac{123{,}2 \cdot 561{,}6^3}{12} - 0{,}5 \cdot 30^2 (4 - \pi) \left(\frac{561{,}6}{2} - 0{,}222 \cdot 30\right)^2$$

$$I_f \approx 1{,}79 \cdot 10^9 \ mm^4$$

Reference

Kollmann, F.F.P and Coté, W.A. (1968). Principles of wood science and technology. Volume I, Solid Wood. Springer Berlin, Heidelberg, Germany, 592 pp. ISBN 0387042970.