Impact of wood species on the timber beam strength and stiffness under fire

K Kmiecik
1 Institute of Building Materials and Structures, Faculty of Civil Engineering, Cracow University of Technology, 31-155 Cracow, Poland
E-mail: kamil.kmieck@pk.edu.pl

Abstract. A lot of different types of wood can be used to build the structure. Main constructions are usually built of solid wood or glued laminated timber. The division into design classes depends on the strength and mechanical properties of wood. One of the most important aspects to consider when designing timber structures is to provide fire resistance. In contrast to other construction materials such as concrete, steel, ceramics, wood is a combustible material. When timber member is subjected to fire, the surface of the wood initially ignites and burns rapidly. At 300°C the pyrolysis takes place which cause loss in mass and decrease the strength and mechanical properties. Charring rate and decreasing of properties depend on the wood species. As a consequence, it has a significant impact on the timber member strength in fire conditions. This article presents a summary from numerical simulations on impact of wood species on the timber beam strength and stiffness in fire conditions. Numerical models of timber beams were made in the SAFIR software. All modeled beams have the same dimensions. Each beam was loaded with a bending load. Also the fire load from four sides of the elements according to the ISO fire curve was given. Species and classes of wood were differentiated. Using the isotherm 300°C from the SAFIR program, time-dependent residual cross-sections were determined. As a result, the reduction of bending capacity and the increase in deflections of timber beams were obtained. It was noticed that higher class wood had a relatively lower load-bearing capacity reduction under fire.

1. Introduction

Wood is one of the oldest known materials used in construction and one of the most sustainable resources available. Timber has a very strength to weight ratio. It is used for variety of structural elements such as girders, columns, beams and trusses. Timber is a good construction material for many reasons: durability, high strength to weight ratio, good environmental influence, aesthetic values, high energy efficiency and quick erection time.

Timber for structural use is graded into strength classes. European strength class system is based on three grade determining properties: strength (f_m,k), modulus of elasticity parallel to the grain (E_0,mean) and density (\rho_k). Other strength and stiffness and density values are derived by empirical formulas from these primary properties [1]. Formulas for these derivative properties have been defined conservatively, for safety reasons. Provided in the current European standard EN 338 [2], the strength class system for softwood is based on edgewise bending properties.

Strength classes offer a number of advantages to both: the designer and the timber supplier. The designer is not obligated to check on the availability and price of a large number of species and grades that might be used. Suppliers can provide any grade that meet the strength class requirements specified in the documentation. EN 338 defines 18 strength classes: 12 for softwoods (C classes) and 6 for hardwoods (D classes). Table 1 presents strength and stiffness properties and density values for timber strength classes analysed in this paper.

As mentioned above, timber is a combustible material. Fire causes chemical and physical changes in timber structure [3, 4]. When the temperature of timber reaches 300°C the pyrolysis occurs. The result is mass loss and reduced strength. As a result of pyrolysis a char layer is formed. The charred layer
does not carry loads. Therefore, the cross-section of the member is reduced. In the residual cross-section the stress increases. EN 1995-1-2 [5] provides the constant charring rate. In this paper, residual cross-sections were estimated using computer numerical methods.

Table 1. Strength and stiffness properties and density values for various timber strength classes.

| Strength class | Bending strength [MPa] | \(E_{0,\text{mean}}\) [GPa] | Density \(\rho_k\) [kg/m\(^3\)] |
|----------------|------------------------|-----------------------------|-------------------------------|
| C20            | 20                     | 9.5                         | 330                           |
| C30            | 30                     | 12                          | 380                           |
| C50            | 50                     | 16                          | 460                           |
| GL20h          | 20                     | 9                           | 340                           |
| GL30h          | 30                     | 13                          | 430                           |
| D30            | 30                     | 10                          | 530                           |
| D50            | 50                     | 14                          | 650                           |

2. A description of the model

2.1. Assumptions for modeled beams
The main purpose of modelling the timber elements using computer numerical methods were to determine the impact of wood species on the timber beam strength and stiffness under fire. Figure 1 shows the geometry of the beams. A characteristic load was assumed, which was 5 kN/m. The beams were modeled using different wood species: softwood (C20, C30, C50), hardwood (D30, D50) and glued laminated timber (GL20h, GL30h). The samples were exposed to standard ISO fire [8] from four sides.

Figure 1. Geometry of the beams.

2.2. Heat transfer
Timber is a solid material, therefore the basic model is that in which heat is distributed in the structure essentially by conduction. To describe the geometry of the cross section, the fibre model is used. The cross section of the beam is subdivided into small fibres. The material behaviour of each fibre is calculated at the centre of the fibre and it is constant for the whole fibre. The general equation for two-dimensional heat conduction in wood is [6, 7]:

\[
\left( k \frac{\partial^2 T}{\partial x^2} + k \frac{\partial^2 T}{\partial y^2} \right) + Q = \rho c \frac{\partial T}{\partial t}
\]

(1)

where \(k\) is the thermal conductivity of the material, \(T\) is the temperature, \(Q\) is the amount heat generated in the material per unit volume, \(\rho\) is the density, \(c\) is the heat capacity, and \(t\) is time.

The heat flow should be defined as:

\[
k \left( \frac{\partial T}{\partial x} n_x + \frac{\partial T}{\partial y} n_y \right) + q = 0
\]

(2)

where \(q\) is the specified heat flow, and \(n_x\) and \(n_y\) are the components of the outward normal vector parallel to the x and y axes.
The net heat flux in fire conditions, should consist of heat transfer by radiation and convection. The equation is given by:

\[ q^* = h_c (T_f - T_s) + \Phi \varepsilon_{\text{eff}} \sigma (T_f^4 - T_s^4) \]  

Where \( h_c \) (W/m\(^2\)K) is the convection coefficient, \( \Phi \) is the configuration factor, \( \sigma \) is the Stefan-Boltzmann constant, \( \varepsilon_{\text{eff}} \) is the effective emissivity, \( T_s \) (K) is the surface of the member temperature and \( T_f \) (K) is the fire temperature. The convection coefficient \( h_c \) for the standard fire is 25 W/m2K. The efficient emissivity \( \varepsilon_{\text{eff}} \) should be defined as:

\[ \varepsilon_{\text{eff}} = \frac{\varepsilon_f \varepsilon_s}{\varepsilon_f + \varepsilon_s - \varepsilon_f \varepsilon_s} \]

where \( \varepsilon_f \) is emissivity of the fire source, \( \varepsilon_s \) is the surface emissivity.

Other parameters necessary for the wood model are \( w \) – water content [kg/m\(^3\)], \( h_h \) - coefficient of convection on heated surfaces [W/m\(^2\)K], \( h_c \) - coefficient of convection on unheated surfaces [W/m\(^2\)K], and \( r \) – ratio of conductivity along the grain by conductivity perpendicular to the grain.

### 3. Residual cross-sections

Numerical models of heat flow through timber beams were made using the SAFIR software [9]. Material parameters were adopted in accordance with EN 338. Numerical simulations were conducted for seven different classes of wood. Results for two extreme cases are shown in figure 2. It was assumed that the cross-section that reached 300 °C is not able to carry loads.

![Temperature distribution of the timber beam under ISO fire](image_url)

**Figure 2.** Temperature distribution of the timber beam under ISO fire a) C20 b) D50.
Residual cross-section was determined using the isotherm 300. Figure 2 shows temperature distribution through beams made of wood C20 (a) and D50 (b). It is easy to notice that the char layer is formed faster and deeper in cross-section made of C20. The moisture content of the wood has a huge impact on the charring. During fire, timber heats up and the moisture will begin to evaporate. The higher water content in the wood causes delay in pyrolysis. The models assume that all samples have 14% moisture.

Figure 3 shows the reduction of cross-sections during a fire for seven different classes of wood. The slowest formation of a char layer is in hardwood (D30, D50) while the fastest in the softwood (C20, C30, C50). There is a dependence that for a lower value of wood density, the cross-section reduces faster [10]. Comparing different wood species with a bending strength of 30 MPa, it can be noticed that after 60 minutes of fire duration, the cross-section of a beam made of wood class D30 decreased by about 50%. At the same time, for the glued timber beam GL30h, there was a reduction of about 60%, and for a beam made of softwood C30 by 66%.

Figure 3. Residual cross-sections of beams made of different wood species.

4. Load-bearing capacity under fire
Load-bearing capacity of beams under fire depends, among other things, on stresses in residual cross-section. Due to the loss of cross-section, the stress in the element increases. Figure 4 shows the stress increment in beams during a fire. The largest increase in stress was noted in beams made of softwood. After 60 minutes of fire, stresses incremented about 5 times compared to the initial ones. On the other hand, the smallest increase in stresses is for hardwood beams. After the hour of fire, the stresses increased slightly more than 2 times compared to the initial ones. This is closely related to the charring rate.

Stresses in the cross-section are closely related to the load-bearing capacity of the beam. However, the greatest impact on the bearing capacity has bending strength. Beams made of wood of classes: D30, D50, C30 have fire resistance longer than 60 minutes. Beams made of C30 and GL30h provide load-bearing capacity for about 50 min of fire. Beams of the lowest classes (C20, GL20h) will lose their capacity after about 30 minutes of fire. A summary of the results is shown in figure 5.
5. Deflections in fire conditions
Due to the reduction of the cross-section during a fire, the stiffness of the beam is decreased. The variability of the residual section during the fire was used to model the beam deflections. Figure 6 shows deflections of beams made of C20 (a) and D50 (b) after 30 minutes of fire. For each wood species analysed in this article, beam deflections were determined. Figure 7 shows the results of
beam deflections during a fire, obtained from numerical modelling. Up to about 20 minutes of fire, the increase in deflections is relatively small for each case. For wood species with low density and low modulus of elasticity there are the greatest increases in deflection during a fire. For example, for C20 deflections have increased to about 700% after the hour of fire. On the other hand, for hardwood D50 at the same time, the deflections increased to 200% of the initial ones.

![Figure 6. Deflection after 30 minutes of fire for timber beam: a) C20, b) D50.](image)

6. Conclusions
In this paper, numerical models were developed to analyse impact of wood species on the timber beam strength and stiffness under fire. In estimating fire resistance of beams, it is important to model the heat flow in the element. Then a char layer can be determined. Then stresses and stiffness can be obtained in the reduced cross-section.

As a result of numerical modelling, load-bearing capacities and deflections in fire conditions were obtained for beams made of various types of wood. It was noticed that hardwood had a relatively lower load-bearing capacity reduction under fire. The greatest loss of stiffness and strength was observed for beams made of low softwood classes. In numerical strength analyses, the reduction of glued laminated timber properties can be placed between hardwood and softwood.
7. References

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