Bearing capacity assessment for a timber girder when subject to a localised fire

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Abstract. Timber girders are often used as roofs in large-area buildings. One of the most important issues concerning the design of timber structures are fire safety requirements. Safe design requires adequate knowledge and modelling of the physical and chemical reactions inside the timber members exposed to fire. Wood is a combustible material. At 300°C the pyrolysis takes place which cause loss in mass and decrease the strength and mechanical properties. European standards introduce simplified methods for assessing load-bearing capacity in fire conditions. The second approach is advanced numerical modelling. This paper presents results from numerical studies on fire resistance of timber girder when subject to a localised fire. The numerical simulations have been performed with application of the SAFIR computer program. The numerical model of a timber girder was made. European standards recommend estimating the fire resistance of a structure based on the ISO fire curve. The advantage of such an approach is simplicity. It can lead to overestimating load-bearing capacity. Therefore, the cost of construction and fire protection will be higher. Another approach is implementation of appropriate fire models. Then, determining the temperature-time relationship for the analysed structure members. In this paper localised and ISO fire were assumed. The heat was applied for three sides of the beam. An uneven cross-section along the length was also assumed. The obtained results indicate that advanced numerical analysis allows for a more accurate estimation of the load-bearing capacity of timber elements exposed to fire.

1. Introduction

Glue laminated timber is widely used as a construction material for buildings and structures. It is used for public, residential, industrial, warehouse, and other buildings. The biggest disadvantage of using timber in constructions is combustibility. During the fire, the wood heats up and the moisture begins to evaporate. The pyrolysis takes place when the temperature of material is around 300°C. It causes loss in mass and reduces the strength and mechanical properties.

Timber elements have to fulfil fire resistance criteria when used in structures. The most essential in fire safety design is the estimation and selection of fire scenarios that may occur in buildings. Fire development depends on many factors, circumstances and events, which is why each fire scenario is unique. Fire scenarios determine the development of fire and the spread of combustion products throughout the building [1,2]. Therefore, the number of fire scenarios for a building can be very large. It is difficult to analyse every scenario of fire development. Therefore, the most probable cases that provide an acceptable level of safety should be considered.

To determine the load-bearing capacity of structures or members, European standards provide standard fire curve ISO [3]. According to assumptions of the ISO curve, the fire resistance of buildings and each element of the structure is estimated by a fully developed fire scenario [4]. Therefore, the load-bearing capacity of structure is relatively low. This approach is simple in calculations and provides a large safety reserve. The disadvantage is understatement of the load-bearing capacity, which leads to increased building costs. EN 1991-1-2 [5] also provides the possibility of using advanced calculation. Therefore, numerical models of fire development can be made for each building.
2. A description of the structure

2.1. Assumptions
This paper presents an investigation on bearing capacity assessment for a timber girder when subject to a localised fire. The analysis was subjected to a wooden hall with the dimensions 36.00 x 90.00 meters and height to eave of 6.50 m. Wood properties at fire temperature were adopted in accordance with EN 1995-1-2 [5].

![Figure 1. The floor plan of the building.](image)

The location of the fire source is shown in Figure 2. A fire power $Q_{\text{max}} = 25$ MW was assumed. Heat release rate $RHR_f$ was 500 kW/m². Fire area should be calculated using the relationship:

$$A_{\text{fire}} = \frac{Q_{\text{max}}}{RHR_f} = \frac{25\text{MW}}{500\text{kW/m}^2} = \frac{25\text{MW}}{500\text{kW/m}^2} = \left[\text{m}^2\right] \quad (1)$$

The main structure of the roof are double tapered girders with a span of $l = 18$ meters. The height of the girder on the support $h_1$ is 0.72 m, and in the ridge $h_{\text{ap}}$ is 1.67 m. The beam width is fixed at $b = 0.2$ m.

The girders were made of glued laminated timber, class GL24h. Live and dead loads were assumed, which amounted 5 kN/m.

![Figure 2. Double tapered girder.](image)

2.2. Load-bearing capacity in normal conditions
To determine the load-bearing capacity of the girder in normal conditions, several conditions must be fulfilled. First, the shear capacity should be determined. Reduced shear force on the support is equal:

$$V_{d,\text{red}} = \frac{V}{l} \left( l - \frac{l}{2} + h_1 \right) = 123 \text{ [kN]} \quad (2)$$
where $V_d$ is design shear force [kN]. Then a reduced cross-section area should be determined:

$$ h_{red} = h_i \cdot (h_{ap} - h_l) / \left( \frac{1}{2} - h_i \right) + h_i = 80.3 \text{ [cm]}$$

$$ A_{red} = b \cdot h_{red} = 1610 \text{ [cm}^2]$$

The reduced shear stress is equal:

$$ \tau_{d,red} = 1.5 \frac{V_{d,red}}{k_{cr} \cdot A_{red}} = 1.7 \text{ [MPa]}$$

Design shear strength is equal:

$$ f_{r,d} = \frac{f_{s,k} \cdot k_{mod}}{\gamma_M} = 2.4 \text{ [MPa]}$$

where $f_{s,k}$ is characteristic shear strength [MPa], $k_{mod}$ is modification factor, $\gamma_M$ is partial factor for material properties. 0.2 m.

Other, necessary load-bearing capacity conditions were also checked. The results are shown in table 1.

### Table 1. Ultimate Limit States for timber girder.

| Ultimate Limit States | Design stress $\sigma_i$ [MPa] | Design strength $f_i$ [MPa] | $\frac{\sigma_i}{f_i}$ |
|-----------------------|---------------------------------|-----------------------------|------------------------|
| Shear                | 1,70                            | 2,40                        | 0,71                   |
| Bending              | 9,18                            | 16,60                       | 0,55                   |
| Bending at an angle $\alpha$ to the grain | 9,18 | 14,90 | 0,62 |

3. Fire model

3.1. Heat transfer

To analyse the heat transfer within the timber girder in fire conditions, three modes of heat transfer should be considered: convective and radiative heat transfer from fire to element boundary and conduction in the element. The net heat flux in fire conditions, should consist of heat transfer by radiation and convection. The equation is given by:

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

where $h_c$ (W/m$^2$K) is the convection coefficient, $\Phi$ is the configuration factor, $\sigma$ is the Stefan-Boltzmann constant, $\varepsilon_{eff}$ 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/m$^2$K. The efficient emissivity $\varepsilon_{eff}$ should be defined as:

$$ \varepsilon_{eff} = \frac{\varepsilon_f \varepsilon_s}{\varepsilon_f + \varepsilon_s - \varepsilon_f \varepsilon_s}$$

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

In the literature are analytical models [6]. The governing partial differential equation should be defined:
\[
\frac{\partial}{\partial x} \left( \lambda_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \lambda_y \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( \lambda_z \frac{\partial T}{\partial z} \right) + Q = \rho c \frac{\partial T}{\partial t} \tag{9}
\]

where \(T(\text{K})\) is temperature, \(\lambda_{x,y,z} (\text{W/mK})\) are thermal conductivities in \(x, y, z\) directions, \(Q (\text{W/m}^3)\) is internally generated heat, \(\rho (\text{kg/m}^3)\) is density, \(c (\text{J/kgK})\) is specific heat, and \(t (\text{s})\) is time.

3.2. Localised fire

In the estimation of fire resistance of structures, it is generally assumed that the scenario of the developed fire for which the flashover point has been achieved is the most suitable for the assessment. This means considering the even temperature distribution of exhaust gases in the entire volume of the load-carrying structures, and this leads to the conclusion that the basic structural members lose their load-bearing capacity relatively quickly. It also provides a safe estimation of the fire resistance of the structure. However, in many cases, this approach is too conservative. Flashover depends on many factors. First of all, on the type and distribution of the combustible materials accumulated in the building and the access of oxygen, which would sustain combustion. The risk of a flashover for a specific building can be estimated on the basis of survey of the building. In further analysis, characteristics describing the intensity of combustion and the mass of inventoried materials should be taken into account. The energy released during the entire duration of the fire will be sufficient only for a localised fire confined only to a part of the building’s internal space. In many cases a localised fire can be considered as a reliable estimate of the fire resistance of the building. A localised fire has much less impact on the building structure than a fully developed fire.

The thermal action of localised fire can be assessed by using the expressions given in EN 1995-1-2 [5]. The flame lengths \(L_f\) of a localised fire is determined using the relationship:

\[
L_f = -1.02D + 0.0148Q^{2/5} \quad [\text{m}] \tag{10}
\]

where \(D\) is the diameter of the fire [m], \(Q\) is the rate of heat release [W] of the fire. When the flame is not impacting the ceiling \((L_f < H)\), the temperature \(T_m(z)\) in the plume along the symmetrical vertical flame axis is given by:

\[
T_m(z) = 20 + 0.25Q^{2/3}(z - z_0)^{-5/3} \leq 900 \text{ [°C]} \tag{11}
\]

where \(Q_c\) is the convective part of the rate of heat release [W], \(z\) is the height [m] along the flame axis, \(H\) is the distance [m] between the fire source and the ceiling. The virtual origin \(z_0\) is given by:

\[
z_0 = -1.02D + 0.00524Q^{2/5} \quad [\text{m}] \tag{12}
\]

![Figure 3. Localised fire based on [5].](image-url)
4. Temperature distributions in a fire situation

4.1. Localised fire in Ozone V3 software
To estimate the temperature distribution, the Ozone V3 software was used. This program deals with two types of natural fire models: compartment fires and localised fires. In large-area buildings, where the flashover does not occur, localised fire should be considered. Localised fire in this software is based on the procedure where the thermal exchanges are drawn by convective fluxes are treated by application of the existing equations available in the EN 1991-1-2 [5].

4.2. Temperature distributions
The simulation results of the fire development are presented in the figure 4. The first curve shows the development of the standard fire. According to ISO-fire curve, temperature reaches about 700 °C after 10 minutes of fire. The temperature increases and after about one hour it is more than 900 °C. Considering the localised fire, the temperature increases to approximately 600 °C after 15 minutes of fire. Then the temperature decreases below 400 °C.

![Figure 4: The standard ISO fire-curve and the temperature for A_FIRE under fire.](image)

Figure 4 shows significant differences in temperature-time relationships depending on the fire scenario. Advanced numerical model that describes a local fire, determines much lower temperatures than those adopted according to the ISO fire curve.

5. Heat transfer through timber girder
The numerical model of the timber double tapered girder was made in the SAFIR software. Material parameters were adopted in accordance with EN 1995-1-1 [7]. For numerical analysis of heat transfer through timber girder, the temperature-time relationship presented in figure 4 were used. The above curves have been implemented in the SAFIR software [8]. It was assumed that the fire acts on three sides of the beam. The results of the numerical simulations are presented in figure 5. Figure 5a shows
the heat transfer through timber girder for the ISO fire curve, while figure 5b for the localised fire at 15, 30, 45 and 60 min, respectively.

Many researchers have conducted studies on the properties of wood in a fire [9, 10]. When timber is subjected to elevated temperature, it undergoes chemical and physical changes. It was investigated that at a temperature of about 300 °C the pyrolysis takes place which cause loss in mass and reduce the strength and mechanical properties. A char layer is created that is not able to carry any loads. Comparing figure 5a and figure 5b it can be seen, that pyrolysis occurs faster and deeper in the case of the ISO-fire curve. In both cases the isothermal distributions turn into U-shape.

![Temperature distribution of the timber girder exposed to: a) standard ISO-fire, b) localised fire A_FIRE.](image)

**Figure 5.** Temperature distribution of the timber girder exposed to:

a) standard ISO-fire, b) localised fire A_FIRE.

Fire resistance of a girder depends on the residual cross-section, which is able to carry loads. Taking into consideration the standard ISO fire, which acts on the girder, the cross-section is significantly
reduced. After 30 minutes, the section was reduced by about 20% and after an hour only 50% of the initial cross-section was left. It is completely different in the case of a localized fire. After an hour of fire, the cross-section was reduced by approx. 13%. The residual cross-section was obtained from the SAFIR program based on the 300 °C isotherm. Figure 6 shows the residual section of the girder for two different fire scenarios, obtained as a result of numerical simulations.

![Figure 6](image)

**Figure 6.** Residual cross-section of the girder in: a) ISO fire, b) localized fire.

6. Load-bearing capacity in fire situation

According to EN 1995-1-2 [11], advanced calculation methods for determining mechanical strength should provide realistic analysis of structures exposed to fire. They should be based on basic physical behaviour of the element. Advanced calculation models should be applied for: the development and distribution of the temperature within structural members, the determination of the charring depth and the evaluation of structural behaviour of the structure. Calculations were made on the basis of decreasing cross-section in time. Therefore, at constant loads, the stresses in the residual cross-section were increased.

![Figure 7](image)

**Figure 7.** Shear strength of the girder in the ISO and localized fire.
Figure 7 shows the decrease in shear capacity in two different fire scenarios: according to IS0 and localized. In the case of IS0 fire, after 35 min, the load capacity is completely lost. In the other case, fire resistance of the girder is ensured for 60 min of fire. Similar conclusions can be obtained by analyzing the bending (figure 8) and bending at an angle $\alpha$ to the grain (figure 9) capacity under fire. In these cases, the fire resistance of the beam is about 50 minutes. However, to consider the localized fire, after the hour of fire will still be 30% of the load capacity reserve.

![Figure 8. Bending strength of the girder in the IS0 and localized fire.](image)

![Figure 9. Bending strength at an angle $\alpha$ to the grain of the girder in the IS0 and localized fire.](image)

7. Conclusions
Estimation of fire resistance of structural elements based on the IS0 standard curve is conservative. The disadvantage of this approach is underestimation of the load-bearing capacity of the structure. This may lead to increased building costs. In this paper, numerical models were developed to analyse bearing capacity assessment for a timber girder when subject to a localized fire. Advanced computer numerical methods allow to estimate more precisely the development of the fire. The number of fire scenarios for the building is very large. It is important to choose the most probable fire scenarios, which provides acceptable levels of safety.

The temperature-time relationship is necessary to determine the heat flow through the element. Based on the temperature distribution in the cross-section, the speed and depth of char layer can be
estimated in fire conditions. Then the fire resistance of the structural element can be determined. Numerical modelling of the fire, taking into consideration the fire source location is necessary for rational and economical design of timber structures. Correction coefficients should be introduced depending on the volume of the building as well as combustible materials that are in the building.

8. References

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Acknowledgments
The authors acknowledge the support of the PROM programme no. PPI/PRO/2018/1/00013/U/001 which is co-financed by the European Social Fund under the Knowledge Education Development Operational Programme.