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FIRE RESISTANCE OF TIMBER JOINTS WITH STEEL FASTENERS

Fire safety is a major concern in the design of timber construction. Wood is combustible material. The thermal response of timber connections is usually the main factor in evaluating the overall load-bearing capacity of wood structures exposed to fire. The analysis of timber joints under fire conditions is difficult and complex. Finite element model is developed to predict the thermal behavior of bolted wood-to-wood joints exposed to fire. In fire, the material characteristic depend on the temperature. The thermal model is continuous, taking into account the thermal continuity between the joint components. Also, the thermal model is used to predict the evolution of the temperature field inside the connection.
The paper presents a summary of results from a numerical studies of the fire behavior of wood-to-wood timber connections with steel bolt. As a result of computer simulations the temperature distribution was obtained. During fire exposure, the timber section is reduced and steel bolt reduces strength. Load-carrying capacity per shear plane in fire conditions was calculated using two methods: design methods according to EN 1995-1-1 [5] and reduced load method according to EN 1995-1-2 [6]. In the first approach, the timber section loss and steel strength reduction during the fire were taken into account.

Keywords: thermal conductivity, fire safety, connections, elevated temperatures

1. Introduction

Currently, timber constructions are commonly used by designers in buildings because of their good environmental influence. High timber buildings are constructed in many countries. One of the most important technical aspects in timber constructions is the fire safety requirements. Wood is a combustible material. The resistance of timber structure depends on the thermo-mechanical behavior of the structural elements represented by the beams, the columns and the connections.

Connections are the weakest parts in timber structures in normal and fire conditions [2,3]. They determine the bearing capacity and the mechanical

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behavior of the structure. The analysis of the fire behavior of timber connections is complex and difficult to predict [8,11]. It depends on several parameters such as the geometry of the connection, the fastener types and different thermal properties of steel and timber.

2. Thermal analysis

2.1. Heat transfer

Timber is anisotropic material. It causes high variability of properties. In fire conditions, timber begins to pyrolyse at about 200°C and chars at about 250°C under the formation of charcoal and combustible gases. Charcoal has a lower thermal conductivity than wood and protects the inner timber members against fire. Thermal actions are given by the net heat flux h_{net} to the surface of the member. In fire conditions the net heat flux should contain heat transfer by radiation and convection [10].

$$h_{net} = h_{net,c} + h_{net,r} \tag{1}$$

where: h_{net} – net heat flux [W/m^2],
$h_{net,c}$ – convective heat flux [W/m^2],
$h_{net,r}$ – radiative heat flux [W/m^2].

Convection is the heat transfer between a solid and a gas. The heat flux depends on the temperature of the gas in the vicinity of the fire exposed member and on the surface temperature of the member. The equation of the net convective heat flux should be defined as follows:

$$h_{net,c} = \alpha_c \cdot (\Theta_g - \Theta_m) \tag{2}$$

where: α_c – coefficient of heat transfer by convection [W/(m^{2}K)],
Θ_g – gas temperature in the vicinity of the fire exposed member [°C],
Θ_m – surface temperature of the member [°C].

Radiation depends on the temperature of the radiation source and the material properties of the surface. The equation of the net radiative heat flux should be defined as follows:

$$h_{net,r} = \Phi \cdot \varepsilon_m \cdot \varepsilon_f \cdot \sigma \cdot [(\Theta_r + 273)^4 - (\Theta_m + 273)^4] \tag{3}$$

where: Φ – configuration factor,
ε_m – surface emissivity of the member,
ε_f – emissivity of fire,

σ – Stephan Boltzmann constant,

Θ_r – effective radiation temperature of environment [°C],

Θ_m – surface temperature of the member [°C].

2.2. Thermal Finite Element simulations

The subject of the research are the timber joints with steel fasteners. Figure 1 shows the geometry of the modeled connections. The joints consist of the solid wood C20 class, and the steel bolt M16 cl.4.6. In the first connection (I), the beams have the following dimensions: 250 × 150 mm. In the other connection (II), the beams are half lower (250 × 75 mm).

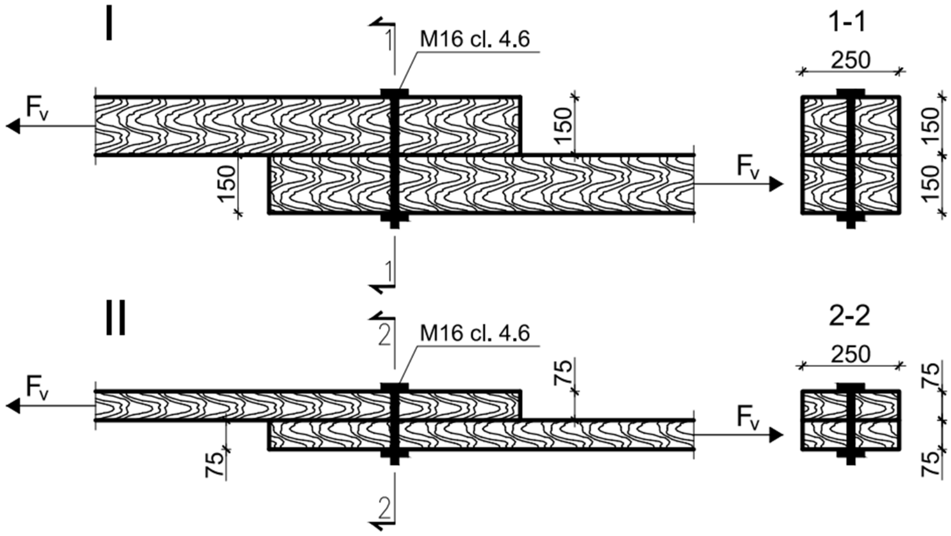


Fig. 1. Geometry of connections

The purpose of modeling the connections using the finite element method was to determine the influence of steel elements in timber connections on the temperature distribution under standard fire curve [1,9,12]. The connections were modeled in 2-dimensional pictures. Thermal radiation and convection as described in chapter 2.1 were applied on four sides. The connections were modeled using the SAFIR software [7].

Steel has high thermal conductivity [4]. The heat flux through the steel elements leads to higher temperatures of the timber interior. It causes faster reduction of the net section. The bolt temperature inside cross-section is much higher than the temperature of timber section (Figure 2).

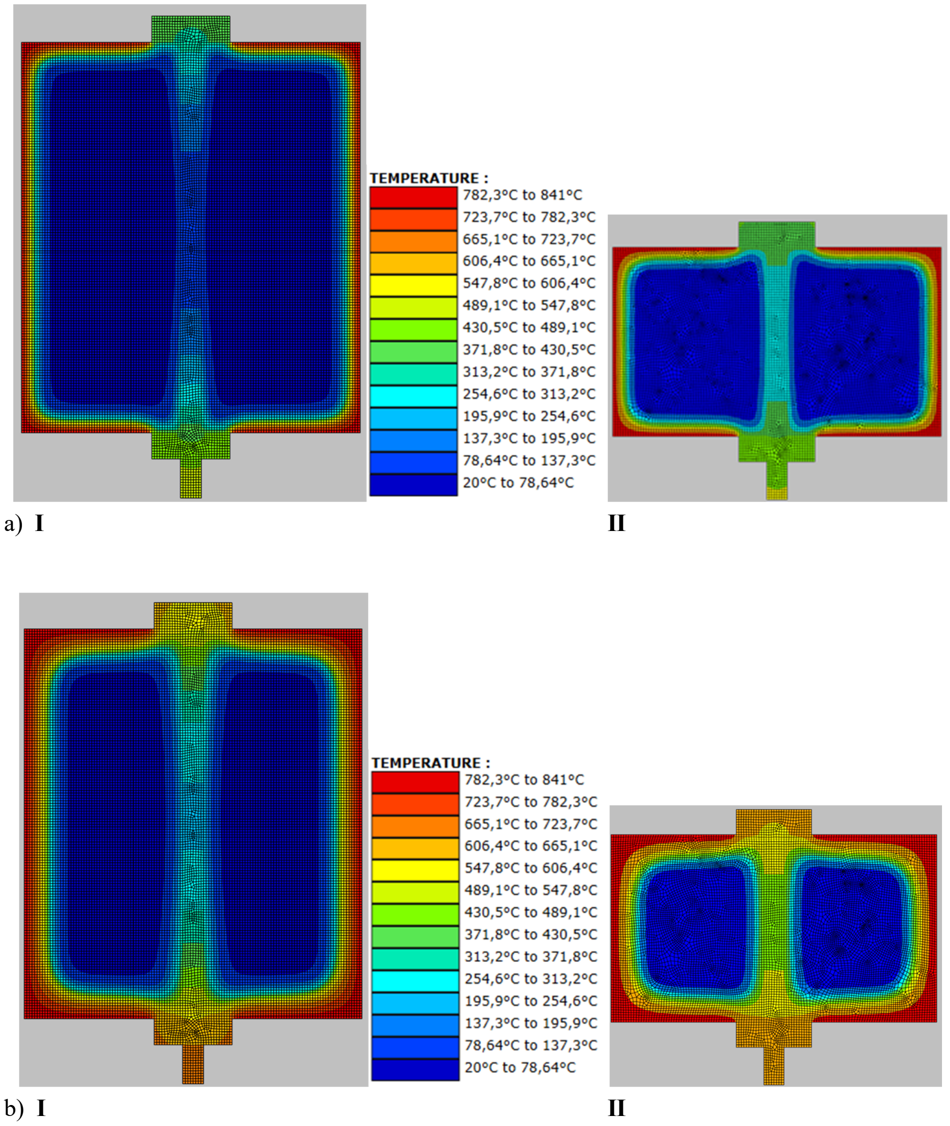
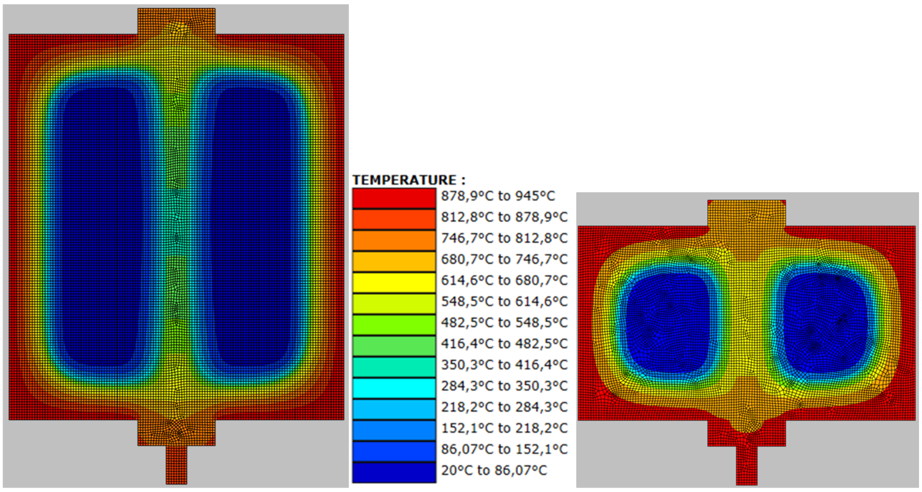
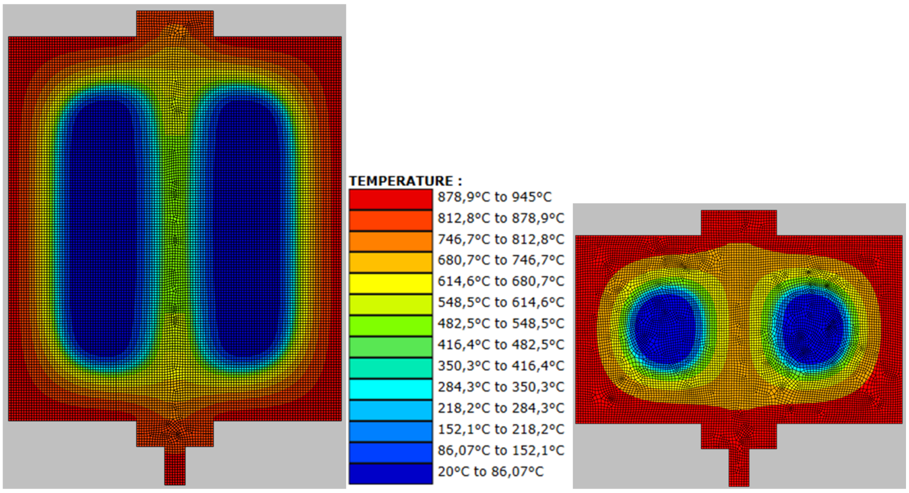


Fig. 2. Heat flux inside cross-sections 1-1 (I) and 2-2 (II) after: a) 15 min, b) 30 min



c) **I** **II**



d) **I** **II**

Fig. 2. (cont.) Heat flux inside cross-sections 1-1 (I) and 2-2 (II) after: c) 45 min and d) 60 min

3. Mechanical analysis

3.1. Lateral load-carrying capacity of metal dowel-type fasteners

Metal dowel type connections have to satisfy the relevant design rules and requirements of Eurocode 5. Connection formed using metal dowel fasteners, when subjected to lateral loading, may fail in a brittle or a ductile mode. For connections in single shear, the characteristic load-carrying capacity per shear plane per fastener $F_{v,Rk}$, is the minimum value equation for the relevant single shear cases given in Figure 3.

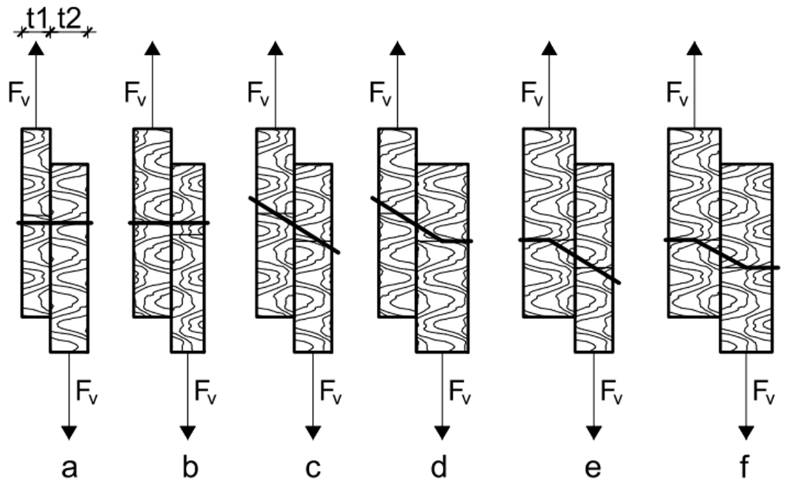


Fig 3. Failure models for timber connections, based on [5]

Because of the fact that there is only one shear plane, this value will also equate to the load-carrying capacity per fastener in the connection and the failure mode will be the mode associated with the minimum value equation. The main functions used in the strength equations are the diameter of the dowel – *d*, the characteristic fastener yield moment $M_{y,Rk}$ and the characteristic embedment strength, $f_{h,i,k}$ of the connected member *i*.

3.2. Lateral load-carrying capacity of metal dowel-type fasteners in fire

The determination of the load-carrying capacity of the connection in fire conditions is complex. It depends on the geometry of the connection, the fastener types and the different thermal properties of steel and timber. During fire exposure, the timber section is reduced and steel bolt reduces strength. Table 1 contains load-carrying capacity for the appropriate failure model in fire conditions. The reduction of the timber cross-section was taken into account using isotherm 300°C in the MES analysis. The reduction of steel strength with time was determined on the basis of EC3 (Figure 4).

Table 1. Load-carrying capacity per fastener during the fire

Duration of fire [min]	**Load-carrying capacity per fastener for the failure model [kN]**							
	a = b		c		d = e		f	
	I	II	I	II	I	II	I	II
0	54.5	27.3	22.6	11.3	20.2	11.7	12.5	12.5
15	50.9	23.6	21.1	9.8	18.8	10.3	11.2	11.2
30	47.3	20.0	19.6	8.3	17.4	8.6	10.1	10.1
45	43.6	16.4	18.1	6.8	16.1	7.5	9.3	9.3
60	40.1	12.7	16.6	5.3	14.7	6.3	8.1	8.1

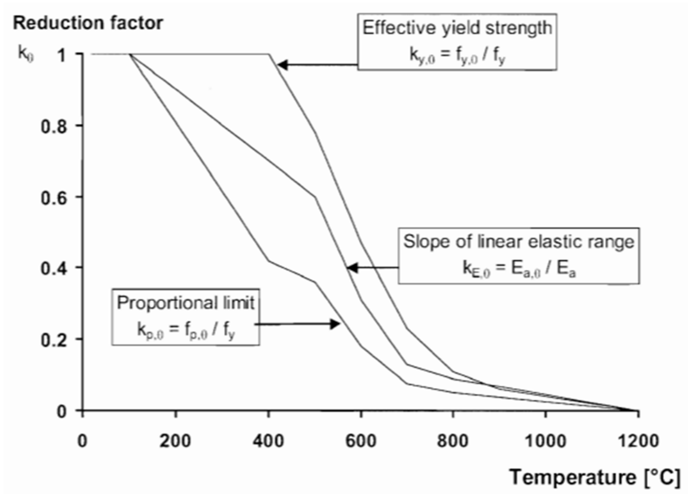


Fig 4. Reduction factors for the stress-strain relationship of carbon steel at elevated temperatures [4]

In the first connection (I), the main failure mode is a destruction of the fastener (f). This failure mode can occur when the timber side elements are very thick. In the other connection (II), the main failure mode is an elongation of fastener holes due to wood crushing and deformation of fasteners (c). This is due to the charring of timber beams and the rapid temperature increasing in steel fastener.

The load-carrying capacity for bolts per fastener should be taken as the minimum value defined by the appropriate failure models. Figure 5 shows the load-carrying capacity of the connection.

In the fire conditions, the wooden section is reduced, especially within the connection. Tensile strength is reduced. Table 2 contains the change of tensile strength during the fire.

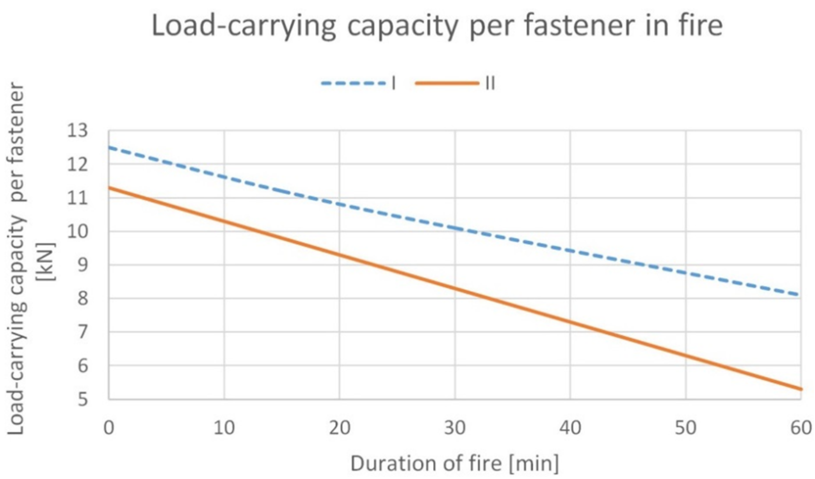


Fig. 5. Load-carrying capacity per fastener in fire

4. Design methods according to EN 1995-1-2

EN 1995 1-2 [6] provides design rules for symmetrical three-member connections with various types of fasteners (nails, bolts, dowels, etc.) exposed to the ISO-standard fire. These apply to laterally loaded joints and are generally limited to fire resistances less than 60 min. The design can be approached in two ways: as the “application of simplified rules” and as the “reduced load method”.

Table 2. Load-carrying capacity per block break

Duration of fire [min]	Load-carrying capacity per block break [kN]	
	I	II
0	417.6	208.8
15	356.2	165.4
30	287.1	121.4
45	224.6	84.2
60	168.9	53.8

4.1. Simplified rules

The fire resistance of unprotected wood-to-wood connections where spacings, edge and distances and side member dimensions comply with the minimum requirements given in EN 1995-1-1 [5] section 8, may be taken from table 3. If the greater fire rating is desirable, the edge distance as well as the thickness and width of the side members should be increased.

Table 3. Fire resistances of unprotected connections with side members of wood

	Time of fire resistance $t_{d,fi}$ [min]	Provisions
Nails	15	$d \geq 2.8$ mm
Screws	15	$d \geq 3.5$ mm
Bolts	15	$t_1 \geq 45$ mm
Dowels	20	$t_1 \geq 45$ mm
Connectors according to EN 912	15	$t_1 \geq 45$ mm
d is the diameter of the fastener and t_1 is the thickness of the side member		

EN 1995-1-2 [6] provides only simplified methods that allow to calculate the load-carrying capacity of the connection in minutes.

4.2. "Reduced load method"

The rules for bolts and dowels are valid where the thickness of the side plate is equal or greater than t_1 in mm:

$$t_1 = \max \begin{cases} 50 \\ 50 + 1,2(d - 12) \end{cases} \quad (4)$$

where: d – diameter of bolt or dowel [mm].

According to the "reduced load method", the load bearing capacity of the connection under fire exposure is obtained by reducing the room temperature capacity by a conversion factor η:

$$\eta = e^{-k \cdot t_{d,fi}} \quad (5)$$

where: k – parameter depending on the connection type,
$t_{d,fi}$ – design fire resistance of the unprotected connection in minutes.

$$t_{d,fi} = -\frac{1}{k} \ln \frac{\eta_{fi} \eta_0 k_{mod} \gamma_{M,fi}}{\gamma_M k_{fi}} \quad (6)$$

where: η_{fi} – reduction factor for the design load in the fire situation,
η_0 – degree of utilisation at normal temperature,
k_{mod} – modification factor,
γ_M – partial factor for the connection,
k_{fi} – coefficient depending on the type of timber,
$\gamma_{M,fi}$ – partial safety factor for timber in fire,

For standard fire exposure, the characteristic load-carrying capacity of a connection with fasteners in shear should be calculated as:

$$F_{v,Rk,fi} = \eta F_{v,Rk} \quad (7)$$

where: η – conversion factor,
$F_{v,Rk}$ – characteristic lateral load-carrying capacity of the connection with fasteners in shear at normal temperature.

"Reduced load method" was used to calculate the load capacity of the analyzed connections. As a result of calculations, the design fire resistance of the unprotected connections were about 18 minutes. The conversion factor η was 0.48.

Specifications for calculations the joints resistance with axially loaded screws under elevated temperatures are also presented. The above take into consideration the configuration of the connection, the edge distance and the embedment depth of screws. Both of the above methods allow to estimate the load-carrying capacity of the connection in minutes.

5. Conclusions

The finite element method was used to carry out a thermal analysis in order to determine the temperature profiles within wood-to-wood timber connections with bolts exposed to fire.. The thermal finite element analysis of timber members with steel bolt was carried out under ISO-fire exposure on four sides. The charring depth is the same on each side of timber members. Due to the high thermal conductivity of steel, the heat flux through the steel dowel led to higher temperatures in the interior of timber member. This approach has to be taken into consideration for the work in progress to provide a design model for the calculation of the fire resistance of shear connections with steel bolts.

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