Thermal investigations on multiple shear steel-to-timber connections

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Summary
The paper presents a summary of results from a series of experimental and numerical studies on the fire behavior of multiple shear steel-to-timber connections with slotted-in steel plates and steel dowels. The combination of timber and steel elements in this type of connection leads to a high load-carrying capacity and ductile failure mode. Therefore, this type of connection is often used in timber engineering. Because of the protection of the slotted-in steel plates against fire by the side timber members, a high fire resistance (without additional fire protection) may be achieved.

As a first step towards developing design models for the calculation of the fire resistance of multiple shear steel-to-timber connections with slotted-in steel plates and steel dowels, fire tests under ISO-fire exposure were performed and compared to finite element thermal simulations in order to analyze the interaction between steel fasteners, steel plates and timber members.

1. Introduction
Connections in timber structures exposed to fire usually have to fulfill the same requirements on fire resistance as the main construction members, like columns or beams for example. The analysis of the fire behavior of multiple shear steel-to-timber connections with slotted-in steel plates and steel dowels is complex due to the influence of several parameters such as the geometry of the connection, the fastener types and the different thermal properties of steel, timber and charcoal. The combination of materials leading to a ductile behavior of the connection is challenging. Steel is heating up quickly and looses its stiffness and strength at high temperatures. For this reason, heat can reduce the load-carrying capacity of connections with steel elements to a great extent.

As part of an intensive research program called “Fire safety and timber construction” currently carried out in Switzerland to allow the use of combustible materials for the fire resistance class of 60 minutes, fire tests on multiple shear steel-to-timber connections with slotted-in steel plates and steel dowels were performed at the ETH Zurich under ISO-fire exposure [1]. The connections were tested in tension parallel to the grain with different thickness, edge and end distances and diameter of the fasteners (6.3 and 12 mm). Temperatures in different depths of the timber members were measured to analyze the heat flux.

The objective of this paper is to compare experimental results with thermal simulations conducted with the finite element method in order to analyze the influence of steel elements on the temperature distribution in timber members. The material and thermal data implemented in the FE-simulations is compared to results of other experimental tests. The aim of the modeling work in conjunction with the fire tests performed at the ETH Zurich is to provide a design model for the calculation of the fire resistance of multiple shear steel-to-timber connections with slotted-in steel plates and steel dowels.
2. Thermal analysis

2.1 Theoretical background

Timber is more complex than most other material. Its anisotropic character and high variability of properties causes difficulties in defining material properties. In most conditions, timber begins to pyrolyse at about 200 °C and chars at about 250 °C under the formation of charcoal and combustible gases. Therefore, the range of interest of timber properties at elevated temperatures is from room temperature to about 250 °C. Charcoal has a lower thermal conductivity than wood and protects the inner timber members against fire while steel exposed directly to fire is heating up quickly and loses its stiffness and strength at high temperatures.

Thermal actions are given by the net heat flux $h_{\text{net}}$ [W/m²] to the surface of the member. On the fire exposed surfaces the net heat flux $h_{\text{net}}$ should be determined by considering heat transfer by radiation and convection according to equation (1).

$$h_{\text{net}} = h_{\text{net,c}} + h_{\text{net,r}}$$  \hspace{1cm} \text{[W/m²]} \hspace{1cm} (1)

- Radiation

The heat transfer due to thermal radiation depends on the temperature of the radiation source and the material properties of the surface. The net radiative heat flux component per unit surface area combines physical and geometrical influences and is determined by equation (2).

$$h_{\text{net,r}} = \Phi \cdot \varepsilon_m \cdot \varepsilon_f \cdot \sigma \cdot [(\Theta_r + 273)^4 - (\Theta_m + 273)^4]$$  \hspace{1cm} \text{[W/m²]} \hspace{1cm} (2)

where

- $\varepsilon_m$ surface emissivity of the member
- $\sigma$ Stephan Boltzmann constant = 5.67·10⁻⁸ W/(m²K⁴)
- $\varepsilon_f$ emissivity of fire
- $\Phi$ configuration factor
- $\Theta_r$ effective radiation temperature of environment [°C]
- $\Theta_m$ surface temperature of the member [°C]

According to Eurocode 1, part 1-2 (EN 1991-1-2) [2] the emissivity of the fire may be taken in general as $\varepsilon_f = 1.0$ and for the material $\varepsilon_m = 0.8$ may be used.

- Convection

The convective heat transfer describes the heat transfer between a solid and a gas. The heat flux depends primarily on the temperature of the gas in the vicinity of the fire exposed member and of the surface temperature of the member. The net convective heat flux component should be determined by equation (3).

$$h_{\text{net,c}} = \alpha_c \cdot (\Theta_g - \Theta_m)$$  \hspace{1cm} \text{[W/m²]} \hspace{1cm} (3)

where

- $\alpha_c$ coefficient of heat transfer by convection [W/(m²K)]
- $\Theta_g$ gas temperature in the vicinity of the fire exposed member [°C]
- $\Theta_m$ surface temperature of the member [°C]

According to Eurocode 1, part 1-2 (EN 1991-1-2) the coefficient of heat transfer by convection $\alpha_c$ under ISO-fire exposure [3] can be assumed to 25 W/(m²K).

- Latent heat and enthalpy

The change of moisture, i.e. the evaporation of water in timber members takes place at a temperature of about 100 °C. Therefore, the required heat quantity is referred to as latent heat $H_{\text{lat}}$ per each volume unit. The implementation of the latent heat into the FE-simulation occurs with the enthalpy $H$ and can be described as shown in (4) and (5).

$$H(T_2) = H(T_1) + \Delta H = H(T_1) + \int_{T_1}^{T_2} \rho \cdot c_p \cdot dT + H_{\text{lat}}$$  \hspace{1cm} \text{[kJ/m³]} \hspace{1cm} (4)

where
\[ H_{\text{lat}} = \rho \cdot r \cdot \frac{u}{100} = 445 \frac{\text{kg}}{\text{m}^3} \cdot 2256 \frac{\text{kJ}}{\text{kg}} \cdot \frac{12}{100} = 120'470 \frac{\text{kJ}}{\text{m}^3} \]  

The density \( \rho = 445 \text{ kg/m}^3 \) was determined as mean value of the timber GL 24h used in the fire tests at a moisture content of 12 % and \( r = 2256 \text{ kJ/kg} \) characterizes the evaporation heat of water [4].

The density and the specific heat capacity \( c_p \) vary with the temperature. In the simulations, charring of timber (i.e. reduction of cross-section) was taken into account by reducing the material and thermal properties with the integration by parts, see equation (4). The temperature-specific heat- and the temperature-density ratio relationships were assumed according to Eurocode 5, part 1-2 (EN 1995-1-2) [5].

Concerning the thermal conductivity, cracks in the charcoal increase the heat flux due to radiation and convection. The thermal conductivity values of the char layer are apparent values rather than measured values of the charcoal in order to take into account the increased heat flux due to shrinkage cracks above about 500 °C and the consumption of the char layer at about 1000 °C. The thermal conductivity values for timber and the char layer perpendicular to the grain are temperature-dependent and were assumed according to Eurocode 5. The thermal conductivity parallel to the grain can be estimated as twice as the amount perpendicular to the grain [6]. The material and thermal properties of steel S 235 at high temperature are investigated well. The thermal conductivity and the specific heat capacity were assumed according to Eurocode 3, part 1-2 [7].

2.2 Temperature development

In a first step, the timber material and thermal properties implemented in the finite element package ANSYS Workbench (in combination with ANSYS Release 10.0) were examined. Therefore, the temperature measurements in different timber depths in the fire tests of König [8] and Lache [9] were compared to the FE-results in Figure 2.

![Fig 2 Comparison of FE-simulated temperatures in different timber depths to the fire tests of König [8] and Lache [9] under ISO-fire exposure on one side](image)

The fire tests of König were performed on four unprotected spruce timber members exposed to ISO-fire exposure on one side. The specimens of König had a moisture content of about 12 %. Temperatures were measured in a depth of 6, 18, 30 and 42 mm from the surface exposed to fire. In Figure 2 the mean temperature values of the four fire tests are shown. Lache also performed fire tests under ISO-fire exposure on spruce with a higher moisture content of about 20 %. He measured temperatures in a depth of 10, 20, 30, 40 and 50 mm. However, no significant influence of the
moisture content on the temperature development was observed in his work. Experimental and numerical results are in good agreement, especially in comparison to the test results of König. Compared to the FE-results conducted with a moisture content of 12 %, the test results of Lache show a higher temperature in the range between room temperature and 100 °C and a lower temperature above 100 °C. A possible reason may be the higher moisture content under 100 °C which leads to a higher thermal conductivity, i.e. the temperatures rise faster until reaching 100 °C.

2.3 Thermal FE-simulations

The objective of modeling the connection using the finite element method was to determine the influence of steel elements in timber connections (steel plates and dowel type fasteners) on the temperature distribution. The simulations of the temperature behavior aimed to confirm the results of the fire tests performed at the ETH Zurich and to study the effects of geometrical and material properties of the connection in the case of fire. The creation of such finite-element models as shown in this paper is the goal of the larger study of which this effort is a part.

Figure 4 shows the geometry of the tested and modeled connection D 01.1 from side view (left) and top view (right). The symmetrical connection D 01.1 consists of the timber member (200 x 200 mm), three slotted-in steel plates with a thickness of 5 mm each and 2 rows of 9 steel dowels with a diameter of 6.3 mm each. The mean value of the fire resistance under ISO-fire exposure was 33 minutes (2 fire tests) loaded with a constant static load level of 30 % of the load-carrying capacity at room temperature (5 tests). The connection was modeled 3-dimensional. No external mechanical load but thermal radiation and convection as described in chapter 2.2 was applied on four sides.

![Fig 4 Connection D 01.1: 200 x 200 mm, 3 steel plates (t = 5mm), 9 x 2 steel dowels (d = 6.3 mm)](image)

The most critical problem in modeling connections with different members and materials is to simulate the contact conditions properly. There are three contact situations to be considered between various surfaces, i.e. (1) the timber and the steel plates, (2) the steel plates and the steel dowels and (3) the timber and the steel dowels. ANSYS Workbench offers several algorithms. For thermal analysis, the MPC-algorithm seems to be suitable for simulating the three contact situations properly. Multipoint constraint (MPC) equations are created internally during the solve procedure to tie the bodies together. It can be helpful if true linear contact is desired. This assumption does not correspond exactly to (1) where the slot was 6 mm but the thickness of the steel plates 5 mm. However, the difference of 1 mm filled with air did not show any influence to the results.

In order to assess how mesh size affects the modeling, both coarse and fine meshes (for steel plates and contact situation) were applied to optimize the FE-simulations. Therefore, 3-D SOLID 70 volume elements were implemented which have eight nodes with a single degree of freedom, temperature, at each node and a 3-D thermal conduction capability. The element is applicable to a steady-state or transient thermal analysis. Surface elements SURF 152 were applied to take into account the different surface loads like thermal radiation and convection.

The temperature distribution of the timber member without any steel elements is shown in Figure 5, left in comparison to the timber member with three slotted-in steel plates (Figure 5, right) according to the geometry shown in Figure 4.
As expected, the temperature gradient for the timber member without steel plates (Figure 5, left) is the same on each side with an increased charring at the corners. Room temperature is still present in the middle of the cross-section. The temperature distribution is much different if steel plates are implemented in the FE-simulations (Figure 5, right). Generally, the timber itself is getting warmer inside. The minimum temperature at 33 minutes is about 74 °C while the maximum on the surface is not different to the timber member without steel elements (Figure 5, left). Due to the high thermal conductivity of steel, the heat flux through the steel plates leads to higher temperatures of the timber inside while the temperature of the steel on the surface remains comparatively low with about

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*Fig 5 Temperature distribution in timber members after 33 minutes ISO-fire exposure on four sides*  
left: timber cross-section 200 x 200 mm without steel plates  
right: timber cross-section 200 x 200 mm with 3 steel plates (geometry according to Figure 4)
465 °C for the side plate and about 427 °C for the inner steel plate compared to the timber surface with about 843 °C. Between the steel plates the temperature distribution is similar to “garlands” with lower temperatures close to the steel plates and higher temperatures in-between. Figure 6 shows the temperature distribution for both steel plates and dowels. The “garlands” are not only observed between the steel plates but also between the steel dowels. The temperature inside the timber member rose to about 114 °C. Close to the steel dowels the temperature is not as high as on the timber surface, i.e. the steel dowels show the same behavior as the steel plates.

For the design of timber in fire the strength for softwood according to Eurocode 5, part 1-2 (EN 1995-1-2) should be multiplied by a temperature dependent reduction factor $k_{\Theta}$ as shown in Figure 7. The relationship includes the effects of transient creep of timber. To give an estimation about how the compression force changes between the two FE-results shown in Figure 5, the middle temperature of each finite element was determined and multiplied with the corresponding reduced compression from Figure 7 considering the different cross-section areas and finite element sizes of the two meshes. The compression force with slotted-in steel plates (Figure 5, left) is about 40 % of the compression force without steel plates, i.e. the heat flux through the steel elements plays an important role in modeling multiple shear steel-to-timber connections with slotted-in steel plates and steel dowels.

3. Residual cross-section

3.1. Laser-scanning

The residual cross-section of the test specimens was surveyed electronically by laser-scanning instead of the often applied manual method. With the laser-scanning method it is possible to generate three-dimensional models of the charred timber members as shown in Figure 8, middle on the example of connection D 01.1. The charring can be determined wherever required with the data points received from the scanner. The laser-scans were carried out with a laser-scanner type Imager 5003 (Zoller + Fröhlich GmbH, Germany) in the Structural Engineering Laboratory in cooperation with the Institute of Geodesy and Photogrammetry of the ETH Zurich. Before scanning the charcoal was removed until the brown char-line appeared and the steel dowels were pulled out. The data received from the scanner was analyzed and the charring was determined by measuring the distances between the surface and the data points.

For the surveying of residual cross-section the laser-scanning method was applied for the first time and shaped up as a quick and more exact alternative to the mainly used manual method. Figure 8, right shows the residual-cross section obtained by laser-scanning on the example of connection D 01.1 in a distance of 60 mm from the gap.
3.2. Comparison of charring to FE-simulations

During the fire tests the two side timber members charred completely. The steel dowels located close to the edge of the timber members were embedded in charred wood which was falling off by removing the test specimens from the furnace, i.e. the steel plates stayed protected during the fire tests. With finite element software the output of defined isothermal structures is possible, i.e. the nodes in the finite element mesh which are below or above a defined temperature can be shown. Figure 9 shows on the example of the modeled connection D 01.1 the remaining isothermal structure for all nodes of the finite element mesh with a temperature below or equal than 250 °C in isometric, front and side view after 33 minutes under ISO-fire exposure on four sides. Nodes with more than 250 °C are masked out.

![Fig 9 Simulated isothermal structure of connection D 01.1 obtained by nodes of the finite element mesh with a temperature below or equal than 250 °C after 33 minutes under ISO-fire exposure](image)

The FE-simulations in Figure 9 compared to the results of the laser-scanning (Figure 8, right) are in good agreement. While the two side timber members and the side steel plates reached more than 250 °C, the inner timber members as well as the slot for the inner steel plate stayed uncharred. These effects were observed in the fire tests (Figure 10) and confirmed the agreement of experimental and numerical results. The rounding of the corners resulted from the superposition of vertical and lateral combustion. According to the FE-simulation shown in the side view of Figure 9, the timber around the steel dowels located closest to the timber surface was completely charred. The dowels located next to them are partially embedded in charred wood with a rest of uncharred timber around, see detail in Figure 9. This was also observed in the fire tests as shown in Figure 10. The 5 steel dowels remained in the middle of the residual cross-section were embedded in uncharred wood.

![Fig 10 Residual cross-section of connection D 01.1 without charcoal and steel elements](image)

4. Conclusions

Thermal analysis on multiple shear steel-to-timber connections with slotted-in steel plates and steel dowels were conducted in order to study the influence of steel elements (steel plates and steel dowels) on the temperature distribution in timber members. The finite element method was used in the thermal simulations. The anisotropic character of timber and its high variability of properties causes difficulties in defining material properties. Therefore, the temperatures obtained by the thermal simulations under ISO-fire exposure were compared to results of fire tests performed in
Sweden and Germany. The FE-results were in good agreement with the experimental tests. The thermal finite element analysis on timber members with and without steel elements was conducted under ISO-fire exposure on four sides with the geometry according to fire tests performed at the ETH Zurich. While the charring depth is the same on each side by using timber members without steel elements the temperature distribution is changing if steel elements are implemented. Due to the high thermal conductivity of steel, the heat flux through the steel plates and the dowels led to higher temperatures of the timber inside while the temperature of the steel itself on the surface remains comparatively low compared to the timber surface. This behavior has to be taken into account for the work in progress to provide a design model for the calculation of the fire resistance of multiple shear steel-to-timber connections with slotted-in steel plates and steel dowels.

The residual cross-section of the fire tests was performed by laser-scanning. This method shaped up as a quick and more exact alternative to the mainly used manual method. Three-dimensional models can be created and the residual cross-section can be determined wherever required. The residual cross-section received from the fire tests was compared to the FE-results. With finite element software the output of defined isothermal structures is possible, i.e. the nodes in the finite element mesh which are below or above a defined temperature can be shown. For a temperature of 250 °C which describes the start of charring of timber, laser-scanning and simulation results are in good agreement. In further steps towards the development of a design model for a fire resistance class of 60 minutes, a parametric study will be carried out to see the influence of timber thickness, dowel diameter, edge and end distances on the fire behavior of this connection type.

5. References


