Predicting the behaviour of dowelled connections in fire: Fire tests results and heat transfer modelling

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Summary

Fire safety is a significant obstacle of the timber market in construction. Despite the fact that recent experimental researches were conducted on the behaviour of timber joints under conventional fire exposure according to ISO 834, the literature is very poor about the extrapolation of test results for the various joint arrangements encountered in practice. A finite element approach is investigated to provide adequate and simple rules for current design. In a first part of this paper, after a brief presentation of the materials and joints properties, the results of fire resistance tests on these joints and some conclusions of the analyse of these tests are given. The second one describes the thermo physical properties of wood and steel used during thermal simulations. The third part detailed the heat transfer calculations. In this part, thermal results are analysed in regards of previous experimental data for timber to timber joints with dowel-type fasteners.

Keywords: Timber connection, fire, heat transfer, finite element modelling

1. Introduction

Facing environmental criteria, timber has to be used more and more in construction. However, a psychological brake exists on the fire behaviour protection of this material. Consequently, a better comprehension of the heat and mechanical transfers within timber under fire exposure is useful for the development of timber use in buildings.

Furthermore, connections represent one of the most important points for the timber construction. On this basis, our research work is focused on their analysis under fire exposure. Considering the development of engineering fire safety approaches, the scope of this project is to set-up simulation model for connection taking into account the thermal and mechanical behaviour.

In this field, it appears necessary to study in first dowelled timber joints. In a first part, the paper summarizes the fire resistance tests done for timber to timber connections. Then, the heat transfers are analyzed aiming to describe the effects of the evolution of internal stiffness. The results are compared to the experimental data.
2. Fire resistance tests

2.1 Materials and joints properties
Considering the implementation of the Eurocode 1995.1.2, experiments were carried out in a French research project [1]. The testing program is related to timber to timber and steel to timber joints with dowel-type fasteners. Only the results for timber to timber joints are presented here. The geometrical characteristics of these joints fulfilled the Eurocode 5 Parts 1.1 and 1.2 requirements (tableau 1).

Tab 1 Geometrical data of timber to timber joints

<table>
<thead>
<tr>
<th>Test series n°</th>
<th>Type of joints</th>
<th>Diameter of fasteners (mm)</th>
<th>Height (mm)</th>
<th>Thickness of side members (mm)</th>
<th>Thickness of central members (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Timber to timber joints</td>
<td>16</td>
<td>254</td>
<td>84</td>
<td>160</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td></td>
<td></td>
<td>64</td>
<td>112</td>
</tr>
</tbody>
</table>

The specimens are glued laminated elements of grade GL28h and the joints comprise two rows of 4 steel fasteners (three dowels and one bolt per row). Joint specimens of the same production were previously tested in normal conditions. The mean load-carrying capacities are respectively equal to 269,4 and 267,9 kN, and they represent the reference values for the fire tests.

The experimental procedure includes at the beginning one loading cycle up to 40% of the mean joint capacity. Then, the tensile force is set to 10, 20 or 30 % of the ultimate capacity and maintained at this level during the fire test. A conventional thermal solicitation is also applied to the four faces of the joints.

2.2 Fire resistance tests results
The fire resistance test results of joints are summarized in the table 2. The figure 1 shows a timber to timber joint after a fire resistance test.

Tab 2 Fire resistance results

<table>
<thead>
<tr>
<th>Test series No.</th>
<th>t₁ (mm)</th>
<th>t₂ (mm)</th>
<th>Loads (kN)</th>
<th>Loading ratio (η)</th>
<th>Time to failure under fire (minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>84</td>
<td>160</td>
<td>26,6</td>
<td>9,9 %</td>
<td>79</td>
</tr>
<tr>
<td>A</td>
<td></td>
<td></td>
<td>80,6</td>
<td>29,9 %</td>
<td>54</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td></td>
<td>26</td>
<td>9,7 %</td>
<td>59</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td></td>
<td>53,7</td>
<td>20 %</td>
<td>46</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td></td>
<td>53,1</td>
<td>19,8 %</td>
<td>45</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td></td>
<td>80,5</td>
<td>30 %</td>
<td>38</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td></td>
<td>80,6</td>
<td>30,1 %</td>
<td>41</td>
</tr>
</tbody>
</table>

Fig. 1 Timber to timber joint after a fire resistance test

The loading ratio given in the table 2 corresponds to the relationship between load applied during fire tests and the ultimate resistance obtained during mechanical tests in normal situation. These results show that for lower ratio time to failure up or greater than 60 minutes could be reached. Considering the design rules, an exponential relation between the loading ratio and the time to failure can be defined. Lastly, the results exhibit large changes in the temperature profiles between bolts and dowels.
3. Thermo-physical properties of the materials

3.1 Steel thermo-physical properties

The thermo-physical properties (thermal conductivity and specific heat) of steel are well-known. For the heat transfer simulations, the properties taken into account are those given in Eurocode 3 part 1.2 [2]. The steel density is taken equal to 7850 kg/m$^3$.

3.2 Timber thermo-physical properties

According to a large review, various relations were found for the thermo-physical characteristics of the timber according to the temperature.

3.2.1 Thermal conductivity of the timber

Hereafter are given some reference works which determine the thermal conductivity evolution of wood according to the temperature. The first method developed by Knudson [3] is based on the theory of Maku which started from the assumption that the thermal conductivity of the timber was proportional to its absolute temperature. Beyond 350 °C, timber is transformed into coal, so Knudson took the conductivity of timber equal to those of the coal (0.04152 W/m.K).

The second method is developed by Fredlund [4], considering the timber a porous material. For given moisture content and specific gravity, conductivity is determined to ambient temperature. Beyond this temperature, he uses equations connecting the thermal conductivity of gas being in the cavities of timber and coal, of solid material and water.

The third method is the model developed by Janssens [4] considering the timber with moisture content “U” at a temperature “T”. This model is only valid between 20 and 200°C. When the timber is carbonized, Janssens gives values tabulated for the conductivity of timber according to density. For timber partially carbonized, it is enough to interpolate linearly between the value of the model and the tabulated value. The figure 2 presents the various evolutions of the thermal conductivity of the timber.

![Fig. 2 Variation of the timber conductivity with the temperature.](image)

3.2.2 Specific heat of wood

The specific heat is probably less known than any of timber’s other thermal properties at high temperatures. Dunlap discovered that for temperatures between 0 and 106 °C the specific heat varied linearly with the temperature.

Knudson [3] used the equation of Dunlap while utilizing the latent heat of vaporization of water (he added a peak to 104.4 °C in the evolution of specific heat according to the temperature). Between 104.4 °C and 200°C, he used the equation of Dunlap for dry timber. Between 200 and 350 °C, he made the assumption that the specific heat varies linearly with the temperature. For temperatures higher than 350 °C, the value of the specific heat of coal (0.17 J/kg.K) is considered.
Fredlund and Janssens [4] also used the Dunlap’s equation. Moreover, these values are very close to those of Knudson (figure 3).

3.2.3 Density

The third property to be considered in the thermal model is the variation of the timber density according to the temperature. The majority of the researchers take as values those obtained by Tang from a thermo-gravimetric analysis carried out on samples of 0.4 m in thickness and a mass of 100mg. Only Fredlund adopted a residual density of 27 % on the basis of calibration analysis between model predictions and experimental results (see figure 4).
4. Thermal simulation results

In a first step, the heat transfer within the timber is simulated using a two-dimensional finite element programme. It allowed to identify the thermo-physical characteristics of Fredlund as those that given the best correlation with the experimental values obtained for the maximum number of fire resistance tests.

These characteristics are used for the 3D simulation of joints.

In a second step, the modelling of heat transfers in a real joint gives the possibility to know the field temperature and its evolution according to time for each element of joint. The figure 5 shows the model. In order to limit the calculation time, symmetric plans are used as shown on the figure 5.

As foreseen for steel, the comparison between the temperatures measured during fire tests (test series B, see paragraph 2) and those obtained by the simulation is very good. Thus, the figure 6 presents the evolution of the steel temperature according to the fire exposition time for a fire resistance test given. The dimensions 32, 64 and 119 mm represent the thickness with regard to lateral fire exposed face of joint.

![Fig. 5 Heat transfer modelling in the joint area](image)

![Fig. 6 Evolution of steel temperature according to time](image)
5. Conclusion

In conclusion, the whole fire tests realised on timber to timber joints in France shows that time of fire resistance higher than 30 minutes even 1 hour can be reached. This is possible with reduced loading ratio (10 to 30% of the load carrying capacity in normal situation). However, simulation by a two-dimensional finite element model allowed to establish a choice among the thermo-physical properties found in the literature. It permits also to fix the properties of Fredlund as those which will be useful at the time of mechanical calculation.

In the future stage, the temperature profile will be taken into account in the mechanical model to consider reduced mechanical properties of the components. The mechanical model thus developed will also take into account the phenomena of contact between the timber and the fastener. The first results show the necessity to determine these evolutions according to the temperature and the residual timber cross-section, mainly regarding the shear capacity of the timber.

6. References


