Applied Thermal Engineering 63 (2014) 254–265

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Thermo-hydric transfer within timber connections under fire exposure: Experimental and numerical investigations

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HIGHLIGHTS

- Experimental and numerical thermo-hydric behaviours under fire exposure on timber-to-timber and timber-steel-timber specimens with dowel and bolt type fasteners are presented.
- The hydric accumulation near a steel plate coupling to heat flux is highlighted.
- The difference of thermal behaviour between a doweled joint and a bolted one in the case of timber–steel–timber connections is highlighted.
- Two simplified numerical models are presented.

ARTICLE INFO

Article history:
Received 19 March 2013
Accepted 26 October 2013
Available online 7 November 2013

Keywords:
Fire
Connections
Timber
Temperature

ABSTRACT

Connections within timber structures are highly vulnerable areas when exposed to fire, especially when made of fasteners with different thermal and mechanical properties. This mechanical cohabitation can generate, because of material permeability differences, additional physico-chemical phenomena. These phenomena are affected by the coupling of heat and moisture transfers, which can alter the mechanical behaviour of timber structures. In order to improve our knowledge of the thermo-hydric timber connection, a series of experimental tests has been carried out and numerical models have been developed by taking the experimental observations into account. The experimental campaign concerns timber-to-timber and timber–steel–timber connections exposed to an "ISO 834" fire. The connections studied are real joints made of timber members, with and without a median metal plate, and maintained using bolts or dowels. The present study was conducted to examine heat transfer while taking the hydric effects at the interface between timber and steel fasteners into account. To analyse the experimental results and adjust the thermo-physical parameters for numerical modelling, numerical thermal fields, finite differences "FDM" and finite elements "FEM", models are developed. Numerical and experimental results are in good agreement. Nevertheless, some observations are made and discussed by comparing numerical results with experimental ones.

1. Introduction

Nowadays, timber structures are well on the way to democratization as regards building uses. They, indeed, present many advantages including light weight, speed of implementation and contribution to sustainable development. These structures are made of timber elements connected together using metal components such as bolts, dowels and nails forming the mechanical joints, which is sometimes reinforced with metal plates. Consequently, the joints are vulnerable areas when exposed to fire. Understanding their mechanical behaviour, therefore, is essential, not only as regards fire exposure, but also as regards the coupling of the thermal and hydric fluxes within the connections.

In the past, the development of timber structures has been seriously hindered by wood combustibility, which aroused many questions about fire safety. However, researches have since shown that wood behaves honourably under fire exposure. Wood, indeed, burns slowly and keeps his mechanical properties longer than other materials [1–3]. Its average carbonization rate is about 0.74 mm/min whereas carbonized layers form an external protection for the inner parts. Nevertheless, the combination of the architectural demand and the material mechanical resistance requires wood materials to cohabit with other materials like steel fasteners. With the presence of steel members, thermo-hydric heat transfer phenomena within

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http://dx.doi.org/10.1016/j.applthermaleng.2013.10.049

Timber–Steel–Timber ("T–S–T") connections under fire exposure increase in speed and complexity [4–7]. This complexity comes from the difference between the materials regarding mechanical rigidity and thermo-hydric permeability. It affects the mechanical and thermo-physical properties of the materials eventually, in particular, thermal conductivity and specific heat subjected to the thermal action of fire [8–12].

When a T–S–T joint is exposed to fire, each material reacts according to its thermo-physical characteristics. The rate of diffusion of the heat flow is then heterogeneous and depends on the thermal conductivity-temperature evolution of each material (timber and steel). As the temperature increases, with time, in the material, the water contained in timber migrates from areas with a high partial pressure toward some with a lower one and accumulates at the timber/steel interfaces. Heat flux is, therefore, necessarily coupled to a hydric flux, which, when the temperature exceeds 90 °C, initiates a change of phase. Thus, this physical process causes the retardation of the material combustion, the nature and duration of which depend on the moisture content of the timber and the permeability of the materials. A considerable amount of effort has been devoted to the observation of this phenomenon on joints equipped with metal plates: metal plates act as moisture barriers and water is stored at the wood/metal interfaces [4,7,10,13,14]. More recently, combustion slowing down has been represented numerically by a peak on timber specific heat, adjusted from experimental values, when the temperature ranges between 90 °C and 110 °C (corresponding to the temperature range where water passes from the liquid to the vapour state) [4,12,15–17].

The more recent experimental studies conducted to examine mechanically loaded joints subjected to fire, show that the mechanical and thermal phenomena can be distinguished [4,7,10,12,13,15,18]. When the instantaneous thermal state is determined using a finite element model ("FEM"), the mechanical response is computed in a realistic way [4,10,13]. On the other hand, the gap effect between fasteners and timber does not cause significant changes in the thermal behaviour of the joints under fire exposure [19,20]. With this aim in view, the present research provides important experimental and numerical data, which are needed in the field of understanding and quantifying thermo-hydric transfer phenomenon within timber–steel connections.

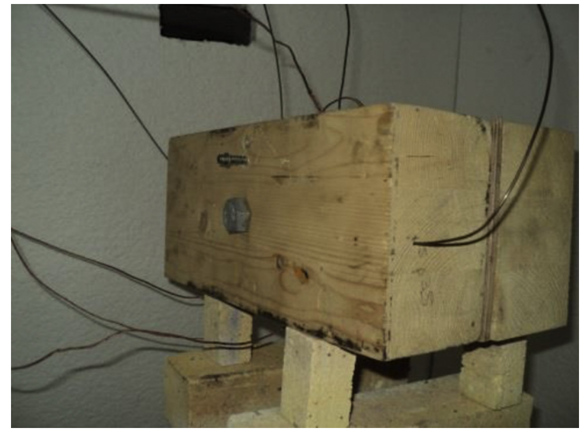

Fig. 1. Test specimen.

The objective of this paper is to present the findings of the investigations carried out to study experimental and numerical thermo-hydric transfer of timber connections subjected to the ISO-834 standard conditions of fire exposure [8,9,21,22]. Six experimental tests conducted on single-rod connections, with and without metal plates, are presented: three specimens with 16-mm diameter rods (T–T with dowel fastener, T–S–T with dowel fastener and T–S–T with bolt fastener); and three specimens with 20-mm diameter rods. The dimensions of these specimens are in conformity with EuroCodes technical recommendations [1,8,9,23].

The experimental tests are performed using a gas oven, with an automatic smoke evacuator, specially designed to meet the experimental conditions of the tests under ISO-834 fire exposure. Output temperatures are controlled using a computer. Some temperature sensors (thermocouples: "TC") are embedded into the timber member and the timber/steel interfaces to record the temperature evolution with time.

Numerically, the modelling of hydric and thermic transfers in timber material can be performed with different continuous and discrete mathematical models [24–26]. These methods take into account the both hydric and thermic effects at the same time. They are in perfect accuracy, but the temperature range still limited

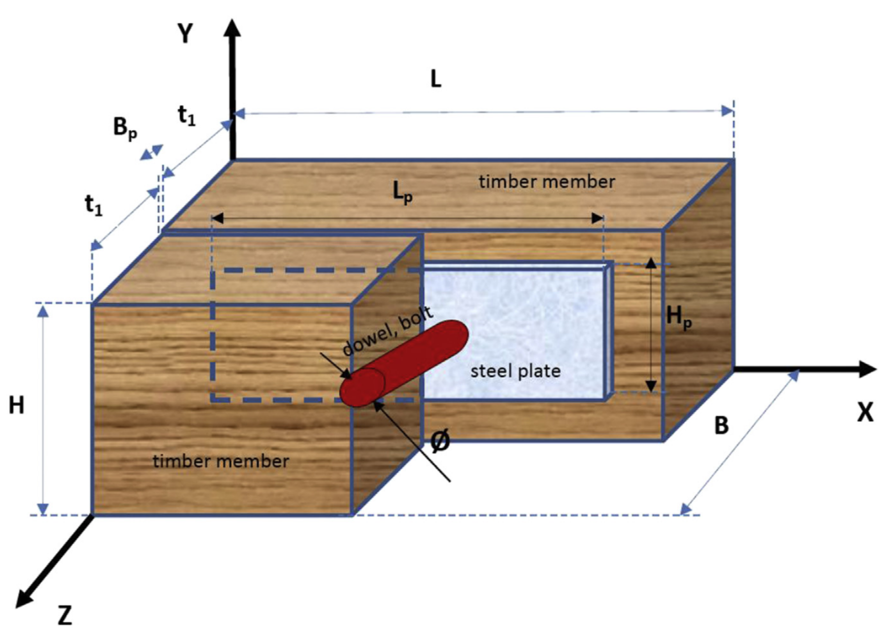

Fig. 2. Geometrical dimensions.