Fire Safety Journal 63 (2014) 125–137

Contents lists available at ScienceDirect

Fire Safety Journal

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

Experimental and numerical analysis of timber connections in tension perpendicular to grain in fire

Maxime Audebert [a,*], Dhionis Dhima [b], Mustapha Taazount [c,d], Abdelhamid Bouchaïr [c,d]

[a] Université de Lyon, Ecole Nationale d'Ingénieur de Saint-Etienne, Laboratoire de Tribologie et Dynamique des Systèmes (LTDS), UMR 5513, 58 rue Jean Parot, 42023 Saint-Etienne Cedex 2, France
[b] CSTB, Centre Scientifique et Technique du Bâtiment, Marne-la-Vallée, France
[c] Clermont Université, Université Blaise Pascal, Institut Pascal, BP 206, F-63000 Clermont-Ferrand, France
[d] CNRS, UMR 6602, Institut Pascal, F-63171 Aubière, France

ARTICLE INFO

Article history:
Received 6 March 2012
Received in revised form
17 November 2013
Accepted 24 November 2013
Available online 27 December 2013

Keywords:
Timber connections
ISO-fire tests
Finite element modeling
Tension perpendicular to grain
Thermo-mechanical behavior
Fire resistance

ABSTRACT

Steel-to-timber connections, loaded in tension perpendicular to grain, are tested in cold and ISO-fire conditions. The experimental results are used to validate a 3D finite element model. This model is based on two different meshes for thermal and thermo-mechanical calculations. To manage the plastic yielding of materials, the mechanical model is based on von Mises criterion for steel and Hill criterion for timber. To take into account the brittle character of wood in transversal directions, Hill criterion is combined with Tsaï–Wu failure criterion. The thermal model, based on a continuous mesh, simulates the evolution of the temperature field inside the connections. The thermal and mechanical models are validated by comparison of their results with those from tests (temperatures, load–displacement curves). The developed thermo-mechanical model considers the mechanical properties evolution as a function of the temperature. The comparisons of calculated and experimental fire resistances show that the model predicts accurately the thermo-mechanical behavior of the connections. The validated model is used to observe mechanical parameters which are difficult to obtain experimentally, such as the load distribution among fasteners in fire conditions.

1. Introduction

The analysis of the fire behavior of timber connections is complex due to the influence of several parameters, such as the geometry of the connection combining various materials (steel and timber), the fastener types, and the different thermo-physical and thermo-mechanical properties of these materials [1]. Timber is the structural material for which the studies on the properties and the tools of simulation in fire situations are the least numerous. The large variety of wooden species and the natural origin of the material, leading to a large variability of its characteristics, make difficult the synthesis of the data and the development of generalized models. Thus, the complex thermo-mechanical behavior of timber connections is difficult to predict.

In recent years, progress has been observed in the regulations relative to the fire performance of timber structures. Eurocode 5 (EN1995-1-2) [2] proposed design rules for symmetrical connections made with various fastener types including a simplified calculation method, the 'Reduced Load Method'. Besides, some experimental and numerical studies concerning the fire resistance of timber connections have been performed [3–9], opening the way for an extended use of timber in buildings. Nevertheless, large limitations still exist due to the lack of data. Thus, the design rules developed are based on a limited number of experimental and numerical results [10,11]. This is due to the high cost of large-scale experiments in fire conditions and the complexity to develop accurate numerical models. As a consequence, the EN1995-1-2 method covers a maximum fire resistance limited to 30 min for doweled steel-to-timber connections and still thus of limited application.

Moreover, most of the available studies concerning the thermo-mechanical behavior of timber connections deal with connections loaded in tension parallel to grain. However, in real doweled timber connections, timber is loaded in tension or compression parallel or perpendicular to grain combined with shear [12]. Due to the brittle character of the material in tension perpendicular to grain, the knowledge of the behavior of the connections in this orthotropic direction is of main importance. The anisotropy of timber can lead in many cases to brittle failures related to the stresses in shear and in tension perpendicular to grain [13]. These failures may result in splitting of the timber member. In normal conditions, the number of published researches on timber connections loaded in tension perpendicular to grain is limited [13–16]. In fire situation, this loading case has not been studied yet.

An extensive experimental and numerical program has been conducted in France from 1999 to 2010 [17–20]. The experimental

* Correspondence to: ENISE Saint-Etienne, 58 rue Jean Parot, 42100 Saint-Etienne, France. Tel.: +33 477437531.
E-mail address: maxime.audebert@enise.fr (M. Audebert).

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http://dx.doi.org/10.1016/j.firesaf.2013.11.011

part of this program allowed determining the fire resistance of timber connections subjected to various loadings: tension parallel and perpendicular-to-grain, tension with an angle of 45° to the grain and bending. These fire tests were completed by tests at normal temperature to obtain the real resistance of the connections to be used as a basis for the load ratio to be applied in fire situations. Numerical models, validated by the experimental results, have been developed for timber connections subjected to a tension parallel to grain [3,4]. These models allowed simulating accurately the thermo-mechanical behavior of the connections [4] and were used to analyze the load distribution among the fasteners of steel-to-timber connections [5].

In this study, these numerical models are adapted for the steel-to-timber connections loaded in tension perpendicular to grain. In a first part, the tested connections are presented and the experimental results in cold and fire conditions analyzed. Then, the three-dimensional (3D) finite element model is developed in two phases. The first one concerns the modeling of the heat transfer inside the connection components under a fire exposure. This model is validated using the temperatures measured inside the connection under fire. Then, the main assumptions considered in the modeling of the mechanical response of the connections in normal situations are presented. The mechanical model is validated using test results performed in cold conditions. Finally, the thermo-mechanical modeling approach, based on the two previous models considering the evolution of the mechanical characteristics of the materials according to the temperature is detailed. The simulated thermo-mechanical behavior of the connections is validated comparing the experimental and the numerical results. As the mechanical load is kept constant during fire test, the evolution of the relative displacement between the connected parts during the time of heating is used as basis of comparison. The validated thermo-mechanical model is then used to analyze the behavior of the connection loaded in tension perpendicular to grain and mainly the load distribution among fasteners in fire conditions.

2. Test program and experimental results

2.1. Experimental setup

Two different types of connections, with different fasteners diameters and timber thicknesses, loaded in tension perpendicular to grain, have been tested under ISO-fire and in normal conditions (~20 °C). They concern double shear steel-to-timber connections with four dowels. Two fastener diameters, 16 and 20 mm, are associated to two timber member thicknesses, respectively 77.5 and 105 mm. The geometrical configurations of the tested connections have been determined for fire design. Thus, in addition to the minimum requirements of EN1995-1-1 [21] for spacing and size, the end and edge distances towards the fasteners have been increased by a value a_{fi}. This additional thickness is recommended by EN1995-1-2 to increase the fire resistance of timber connections up to 20 min [2]. The timber member thickness t_1 is chosen considering the usual glulam dimensions, the thickness to dowel diameter ratio and the dimensions of connections tested under tension parallel to grain [18]. The same geometrical configurations (determined for fire design) have been tested in cold as well as in fire situations. Fig. 1 and Table 1 summarize the geometrical configuration and data values of the tested connections.

Six specimens were tested in normal conditions, at Blaise Pascal University, in order to determine the load–displacement curves of the connections including the main parameters which are the stiffness and the load-carrying capacity [22]. The loading perpendicular to grain was applied to the extremity of steel plate in accordance with the European Norm NF-EN26891 [23]. Firstly, the connections are subjected to a pre-loading cycle: load until 40% of the maximum estimated load (F_{est}) for 30 s, and unload until $0.1F_{est}$ for 30 s. Then, the specimens are reloaded until failure. During tests, the relative slip between the steel plate and the wood side members was measured.

Four specimens, with the same configurations as in normal conditions, were tested at CSTB under ISO-fire exposure. The loads applied in fire are calculated as a ratio of real load-carrying capacities N_u instead of the estimated one F_{est}. After a pre-loading cycle identical to that for tests in normal conditions (NF-EN26891), the specimens are reloaded to the load ratio η_{fi} chosen equal to 10%, 30% or 45% of N_u. Then, the ISO-fire exposure was

Table 1
Geometrical data of the tested connections.

Type	ϕ (mm)	t_1 (mm)	δ_p (mm)	h (mm)	L (mm)	b (mm)	a_1 (mm)	a_2 (mm)	$a_{4,t}$ (mm)	$a_{4,c}$ (mm)	a_{fi}
A16	16	77.5	8	267	2000	115	65	60	65	58	42
A20	20	105	10	320	2000	115	65	60	88	88	42

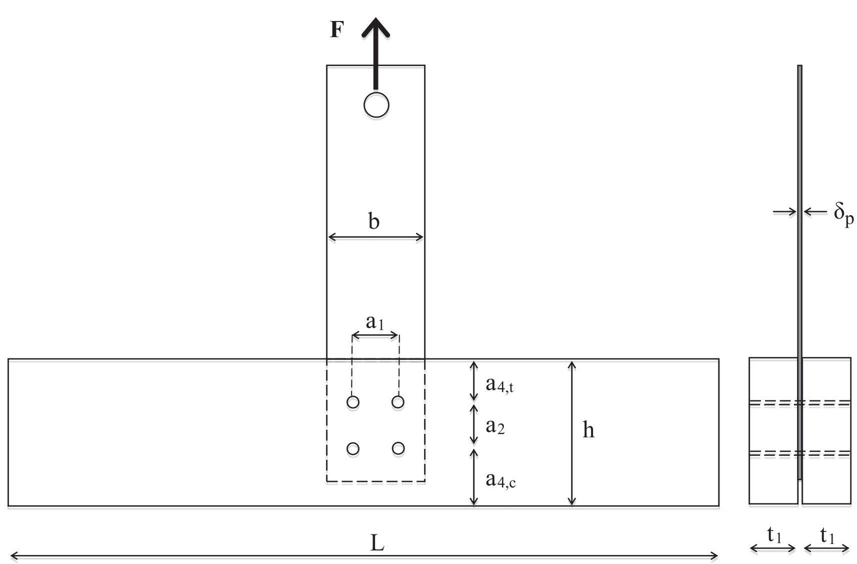

Fig. 1. Geometrical configurations of the tested steel-to-timber connections.