



**4th International Conference on
Numerical and Symbolic Computation
Developments and Applications**

PROCEEDINGS

**April, 11 - 12,
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SYMCOMP 2019 – 4th International Conference on Numerical and Symbolic Computation:
Developments and Applications

Edited by APMTAC – Associação Portuguesa de Mecânica Teórica, Aplicada e Computacional

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April, 2019





1 – Introduction

The Organizing Committee of SYMCOMP2019 – 4th International Conference on Numerical and Symbolic Computation: Developments and Applications, welcomes all the participants and acknowledge the contribution of the authors to the success of this event.

This fourth International Conference on Numerical and Symbolic Computation, is promoted by APMTAC - Associação Portuguesa de Mecânica Teórica, Aplicada e Computacional and it was organized in the context of IDMEC - Instituto de Engenharia Mecânica, Instituto Superior Técnico, Universidade de Lisboa. With this ECCOMAS Thematic Conference it is intended to bring together academic and scientific communities that are involved with Numerical and Symbolic Computation in the most various scientific areas

SYMCOMP 2019 elects as main goals:

To establish the state of the art and point out innovative applications and guidelines on the use of Numerical and Symbolic Computation in the numerous fields of Knowledge, such as Engineering, Physics, Mathematics, Economy and Management, Architecture, ...

To promote the exchange of experiences and ideas and the dissemination of works developed within the wide scope of Numerical and Symbolic Computation.

To encourage the participation of young researchers in scientific conferences.

To facilitate the meeting of APMTAC members (Portuguese Society for Theoretical, Applied and Computational Mechanics) and other scientific organizations members dedicated to computation, and to encourage new memberships.

We invite all participants to keep a proactive attitude and dialoguing, exchanging and promoting ideas, discussing research topics presented and looking for new ways and possible partnerships to work to develop in the future.

The Executive Committee of SYMCOMP2019 wishes to express his gratitude for the cooperation of all colleagues involved in various committees, the Scientific Committee, the Programm Committee, Organizing Committee and the Secretariat. We hope everyone has enjoyed helping to consolidate this project, which we are sure will continue in the future. Our thanks to you all.

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FIRE SAFETY OF WOOD-STEEL CONNECTIONS

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Keywords: Thermal, wood-steel connections, computational model, fire.

Abstract *The main objective of this work is to present different analytical and computational methods which permit the safe design calculation of the wood-steel connections, under fire conditions. Wood is an anisotropic, heterogeneous and porous material and its behaviour varies with temperature. The increase of temperature influences the progressive degradation of wood properties. During fire exposure, it is need to determine if the charred wood connections are safe in use. Design methods require the use of analytical methodologies and computational modelling to predict the fire exposure and the components capacity to resist to this action. In this work, the authors present studied cases, that will help professionals to analyse wood-steel connections and focus the type of information needed to decide whether the charred elements are adequate or not to use. For the same wood-steel connections, different insulation materials will be analysed to compare their behaviour and determine the fire resistance in time domain.*

1. INTRODUCTION

Wood-steel connections are the weak member for any structure. When submitted to fire conditions, an increased weakness occur due to the heat flow into the wood components, driven by the steel fasteners which cause faster wood charring, especially when exposed during long time. The fire resistance of the wood-steel connection depends on the wood charring, the strength reduction of the steel dowels and the residual cross section of the wood members. The wood embedment strength needs to be investigated for different fire ratings, as well the temperature field through the connection. It seems that the effect of the steel fasteners temperature on the wood member needs to be investigated. The fire performance analysis is complex because there are different materials involved and different parameters, geometries and dowels arrangements. Considering the behaviour of wood members when submitted to a developing fire, wood-based materials will burn and are rated as combustible. Wood material, when exposed to fire, produces a surrounding charring depth layer, with no mechanical resistance, resulting in a reduced cross-section. The constructive elements should be designed in accordance, to prevent and delay the fire damage effect, allowing that the wood-steel connection could remain in service for long time. The number of steel dowels influence the fire effect on wood.

Several researchers have presented experimental and analytical methods to calculate the physical degradation of wood due to high temperatures, [1] [2] [3]. The charring rate of different species when exposed to fire conditions has been examined by others researchers in different countries, [4] [5] [6] [7] [8] [9] [10] [11]. Also, empirical models for determining the charring rate and the heat transfer conditions were developed by White *et al.* [4].

The main goal of this work is to present analytical and numerical methodologies to predict the safe wood-steel connection design during a fire scenario. Different constructive solutions of wood-steel connections (wood-steel-wood and wood-wood-wood, both in double-shear, joined by steel dowel fasteners) will be analysed. This study brings new results to the previous investigations developed by the authors [12] [13] [14] [15] [16]. Rules to protected the wood-steel connections will be presented to demonstrate the performance and calculate the fire resistance in these elements. To simulate the fire resistance of the wood-steel connection, a numerical thermal and transient model, based on the finite element method was used. The non-linearity due to the thermal material properties dependence will be considered in the numerical simulation.

2. ANALYTICAL METHODOLOGY

According Eurocode 5 CEN EN1995-1-1, 2004 [17], the design tensile strength along the grain, $f_{t,0,d}$, must be equal or higher than the design tensile stress along the grain. The tensile strength represents a reduced value of the characteristic tensile strength along the wood grain, due to the application of safety factors: the modification factor for load duration and moisture content, k_{mod} , and the partial factor for material properties, γ_M , equation 1.

$$f_{t,0,d} = \frac{k_{mod} \times f_{t,0,k}}{\gamma_M} \quad (1)$$

Considering E_d as the applied load and A_s the cross-section of the member, the design tensile stress along the grain, $\sigma_{t,0,d}$, is according equation 2, Eurocode 5 CEN EN1995-1-1, 2004 [17].

$$\sigma_{t,0,d} = \frac{E_d}{A_s} \quad (2)$$

Using all proposed simplified equations from Eurocode 5 CEN EN1995-1-1, 2004 [17], and assuming a connection with a central steel plate in double shear stress applied to the fasteners, the characteristic load-carrying capacity, per shear plane and per fastener, must be calculated with equation 3. If the connection is only in wood with dowel fasteners the characteristic load-carrying capacity, per shear plane and fastener, in double shear is determined according 4.

$$F_{v,Rk} = \min \left\{ \begin{array}{l} f_{h,1,k} t_1 d \left[\sqrt{2 + \frac{4M_{y,Rk}}{f_{h,Rk} d t_1^2}} - 1 \right] + \frac{F_{ax,Rk}}{4} \\ 2,3 \sqrt{M_{y,Rk} f_{h,1,k} d} + \frac{F_{ax,Rk}}{4} \end{array} \right. \quad (3)$$

$$F_{v,Rk} = \min \left\{ \begin{array}{l} f_{h,1,k} t_1 d \\ 0,5 f_{h,2,k} t_2 d \\ 1,05 \frac{f_{h,1,k} t_1 d}{2 + \beta} \left[\sqrt{2\beta(1 + \beta) + \frac{4\beta(2 + \beta)M_{y,Rk}}{f_{h,Rk} d t_1^2}} - \beta \right] + \frac{F_{ax,Rk}}{4} \\ 1,15 \sqrt{\frac{2\beta}{1 + \beta}} \sqrt{2M_{y,Rk} f_{h,1,k} d} + \frac{F_{ax,Rk}}{4} \end{array} \right. \quad (4)$$

where $\beta = \frac{f_{h,2,k}}{f_{h,1,k}}$

and: t_1 represents the thickness of the wood members; $f_{h,1,k}$ is the characteristic embedment strength in timber member; d is the dowel diameter; $M_{y,Rk}$ is the characteristic yield moment of the fastener; $F_{ax,Rk}$ represents the characteristic axial withdrawal capacity of the fastener and β is the ratio between the embedment strength of the members. The value of $M_{y,Rk}$ is calculated according the dowel diameter and the material strength of the bolt.

$$M_{y,Rk} = 0,3 f_{u,k} d^{2,6} \quad (5)$$

The value of the characteristic embedment strength in timber elements, is obtain by the value

of the dowel diameter and the characteristic wood density, ρ_k , see equation 6.

$$f_{h,1,k} = 0,082(1 - 0,01d)\rho_k \quad (6)$$

With the calculation from $F_{v,Rk}$, it is possible to obtain the number of the bolts, equation 7.

$$N = \frac{E_d}{F_{v,Rd}} \quad (7)$$

At last, the spacing parallel to grain of fastener and within one row, a_1 , perpendicular to grain and between rows, a_2 , the distance between fasteners and loaded end, $a_{3,t}$, and unloaded edge, a_4 , c , depend on the dowel diameter. The designed connection at room temperature guarantees the applied load design.

The second step is to apply the Eurocode 5 CEN EN1995-1-2, 2004 [18], using two methodologies for safety verification under fire conditions: the simplified method and the reduced load method. In this paper the simplified method will be used in all wood-steel connections.

The following calculations are presented for a maximum time of fire exposure, thirty minutes of fire rating, for unprotect connections. The first step shall verify if the connection has a fire resistance for the established time, if not, the geometry must be modified, increasing the wood cross section, or protecting the connection with an insulating material. The design effect for fire exposure $E_{d,fi}$ needs to be calculated. The conversion factor for slip modulus is η_f .

$$E_{d,fi} = E_d \eta_f \quad (8)$$

The design strength in fire, $f_{d,fi}$, is calculated using the modification factor for fire, $k_{mod,fi}$, the partial factor for timber, $\gamma_{M,fi}$ and the yield strength at normal temperature, f_{20} .

$$f_{d,fi} = k_{mod,fi} \frac{f_{20}}{\gamma_{M,fi}} \quad (9)$$

Using the equation 10 it is possible to verify if the connection resists for a specific fire rating, such as thirty minutes under fire.

$$\frac{E_{d,fi}}{A_s} < f_{d,fi} \quad (10)$$

In case the above equation is not verified, one of two solutions must be chosen: add wood

material to the cross section or add insulating material. For unprotect connection, Eurocode 5 CEN EN1995-1-2, 2004 [18] ensures a time of the fire resistance, $t_{d,fi}$, according with the connector. For dowels, this time is 20 minutes, however the minimum value for t_1 is 45mm. The extra thickness of the member to improve the fire resistance in the connections, a_{fi} , is obtained following the equation 11.

$$a_{fi} = \beta_n k_{flux} (t_{req} - t_{d,fi}) \quad (11)$$

The β_n value is the design notional charring rate under fire exposure, k_{flux} is the heat flux coefficient for fasteners, and at last, t_{req} represents the required time of fire resistance.

For connection with insulating material, the Eurocode 5 CEN EN1995-1-2, 2004 [18] proposes two options for the protection material: gypsum (type A, F or H) or wood-based panels. Different equations are presented for each material. The value t_{ch} refers to the delay of start of charring rate due to protection, h_p is the fire protective panel thickness and β_0 represents the design charring rate for one-dimensional charring rate, under standard fire exposure.

For wood panels:

$$t_{ch} \geq t_{req} - 0,5 t_{d,fi} \quad (12)$$

$$h_p = t_{ch} \beta_0 \quad (13)$$

For gypsum, type A or H:

$$t_{ch} \geq t_{req} - 0,5 t_{d,fi} \quad (14)$$

$$h_p = \frac{t_{ch} + 14}{2,8} \quad (15)$$

For gypsum, type F:

$$t_{ch} \geq t_{req} - 1,2 t_{d,fi} \quad (16)$$

$$h_p = \frac{t_{ch} + 14}{2,8} \quad (17)$$

3. THERMAL PROPERTIES

Using the Eurocode 5 CEN EN1995-1-1, 2004 [18] and other references the literature, it is possible to establish the wood and gypsum thermal properties. In this work two different types of gypsum material were used from the references, [19] [20]. Figure 1 presents the thermal properties of each gypsum type and wood material, with different densities (GL20h, GL24h and GL32h).

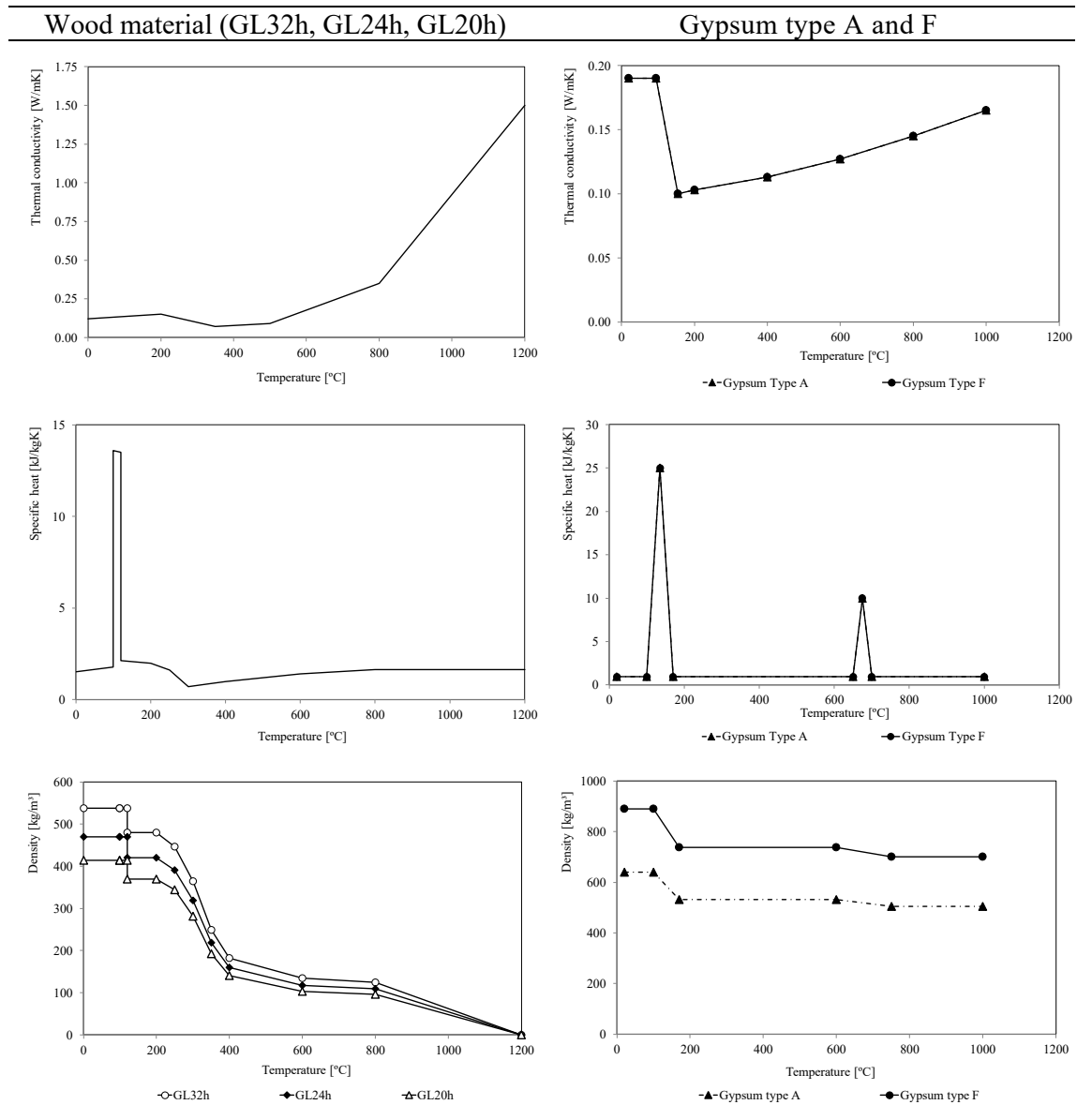


Figure 1. Material properties

4. NUMERICAL MODEL: RESULTS AND DISCUSSION

To simulate the fire resistance of the wood-steel connections, a numerical thermal and transient model, based on the finite element method, was used. Due to the symmetry of the geometry and the applied boundary conditions, the numerical calculation was performed for two dimensional plane of the connection. The size of the finite element is equal to 2mm of length. Each element has eight nodes with one degree of freedom per node (temperature). Different numerical models were developed, using different designed connections, obtained from the previous calculation for room temperature, and submitted to fire at one exposed side. Wood material when exposed to fire presents a thermal physical degradation. The interface between charred and no charred wood is called the transition phase, usually identified between black and brown material and is characterized by a threshold value of 300 °C, according Eurocode 5 CEN EN1995-1-2, 2004 [18]. The typical values for charring rate of wood changes between 0.5-1.0mm/min. Eurocode 5 CEN EN1995-1-2, 2004 [18] suggests a charring rate equal to 0.65mm/min or 0.7mm/min for softwood or hardwood, with density higher than 290kg/m³. The evaluation of the char layer thickness, depends on the exposed time and determines the charring rate in mm/min. The char layer thickness was determined for each model, using different measurements in different locations.

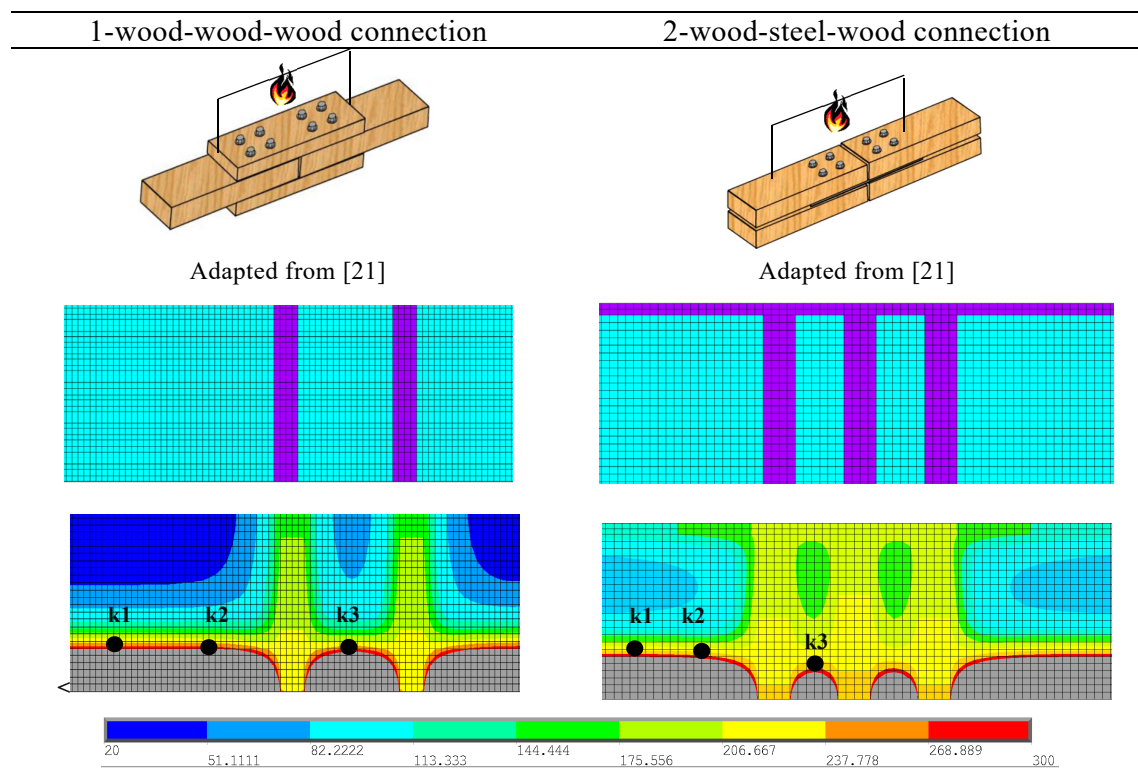


Figure 2. Wood-steel connections and charring layer formation at 15min

As an example, figure 2 presents a half of two cross-sections for unprotected connections (wood-wood-wood and wood-steel-wood), designed according to the previous equations and using steel dowels with a diameter of 8mm. In the numerical model, the blue zone represents the wood material and violet represents the steel material (dowels and middle plate). The results were obtained for GL20h and represent the charring layer on the wood, in grey colour.

Table 1 presents the calculated charring rate in different locations of the wood-steel connections, as represented in figure 2: k1 faraway of the steel dowels, k2 in the neighboured of the dowel and k3 in the wood between two dowels.

Points	1-wood-wood-wood connection			2-wood-steel-wood connection		
	GL20H	GL24H	GL32H	GL20H	GL24H	GL32H
k1	0.77	0.72	0.67	0.80	0.83	0.77
k2	1.00	0.93	0.80	0.65	0.63	0.60
k3	1.13	1.00	0.87	0.51	0.47	0.43

Table 1. Numerical calculated values for charring rate

The results show that the connections present a charring layer with nonlinear variation after the fire exposure. Using only the Eurocode 5 CEN EN1995-1-2, 2004 [18] it is impossible to understand the fire effect through and inside the wood-steel connection. The charring rate is considered as a standard and constant value, however using the numerical results, the charring rate varies in the connection, due to the effect of the steel and wood density. It is important to point out that steel provides a heat flow to the inside of the connection, but the wood part of the elements give them some insulation. This way, both materials participate in the evolution of the char layer in the connection.

Point k1 gives values of charring rate close to the proposed values in Eurocode, but increases with the density of wood material and for connections with a central steel plate. Point k2 presents the higher charring rate, also in wood connections in GL20h, reaching the maximum values in wood-wood-wood connections. When compared with point k3, neighbour with steel dowels, and until this time of fire exposure, a delay in the charring rate evolution is observed.

The steel plate, as central member, remains at lower temperature if the exposure time is small, but could increase when fire exposure increases, producing an increase in the charring rate. In the begin of fire the wood elements give some thermal insulation, but with the increase of fire exposure, the steel fasteners bring heat to the inside of the connection.

According Eurocode 5 CEN EN1995-1-2, 2004 [18], the studied protected connections, requires a protection layer thickness of the panel equal to 18mm for gypsum plasterboard type F and 23mm for gypsum type A or H, assuming standard fire resistance period of 60 min and for any type of chosen wood densities.

5. CONCLUSIONS

A procedure with all analytical and simplified equations was presented to assess the cross-section behaviour, all dimensions for an applied tensile load, and fire safety verification. The number of fasteners increases with load, according to standards at room temperature. Lower dowels diameter, has a higher pronounced effect in the number of fasteners. The effect due the strength of material for GL20h, GL24h and GL32h is not significant, but the wood density variation affects the thermal behaviour.

In addition, a numerical model, using the finite element method, was developed in order the obtain the wood char layer. These numerical models help to better understand the behaviour of the connection under fire exposure, in comparison to the simplified method. The numerical model gives an acceptable prediction of the fire resistance of wood-steel connections, and allows to determine the fire resistance of different types and sizes of connections.

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