

THE FIRE RESISTANCE OF (W-W-W) WOOD-TO-WOOD CONNECTIONS PROTECTED WITH DIFFERENT TYPES OF GYPSUM PLASTERBOARD



Pedro A. S. Leite
MSc in MEM
ISEP/IPP
Porto



Lino Silva
MSc in MEM
ISEP/IPP
Porto



Elza M. M. Fonseca*
Professor
ISEP/IPP
Porto

ABSTRACT

The main objective of this work is to verify the fire resistance of unprotected (W-W-W) wood-to-wood connections and compare the results with protected connections using gypsum plasterboard. According Eurocode 5, part 1-2 the connections could be protected by the addition of wood panelling, wood-based panels or gypsum plasterboard type A, H or F. To obtain conclusions according the application of different type of gypsum plasterboard in the designed W-W-W connections in different densities material, numerical models were building to verify the level of protection in fire action. The wood behaviour varies with temperature and its influences the progressively properties degradation. After fire exposure, it is need to determine if the charred wood connections will rest safe for 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. Results of the temperature field in the studied connections under fire will be presented, with the measured char layer in unprotected members and comparing the protected efficiency with different types of gypsum plasterboard.

Keywords: W-W-W Connection; Fire; Protected Connection; Eurocode 5.

1. INTRODUCTION

The fire resistance of the wood connections depends on the char layer evolution, the strength reduction of the steel dowels and the residual cross section of the members. The fire performance

*Autor correspondente – Dep. de Engenharia Mecânica, Instituto Politécnico do Porto. ISEP | Instituto Superior de Engenharia do Porto, 4249-015 Porto. Telef.: +351 228 340 500, Fax: +351 228 321 159, E-mail: elz@isep.ipp.pt

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, they will burn and are rated as combustible.

The behaviour of wood connections subjected to fire require more research. The assessment of the connection (wood member with steel fasteners) and their failure modes due its fire exposure is complex.

Wood material when exposed to fire presents a thermal physical degradation. The interface between the charred and noncharred wood is the transition phase between the black and brown material and is characterized by a threshold value of 300°C, according Eurocode 5 part 1-2 [1]. Also the thermal properties of wood vary considerably with temperature and should be defined according the Eurocode 5 part 1-2 [1]. This standard code provides the design values for density, thermal conductivity and specific heat of wood.

According Eurocode 5, part 1-2 the wood connections could be protected by the addition of wood panelling, wood-based panels or gypsum plasterboard type A, H or F [1].

Raw materials of the gypsum plasterboards are gypsum, paper and additives. Gypsum consists of a porous core between two layers of paper, creating a sandwich structure. Usually, gypsum plasterboards have a thickness range between 9 to 30mm. Gypsum is a non-combustible material and makes no contribution to fire, it works, in fact, as a built-in sprinkler [2].

Gypsum Type A corresponds to the conventional gypsum plasterboard with porous core and no reinforcement, except the paper laminated surface. Gypsum Type H with water-resistant properties. And Type F refers to 'fire-resistant' gypsum plasterboard with improved core cohesion at high temperatures.

This article first describes the basic idea of the design W-W-W connection at room temperature. Then, the main results of thermal and transient numerical analyses on unprotect connections and protected connections with gypsum plasterboards are presented. The results enlarge the knowledge of the fire behaviour in unprotected and protected connections with gypsum plasterboard, that allow the calculation of the charring rate of the designed W-W-W models and the verification of the material density effect. This study carries out more results to the previous investigations developed by the authors [3] [4].

2. DESIGNED W-W-W CONNECTIONS ACCORDING EUROCODE 5

The W-W-W connections were designed with simplified equations from Eurocode 5 part 1-1, at ambient temperature [5]. Three types of wood material with different densities (GL20h, GL24h and GL32h) were used to building the W-W-W connections with different steel dowels, as fastener members.

According Eurocode 5 part 1-1 [5], 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

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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 , as the following expression:

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

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:

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

According the simplified equations from Eurocode 5 part 1-1 [5], the characteristic load-carrying capacity, per shear plane and fastener, for a connection W-W-W with dowel fasteners, is determined according equation 3.

$$F_{v,Rk} = \min \left\{ \begin{array}{l} \frac{f_{h,1,k} t_1 d}{2 + \beta} \left[\sqrt{2\beta(1 + \beta) + \frac{4\beta(2 + \beta)M_{y,Rk}}{f_{h,Rk} d t_1^2} - \beta} \right] + \frac{F_{ax,Rk}}{4} \\ 1,15 \sqrt{\frac{2\beta}{1 + \beta}} \sqrt{2M_{y,Rk} f_{h,1,k} d + \frac{F_{ax,Rk}}{4}} \end{array} \right. \quad (3)$$

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.

$$M_{y,Rk} = 0,3 f_{u,k} d^{2,6} \quad (4)$$

The value of the characteristic embedment strength in timber elements, is obtain by the value of the dowel diameter and the characteristic density of the wood ρ_k , as represented in equation 5.

$$f_{h,1,k} = 0,082(1 - 0,01d)\rho_k \quad (5)$$

With the calculation from $F_{v,Rk}$, it is possible to obtain the number of the bolts, equation 6.

$$N = \frac{E_d}{F_{v,Rd}} \quad (6)$$

The design equations are only valid if there is no premature splitting or shearing of the wood resulting in brittle type failure. To reduce the risk of such failures, minimum edge, end and spacing criteria for connections with dowel type fasteners have been developed and the procedure for bolts are given from the Eurocode 5 part 1-1 [5]. So, the designed connection at room temperature guarantees the applied load design.

With all design equations a worksheet was developed to allows the calculation of different W-W-W connections. Different parameters were considered: four dowel diameters, three applied tensile load and three wood materials. The obtained results allow to verify a linear correlation between the applied load and the necessary fasteners diameter, with a higher increase for lesser dowels diameter, figure 1.

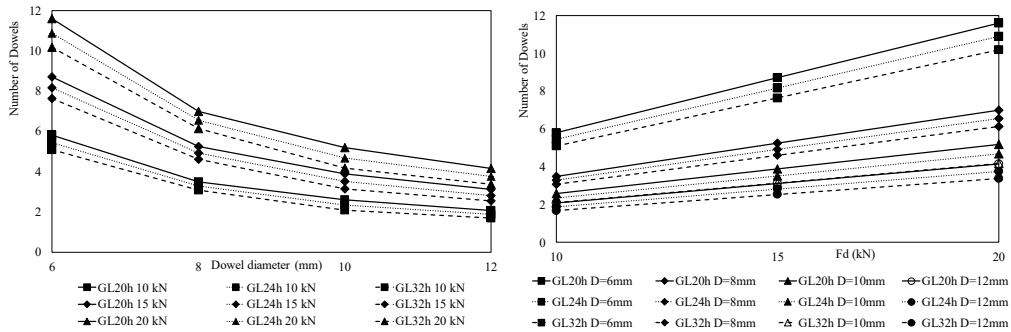


Figure 1: Comparison between dowels diameter and number of dowels; applied load and number of dowels; for any type of three types wood material.

Simplified rules from Eurocode 5, part 1-2 [1] were used to analyse the same connections with side members of wood under standard fire exposure. The structural fire resistance in these type of wood material is equal to 0.7mm/min in accordance to Eurocode 5, part 1-2 [1], that represents the design charring rate under standard fire exposure.

For connections with insulating material, the Eurocode 5 part 1-2 [1] proposes two options for the protection material: gypsum (type A, F or H) or wood-based panels. In this work gypsum panel was chosen for protecting the wood connections.

For gypsum, type A or H:

$$t_{ch} \geq t_{req} - 0,5 t_{d,fi} \quad (7)$$

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

For gypsum, type F:

$$t_{ch} \geq t_{req} - 1,2 t_{d,fi} \quad (9)$$

$$h_p = \frac{t_{ch} + 14}{2,8} \quad (10)$$

The value t_{ch} refers to the delay of start of charring rate due to protection, h_p is the fire protective panel thickness. The time of the fire resistance $t_{d,fi}$, is according with the connector. For dowels, this time is 20min, however the minimum value for t_1 is 45mm. t_{req} represents the required time of fire resistance.

In this work 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 60min and for any type of chosen wood densities.

3. NUMERICAL MODEL OF W-W-W CONNECTIONS

In addition, a numerical program was used to produce simulations focused on thermal and transient analysis to study W-W-W connections. This methodology allows to obtain the temperature field in the studied connections under fire, measuring the char layer in the wood members with different densities, when unprotected, and compare the efficiency in protected connections with different types of gypsum plasterboard.

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. The initial temperature in the numerical model was considered equal to 20°C. The external surface of the connection is exposed to the standard fire curve ISO834 during one hour and the convection coefficient is taken equal to 25W/m²K [6]. The surface emissivity is taken constant and equal to 1 for exposed side [6]. The non-linearity due to the thermal properties dependence will be taken into account in the numerical simulation.

Figures 2 and 3 present all thermal properties (thermal conductivity, specific heat and density) used in the numerical model, based on standard codes and the literature: steel is according the Eurocode 3 part 1-2 [7], Eurocode 5 part 1-2 [1] is used for wood with different densities (GL20h, GL24h and GL32h) and each gypsum type is obtained from the literature, [8] [9]. The density for steel is constant, equal to 7850 kg/m³.

Numerical models were developed, using the designed connections obtained from the previous calculation at room temperature. Figure 4 presents a typical zone in study for half cross-section of the unprotected W-W-W connection, 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 dowels in steel material. For protected connections a regular mesh was increased in depth, with h_p value for the fire protective panel thickness.

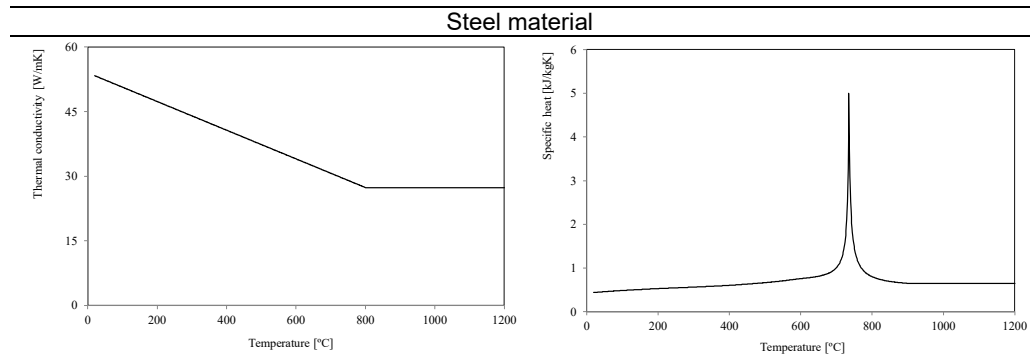


Figure 2: Properties for steel material.

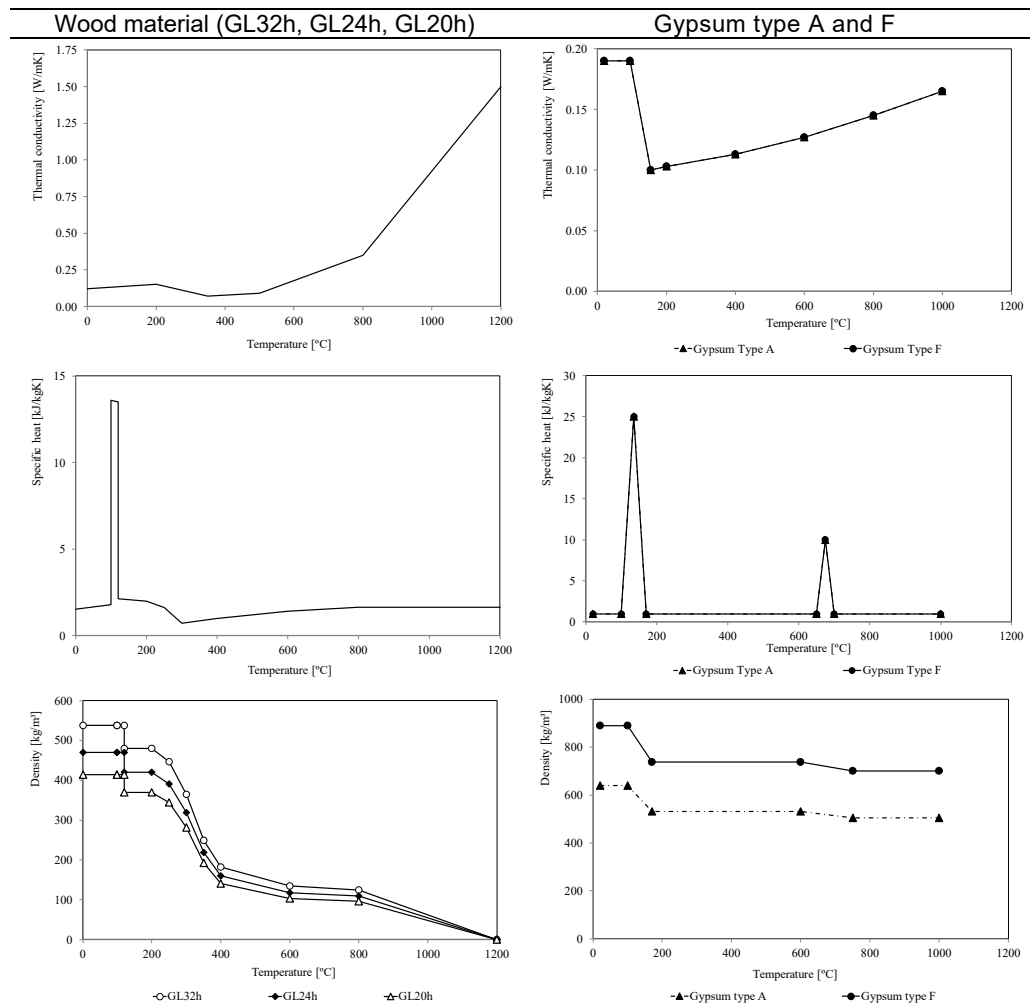


Figure 3: Properties for wood and gypsum materials.

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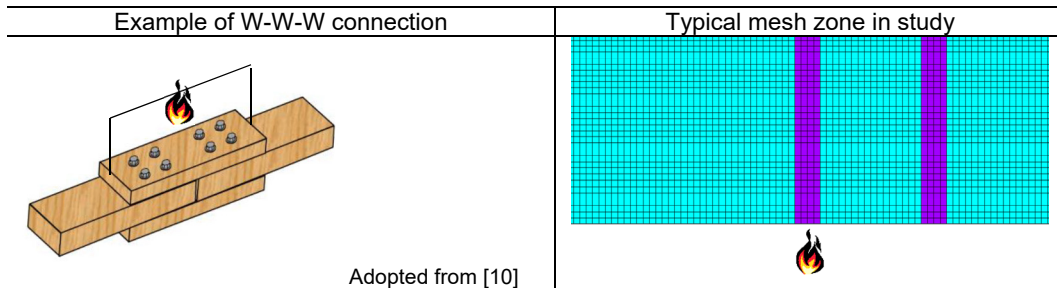


Figure 4. W-W-W connection and numerical model.

4. RESULTS AND DISCUSSION

The results were obtained for the three types of wood densities and represent the char layer on the wood, in grey colour, figure 5.

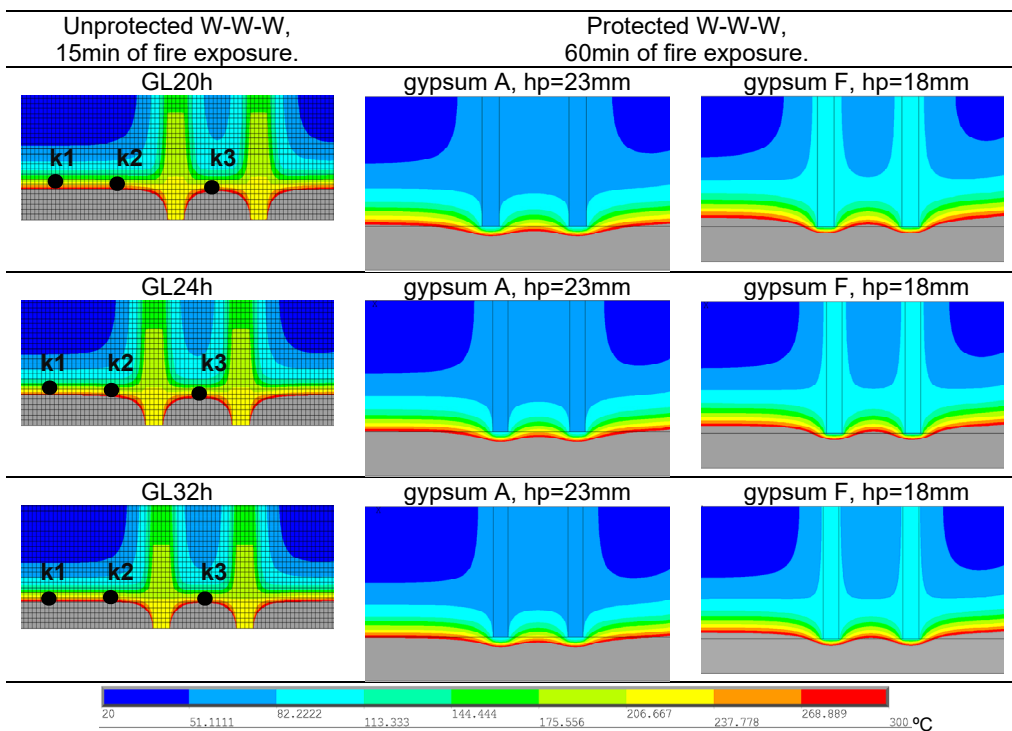


Figure 5. Numerical results for unprotected and protected W-W-W connections.

Figure 5 represents the comparison between char layer on the wood and the protect effect using gypsum panels during 60min of fire. Grey colour also represents the thickness hp of the gypsum panel (A or F) when reaches 300°C. Every protected connection is prepared analytically to resist during 60min at fire exposure. Gypsum type F has a lesser thickness hp , and in generally protect

the wood, but produces higher temperatures. In general, both gypsum panels are a good thermal protector of the wood connections, during 60min of fire.

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.

Table 1 presents the calculated charring rate for unprotected W-W-W connections in different locations: k1 faraway of the steel dowels, k2 in the vicinity of the dowel and k3 in the wood between two dowels, as represented in figure 5.

Table 1: Numerical calculated charring rate in mm/min.

Points	GL20h	GL24h	GL32h
k1	0.77	0.72	0.67
k2	1.00	0.93	0.80
k3	1.13	1.00	0.87

The results show that the connections present a char layer with nonlinear variation after the fire exposure. Using only the Eurocode 5 part-1-2 [1] it is impossible to understand the fire effect through and inside the 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 members give some insulation. This way, both materials participate in the char layer development in the connection.

Point k1 gives values of charring rate close to the proposed values in Eurocode, but decreases with higher density of wood material. Point k3 presents higher charring rate, also in wood connections in GL20h. Point k2 is in the vicinity with the steel dowels, and until this time of fire exposure, presents higher charring rate evolution. 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.

The gypsum material allows to vary the thermal insulant effect, reducing the wood char layer in the connections, due their wide range of physical properties.

The previous analyse (figure 1) is very important because permits to verify the number of steel dowels which provide a higher heat flux inside the connection.

As a general conclusion, the numerical methodology shows a good process to understand the connection behaviour (wood and steel in conjunction) under fire, when compared with the analytical results from the simplified equations.

5. CONCLUSIONS

A procedure with all analytical and simplified equations were presented to assess the dimensions of the connection cross-section for any 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 needed 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 W-W-W connections, and allows to determine the fire resistance of different types and sizes of connections.

After the fire exposure, the connections present higher values of char layer evolution with nonlinear variation in the vicinity of the steel dowels. For unprotected connections with a time of fire exposure greater than 15min, the steel dowels induce heating inside the wood core section. The wood in the vicinity of dowels presents a char layer that is unfeasible for the connection. Due this situation will be better the option for protected connections. As concluded previous, for the time fire exposure of 60min the calculated thickness panel allows to protected all connection (wood and steel materials) remaining intact the designed connection at room temperature.

The numerical method, both for the protected and unprotected connections, shows a good process to understand the behaviour of the connection under fire exposure, an enhanced methodology when compared with the analytical results obtained from the simplified equations. The gypsum material is a good thermal insulant reducing the char layer compared to the unprotected connections.

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