THE DENSITY EFFECT IN (W-S-W) WOOD CONNECTIONS WITH INTERNAL STEEL PLATE AND PASSIVE PROTECTION UNDER FIRE

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ABSTRACT

The main objective of this work is to understand the fire behaviour of unprotected wood-to-wood connections with internal steel plate (W-S-W) in comparison with connections using passive protection with gypsum plasterboard. Passive fire protection uses systems that help prevent the spread of fire. Analytical methodologies according Eurocode 5 part 1-1 were used to the designed connections in different wood densities material. After that, to predict the fire exposure and the connection capacity a computational modelling was performed. Results of the temperature field and the char layer formation, for unprotected and protected members, were compared. Two different cross sections, only in wood or in wood-steel, were chosen to verify the evolution of charring rate effect.

Keywords: W-S-W Connection; Fire; Passive Protection; Eurocode 5.

1. INTRODUCTION

Gypsum plasterboards systems are widely used in buildings, as walls or ceilings, to provide passive fire protection [1]. Contrary to active fire protection procedures, passive fire protection means normally do not need electronic activation or a degree of motion. Passive fire protection remains inactive in the coating system until a fire occurs. The aim is the fire protection and life

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safety. This is generally accomplished by maintaining structural integrity for a time during the fire, and limiting the fire spread and the effects.

The basis of the fire resistance of gypsum plasterboards lies in low thermal conductivity and the water content evaporation, which absorbs a considerable amount of heat, thereby delaying temperature rise through the system. Thermal properties of gypsum are temperature-dependent and among them, thermal conductivity has a critical influence, with a wide range in literature [2]. The variety of thermal properties (density, specific heat and conductivity) influencing the fire protection ability of different products of gypsum is very large.

Three different wood species in homogeneous glued laminated (glulam) were considered for the wood-to-steel designed connections, where the density properties varies between 370 and 480 kg/m^3. Glulam is manufactured by bonding together individual laminations of solid timber, in rectangular cross-sections and adaptable in design. (CEN, BS EN 1194, 1999) [3] lists eight glulam strength classes. To distinguish them from the timber categories, they are designated by GLxh as homogeneous lay-up, meaning that all of the laminations are of the same strength class, or GLxc as combined, where the outer laminations are of a higher strength class.

The fire behaviour of unprotected and protected wood-to-steel connections have the spacing, edge and end distances and side member dimensions calculated with the minimum requirements given in Eurocode 5 part 1-1 [4] designed at ambient temperature. In this work, numerical methodologies were used to obtain the temperature field distribution in the connections. Simplified rules from Eurocode 5 part 1-2 [5] were used to analyse connections with side members under standard fire exposure. The start of charring time is taken as the time of reaches 300 ºC on wood-to-steel connection surface, in accordance with Eurocode 5 part 1-2 [5].

As a conclusion, the number of fasteners increases accordingly the standards at ambient temperature, function of the applied load. For lesser dowels diameter, higher number of fasteners is need. The effect due the strength of material for GL20h, GL24h and GL32h is no significant, but the wood density variation affects the thermal characterization. All the designed (W-S-W) wood-to-steel connections were measured at fire resistance according the study in different cross-sections. The cross-sections were thermally studied to verify the heat conduction effect due the increased number of steel dowels inside the protected and unprotected W-S-W connections. The steel plate as internal member remains at lower temperature if the exposure time is shorty, but increases when fire exposure increases, namely near of the steel dowels.

According Eurocode 5 part 1-2 [5] the studied protected W-S-W connections need a thickness of the panel equal to 18mm for gypsum plasterboard type F and 23mm for gypsum type A or H, for a required standard fire resistance period of 60min and any type of chosen wood densities. 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. Nevertheless, using numerical models, it will be possible to verify the effect of wood density and steel materials in conjunction. All results of this work will complement previous research from the authors [6-8].

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

The W-S-W connections were designed with simplified equations from Eurocode 5 part 1-1 [4], at ambient temperature. Three types of wood material with different densities (GL20h, GL24h and GL32h) were used to building the W-S-W connections with different steel dowels and an internal plate with a constant thickness. For protected connections two types of gypsum material were considered.

The first step is to verify the design tensile strength along the grain $f_{t,0,d}$, that 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) as the following expression:

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

E_d is 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 [4], the characteristic load-carrying capacity, per shear plane and fastener, for a connection W-S-W with dowel fasteners, is determined according equation 3.

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

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; $F_{\alpha x,Rk}$ 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, 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 with the following expression.

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

To reduce the risk of failures modes and guarantees the applied load design, minimum edge, and end spacing criteria for connections with dowel type fasteners, all procedure has been developed according Eurocode 5 part 1-1 [4].

A worksheet was developed with all designed parameters (dowel diameters, applied tensile load, material properties) to allows the calculation of different W-S-W connections.

Simplified rules from Eurocode 5, part 1-2 [5] were used to analyse the same connections with side members of wood under 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 [5], that represents the charring rate under standard fire exposure.

For connections with insulating material, the Eurocode 5 part 1-2 [5] 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, with a layer thickness of the panel equal to 18mm for gypsum plasterboard type F (equations 7 and 8) and 23mm for gypsum type A or H (equations 9 and 10). A fire resistance period of 60min was assumed, and for any type of chosen wood densities.

For gypsum, type F:

$$t_{ch} \geq t_{req} - 1{,}2\, t_{d,fi} \quad (7)$$

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

For gypsum, type A or H:

$$t_{ch} \geq t_{req} - 0{,}5\, t_{d,fi} \quad (9)$$

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

In these equations, 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.

3. MATERIAL PROPERTIES

Figures 1, 2 and 3 present all thermal properties used in the numerical model, based on standard codes and in the literature.

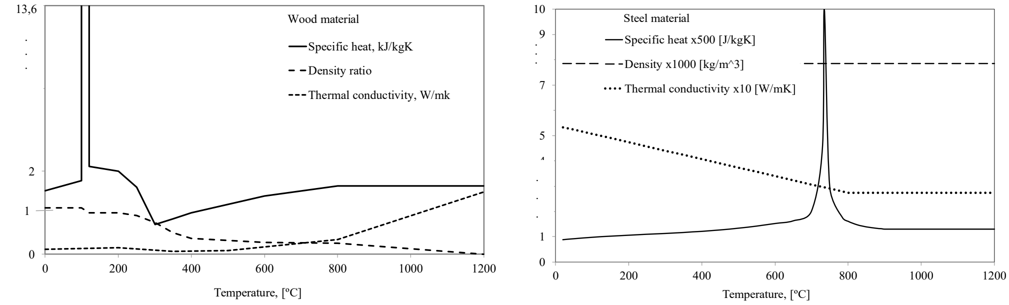

Figure 1: Specific heat, thermal conductivity and density for wood and steel, respectively.

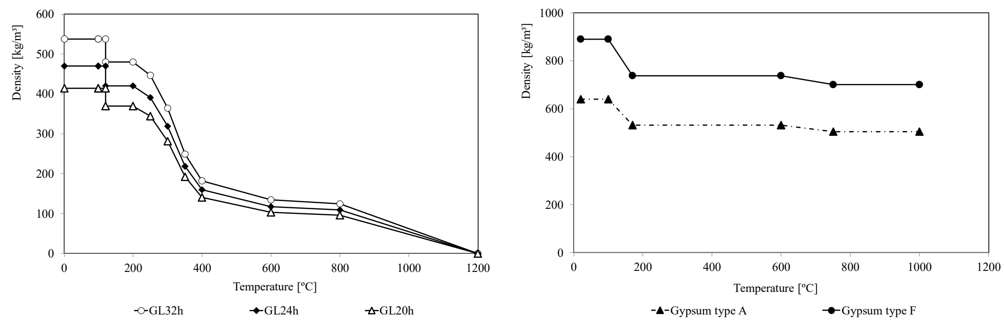

Figure 2: Density for wood (GL32h, GL24h, GL20h) and gypsum (type A and F).

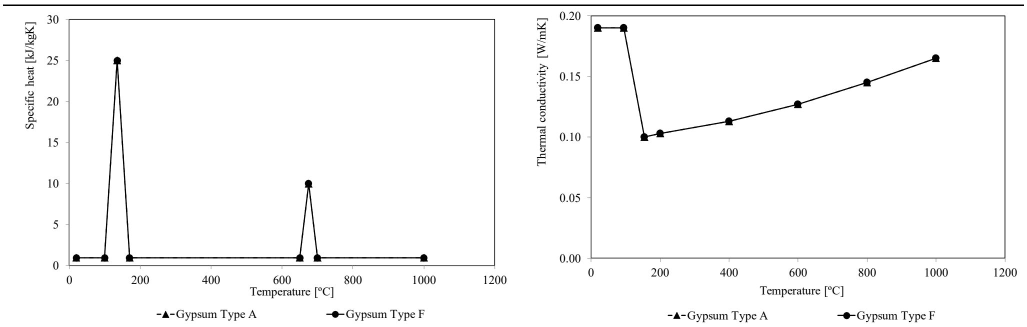

Figure 3: Specific heat and thermal conductivity for gypsum (type A and F).

Figure 1 presents the specific heat, thermal conductivity and density for wood and steel. Steel is according the Eurocode 3 part 1-2 [9] and Eurocode 5 part 1-2 [5] is used for wood. The density for steel is constant, equal to 7850 kg/m^3. The densities (GL20h, GL24h and GL32h) for wood and gypsum type from the literature, [10] [11] are represented in figure 2. Figure 3 represents the specific and thermal conductivity for gypsum plasterboard, without any difference between the gypsum types. The properties are influenced by moisture mass transfer into or out of the gypsum board as well as cracking and ablation. In order to consider these effects, the properties are usually calibrated with results of fire tests [11].

4. NUMERICAL MODEL OF W-S-W CONNECTIONS

A numerical program was used to produce simulations focused on thermal and transient analysis to study W-S-W connections, designed according to the previous equations and using steel dowels with a diameter of 8mm. The non-linearity due to the thermal properties dependence were introduced in the numerical simulation. The main objective is 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 protected efficiency 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, in a typical cross section in wood and wood-steel material, figure 4. The blue zone represents the wood material and violet represents the steel material. For protected connections a regular mesh is increased in depth, with *hp* value for the fire protective panel thickness. The size of the finite element is equal to 2mm.

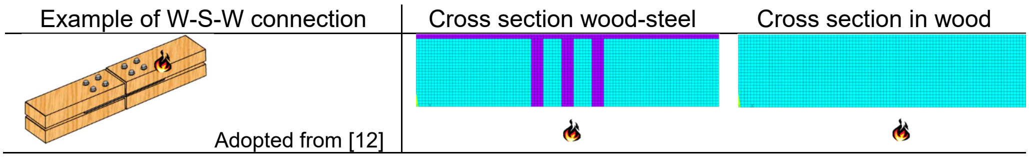

Figure 4. W-S-W connection and different typical meshes in study.

The initial temperature in the model was considered equal to 20ºC. The external surface of the connection is exposed to the standard fire curve ISO834 during 60min and the convection coefficient is 25W/m^{2}K [13]. The surface emissivity is constant and equal to 1 [13].

5. 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, figures 5 and 6.

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 5 presents the numerical results of the temperature at two different time instants (15 and 30min) in the wood cross section, comparing the three wood densities. The heat conduction and char layer evolution inside the wood with lesser density are more pronounced.

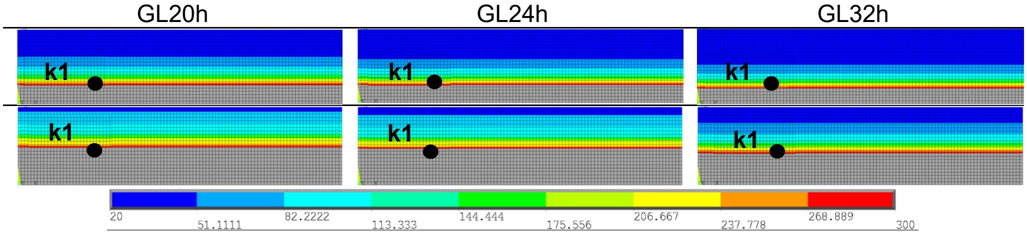

Figure 5. Unprotected connections (cross section in wood) at 15min and 30min under fire.

Figure 6 represents the comparison between char layer on the wood and the protect effect using gypsum panels during 60min of fire. Grey colour represents the thickness *hp* of the gypsum panel (A or F) when reaches 300ºC. 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, increasing with lesser wood density. In general, both gypsum panels are a good thermal protector of the wood connections, during 60min of fire. The used material properties for gypsum plasterboard have a good performance with the needed designed thickness *hp* of each panel.

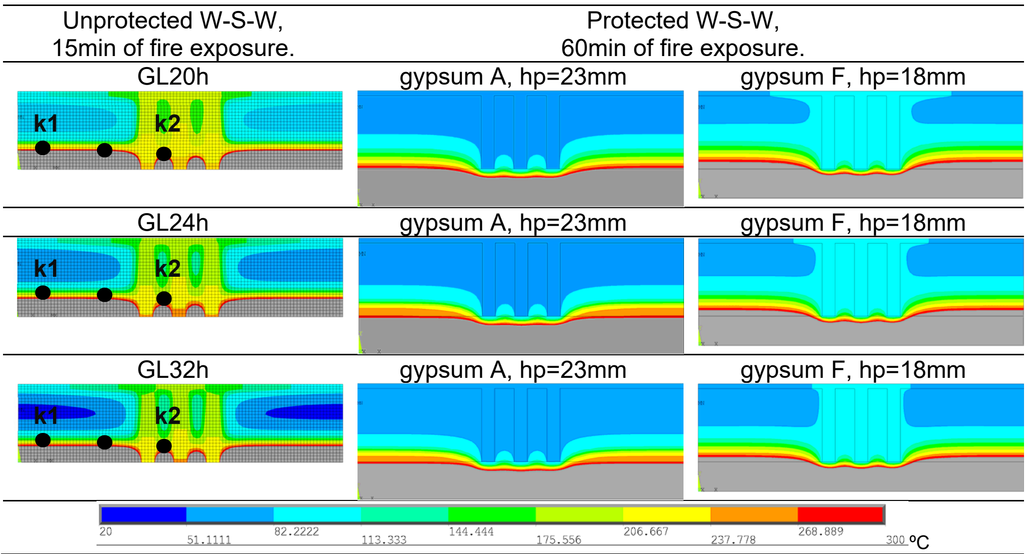

Figure 6. Unprotected and protected connections, cross section in wood-steel.

Table 1 presents the average value of the calculated charring rate in the wood connection at position k1 in different two dimensional cross sections (in wood or in wood-steel), as represented in figures 5 and 6.

Table 1: Numerical calculated charring rate in mm/min for k1.

Cross section in:	**GL20h**	**GL24h**	**GL32h**
wood	0.73	0.72	0.67
wood-steel	0.80	0.77	0.70

The values were obtained for different wood densities. When wood density increases the charring rate decrease. In wood cross section the value of charring rate close to the proposed values in Eurocode, but it is dependent of the wood density. When the cross section in study is wood-steel the charring rate is variable, and dependent of the steel heat spread effect.

Table 2 presents the calculated charring rate in more two different locations in wood-steel cross section, as represented in figure 6.

Point k2, neighbour with steel dowels, and until this time of fire exposure, presents the higher charring rate evolution and also in GL20h. When compared with k3 (position in wood between two dowels), in the begin of fire, the wood elements give some thermal insulation and the charring rate is lesser, but with the increase of fire exposure, the steel fasteners bring heat to inside the connection.

Table 2: Numerical calculated charring rate in mm/min, cross section in wood steel.

Points	**GL20h**	**GL24h**	**GL32h**
k2	0.65	0.63	0.60
k3	0.51	0.47	0.43

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 [5] 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 the wood density. It is important to point out that steel provides a heat flow to the inside of the connection, but the wood elements in the vicinity give some insulation. This way, both materials participate in the evolution of the char layer in the connection.

6. CONCLUSIONS

In this work the results of the charring rate in wood connections were compared, with the effect of additional elements in steel and under the protection of gypsum plasterboards.

The calculated charring rate for cross sections only in wood approximates the values proposed by the Eurocode. However, there is a variation of values for different wood densities. The introduction of steel, as a dowel material or an internal plate, induces internal heating after fire exposure. For this reason, the charring rate of wood increases in the vicinity of the steel. The internal plate produces an increased effect of this heat. To ensure the fire resistance of these components, it is necessary to protect them.

The passive fire protection with gypsum plasterboards is an option that guarantees this effect. The obtained results with the numerical model show the connection ability to the fire resistance with the calculated panel thickness. It is also possible to verify that the properties adopted for the two types of gypsum were thus calibrated, since they guarantee the time of fire resistance of the intended connection.

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