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FIRE BEHAVIOUR OF PROTECTED W-S-W CONNECTIONS WITH A STEEL PLATE AS THE CENTRAL MEMBER AND DIFFERENT DOWELS DIAMETER

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Abstract

The main objective of this work is to present wood-steel-wood (W-S-W) connections in double-shear, joined by steel dowel fasteners and a steel plate as the central member. For each studied connection, different dowel diameters and external applied tensile loads in fire situation shall be taken in account. Considering the rules presented in Eurocode 5, part 1-1 and 1-2, the calculated number of dowels will be arranged in lines and columns and carry out an imposed spacing between the connectors. This work is intended to study the W-S-W connection exposed to fire using the standard curve ISO834. In the wood plates will be used a glue laminated wood, as yellow birch, with characteristics equals to GL28H. For protected connections three types of gypsum will be used in order to obtain a better insulation. Simplified equations from Eurocode 5, part 1-1 and 1-2, will be used to verify the behaviour of the connections at high temperature. A numerical procedure based on finite element method was also implemented to produce *simulations focused on thermal analysis. The comparison of several results between analytical and numerical calculations showed a favourable accordance. The numerical model permits verify the effect of the steel dowels, steel plate and gypsum in the wood charring rate evolution. Even though the connection can resist for thirty minutes, is possible to observe the char layer both on protected and unprotected connection being the last the most affected.*

Keywords

W-S-W Connection, Wood, Steel, Gypsum, Dowel, Char Layer, High Temperature

1. Introduction

Wood connections have been investigated due their significance in construction and industrial engineering in terms of strength, ductility and all capacity to improve the structural performance in service. In heavy timber structures, double-shear connections, including wood-steel-wood (W-S-W) connections with steel fasteners, are widely used to assembly structural members and transfer loads (Peng, Hadjisophocleous, Mehaffey & Mohammad, 2011). Joints with dowels are used in timber construction to transmit high loads. Timber structure architecture consumes less energy during productions and manufacturing, as referred by different authors (Pang Yicunm 2018). This material is sustainable, reproducible, recycle and appears in use of modular productions to assembly different type of constructions.

The motivation of this work is to design a connection with fire resistance to double-shear with safety and appropriate dimensions to transfer the imposed loads in the structural member. Recently many numerical approaches using the finite element method have been carried out to analyse the behaviour of wooden connections, due the possibility to assess different combined parameters (Abderrahim Aissa, Fonseca & Lamri, 2017), (Aissa, Fonseca & Lamri, 2017). Few 3D numerical models have been published the majority publications are based on 2D approach (Resch & Kaliske, 2012).

Empirical methods were used in order to simplify the calculations already existent for W-S-W, W-W-W and S-W-S connections using dowels as fasteners. It was possible to obtain values with relative errors of 15% for W-W-W and W-S-W connections and 10% for S-W-S connections. For unprotected connections adding wood thickness was as much effective as using gypsum insulation material (Peng, Hadjisophocleous, Mehaffey & Mohammad, 2011).

At 100ºC, most of the water inside the wood evaporates, and when the temperature rises beyond that, the wood starts to lose some of their mechanical properties. When it finally reaches the 300ºC, the wood is no long and a char layer is formed. As much as the wood, the char layer acts like a thermal insulating, delaying the heat flux to the connection core. In this way, the wood elements have a heated surface, which mechanical properties are changed, and an unchanged layer beneath (Moraes & Figueroa, 2009). Besides steel, that the collapse, while in fire exposure, results from the decreasing in mechanical properties, the wood elements collapse along with the cross-section char layer.

Due the potential for a multitude of materials and design arrangements such as gypsum board, are requested means of determining fire resistance rating on an engineering basis, using mathematical models, (Sultan, 1996). Other studies were developed using gypsum material as insulation on dry walls achieving satisfactory results (Alves & Batista, 2007), (Piloto, Khetata, & Gavilán, 2017).

In this work, a developed spreadsheet, proved with numerical results, illustrates the design of W-S-W connections according European standards (CEN EN1995-1-1, 2004), (CEN EN1995-1-2, 2004), (DIN 6325 EN ISO 8734, 1997), considering a homogeneous glued laminated in birch timber, and steel dowels as fasteners.

All obtained conclusions in this work are important to increase the knowledge in wood-steel connections, but also as relevant additional numerical application, where the authors of this work have different field investigations, (Abderrahim Aissa, Fonseca & Lamri, 2017), (Aissa, Fonseca & Lamri, 2017), (Fernandes, Fonseca, Teixeira & Jorge, 2017).

2 Methodology

To determine the configuration in study, W-S-W connection submitted to fire, all requirements according standards will be conducted. The final configuration with all dimensions, cross-section size, number of dowels and spacing between dowels, due to an applied tensile load will be characterized.

The analysis of timber connections can be a challenge due their complexity, various connections types, different geometries, fasteners arrangements and also the great variability of the material properties.

A database was elaborated with different variables and parameters, to improve design connection solutions, and to intent a comparison between all chosen variables. In the developed spreadsheet, different applied loads and dowel diameters will be used, which demonstrate the correlated results for design a safety double-shear W-S-W connection at high temperature. In literature, other study demonstrate that the fire resistance of a structure is related with the mechanical load applied to the connection using experimental tests and a numerical model, obtaining an error of ±8,32% between them, when related to the time that a the structure resists (Akotuah, Ali, Erochko, Zhang & Hadjisophocleous, 2015).

The designed connections will be implemented also using a numerical program based on finite element analysis for 3D analysis where the majority publications are based on 2D approaches.

3 Fire behaviour of W-S-W connection in accordance with Eurocode 5

Fig. 1 represents a typical W-S-W connection under double-shear with the main dimensions (width, height and thickness of the wood plates and steel plate, minimum spacing and edge/end distances between the dowels and the wood plate). The calculated number of dowels will be arranged in lines and columns *(LN* and *CN)*. In this work the dowels were disposed in two rows or in only one.

During this study will be analysed tensile loads (E_d) of 25, 50, 75 and 100 kN, dowels diameters (d) of 10, 12, 14 and 16 mm. The wooden board thickness (t_1) was equal to 45, 50, 55 and 60 mm and steel plate thickness (t_s) of 5, 6, 8 and 10 mm.

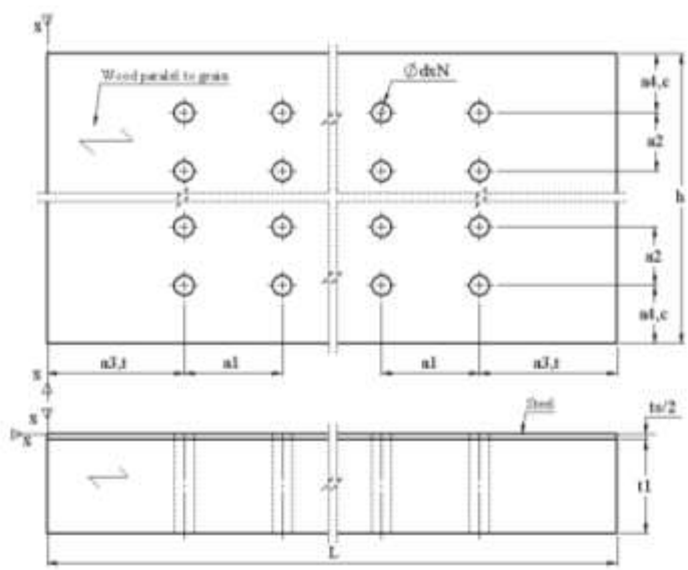

Figure 1: *Typical W-S-W dimensions*

In order to calculate the shape of the connection, the load was considered as parallel to the grain direction, as well as, the rows of fasteners.

According Eurocode 5, part 1-1 (CEN EN1995-1-1, 2004), 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 two safety factors: the modification factor for load duration and moisture content, k_{mod} , and the partial factor for material properties, γ_M , according equation 1.

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

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 calculated using the equation 2, Eurocode 5, part 1-1 (CEN EN1995-1-1, 2004).

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

Also, using all proposed simplified equations from Eurocode 5, part 1-1 (CEN EN1995-1-1, 2004), and being 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 using the equation 3.

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

where:

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.

The value of $M_{y,Rk}$ is calculated according the dowel diameter and the material strength of the bolt.

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

The value of the characteristic embedment strength in timber member, is obtain due to the value of the dowel diameter and the characteristic wood density, ρ_k.

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

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

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

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, varie in order of the dowel diameter.

In this work four variables were considered, the dowel diameter, the steel plate thickness, the thickness of the wood elements and the applied tensile load. The designed connection at ambient temperature guarantees the applied load design (25kN, 50kN, 75kN, 100kN).

The second step is to apply the Eurocode 5, part 1-2 (CEN EN1995-1-2, 2004), according 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 W-S-W connections.

The following calculations are presented for a maximum exposure fire, according a time of thirty minutes, for unprotect connections. The first step shall be verifying if the connection has a fire resistance for the established time, if not, the geometry must be increased in wood cross section, or using in addition an insulating material. The action design effect for un exposure fire $E_{d,fi}$ must be calculated. The conversion factor for slip modulus is nominated as η_f.

$$E_{d,fi} = E_d\, \eta_f \qquad (7)$$

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 twenty per cent of the yield strength at normal temperature, f_{20}.

$$f_{d,fi} = k_{mod,fi} \frac{f_{20}}{\gamma_{M,fi}} \qquad (8)$$

The value of f_{20} corresponds to the wood strength multiplied by the coefficient k_{fi}.

Using the equation 9 it is possible to verify if the connection resists thirty minutes under fire.

$$\frac{E_{d,fi}}{A_s} < f_{d,fi} \quad (9)$$

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, part 1-2 (CEN EN1995-1-2, 2004) ensures a time of the fire resistance, $t_{d,fi}$, according with the connector. For dowels, this time is twenty minutes, however the minimum value for t_1 is 45mm.

The extra thickness of the member for improved a fire resistance in the connections, a_{fi}, is obtained following the equation 10.

$$a_{fi} = \beta_n \, k_{flux} \left(t_{req} - t_{d,fi}\right) \quad (10)$$

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, part 1-2 (CEN EN1995-1-2, 2004) gives two options for the material: gypsum (type A, F or H) or wood-based panels. For each one, it is present different 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 and β_0 represents the design charring rate for one-dimensional charring rate under standard fire exposure.

For gypsum, type A or H:

$$t_{ch} \geq t_{req} - 0{,}5 \, t_{d,fi} \quad (11)$$

$$h_p = \frac{t_{ch} + 14}{2{,}8} \quad (12)$$

For gypsum, type F:

$$t_{ch} \geq t_{req} - 1{,}2 \, t_{d,fi} \quad (13)$$

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

3.1 Gypsum thermal properties

Using the literature, it is possible to find the gypsum thermal properties, but with different designations from the Eurocode 5. In this work different types of gypsum material were used from the references, (Aissa, Fonseca & Lamri, 2017), (Alves & Batista, 2007), (Sultan, 1996) or (Piloto, Khetata, & Gavilán, 2017).

Figures 2, 3 and 4 present the thermal conductivity, specific heat and density of each gypsum type, respectively. The emissivity of the material was considered equal to 0,8.

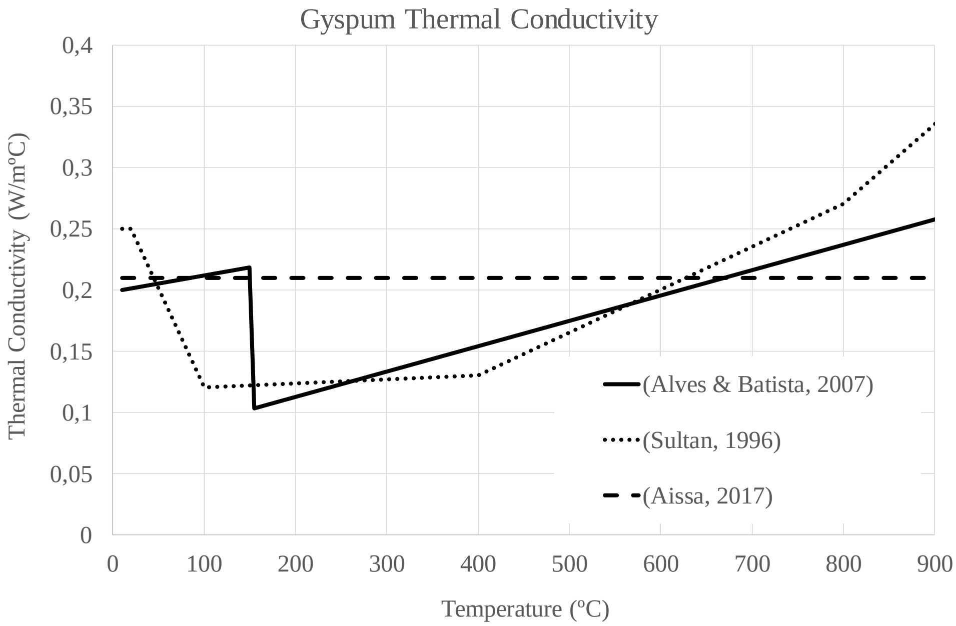

Figure 2: *Thermal conductivity determined according several documents*

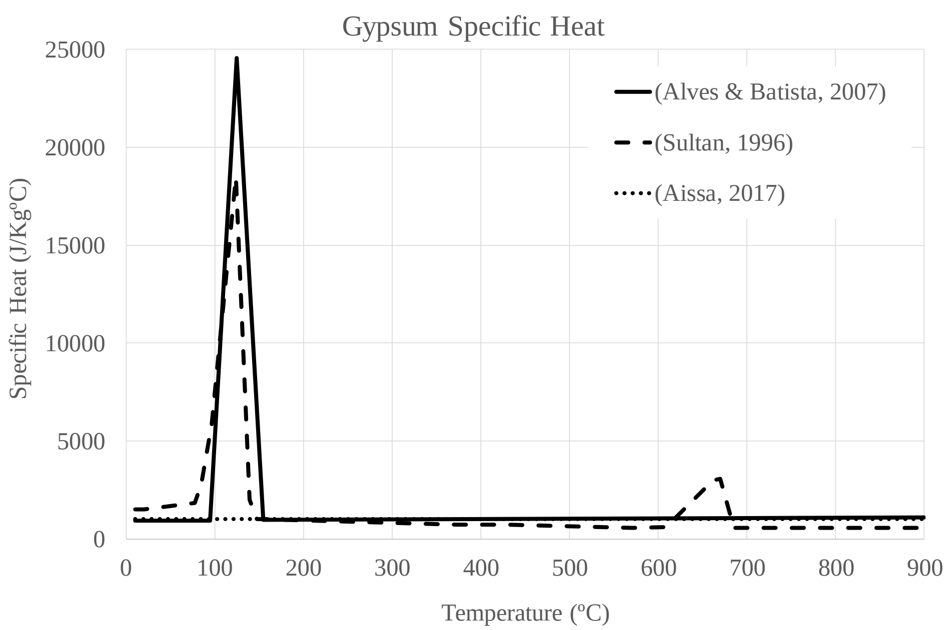

Figure 3: *Specific heat determined according several documents*

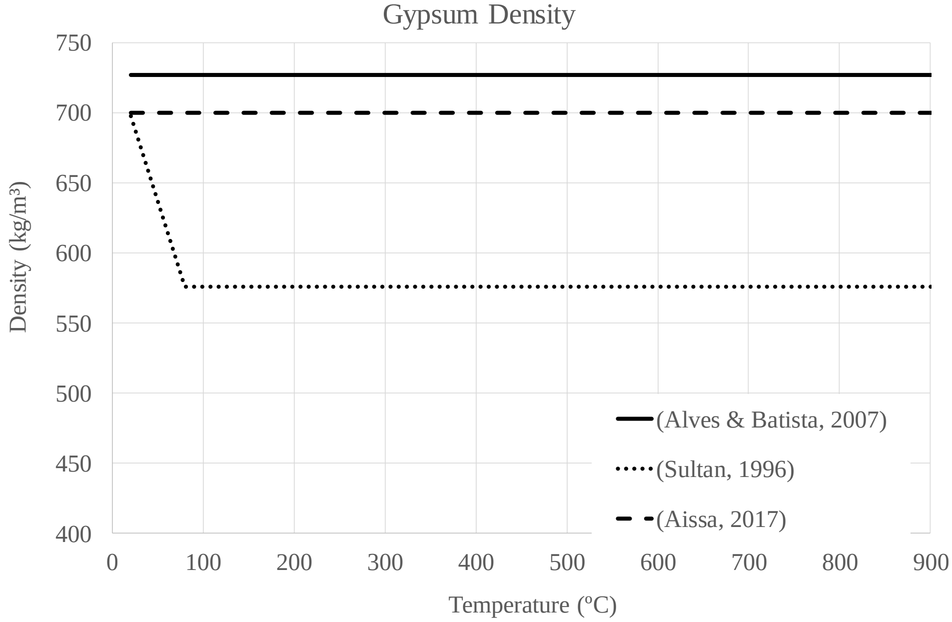

Figure 4: *Density determined according several documents*

4. W-S-W Thermal and Transient Numerical Model

To simulate the fire resistance of the W-S-W connection, a numerical thermal and transient model based on the finite element method was used. Due the geometry symmetry, the numerical calculation was performed for a quarter of the W-S-W connection.

The finite element chosen has eight nodes and one degree of freedom per node, correspondent to the temperature. The non-linearity due to the thermal material properties dependence will be taken into account in the numerical simulation.

Eight different numerical models were performed (four unprotected and four protected) due different designed W-S-W connections, obtained from the previous calculation. Table 1 presents the four unprotected connections in study with all dimensions. The four protected connections were added a 12,1 mm gypsum layer on affected surface, correspondent to the minimum value for h_p to delay the charring rate for a 30 minutes fire exposure according to the Eurocode 5, part 1-2 (CEN EN1995-1-2, 2004), according equation 12. Even though the type of gypsum does not correspond to type A, the same thickness will be used in order to compare results.

Table 1: *Specifications of the W-S-W connections*

W-S-W connection	*d*, mm	t_1, mm	*CN*	*LN*	*h*, mm	*L*, mm	t_s, mm
A	10	45	6	1	60	390	5
B	10	45	12	1	60	690	5
C	10	45	9	2	90	540	5
D	10	45	12	2	90	690	5

Figure 5 represents eight connections in study (a quarter of W-S-W), where the left column represents unprotected connections and right side the protected models, with the applied mesh. The material properties for wood and steel are represented in two different colours, blue and purple respectively. The insulation material is represented in red colour.

In the numerical analysis, the boundary conditions used are related to the convection and radiation due to the exposed fire in front of the external surface of the protected or unprotected connection. The initial temperature in the numerical model was considered equal to 20 ºC. The environment surface emissivity in the connection will be taken as a constant value and equal to one, Eurocode 1 part 1-2 (CEN EN1991-1-2, 2002). The external surface of the connection is exposed to the standard fire curve ISO834 during 1800 seconds and the convection used is equal to 25 W/m^2K, Eurocode 1 part 1-2 (CEN EN1991-1-2, 2002).

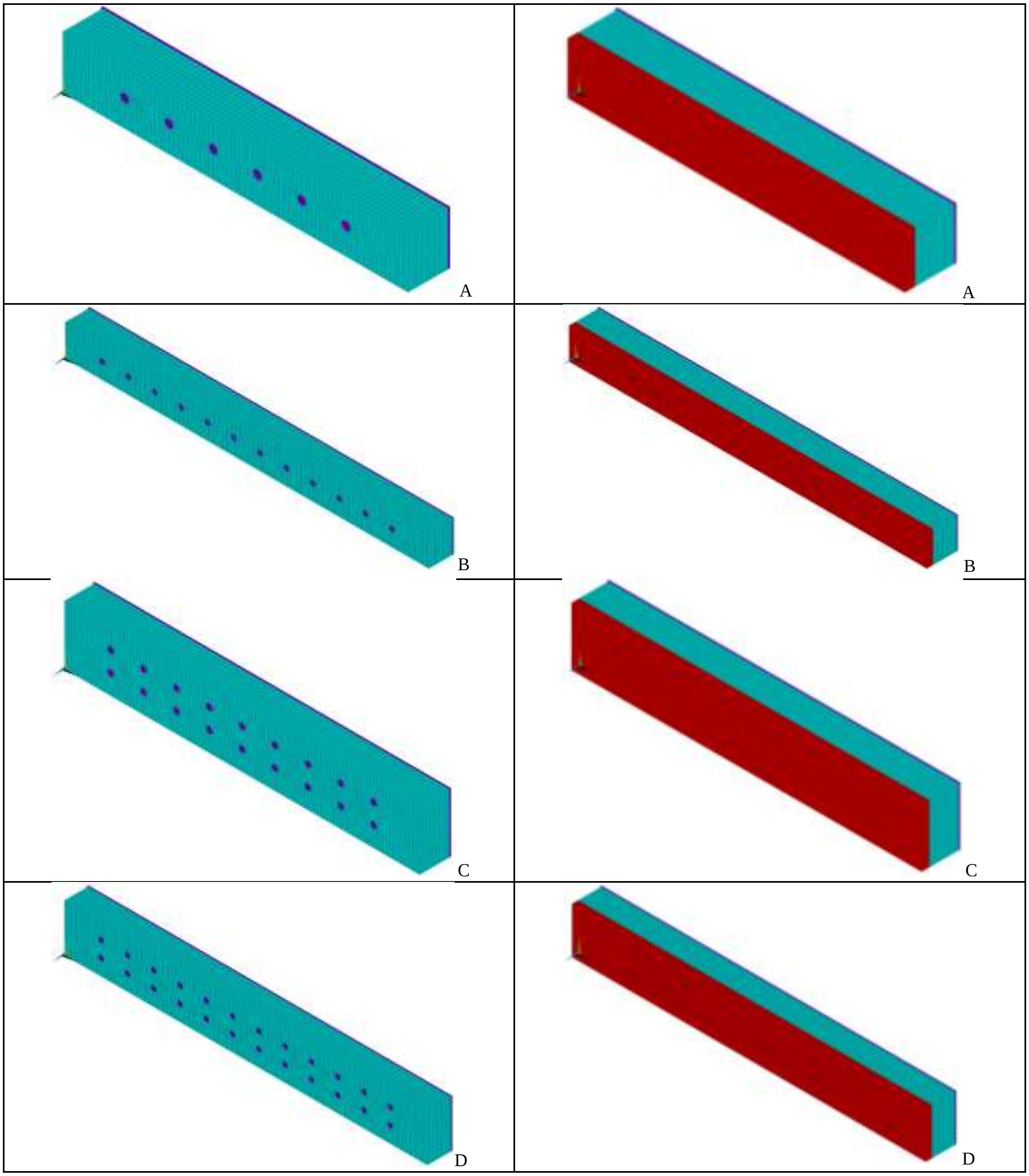

Figure 5: *Eight unprotected and protected W-S-W connections with the applied mesh*

5. Results and Discussion

The results presented were conducted according the Eurocode 5 part 1-2 (CEN EN1995-1-2, 2004), (CEN EN1995-1-2, 2004). A worksheet considering all parameters was developed, which permits verify the load-carrying capacity of the connection, the cross-section, the number of fasteners, the minimum spacing in edges and the resistance to the fire, per each situation in study.

The results are presented in different tables, according to the parameters combination. Table 2 represents a part of the study. The results show that every connection calculated using the Eurocode 5 part 1-1 (CEN EN1995-1-1, 2004), resists after thirty minutes of fire exposure.

Using only the Eurocode 5 part 1-2 (CEN EN1995-1-2, 2004), it is impossible to understand the fire evolution through and inside the connection. The charring rate is considered as a standard and constant value in all the connection, however in the numerical results is proven that the charring rate value vary in the connection to the effect of the steel heat conduction.

Figure 6 presents the numerical results of the wood char layer and the temperature inside the dowel holes. Is possible to notice that even though steel provides a higher heat flux on the inside of the connection, the wood elements give some insulation. This way, both material participate in the evolution of the char layer in the connection. For thirty minutes of fire exposure, the steel plate as central member remains at lower temperature.

In the dowels on the near of the centre connection the temperature is higher in comparison to the dowels neighbouring to the edges. However, the difference does not exceed twenty degrees Celsius. This difference can be explained due the higher dimension wood on the edges that in the middle, where the amount dowels is higher.

Figure 7 presents the wood elements temperature of each type of gypsum on each connection. Using the thickness of 12,1 mm, equation 12, a part of the wood elements reaches and exceed the limit of 300ºC, criterion of char layer formation applied by this isothermal, Eurocode 5 part 1-2, (CEN EN1995-1-2, 2004).

In Figure 7 is shown the temperature field that the wood element reaches. The charred area is smaller than compared to the non-protected connection.

In figure 8 is presented the charred layer of the wood elements in protected connections.

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Table 2: *W-S-W design connections at ambient temperature*

Applied load, E_d kN	t_1 mm	Dowel diameter, d mm	Fv,Rk kN	N, Dowels number (symmetry, S)	Spacing in edges mm				Height, h mm	Width, L mm	$E_{d,fi}$ kN	$f_{d,fi}$, kN
					a_1	a_2	$a_{3,t}$	$a_{4,c}$				
25	45	10	7,1	1x6	50	30	70	30	60	390	15	17,94
25	50	10	4,8	1x6	50	30	70	30	60	390	15	17,94
25	55	10	5,2	1x5	50	30	70	30	60	340	15	17,94
25	60	10	5,5	1x5	50	30	70	30	60	340	15	17,94
(…)												
100	45	16	13,1	3x4	80	48	112	48	96	1104	60	17,94
100	50	16	13,7	3x4	80	48	112	48	96	1104	60	17,94
100	55	16	14,2	3x4	80	48	112	48	96	1024	60	17,94
100	60	16	14,9	2x6	80	48	112	48	96	1024	60	17,94

Fv,Rk=characteristic load-carrying capacity per shear plane per fastener; Ed,fi=design effect of actions for the fire situation; fd,fi=Design strength in fire.

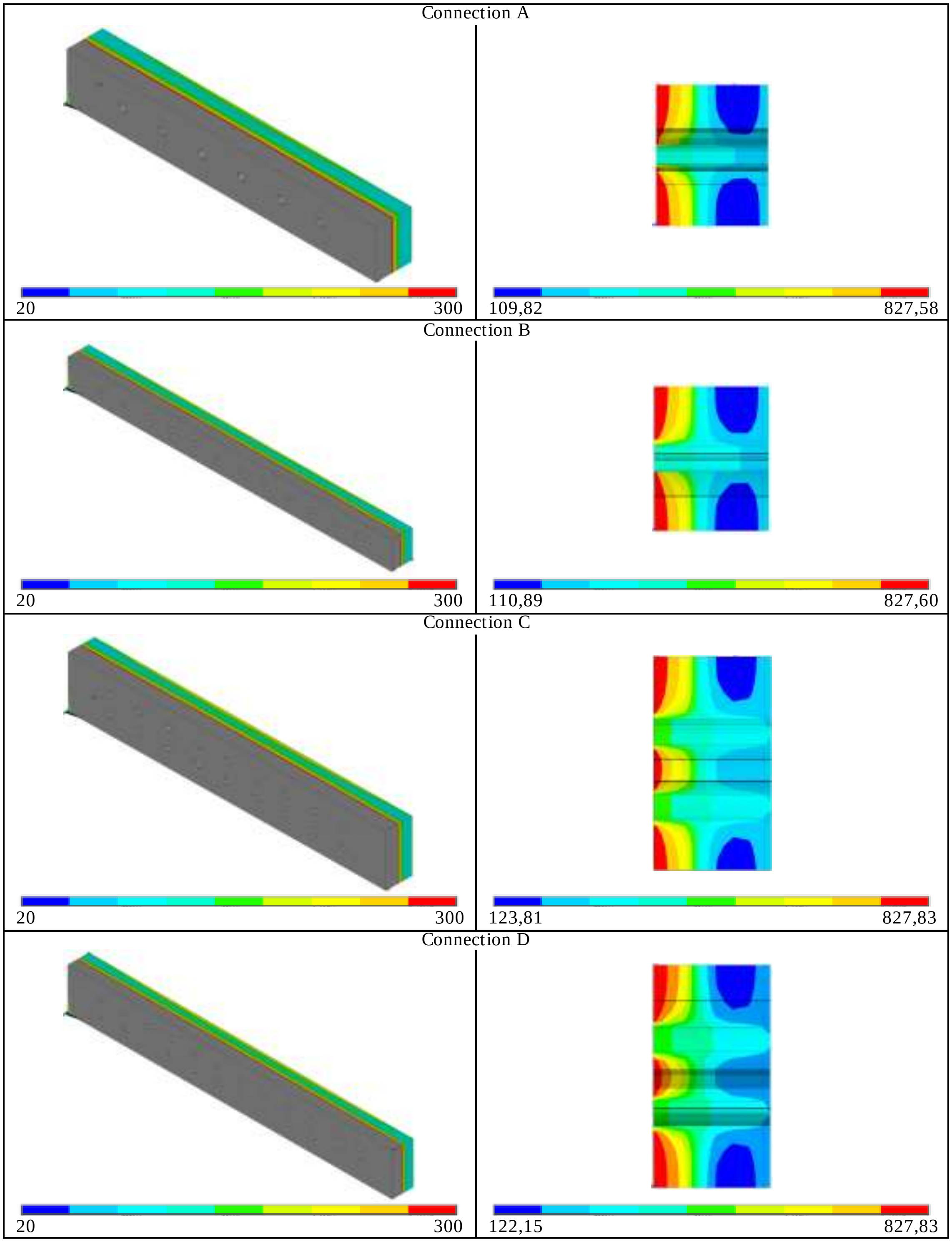

Figure 6: *Unprotected W-S-W connections. On the left, the wood char layer, in ºC. On the right, the temperature inside the dowel hole, in ºC*

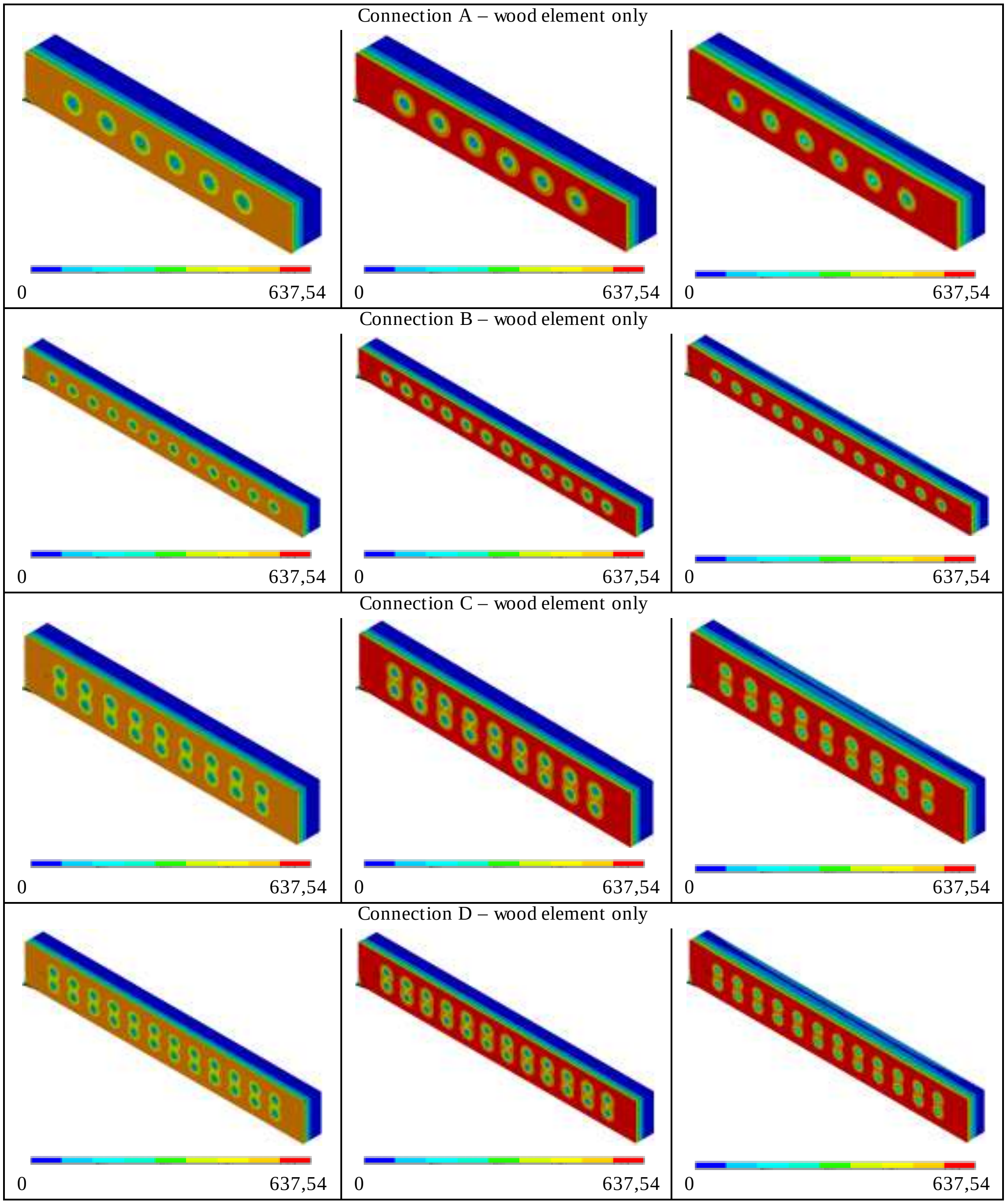

Figure 7: *Temperature (ºC) in protected W-S-W connections with different type of gypsum, from the left to the right (Alves & Batista, 2007), (Sultan, 1996), (Aissa, 2017).*

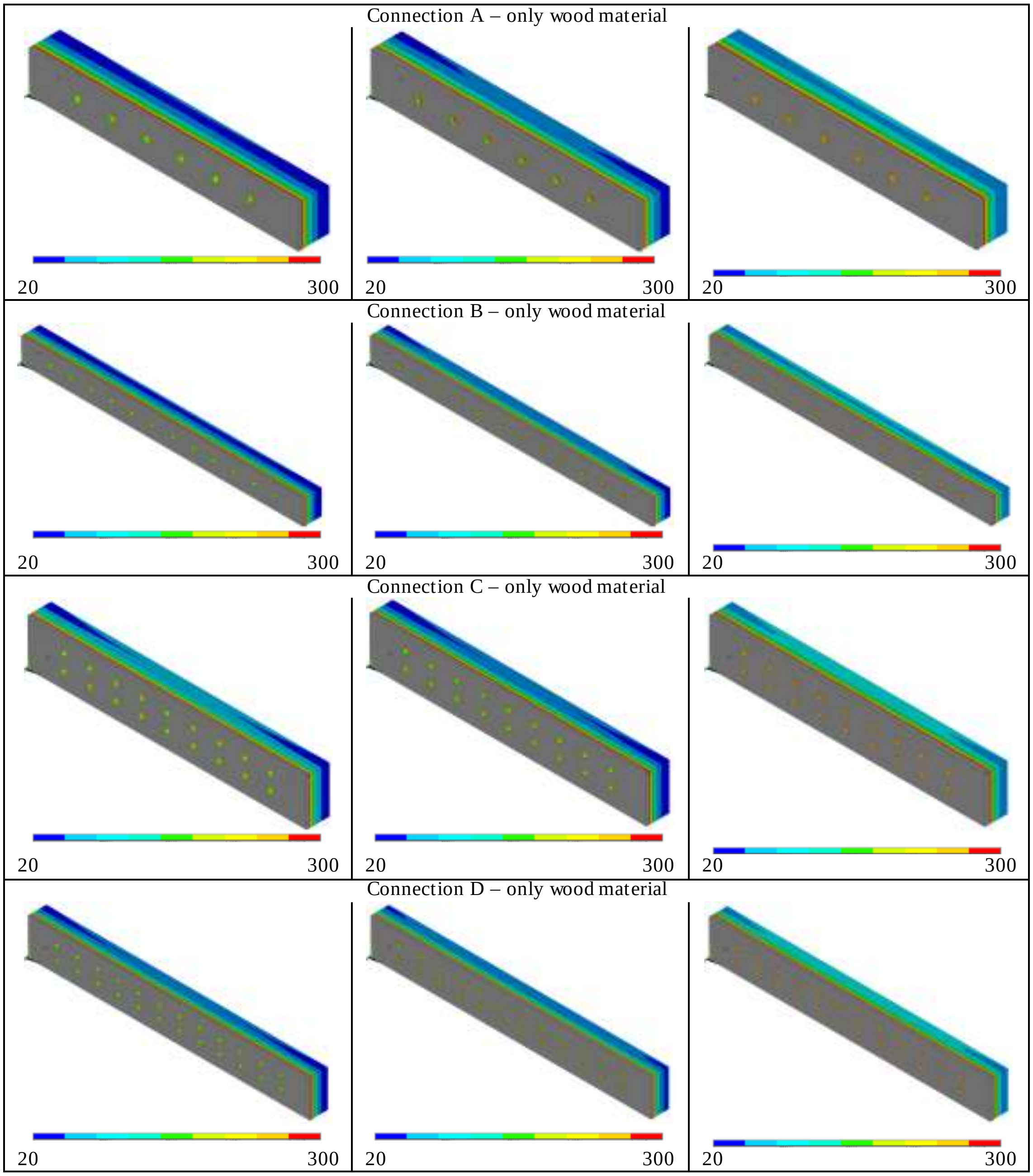

Figure 8: *Char layer in protected W-S-W connections with different type of gypsum, from the left to the right (Alves & Batista, 2007), (Sultan, 1996), (Aissa, 2017). Temperature in ºC.*

6. Conclusions

This work, present different methodologies applied to the design of a typical W-S-W connections, with a steel plate as the central member, used in building construction in order to determine the fire resistance. A procedure with all analytical and simplified equations were presented to assess the cross-section, all dimensions for an applied tensile load, and the fire safety verification. A spreadsheet was developed for calculating different W-S-W configurations, dimensions and its load-carrying capacity. In addition, a numerical program using the finite element method was used to produce different 3D simulations focused on thermal and transient analysis. 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. Even though the three types of gypsum material were different from the Eurocode, it is possible to observe that this material is a good thermal insulant reducing the char layer compared to the unprotected connections.

The numerical simulations were very relevant and to facilitate the fire behaviour in W-S-W connections. The proposed numerical model could be used for temperature calculation and verification of the char layer in timber materials, as an alternative methodology, to prevent any accidental action before the construction. This study carries out the results according others previous investigations developed by the authors of this work. For this reason, future work using numerical models can be used for verification other type of connections exposed to fire, and determine how quickly the cross-section size decreases to a critical level at high temperatures and how other tested insulation materials can retard this effect. The numerical model can easily be adjusted for other constructive timber solutions, to facilitate the fire safety validation, in several timber assemblies used in construction. Other future developments in this area should consider the experimental validation in typical timber connections using a fire resistance furnace with imposed standard and natural fire conditions.

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