Journal of Computational Applied Mechanics 2021, 52(1)
DOI: 10.22059/jcamech.2021.315728.579

RESEARCH PAPER

Design of steel-wood-steel connections at the ambient and elevated temperature

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Abstract

The goal of this work is to study steel-wood-steel (S-W-S) connections in double shear with steel dowels submitted to fire. The design at the ambient temperature was based in Eurocode 5 part 1-1 to determine the number of dowels required based on the connection characteristics. To analyze the influence of these characteristics, connections with dowels diameters with 6, 8, 10 and 12 mm, wood type GL20h, GL24h, GL28h and GL32h and the applied load of 10, 15 and 20 kN were studied. The design at the elevated temperatures was based on the Eurocode 5 part 1-2 and Eurocode 3 part 1-2, to obtain the protection thickness required for fire safety. The protection materials used were the glued laminated timber (Glulam) and type F gypsum plasterboard. The analysis of different parameters and how they influence the connection, was studied clearly using the finite element method. The temperature field allows to determine the char layer in the connections with different wood densities, when unprotected, and compare the protection efficiency with two different types of materials. As conclusion, decreasing the dowels diameter and increasing the applied load, the number of the dowels will increase. With the increasing of the dowel diameters and the wood density, it is possible to observe that the fire capability in the S-W-S connections increases.

Keywords: S-W-S connection, Dowel, Fire, Protection, Wood density

1. Introduction

Wood is an easily available material, thus providing its use for the construction. The wood has properties that vary according to the species and fibers orientation, which can be considered as unfavorable factor for the design process. However, it has a good relationship between the mechanical strength and the density, abundance in nature, versatility of shapes and dimensions. The wood connections are fundamental part of the structure because they are responsible for its support and stability. In the case of wood, there are several connections solutions, and this paper will cover the S-W-S connections with steel dowels. On the other hand, the wood connections between different structural elements start to have a relevant and important role [1]. Several published studies using different numerical and experimental methodologies allowed to analyze the behavior of wood elements.

In 1997, Tavakkol-khah and Klingsch proposed a study of wooden structures in case of fire, using the finite difference method. Comparing the results with those obtained

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experimentally, they concluded that the developed program accurately predicts the behavior of structures exposed to fire [2].

In 2006, Laplanche et al. focused on the thermo-mechanical analysis of connections under fire using a 3D finite element model. The results showed the influence of the wood thickness and the connectors diameters on the fire resistance of the connections [3].

In 2010, Andrea Frangi et al. carried out an experimental and numerical study of protective cladding made of gypsum plasterboards and wood-based panels behavior under fire action. The results allowed to verify the insulation and integrity criteria of light wood structures [4].

In 2010, Cachim and Franssen proposed an improvement of the equations already presented in Eurocode 5 part 1-2 [5], which consisted of using a new expression of the charring rate, as a function of wood density and moisture content [6].

In 2010, Frangi et al. carried out an experimental study of timber connections with nails and dowels under the fire and at normal temperature [7]. The work shows different approaches in order to increase the fire resistance of the timber connections [7].

In 2011, Fonseca and Barreira proposed an experimental and numerical study to determine the char layer of the pine wood subjected at elevated temperatures. For the experimental analysis, a thermal unit with electro-ceramic resistance was used to apply elevated temperatures. The numerical method aimed to compare the obtained results experimentally which had a good agreement [8].

In 2011, Lei Peng et al. used a finite element method to perform a thermal analysis to determine the temperature within wood-steel-wood timber connections with bolts and dowels under fire condition [9]. They concluded that the wood-steel-wood timber connections have a similar behavior with the wood-wood-wood connections, because the major failure occurs in the external wood face which is exposed to fire [9]. The thickness of the wood side member has a greater influence on the load-carrying capacity of the connection under fire than the diameter of the connectors [9]. The authors proposed a formula that provide an alternative for the calculation of the fire resistance rating in these connections.

In 2011, Lei Peng et al. made an analysis of some existing models based on data related with the fire resistance of double shear connections. The correlations allowed to check the fire resistance of unprotected W-W-W, W-S-W and S-W-S connections using dowels or bolts as fasteners, only considering the applied load, the wood thickness and the connection diameter. Comparing with the experimental results, they found that the method used has an accuracy of 15% in W-W-W and W-S-W connections and 10% in S-W-S connection. They concluded that, increasing the diameter or number of fasteners, the ambient load capacity of timber connections increased [10]. To achieve a better fire resistance, for the same connection type, the choice of dowels over the use of bolts allows for higher fire resistance [10].

In 2012, Fonseca et al. identified analytical equations capable to determine the stress level in simply supported wooden beams under mechanical and thermal loads. These equations can be used to check the cross-section dimension that guarantees a fire resistance [11].

In 2013, Norgaard and Mydin studied the thermal properties of drywall boards when exposed to high temperatures and when exposed to fire condition. The study was focused on analyzing the results obtained by different researchers over the years, with different thermal properties (specific heat, thermal conductivity, density, among others) as a function of temperature. They concluded that, despite extensive research on the topic, the results were still different [12].

In 2013, E. Fonseca et al. performed a thermal numerical analysis of hybrid wood-steel profiles when subjected to fire considering the nonlinear properties of the materials, using ANSYS. They used two models to compare the obtained results. They concluded that hybrid wood-steel profiles showed a better performance when compared with unprotected steel elements under fire [13].

In 2016, Loss et al. presented an investigation whose main objective was the development of multi-story prefabricated modular buildings with a new hybrid steel–timber construction. One part of the research that focuses on the numerical analyses helps to understand the role of each connection in the building construction. They found that connections are more sustainable and a light solution for anti-seismic construction. Experimental tests were carried out on different types of connections, as well as an analysis by finite element method. A prototype was also developed with industrialized connections for wall and floor components [14].

In 2020, Fonseca et al. conducted a study to verify the fire resistance of W-W-W connections protected by different types of gypsum plasterboard. In order to observe the effect of gypsum plasterboard (type A, H or F) on wood connections with different densities, they used numerical models in order to predict the fire resistance time. Both plasterboards had a fire resistance of 60 min, however, type A gypsum was 23 mm thickness while type F gypsum plasterboard had a thickness of 18 mm. They therefore concluded that gypsum plasterboard is a good insulation material and is capable to reduce the char layer when compared to unprotected connections [15].

In 2020, Fonseca et al. studied the effect of wood density on W-S-W connections with internal steel plate and passive fire protection. The main objective of this investigation was to verify the behavior of the connection without any type of protection. In conclusion, they found that the heat propagation and the charring rate evolution is greater in connections with lower wood density [16].

Recently, analytical, numerical and experimental methodologies have been introduced by the authors of this work to analyze the fire behavior of different unprotected and protected (W-S-W and W-W-W) connections and other elements used in building construction [15-21].

The goal of this manuscript is to enlarge this knowledge, using the same methodologies, in other type of (S-W-S) connections. Different parameters as, wood densities, dowel diameters and different applied loads, will considered to increase the results for construction engineering application. According this purpose, the main objectives of the study were as follow:

- To design S-W-S connections at the ambient temperature.
- To obtain results due to different load level versus the number of dowels, depending on wood density and the dowel diameter.
- To design unprotected and protected S-W-S connections under fire exposure. The protection materials used were the glued laminated timber GL20h and type F gypsum plasterboard.
- To obtain results applying a specific methodology to calculate the charring rate in wood elements and the thickness of the fire protection material capable to guarantee the protection S-W-S connection.

2. Material Properties

The materials properties were considered isotropic and they are presented to use in analytical equations and thermal model. The mechanical properties of wood and steel are referred in Tables 1 and 2. Glued laminated members may be assumed to comply with the requirements for a strength class provided they meet the requirements to the strength classes given in Table 1, derived from tests in accordance with standards [22].

Figure 1 presents the thermal properties for steel and wood material used in the numerical model, based on standard codes and in the literature.

Steel is in accordance with the Eurocode 3 part 1-2 [24] and Eurocode 5 part 1-2 [5] is used for the wood assuming initial moisture of 12%. This value is used to determine the wood density at elevated temperature considering the characteristic density at ambient temperature

$\rho_{g,k}$. The steel emissivity is equal to 0.7 [24]. The densities (GL20h, GL24h, GL28h and GL32h) for wood are from the literature [15-16], [22]. The emissivity of wood was taken equal to 0.8 [5].

Table 1 Characteristic strength and stiffness properties for homogeneous glulam [22].

Designation		GL20h	GL24h	GL28h	GL32h
Characteristic tensile strength along the grain, MPa	$f_{t,0,g,k}$	16	19,2	22,3	25,6
Characteristic density, kg.m^{-3}	$\rho_{g,k}$ (to ambient temperature)	340	385	425	440
	ρ_p (to elevated temperature)	370	420	460	480

Table 2 Characteristic strength and stiffness properties for steel at ambient temperature [23].

Designation		S275
Yield strength, MPa	f_y	275
Ultimate strength. MPa	f_u	430
Modulus of elasticity, MPa	E	210 000
Poisson's ratio	ν	0,3
Density, kg.m^{-3}	ρ_a	7850

Gypsum material was used in the thermal analysis and the material properties considered constants [25]. The gypsum emissivity is equal to 0.8 [25]. The base value of the specific heat is c_p = 950 J/kg°C, as reported by Mehaffey et al [25] The thermal conductivity of solid dried gypsum is λ_p = 0.19 W/m°C and the density equal to ρ_p = 889 kgm^{-3}.

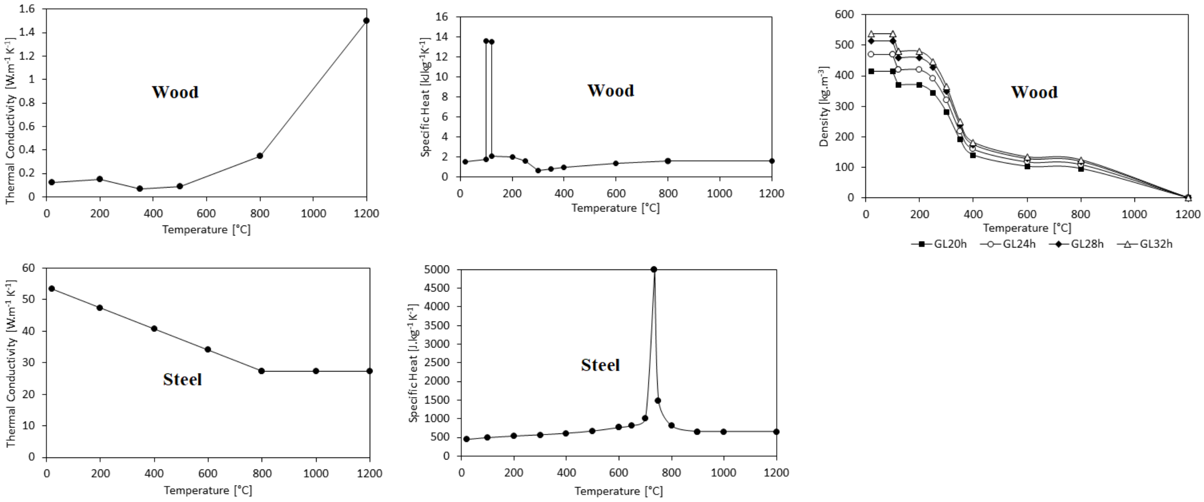

Fig. 1 Specific heat, thermal conductivity and density.

3. S-W-S connections at ambient temperature

The S-W-S connections were designed with simplified equations from Eurocode 5 part 1-1 [26] at the ambient temperature. Four types of wood material with different densities (GL20h, GL24h, GL28h and GL32h), between 370 e 480 kg.m^{-3}, were used to model the S-W-S connections. Also, different steel dowels (diameters equal to 6, 8, 10 and 12mm) and an external steel plate t_c with a constant thickness equal 3 mm were used. To protect the connections, two types of material were assumed (Glulam and type F gypsum plasterboard) [15-16, 19]. Figure 2 represents the connections in study and all dimensions that will be used in the following equations.

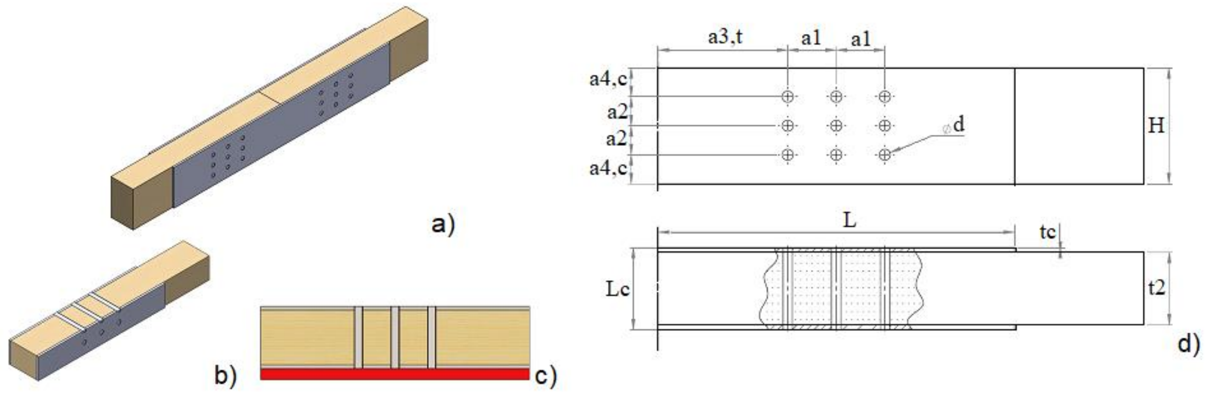

Fig. 2 S-W-S connections: a) 3D view, b) unprotected plane, c) protected plane, d) dimensions.

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 $\sigma_{t,0,d}$, according the Eq. (1) [5], [15-16], [26]:

$$\sigma_{t,0,d} \leq f_{t,0,d} = f_{d,fi} \tag{1}$$

The design value of strength in fire $f_{d,fi}$ represents a reduced value of the characteristic tensile strength along the wood grain, due to the application of safety factors (the modification factor for fire $k_{mod,fi}$ and the partial safety factor for wood in fire $\gamma_{M,fi}$ and the 20% fractile of a strength property at normal temperature f_{20}, as the following expression [5], [15-16]:

$$f_{d,fi} = k_{mod,fi} \frac{f_{20}}{\gamma_{M,fi}} \tag{2}$$

The design tensile stress along the grain $\sigma_{t,0,d}$, is defined according Eq. (3):

$$\sigma_{t,0,d} = \frac{F_d}{A_s} \tag{3}$$

where F_d is the applied load and A_s the cross-section of the member.

According the simplified equations from Eurocode 5 part 1-1 [26], the characteristic load-carrying capacity, per shear plane and fastener, for a S-W-S connection with dowel fasteners and for thin plate as the outer member of a double shear connection, is determined according to Eq. (4).

$$F_{v,Rk} = min \begin{cases} 0{,}5\, f_{h,2,k}\, t_2\, d \\ 1{,}15 \sqrt{2\, M_{y,Rk}\, f_{h,2,k}\, d} + \frac{F_{ax,Rk}}{4} \end{cases} \tag{4}$$

t_2 represents the thickness of the middle wood member considered equal to 45 mm; $f_{h,2,k}$ is the characteristic embedment strength in timber member; *d* is the dowel diameter; $M_{y,Rk}$ is the characteristic fastener yield moment; $F_{ax,Rk}$ represents the characteristic withdrawal capacity of the fastener.

The value of $M_{y,Rk}$ is determined according the dowel diameter d and the material strength f_u of the steel dowel [26].

$$M_{y,Rk} = 0{,}3\, f_u\, d^{2{,}6} \tag{5}$$

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 $\rho_{g,k}$, Eq. (6) [26].

$$f_{h,2,k} = 0{,}082(1 - 0{,}01d)\rho_{g,k} \tag{6}$$

With the calculation from $F_{v,Rk}$, it is possible to obtain the number of the dowels N with the Eq. (7).

$$N = \frac{F_d}{F_{v,Rd}} \tag{7}$$

The number of dowels is assumed in excess by an integer number. The calculated number of dowels are rearranged in lines and columns. The number of columns n_c is fixed equal to 3, varying only the number of rows n_r, depending on the total number of dowels. It becomes easier to standardize the connection and to make the thermal analysis in two-dimensional plane always affected by three dowels.

To reduce the risk of failures modes and guarantees the applied load design, the minimum edge, and end spacing criteria for connections with dowel type fasteners are applied, as depicted in Figure 1 according dimensions a_1, a_2, $a_{3,t}$ and $a_{4,c}$. All procedure has been developed according to Eurocode 5 part 1-1 [15-16], [26].

4. Applied load versus number of dowels, depending on the wood density and dowel diameter

Applying all requirements at the ambient temperature and for all designed connections it is possible to conclude about the number of fasteners. This number increases with the applied load.

A worksheet is presented in Table 3. It was developed with all design variables (dowel diameters, applied tensile load, dimensions, material properties) to allow the safe design of different S-W-S connections.

Observing Figure 3 it is noticeable that with smaller dowel diameter and for higher load, the number of dowels increase in the connection. In general, the wood density is not considerably affecting the number of dowels needed when analysing the connections with the same dowel diameter. Nevertheless, the results show that smaller wood densities require higher number of dowels. Recent publications [15-16] of wooden connections, namely type W-W-W and W-S-W have obtained similar results. The main results obtained with the worksheet (Table 1) are shown in Figure 3.

5. S-W-S connections under fire exposure

Mathematical models of heat conduction can be solved numerically [15-16]. Using the finite elements, the main objective is discretizing the heat transfer equation and then solve an algebraic system. According to this procedure, a numerical program based on finite element method (Ansys), is used to produce simulations focused on thermal and transient analysis to study S-W-S connections, designed according to the previous equations and using steel dowels [15-16]. The non-linearity due to the thermal properties dependence of steel and wood were introduced in the numerical simulation [15-16]. Also, constant properties of type F gypsum plasterboard were considered.

Table 3 Designed S-W-S connections.

Glulam	Load, kN	Dowel, mm		Arrangement			Edge distances, mm				Wood dimensions, mm			Steel plate, mm	Design tensile strength, MPa	Characteristic load-carrying, N
	F_d	d	L_c	N	n_c	n_r	a_1	a_2	$a_{3,t}$	$a_{4,c}$	t_2	L	H	t_c	$f_{t,0,d}$	$F_{v,Rd}$
GL20h	10	6	51	9	3	3	30	18	80	18	45	440	72	3	10,24	1393,12
		8	51	6	3	2	40	24	80	24	45	480	72	3	10,24	2313,17
		10	51	3	3	1	50	30	80	30	45	520	60	3	10,24	3418,79
		12	51	3	3	1	60	36	84	36	45	576	72	3	10,24	4239,54
	15	6	51	12	3	4	30	18	80	18	45	440	90	3	10,24	1393,12
		8	51	9	3	3	40	24	80	24	45	480	96	3	10,24	2313,17
		10	51	6	3	2	50	30	80	30	45	520	90	3	10,24	3418,79
		12	51	6	3	2	60	36	84	36	45	576	108	3	10,24	4239,54
	20	6	51	15	3	5	30	18	80	18	45	440	108	3	10,24	1393,12
		8	51	9	3	3	40	24	80	24	45	480	96	3	10,24	2313,17
		10	51	6	3	2	50	30	80	30	45	520	90	3	10,24	3418,79
		12	51	6	3	2	60	36	84	36	45	576	108	3	10,24	4239,54
GL24h	10	6	51	9	3	3	30	18	80	18	45	440	72	3	12,29	1482,44
		8	51	6	3	2	40	24	80	24	45	480	72	3	12,29	2461,49
		10	51	3	3	1	50	30	80	30	45	520	60	3	12,29	3638,00
		12	51	3	3	1	60	36	84	36	45	576	72	3	12,29	4800,66
	15	6	51	12	3	4	30	18	80	18	45	440	90	3	12,29	1482,44
		8	51	9	3	3	40	24	80	24	45	480	96	3	12,29	2461,49
		10	51	6	3	2	50	30	80	30	45	520	90	3	12,29	3638,00
		12	51	6	3	2	60	36	84	36	45	576	108	3	12,29	4800,66
	20	6	51	15	3	5	30	18	80	18	45	440	108	3	12,29	1482,44
		8	51	9	3	3	40	24	80	24	45	480	96	3	12,29	2461,49
		10	51	6	3	2	50	30	80	30	45	520	90	3	12,29	3638,00
		12	51	6	3	2	60	36	84	36	45	576	108	3	12,29	4800,66
GL28h	10	6	51	9	3	3	30	18	80	18	45	440	72	3	14,27	1557,55
		8	51	6	3	2	40	24	80	24	45	480	72	3	14,27	2586,20
		10	51	3	3	1	50	30	80	30	45	520	60	3	14,27	3822,32
		12	51	3	3	1	60	36	84	36	45	576	72	3	14,27	5247,76
	15	6	51	12	3	4	30	18	80	18	45	440	90	3	14,27	1557,55
		8	51	6	3	2	40	24	80	24	45	480	72	3	14,27	2586,20
		10	51	6	3	2	50	30	80	30	45	520	90	3	14,27	3822,32
		12	51	3	3	1	60	36	84	36	45	576	72	3	14,27	5247,76
	20	6	51	15	3	5	30	18	80	18	45	440	108	3	14,27	1557,55
		8	51	9	3	3	40	24	80	24	45	480	96	3	14,27	2586,20
		10	51	6	3	2	50	30	80	30	45	520	90	3	14,27	3822,32
		12	51	6	3	2	60	36	84	36	45	576	108	3	14,27	5247,76
GL32h	10	6	51	9	3	3	30	18	80	18	45	440	72	3	16,38	1584,80
		8	51	6	3	2	40	24	80	24	45	480	72	3	16,38	2631,44
		10	51	3	3	1	50	30	80	30	45	520	60	3	16,38	3889,19
		12	51	3	3	1	60	36	84	36	45	576	72	3	16,38	5339,56
	15	6	51	12	3	4	30	18	80	18	45	440	90	3	16,38	1584,80
		8	51	6	3	2	40	24	80	24	45	480	72	3	16,38	2631,44
		10	51	6	3	2	50	30	80	30	45	520	90	3	16,38	3889,19
		12	51	3	3	1	60	36	84	36	45	576	72	3	16,38	5339,56
	20	6	51	15	3	5	30	18	80	18	45	440	108	3	16,38	1584,80
		8	51	9	3	3	40	24	80	24	45	480	96	3	16,38	2631,44
		10	51	6	3	2	50	30	80	30	45	520	90	3	16,38	3889,19
		12	51	6	3	2	60	36	84	36	45	576	108	3	16,38	5339,56

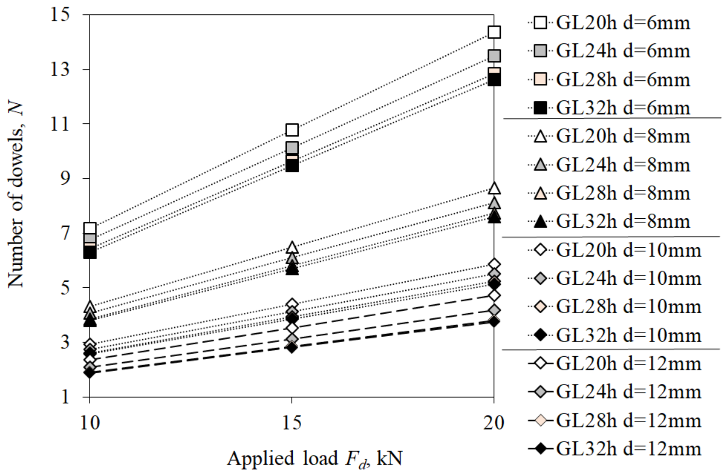

Fig. 3 Applied load F_d, versus number of dowels N, function of wood density (GL20h, GL24h, GL28h and GL32h) and dowel diameter d (6, 8, 10 and 12 mm).

In order to satisfy the thermal conditions of the problem it is required to employ an iterative procedure in each time step. A modified Newton-Raphson method was adopted to solve the thermal and transient problem with the time step equal to 10 s [15-16], and the minimum time increment 0,1 s. The convergence criterion is based on the heat flow calculation, for an absolute tolerance of 0,1 using a maximum number for iterations equal to 15.

The mesh of the numerical model uses a two-dimensional thermal plane element with interpolating linear functions, 8 nodes and a single degree of freedom, temperature, at each node. A regular mesh was considered with a finite element size equal to 2 mm, also used in previous investigations [15-18]. Both protected and unprotected connections have the same regular mesh. In the numerical models, perfect contact has been assumed between all different parts of the model.

The boundary conditions of the problem consist of an exchange of energy with the surroundings and the energy flow at the boundary that comprises radiation and convection. The energy source due to the pyrolysis effect was not considered in this process. The initial temperature in the model was considered equal to 20 ºC. The external surface of the connection is exposed to the standard fire curve ISO834 and the convection coefficient is 25 W/m^{2}K [27]. The emissivity of the flames is constant and equal to 1 [27].

The main objective is to obtain the temperature field in the studied connections under fire, measuring the char layer in the S-W-S connections using different wood densities, when unprotected, and compare the protection efficiency with two different types of materials. Due to the symmetry of the geometry and the applied boundary conditions, the numerical simulation was performed for two-dimensional plane of the connection, in a typical cross-section of the S-W-S connection, Figure 4.

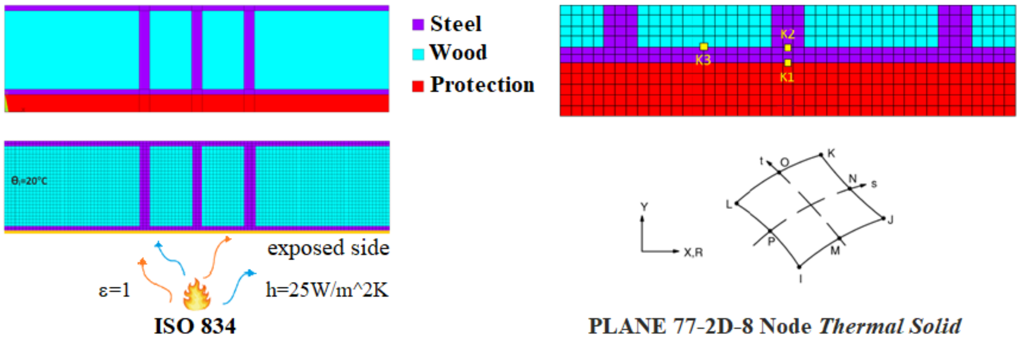

Fig. 4 Materials, mesh and boundary conditions.

To obtain the temperature evolution, different node locations were selected, point K1 (in the steel material), K2 inside the steel dowels, point K3 at the interface wood-steel plate and between two dowels, as shown in Figure 4.

6. Unprotected S-W-S connections

For unprotected (S-W-S) connections with external steel plates the load-bearing capacity of the external steel plate should be determined by the rules given in Eurocode 5 part 1-2 [5]. For section factor calculation, the internal steel sides in close contact with wood material are not exposed to fire. Simplified rules from Eurocode 5 part 1-2 [5] were used to analyse the fire safety of the wood component in study.

The char layer is the distance between the outer surface of the original member and the position of the char-line, taken as the position of the 300 °C isotherm, and should be calculated from the time of fire exposure and the relevant charring rate [5].

According the Eurocode 5 part 1-2 [5], the charring rate for one-dimensional charring should be taken as constant with time. For connections under standard fire, the design charring rate may be assumed to be β_0 = 0.65 mm/min, when assuming one-dimensional charring depth. To include the effect of corner rounding and cracks, the notional design charring rate is β_n = 0.7 mm/min in accordance with Eurocode 5 part 1-2 [5]. These values will be compared with the results from the thermal analysis, where the char layer depth calculation of wood members will be determined. The wood char layer is due the effect of the steel plate exposed to fire and the heated steel dowel.

Figure 5 represents the dimensions to be calculated at the isotherm position. Parameter $d_{char,0}$ represents the design char layer depth for one-dimensional charring and $d_{char,n}$ is the notional design char layer depth, which incorporates the rounding corner effect.

The standard fire ISO 834 curve is applied to define the fire resistance of the connection, see Figure 5. This standard uses a logarithmic formula that should be used for the bulk temperature, Eq. (8), where t stands for time in minutes and □ stands for temperature in °C [27].

$$\theta_{\alpha} = 20 + 345\, log_{10}\,(8\,t + 1) \tag{8}$$

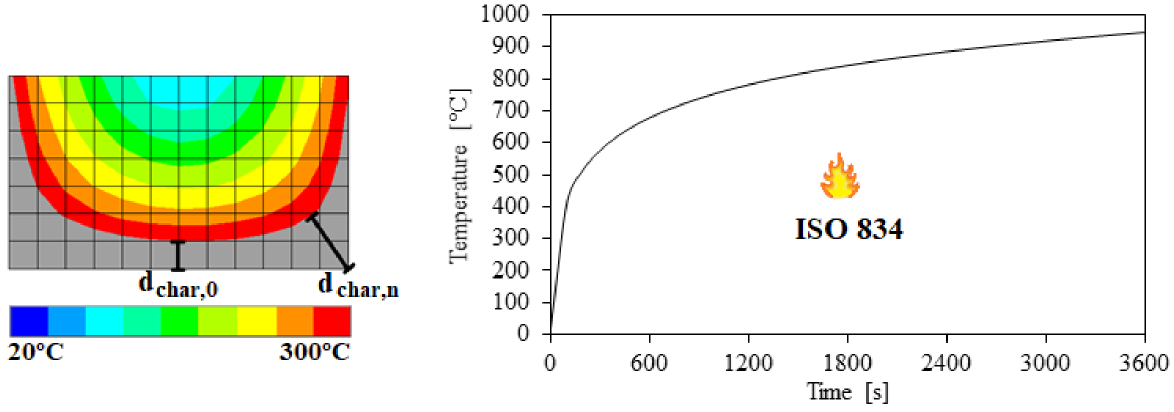

Fig. 5 Isotherm position in wood element and standard ISO 834 curve.

Table 4 presents the calculated average charring rate in all studied unprotected S-W-S connections at different wood positions. The point positions are referred according the wood mesh size equal to 2 mm, counting the number of charred finite elements in different time instants, when wood reaches 300 °C. The values were obtained for different wood densities, dowel diameters and for a fire exposure time of 600, 700 and 800 s, in the wood elements immediately after the steel plates between two dowels.

Table 4 Numerical average charring rate in unprotected S-W-S connections.

Glulam	*d*, mm	β_0 , mm.min^{-1}			β_n ,mm.min^{-1}		
		600 s	700 s	800 s	600 s	700 s	800 s
GL20h	6	0,20	0,34	0,54	0,45	0,66	0,77
	8	0,20	0,27	0,38	0,41	0,62	0,70
	10	0,20	0,29	0,33	0,40	0,58	0,68
	12	0,20	0,29	0,33	0,43	0,59	0,71
GL24h	6	0,20	0,33	0,45	0,44	0,60	0,73
	8	0,18	0,26	0,30	0,41	0,56	0,66
	10	0,18	0,26	0,30	0,38	0,55	0,65
	12	0,20	0,27	0,30	0,38	0,42	0,64
GL28h	6	0,18	0,29	0,39	0,40	0,55	0,67
	8	0,18	0,24	0,30	0,34	0,63	0,63
	10	0,18	0,24	0,29	0,31	0,50	0,60
	12	0,20	0,22	0,20	0,33	0,49	0,44
GL32h	6	0,16	0,26	0,38	0,40	0,51	0,65
	8	0,16	0,22	0,29	0,34	0,49	0,59
	10	0,18	0,22	0,29	0,32	0,48	0,44
	12	0,20	0,22	0,27	0,27	0,38	0,50

The results in Table 4 show that the charring rate increases as fire progresses, however it decreases with the increase in both, the dowel diameter and with the wood density considering or not the effect of corner rounding. Comparing both, the corner rounding increases the charring rate almost in double. It is noticeable that the existence of the steel plate slows down the charring rate, in 97% of the studied cases. This effect could be related with the cold steel plate at the begin.

In models where the charring rate exceeded the reference values, they corresponded to the largest time fire exposure (800 s) and, consequently, to the highest charring rate with the rounding effect.

Using the Eurocode 5 part 1-2 [5], the charring rate may be considered as constant value, however using the numerical results, one may conclude that the charring rate varies in the connection, due the effect of the steel and the wood density, since the referenced values only represent connections with external members in wood directly exposed to fire, as referred before in other studies [15-16]. Also, in the initial heat exposure time, steel plate and dowels act as a heat sink, reducing the heat propagation to the wood, as mentioned in other previous studied [15-16]. According to the experimental tests and studies from Harman and Lawson [28], the metal plates help to protect the wood below the plates. At elevated temperatures, the steel dowels increase the temperature quickly inside the wood connection, they lose their stiffness and strength and cause a wood char layer moving faster [29]. The presented results in this work agree with our previous outcomes [15-18].

Figure 6 represents the results of temperatures in all studied unprotected connections at positions K1, K2 and K3 during one hour of fire exposure.

According to the results, the higher temperature occurs in connections with higher dowel diameters in position K3 (grey colour), at the interface between wood and steel plate and between two dowels. In these observations, the temperature evolution at the steel plate interface doesn’t depends of the density wood effect. The lower temperatures appear in position K2 (brown colour) close to position K1 (black colour), both in steel parts.

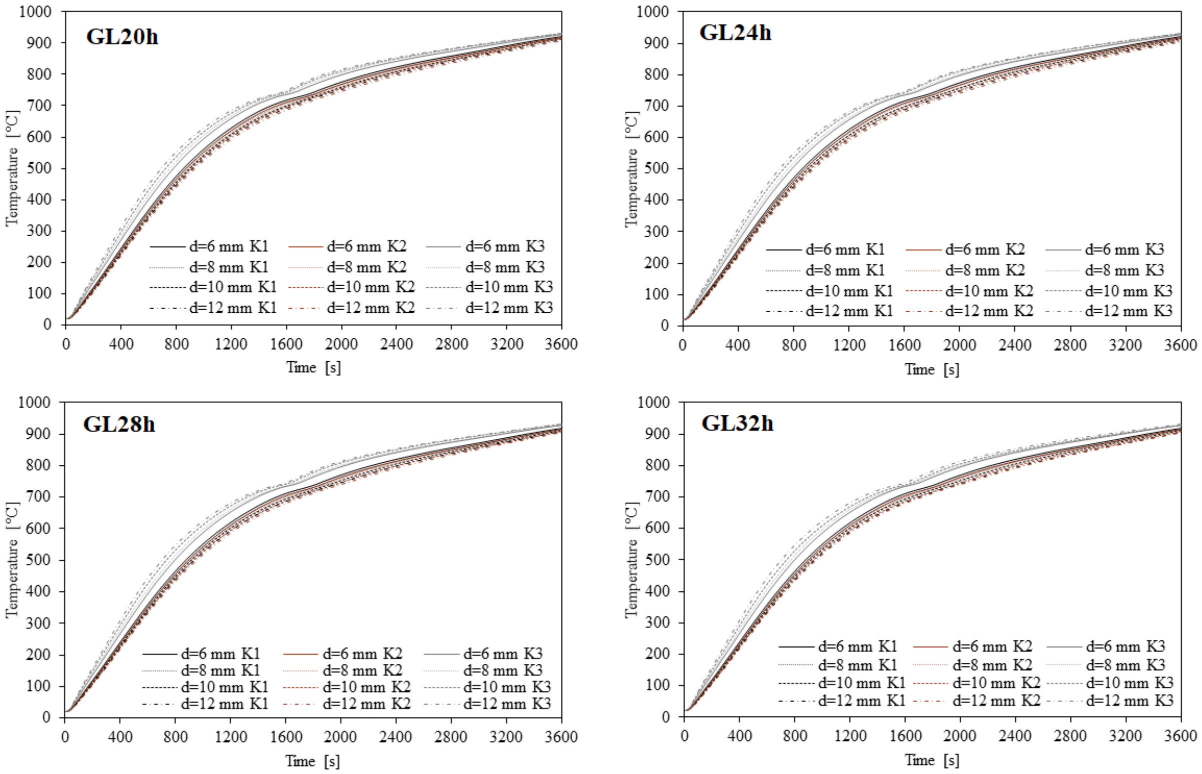

Fig. 6 Time-temperature history for unprotected connections, function of wood density and dowel diameter.

7. Protected S-W-S connections

For protected (S-W-S) connections, the steel plates used as side members, may be considered as protected if they are totally covered, including at edges of plate. In this type of connection, fire protections should be calculated according Eurocode 3 part 1-2 [24].

In this work, Glulam and type F gypsum plasterboard, were chosen as boards for the insulation protection of the S-W-S connections.

There are many solutions of passive fire protection systems available to control the rate of temperature rise in steel members exposed to fire [30]. Eurocode 3 part 1-2 [24] provides a simple design method to evaluate the temperature development of insulated steel members. Assuming uniform temperature distribution, the temperature increases $\Delta\theta_{a,t}$ of an insulated steel member during a time interval Δt, is given by:

$$\Delta\theta_{a,t} = \frac{\lambda_p \, A_p/V \ (\theta_{g,t} - \theta_{a,t})}{d_p \, c_a \, \rho_a \, (1+\phi/3)} \Delta t - \left(e^{\frac{\phi}{10}} - 1\right) \Delta\theta_{g,t} \tag{9}$$

Where: A_p/V is the section factor for steel members insulated by fire protection material, m^{-1}; A_p is the appropriate area of fire protection material per unit length of the member, m^2/m; V is the volume of the member per unit length, m^3/m; λ_p is the thermal conductivity of the fire protection material (Glulam or type F gypsum plasterboard), W/mK; d_p is the thickness of the fire protection material, m; $\theta_{g,t}$ is the ambient gas temperature at time t °C; $\Delta\theta_{g,t}$ is the increase of the ambient gas temperature during the time interval Δt, °C; ρ_a is the unit mass of steel, 7850 kg/m^3; c_a is the steel specific heat, ϕ is the amount of heat stored in the protection and Δt the time interval ≤ 30 s [30].

The amount of heat stored in the protection is given by the Eq. (10):

$$\phi = \frac{c_p d_p \rho_p}{c_a \rho_a} \cdot \frac{A_p}{V} \tag{10}$$

The method given [30] suggests that the thickness of the fire protection material d_p could be calculated using the Eq. (11).

$$Protection\ factor = \frac{A_p}{V} \cdot \frac{\lambda_p}{d_p} \left(\frac{1}{1 + \frac{\phi}{2}} \right) \tag{11}$$

The value of the protection factor, in $W.K^{-1}m^{-3}$, is obtained according the nomogram presented in Figure 7. This graphic allows the calculations of this factor, function of the steel temperature in protected components submitted to fire during an exposure time.

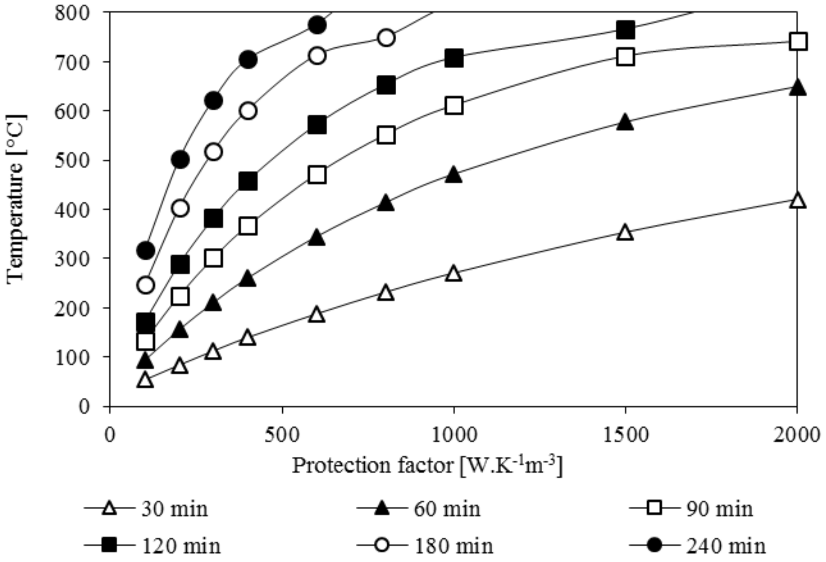

Fig. 7 Protection factor for protected steel elements.

The thickness d_p (from Eq. (10)) of the fire protection material was obtained for each S-W-S connection, function of wood density and dowel diameter, as represented in Table 5.

In the present study, a period of 30 min at fire exposure was assumed, and with the temperature that the steel material reaches 300 °C, it is possible to obtain the protection factor used in Eq. (11).

Figure 8 shows the temperature evolution in protected and unprotect S-W-S connection, for a fire exposure time of 30 min. As an example, the chosen S-W-S protection is in GL20h material and has a dowel diameter equal to 6 mm.

Protected connections have lower temperatures when exposed to fire during 30 min, but unprotected connection does not resist because all regions of the connection have temperatures higher than 280 °C. The protection with Glulam is little more efficient than type F gypsum plasterboard, because reaches higher temperature for the same fire exposure time.

To assess the previous calculated d_p thickness of the fire protection material in S-W-S connections, now at 60 min under fire conditions, additional numerical results were obtained. Figure 9 represents the obtained temperature in S-W-S connections for this condition. As shown the temperature inside wood element is below 300 °C.

Table 5 Thickness d_p of the protected S-W-S connections, fire exposure time 30 min when steel reaches 300 ºC.

Dowel, mm	Glulam	Thickness of the fire protection material	
		Type F gypsum, mm	Glulam , mm
6	GL20h	14	10
	GL24h	14	10
	GL28h	14	10
	GL32h	14	10
8	GL20h	14	9
	GL24h	14	9
	GL28h	14	9
	GL32h	14	9
10	GL20h	13	9
	GL24h	13	9
	GL28h	13	9
	GL32h	13	9
12	GL20h	13	9
	GL24h	13	8
	GL28h	13	8
	GL32h	13	8

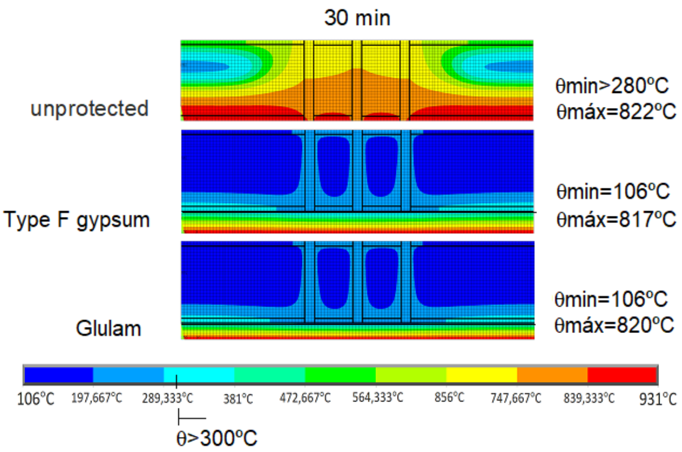

Fig. 8 S-W-S connections under fire during 30 min, GL20h and dowel diameter of 6 mm.

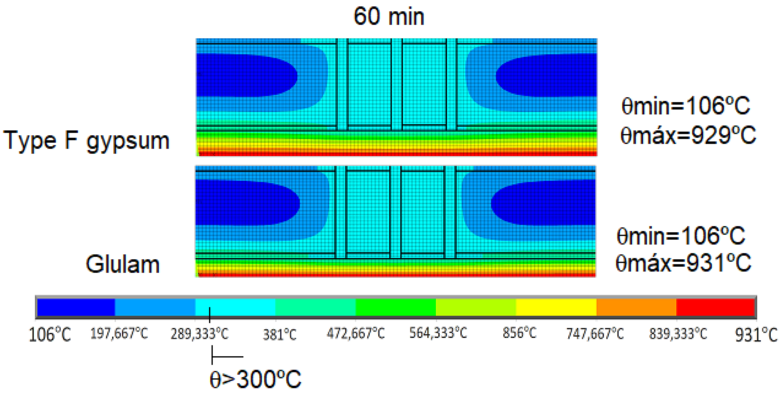

Fig. 9 S-W-S connections under fire during 60 min, GL20h and dowel diameter of 6 mm.

Using this fact, and with the same calculated d_p fire protection thickness, one may use any dowel diameter or wood density at 60 min under fire exposure, as explained in the following graphics, in Figures 10 and 11. The following Figures represent the temperature history obtained numerically in the positions K1, K2 and K3.

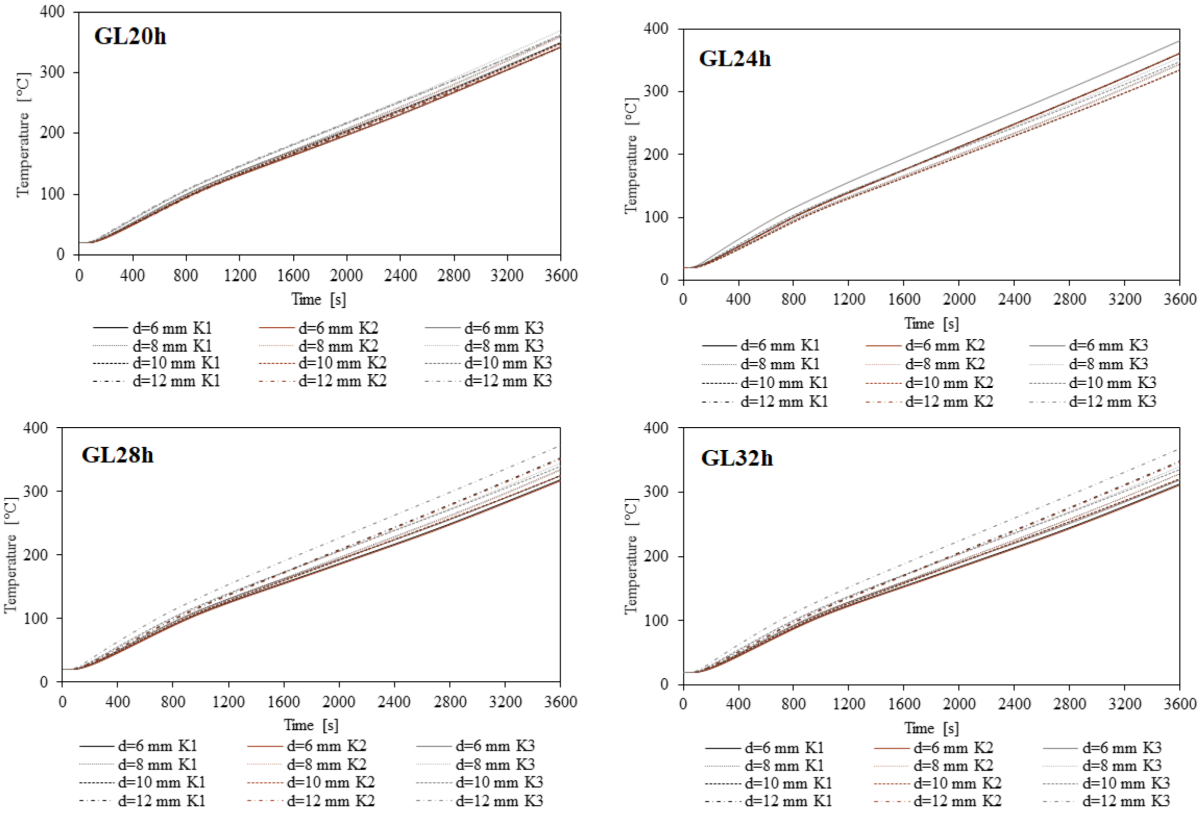

Fig. 10 Temperature history for protected connections with Glulam.

As discussion, during 47 min (2820 s) S-W-S connections are protected due the obtained results in position K3, considering the threshold of 300 ºC that impose the starting of the wood char layer. Positions K1 and K2, in steel element have a similar behaviour, and the temperatures in these points are like point K3. Any external position in front of fire follows, approximately, the ISO834 fire curve.

The higher difference between the obtained temperature in points K1, K2 or K3 is in protected S-W-S connection with Glulam. The connection in GL32h material and using dowel diameter equal to 12 mm shows the better behaviour to resist until 3600 s in fire conditions. Wood with high density presents lower temperature inside. Also, with higher dowel diameters the contribution of heat is smaller inside the wood. Higher dowel diameters allow more spacing between fasteners and this helps to protect the wood core connection.

All S-W-S connections use an external steel plate, and by that reason all connections have a close behaviour when protected. In general, comparing all results between the connections with different panels, the protection inside the wood connection slightly increases when using higher wood density and higher dowel diameters. According to the results, the Glulam gives more protection when compared with type F gypsum plasterboard.

With respect to the different types of connections previous studied [15-19], although some characteristics are not the same, W-W-W and W-S-W connections can withstand an hour of fire exposure, however, the protection thicknesses were bigger, when compared to those S-W-S under investigation.

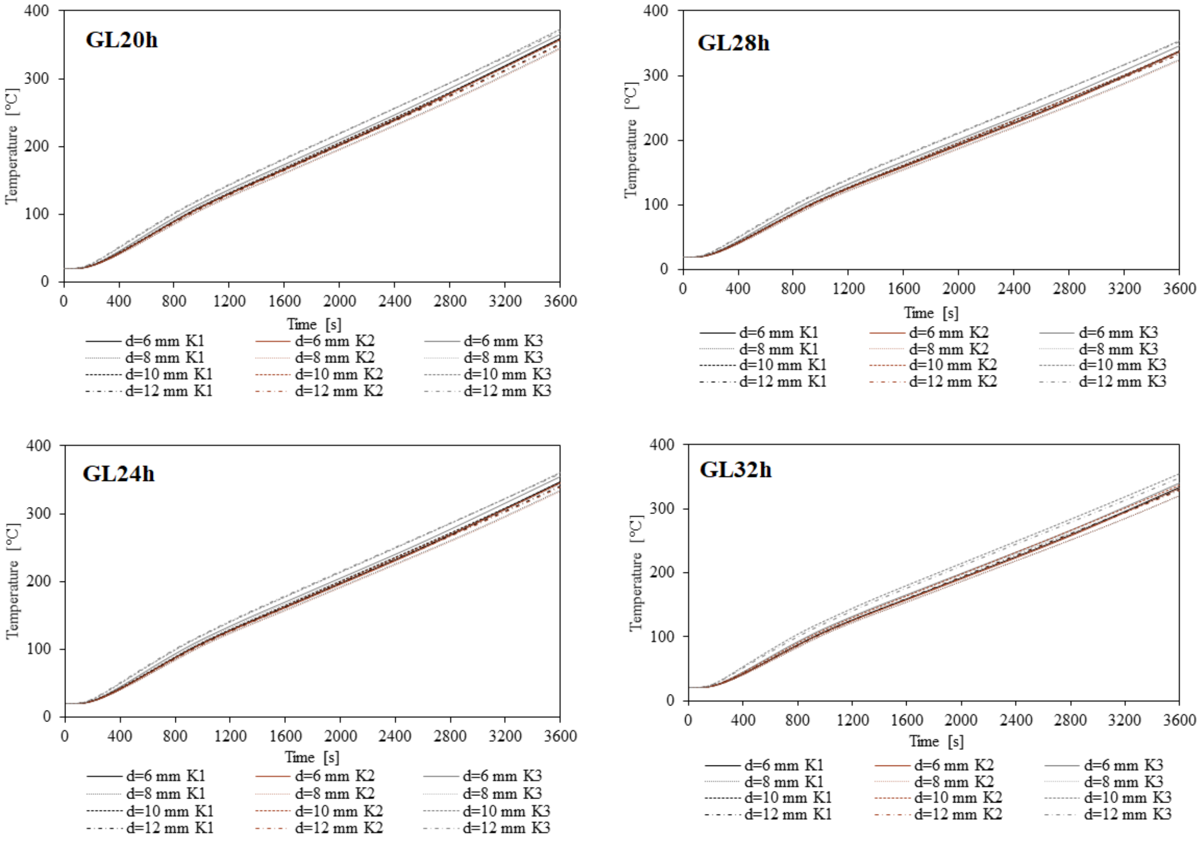

Fig. 11 Temperature history for protected connections with type F gypsum plasterboard.

8. Conclusions

Eurocode 5 part 1-1 provides all the equations and rules for design of S-W-S connections at the ambient temperature. The analysis of different parameters and how they influence the connection, was clearly presented. It was concluded that the decreasing in dowel diameter and increasing in the applied load contributes to increase the number of dowels in the connection. On the other hand, it was found that the wood density has little influence on the number of dowels, and even when used higher dowel diameter, this influence tends to be smaller. The major challenge of this work was the S-W-S design connections at elevated temperatures according to Eurocode 5 part 1-2 as it focuses mainly on connections whose external members are made of wood. There is a lack of detailed information regarding connections with external steel members. For other protection materials beyond wood, it is suggested to follow Eurocode 3 part 1-2. After the numerical results analysis, it is concluded that unprotected connections have a low bearing capacity in fire situations, thus reinforcing the suggestion of Eurocode 5 part 1-2 to avoid the use of unprotected S-W-S connections when subjected at elevated temperatures. Eurocode 5 part 1-2 presents charring rate for wood members. However, in S-W-S connections the external member is steel and the use of different wood density, causes a wide range in charring rates. From the point of view of the connection characteristics, it was found that the connection with the major dowel diameter in high density wood had higher fire resistance. However, only using protection in S-W-S connections provides sufficient resistance to withstand fire exposure in at least 30 min. The protection panel needs safe thickness to guarantee this requirement, thus making Glulam the best fire protection material for this connection type.

As a future work the authors consider extending the present methodology in different parametric S-W-S connections. More studies should be considered, both protected and unprotected connections at fire conditions. Also, it is intent to enlarge the presented methodology in the study of connections under fire using all different nominal temperature-time curves. With more results it is intended to propose, at the end, analytical expressions that could be used in design of these type of connections.

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