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LOAD-CARRYING CAPACITY IN W-S-W CONNECTIONS IN DOUBLE-SHEAR AT AMBIENT TEMPERATURE

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ABSTRACT

The present work aims to evaluate the behavior of the W-S-W connections, wood material with steel plate as the central member, connected by steel dowel fasteners in double-shear. The load-carrying capacity per shear plane and per steel fastener will be evaluated in all studied W-S-W connections. Simplified and analytical equations according Eurocode 5, part 1-1 (CEN EN1995-1-1, 2004) will be used to assess the designed connections with safety. A numerical model using the finite element method (FEM) will be used to demonstrate the entire analysis in the W-S-W connections identifying also the load-carrying capacity, and in simultaneous, verifying the influence of the chosen position between all dowels. Several W-S-W connections were designed for five different applied loads, considering the wood elements with two different thicknesses and two dowels diameters. The numerical model was calibrated with the analytical solution, the results showed a similar load-carrying capacity and allow verify the arrangement influence and sizes of the fasteners for each connection.

Keywords: W-S-W connection, wood, steel, load-carrying capacity.

INTRODUCTION

Wood connections with fasteners are very important parts of a structure. Mechanical connections are used in wood constructions and can be classified into three major categories: dowel, metal connector plates with integral teeth or shear, and split-rings. Connections with metal fasteners follow the rules according Eurocode 5 part 1-1 [1].

Wood is a heterogeneous, hygroscopic, cellular and anisotropic material. Wood is classified into two main groups, softwoods and hardwoods. Wood material may be described as an orthotropic material, that is, it has unique and independent mechanical properties in the directions of three mutually perpendicular axes: longitudinal, radial, and tangential. The longitudinal axis (L) is parallel to the fiber (grain), the radial axis (R) is normal to the growth rings (perpendicular to the grain in radial direction), and the tangential axis (T) is perpendicular to the grain and tangent to the growth rings [2].

Wood members connected with dowel-type fasteners are probably the most common mechanical connections type because they are effective at transferring loads while also being relatively simple and efficient to install. Dowelled connections transfer the load between members through a combination of dowel bearing and bending of the dowel fastener. Dowels are usually round, fitting into holes in two adjacent pieces to prevent their slipping or to align them, and used to reinforce. Nails are generally used when loads are relatively light, as in multi-family and light commercial buildings. Staples can be used in place of nails, but equivalent capacities need to be determined. Screws may be more satisfactory than nails under certain conditions (such as exposure to moisture) since they have less tendency to work loose and generally have high wind withdrawal resistance under severe events [3].

The analysis of connections (wood and steel) can be a challenge due their complexity, various connections types, different geometries, fasteners arrangements and also the great variability of the material properties. Wood and steel are materials with different characteristics.

In this work, the calculations for designed connections at ambient temperature follow the Eurocode 5 part 1-1 5 [1] and DIN 6325 [4], considering a homogeneous glued laminated in birch timber and steel dowels for metallic fasteners. The wood plates have different thicknesses, the central steel plate member does not vary and the dowels were considered with different diameters. The applied tensile load in the W-S-W connection is parallel to the wood fiber, as guarantee for high load-carrying capability in the designed connections. Using a numerical program based on the FEM it will become possible also to calculate the mechanical resistance of the W-S-W connections, as an alternative methodology. Beyond the determination of the load-carrying capacity, as a parameter in compliance with safety rules and design, in addition, and with all the entire connection analysis it will be possible to grow the knowledge and behavior in these type of structures.

MATERIALS

To determine the configuration in study, W-S-W connection at ambient temperature, all requirements according standards will be conducted. The final configuration with all dimensions is presented in Figure 1. The proposed model is calculated in cross-section size, number of dowels and spacing between dowels, due to an applied tensile load.

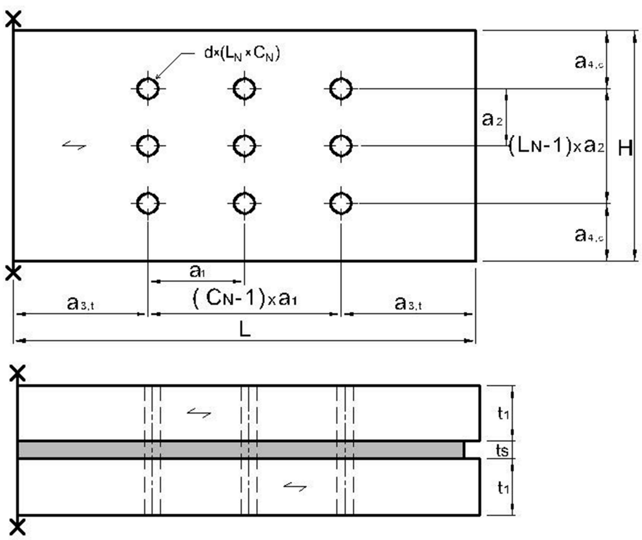

Fig. 1 - Schematic W-S-W connection.

The variables adopted in this work are the applied load, E_d, the dowel diameter, d, and the wood plate thickness, t_1.

There are different glued laminated timber (glulam) materials considered for different applications, as well as for W-S-W connections. Glulam is manufactured by bonding together individual laminations of solid timber, in rectangular cross-sections and very adaptable in design. The standard [5] lists eight glulam strength classes. For homogeneous lay-up solid timber, meaning that all of the laminations are of the same strength, the category is GLxh. In this work GL28h wood glulam was considered and all properties are presented in Table 1.

Table 1 - Values of strength, stiffness and density of GL28h wood glulam.

Designation	symbology	Value
Strength [MPa]		
Bending strength	$f_{m,g,k}$	28,00
Tension parallel to the grain	$f_{t,0,k}$	19,50
Tension perpendicular to the grain	$f_{t,90,k}$	0,45
Compression parallel to the grain	$f_{c,0,k}$	26,50
Compression perpendicular to the grain	$f_{c,90,k}$	3,00
Stiffness [MPa]		
Modulus of elasticity parallel to the grain	$E_{g,0,mean}$	12600,00
Modulus of elasticity perpendicular to the grain	$E_{g,90,m}$	420,00
Shear modulus	$G_{g,mean}$	780,00
Density [kg/m^3]		
Density	$\rho_{g,k}$	410,00

Considering the values of strength and stiffness for GL28h, a typical yellow birch could be used. Tables below give the properties for this specie as an orthotropic material, that is, it has unique and independent mechanical properties in the directions of three mutually perpendicular axes: longitudinal or parallel to the fiber or grain (L), radial normal to the growth rings (R) and tangential perpendicular to the grain but tangent to the growth rings (T). The strength in the longitudinal direction is the greatest usually about 10 times the other directions. Tables 2 and 3 represents the material properties at ambient temperature for this specie.

Table 2 - Elastic ratios at approximately 12% moisture content, [2].

Specie	E_T/E_L	E_R/E_L	G_{LR}/E_L	G_{LT}/E_L	G_{RT}/E_L
Birch, yellow	0,050	0,078	0,074	0,068	0,017

Table 3 - Poisson ratios at approximately 12% moisture content, [2].

Specie	μ_{LR}	μ_{LT}	μ_{RT}	μ_{TR}	μ_{RL}	μ_{TL}
Birch, yellow	0,426	0,451	0,697	0,426	0,043	0,024

For metal fasteners steel material S275 was considered, according Eurocode 3 part 1-1 [6], where the yield strength f_y is equal to 275MPa and ultimate tensile strength f_u equal to 430MPa.

ANALYTICAL MODEL

According Eurocode 5 part 1-1 [1], 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 the safety factors: modification factor for load duration and moisture content, k_{mod}, and partial factor for material properties, γ_M, equation 1.

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

Considering E_d as the applied load and A_s the cross-section area of the W-S-W connection, the design tensile stress along the grain, $\sigma_{t,0,d}$, is calculated using the equation 2, Eurocode 5 part 1-1 [1].

$$\sigma_{t,0,d} = \frac{E_d}{A_s} \tag{2}$$

Using all simplified analytical equations from Eurocode 5 part 1-1 [1], and being a connection with a central steel plate in double shear stress applied to the fasteners, the load-carrying capacity per shear plane and per fastener is calculated according the equation 3.

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

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, equal to 0 for dowels applications.

The characteristic yield moment of the fastener $M_{y,Rk}$ is dependent of the dowel diameter and the material bolt strength:

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

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.

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

With the calculation from $F_{v,Rk}$, it is possible to obtain the number *N* of the dowels, according the design load-carrying fastener capacity calculated $F_{v,Rd}$, equations 6 and 7.

$$F_{v,Rd} = \frac{k_{mod}\, F_{v,Rk}}{\gamma_M} \quad (6)$$

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

Finally, 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, vary in order of the dowel diameter.

SPREADSHEET CALCULATION

In this work ten W-S-W connections will be designed to analyze the load-carrying capacity, with different applied tensile load (10, 20, 30, 40 and 50 kN), two different wood plate thickness (25 and 50 mm) and two dowel diameters (8 and 12 mm). The central steel plate has the same dimension in studied connections with a thickness equal to 6 mm.

Table 4 - W-S-W connections with different thickness, dowels diameters and applied loads, GL28h.

E_d	t_1	d	$f_{t,0,k}$	$F_{vR,k}$	$F_{v,Rd}$	Nº dowels	LN	CN	a_1	a_2	a_{3t}	a_{4c}	L	H	Cross- section
kN	mm	mm	N/mm²	N	N	-			mm	mm	mm	mm	mm	mm	mm²
10	25	8	19,5	3963,1	2536,4	4	1	4	40	24	80	24	280	48	2400
	50	12	19,5	9437,0	6039,7	2	1	2	60	36	84	36	228	72	7200
20	25	8	19,5	3963,1	2536,4	8	2	4	40	24	80	24	280	72	3600
	50	12	19,5	9437,0	6039,7	4	1	4	60	36	84	36	348	72	7200
30	25	8	19,5	3963,1	2536,4	12	3	4	40	24	80	24	280	96	4800
	50	12	19,5	9437,0	6039,7	6	2	3	60	36	84	36	288	108	10800
40	25	8	19,5	3963,1	2536,4	16	4	4	40	24	80	24	280	120	6000
	50	12	19,5	9437,03	6039,70	8	2	4	60	36	84	36	348	108	10800
50	25	8	19,5	3963,06	2536,36	20	5	4	40	24	80	24	280	144	7200
	50	12	19,5	9437,03	6039,70	9	1	9	60	36	84	36	648	72	7200

Fv,Rk=characteristic load-carrying capacity per shear plane per fastener; Fv,Rd=design load-carrying capacity per shear plane per fastener; Ed=load design; LN=number of lines; CN=number of columns.

A worksheet was developed to calculate all connections and determine the design parameters of each model, Table 4. The spreadsheet was developed taking into account the rules presented in Eurocode 5, part 1-1 [1] and facilitate the analytical calculations for all connections. Considering the calculated number of dowels, it is possible to choose the arrangement (LN and CN) between the connectors, but carrying out the spacing imposed by the rules.

NUMERICAL MODEL

The numerical model of the mechanical analysis uses a 3D finite element, defined by 8 nodes with three degrees of freedom by node (nodal translations in the x, y and z directions).

In the present work, one representative ¼ W-S-W connection was reproduced in FEM analysis. Due the geometric symmetry and loading conditions, only ¼ (one quarter) of the model was analyzed, Figure 2. Boundary conditions were introduced in the symmetrical planes of the central steel plate. Due the contact interface between wood-steel plate and dowels a static friction coefficient equal to 0.3 was considered.

The structural analysis was incremental, where a tensile load was increased linearly on the lateral wood member of the connection. The time control is set for a time step equal to 10, minimum time step equal to 1 and maximum time step equal to 10s, with maximum 4 equilibrium iterations for each time step. Newton's method was used, as the most rapidly convergent process for solution of problems. The convergence criteria and tolerances must be carefully chosen to provide accurate solutions; it will be adopted the one which satisfies the solution equilibrium, usually based on some norm of the force or displacement control. Different size meshes were implemented until the results reach a satisfactory value.

Figure 2 presents the numerical model for the first connection displayed on Table 4, with 4 dowels and two different arrangements between the dowels (case I: LN=1 and CN=4, on the left and case II: LN=2 and CN=2, on the right). Two different material properties were considered, as mentioned in previous. In this work, the mechanical properties of the materials were considered as isotropic for steel and orthotropic for timber, both materials are considered non-linear, that is, they are multilinear materials with elastic-plastic behavior. For the structural analysis, the material strength and elastic properties are the major determining factors to obtain desired results.

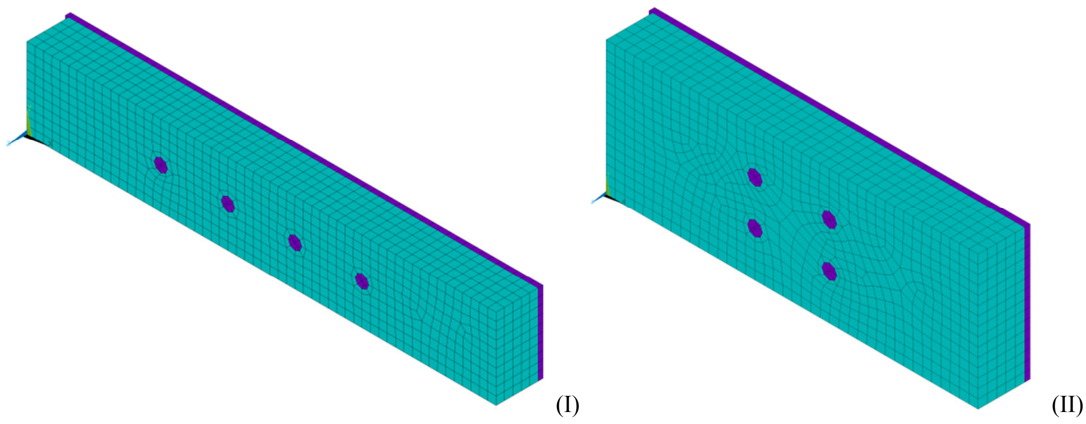

Fig. 2 - Numerical model for the first W-S-W connection (E_d=10kN, t_1=25mm, d=8mm).
I) LN=1, CN=4, II) LN=2, CN=2.

The numerical models were developed in order to obtain the load-carrying capacity and compare with the results from the analytical calculations presented in Eurocode 5 part 1-1.

COMPARISON OF RESULTS

The load carrying capacity of the connection is checked by the shear stress of the fasteners. The comparison of the results obtained according to Eurocode 5 part 1-1 and the numerical results are presented in Table 5.

Table 5 - Comparison between the analytical and the numerical results.

Ed, kN	t1, mm	d, mm	Load carrying capacity (analytical), N	Load carrying capacity (numerical), N	Error, %
10	25	8	31704	36000	13,55
	50	12	37748	36000	4,63
20	25	8	63409	73173	15,40
	50	12	75496	83885	11,11
30	25	8	95113	92500	2,75
	50	12	113244	116000	2,43
40	25	8	126818	116000	8,53
	50	12	150992	146500	2,97
50	25	8	158522	141620	10,66
	50	12	169866	160620	5,44

It was evident that in the connections with t_1 equal to 25 mm the tensile strength parallel to grain is reached. In these connections the rupture occurs due to the failure on lateral wood member that reaches its limit.

The designed connections with t_1 equal to 25 mm presented a greater error when compared with the connections with t_1 equal to 50 mm. Considering that the connections with smaller t_1 were made with smaller dowels diameter, equal to 8 mm, and the connections with larger t_1 have dowels with higher diameter, equal to 12 mm, it becomes evident that the standard does not considers the variation of these parameters in the design of the W-S-W connection. Eurocode 5 part 1-1 [1] does not refer to the arrangement of the dowels in the connection design.

Figure 3 represents the obtained numerical results for the first connection, as referred in Figure 2, with the normal and shear stress calculations at the ultimate load capacity for each arrangement of doweled connection.

Choosing two rows and two columns of dowels, case II (LN = 2 and CN = 2), the load-carrying capacity (numerical) it was equal to 61000 N, this value increased 69.44% in the resistant capacity when compared with the obtained value 36000 N from the case I. This confirms that the arrangement of the dowels it is important to take in attention, and the numerical simulation could help to determine the real load-carrying capacity of the connection.

Figure 3 exhibits the stress distribution for each case. The normal stresses in wood and steel member decrease in case II in comparison with case I, but the shear stress in the dowels increased in the arrangement. In general, the central steel plate exhibits larger stresses near at the end of the wood plate. The load that is applied to the wood plate is transmitted to the dowels and subsequently to the central steel plate, these forces cause high level of stress that can reach the yield stress of the steel or cause excessive deformation.

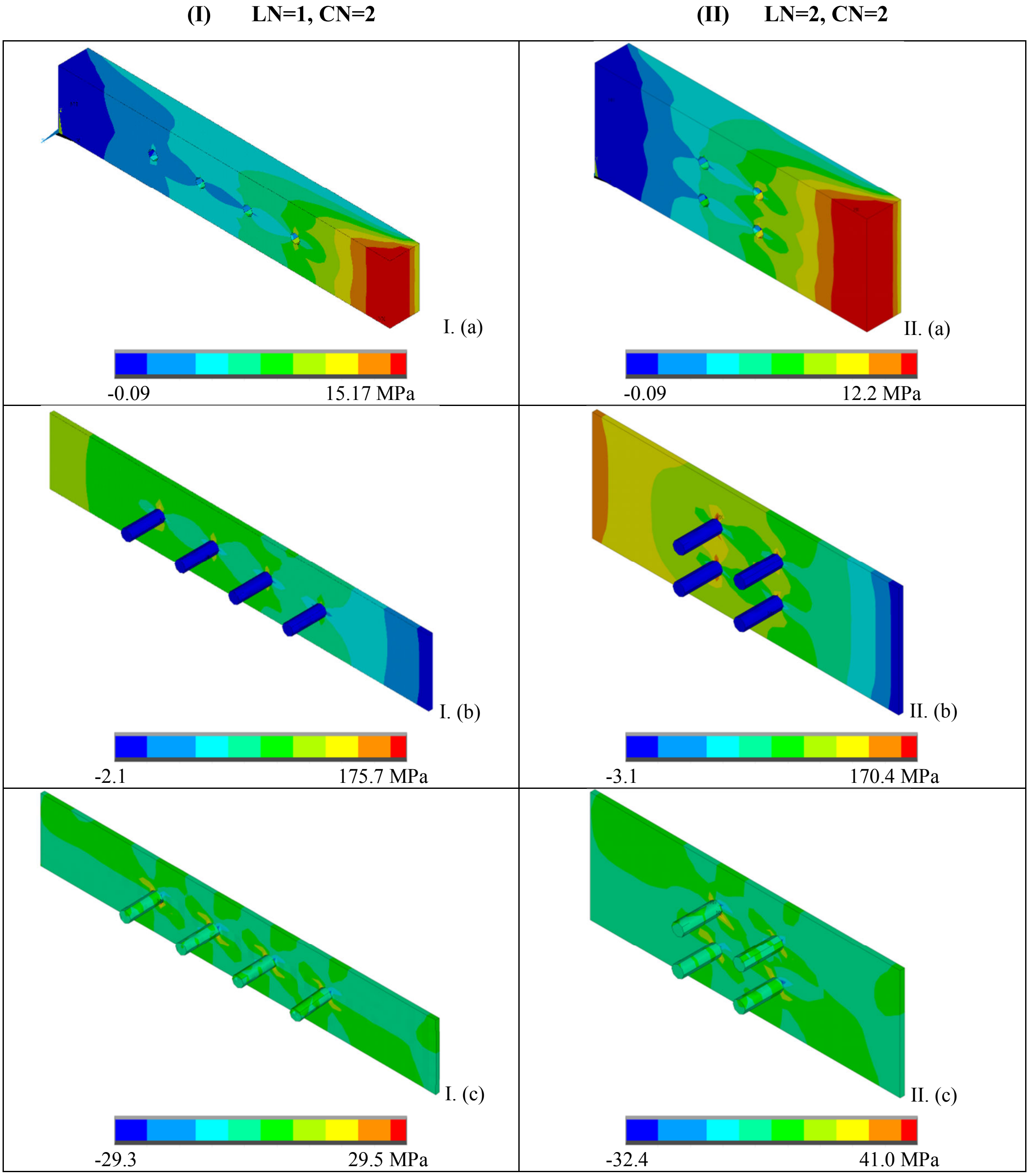

Fig. 3 - Stress distribution for study case with E_d=10kN, t_l=25mm, d=8mm: (a) σ_{xx} in 1/4 of the wood connection, (b) σ_{xy} in 1/4 of the dowels and central steel plate, (c) τ_{xy} in 1/4 of the dowels and central steel plate.

CONCLUSIONS

This work present different two methodologies applied to a designed W-S-W connections used in building construction. A procedure with all analytical equations were presented to assess the cross-section and all dimensions for an applied tensile load at ambient. A spreadsheet was developed for calculating different W-S-W configurations, dimensions and its load-carrying capacity. A numerical procedure based on FEM was also implemented to produce different 3D simulations focused on mechanical analysis. The numerical model represents the W-S-W connection with an applied incremental tensile load, in order to obtain the maximum critical load and to determine the maximum load-capacity of each fastener.

The comparison of several results obtained between analytical and numerical calculations showed a favorable accordance. The numerical simulations are very relevant, the models can be used for verification in other type of connections and submitted at different loading conditions. The proposed numerical model could be used for stresses calculation and verification of the distribution for any materials or components of the W-S-W connection in study, as an alternative methodology, to prevent any damage before the construction. The presented numerical solution gives good results and are in accordance with the previous analytical load-carrying capacity per shear and by each fastener, for each connection in study.

The acquired results are in agreement with the analytical calculations, nevertheless in the connections with a smaller thickness t_1 it's a challenging to determine the load-carrying capacity, where different set controls need to be introduced in the numerical solution. The wood tensile strength was reached before the shear strength of the connectors. This behavior is what happened in real situation. About the arrangement of the dowels, Eurocode 5 part 1-1 (CEN EN1995-1-1, 2004) [1] does not refer about the number of columns or lines in the arrangement. After the calculated number of dowels, the designer needs only to verify the dimensions between them. This situation could lead designers to oversized connections where the load-carrying capacity of the connection is much larger than the required, with larger cross sections.

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