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DOUBLE-SHEAR W-S-W CONNECTIONS AT AMBIENT TEMPERATURE, WITH DIFFERENT APPLIED TENSILE LOADS AND STEEL 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 with steel dowel fasteners. For each studied connection, different dowel diameters and external applied tensile loads shall be taken in account. 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. It is intended to obtain the number of dowels per each W-S-W connection, their arrangement and the general dimensions of the connection. In the wood plates will be used a glue laminated wood, as yellow birch, with characteristics equals to GL28H. Using the proposed simplified equations from Eurocode 5, part 1-1, all analytical results will be obtained at ambient temperature. The comparison of the results will be achieved using a numerical analysis with the finite element method.

Keywords: W-S-W connection, wood, steel, dowel, double-shear.

INTRODUCTION

There is a wide range of double-shear connections application in heavy timber structures in building construction. The main objective of the connections is to assemble members and loads transfer in the structural system, such as multi storey offices, educational buildings, health buildings, residential buildings and other type of public buildings. Examples include wood-wood-wood, wood-steel-wood and steel-wood-steel connections with steel bolts or dowels as fasteners (Lei Peng, 2011).

In connections in double shear (two sides members and one middle member) the main part of the external load is transferred by contact pressure between the wood sides members and the dowel fasteners, that are in shear and bending. This type of connections is widely used in tensile members in construction and industrial engineering.

The design of connections-dowel type according Eurocode 5 (CEN EN1995-1-1, 2004) is based on theories developed by Johansen. The parameters, which influence the load-carrying capacity, are the bending capacity of the dowel or yield moment, the embedding strength of the wood and the withdrawal strength of the dowel (Resch, 2012).

Wood connections have been investigated due their importance in construction and industrial engineering in terms of strength, ductility and all capacity to improve the structural performance in service. 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 parameters in conjunction (Aissa, 2017), (Guan, 2000), (A. Frangi, 2010), (Maraveas, 2013). Few 3D numerical models have been published; the majority publications are based on 2D approach (Resch, 2012). Nevertheless, due the complexity of the connection failure mechanisms, the numerical modelling is very challenging to obtain the exact failure and behaviour of the wood connection.

In other studies, using bolts as fasteners, it was found that the spacing between the bolts has the largest influence in connection. In other hand, the number of fasteners, the number of rows, the bolt slenderness and the loaded end distance are less relevant (Jorissen, 1999).

The main objective of this study was to evaluate the effect of different applied tensile loads, parallel to grain, and different dowels diameters to guarantee WSW safety connections to be used by easily designers.

W-S-W CONNECTION AT AMBIENT TEMPERATURE IN ACCORDANCE WITH EUROCODE 5

Figure 1 represents a typical W-S-W connection under double-shear with the main dimensions in study (width, height and thickness of the wood plates, minimum spacing and edge/end distances between the dowels and the wood plate).

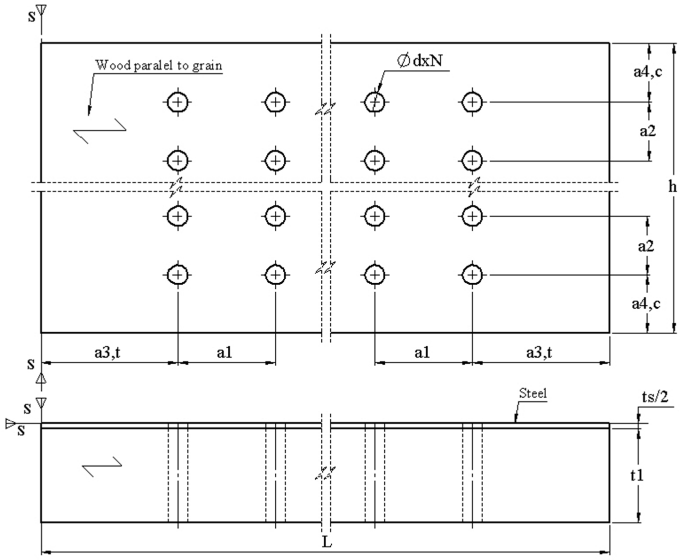

Fig. 1 - Typical W-S-W dimensions.

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 (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.

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

Considering E_d as the applied load and A_s the cross-section area of the member, the design tensile stress along the grain, $\sigma_{t,0,d}$, is calculated using the equation 2, Eurocode 5 (CEN EN1995-1-1, 2004).

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

Also, using all proposed simplified equations from Eurocode 5 (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

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

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.

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

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

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.

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

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

$$F_{v,Rd} = \frac{k_{mod}\, F_{v,Rk}}{\gamma_M} \tag{6}$$

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

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, vary 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 load.

In order to perform a further comparison with numerical results is necessary to know the maximum load that a W-S-W connection can support. With this purpose, a new E_d value must be calculated using equation 2 and a final designed cross-section area. After obtaining the new value, this one must be multiplied by the coefficient 1.56, as the applied safety factor before during the designed methodology.

W-S-W MECHANICAL NUMERICAL MODEL

To simulate the mechanical resistance of the W-S-W connection, a numerical and computational program 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 three degrees of freedom per node, correspondent to the translations in x, y and z directions.

Two different material properties are considered. For mechanical analysis, the material strength and elastic properties (isotropic for steel and orthotropic for timber) are the major determining factors to obtain desired results of the structural capacity.

Four different numerical models were performed due different designed W-S-W connections, obtained from the previous calculation. Table 1 presents the four connections in study with all dimensions. Figure 1 represents all connections (a quarter of W-S-W) and the applied mesh.

Table 1 - Specifications of the W-S-W connections.

W-S-W connection	d(mm)	t1(mm)	Cn	Ln	h(mm)	L(mm)	ts (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

In this type of W-S-W connection, many contacts occur between surfaces (dowels, wood and steel plates interactions). Contact elements and algorithms are needed to predict the friction forces between the wood-steel elements and the dowels. The numerical program introduces these contact through the contact and interaction properties, with pairs of surfaces known as ‘’contact pairs’’, generated automatically. In this study a friction coefficient equal to 0,3 was used, based on the friction Coulomb’s law.

In the numerical analysis, an incremental and linear tensile load (pressure) was implemented in the lateral right edge. All symmetry boundary conditions were introduced in the quarter model representation. The numerical program conducts an analysis in steps and applies the load in increments in order to obtain a converged solution. This concept of time increments and the proportional applied load was used to estimate the load to cause ultimate failure or damage in the W-S-W connection. The ultimate capacity of the connection leads to a failure mode, as maximum stresses reached in the W-S-W in the parallel direction to wood grain.

According the obtained numerical results, the estimation of the ultimate capacity from the structural W-S-W model will be calculated and compared with the ultimate load capacity recorded from the designed analytical solution.

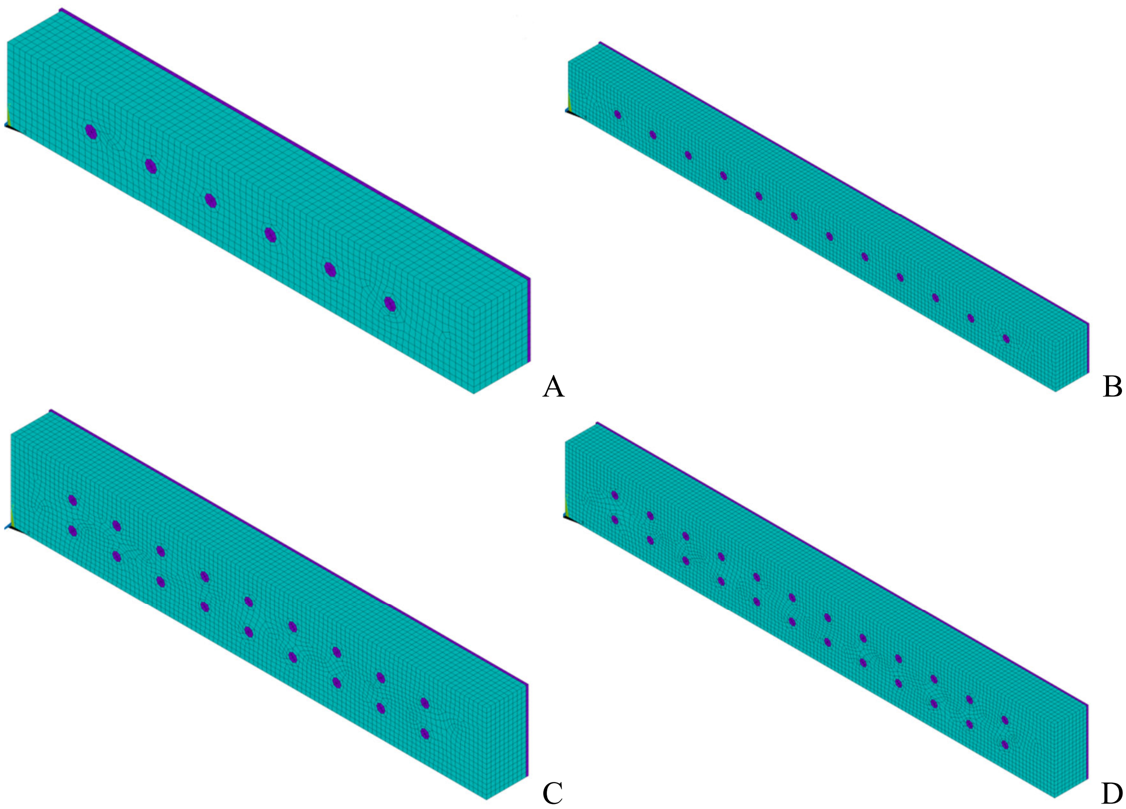

Fig. 2 - Four W-S-W connections and applied mesh.

RESULTS AND DISCUSSION

In this work the results presented were conducted according the Eurocode 5 (CEN EN1995-1-1, 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 and the minimum spacing in edges, 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 a proportional relationship between the increased applied tensile load and the design dimensions for wooden elements, as the increased number of fasteners. The developed spreadsheet appears as an easy tool adequate for W-S-W design connections at ambient temperature.

As a conclusion, the steel plate thickness as no relevant influence in the load capacity of the connection. In other hand, a higher thickness of the wood elements produces a higher resistance of the connection to an applied load, as well as the dowel diameter.

The applied load consists only in an easier way to understand the size of the connection. Therefore, is pertinent to affirm that two of the variables does not influence in the total load the connection can support without failure. The maximum load the connection A and B can support is 111,150 kN and for connection C and D is 166,725 kN. Both A and B connections have the same maximum load because both have the same cross section area. The same is applied for connection C and D. In finite element analyses the connection D has a minor relative error (compared to the Eurocode 5) equal to 3,20% and a maximum error of 4,87% in connection C. For this case, the result obtained are present in Table 3.

Table 2 - W-S-W design connections at ambient temperature.

Applied tensile load, E_d kN	t_1 mm	Dowel diameter, d mm	Fv,Rk kN	Fv,Rd kN	N, Dowels number (symmetry, S)	Spacing in edges mm				Height, h mm	Width, L mm
						a_1	a_2	$a_{3,t}$	$a_{4,c}$		
25	45	10	7,1	4,5	1x6	50	30	70	30	60	390
25	50	10	7,6	4,8	1x6	50	30	70	30	60	390
25	55	10	8,1	5,2	1x5	50	30	70	30	60	340
25	60	10	8,6	5,5	1x5	50	30	70	30	60	340
(…)											
100	45	16	13,1	8,4	3x4	80	48	112	48	192	464
100	50	16	13,7	8,7	3x4	80	48	112	48	192	464
100	55	16	14,2	9,1	3x4	80	48	112	48	192	464
100	60	16	14,9	9,5	2x6	80	48	112	48	144	624

Fv,Rk=characteristic load-carrying capacity per shear plane per fastener; Fv,Rd= Design load-carrying capacity per shear plane per fastener.

Table 3 - Numerical results.

Connection	Final Analytical Result kN	Numerical Result kN	Relative Error
A	111,150	107,210	3,72%
B	111,150	116,063	4,42%
C	166,725	174,840	4,87%
D	166,725	172,060	3,20%

Figure 3 presents the shear stress in wood elements and steel plate with dowels. In the wood elements, the maximum and the minimum shear stress appear on the dowels holes. In the steel plate, the maximum and minimum stress values were also obtained around the dowels holes.

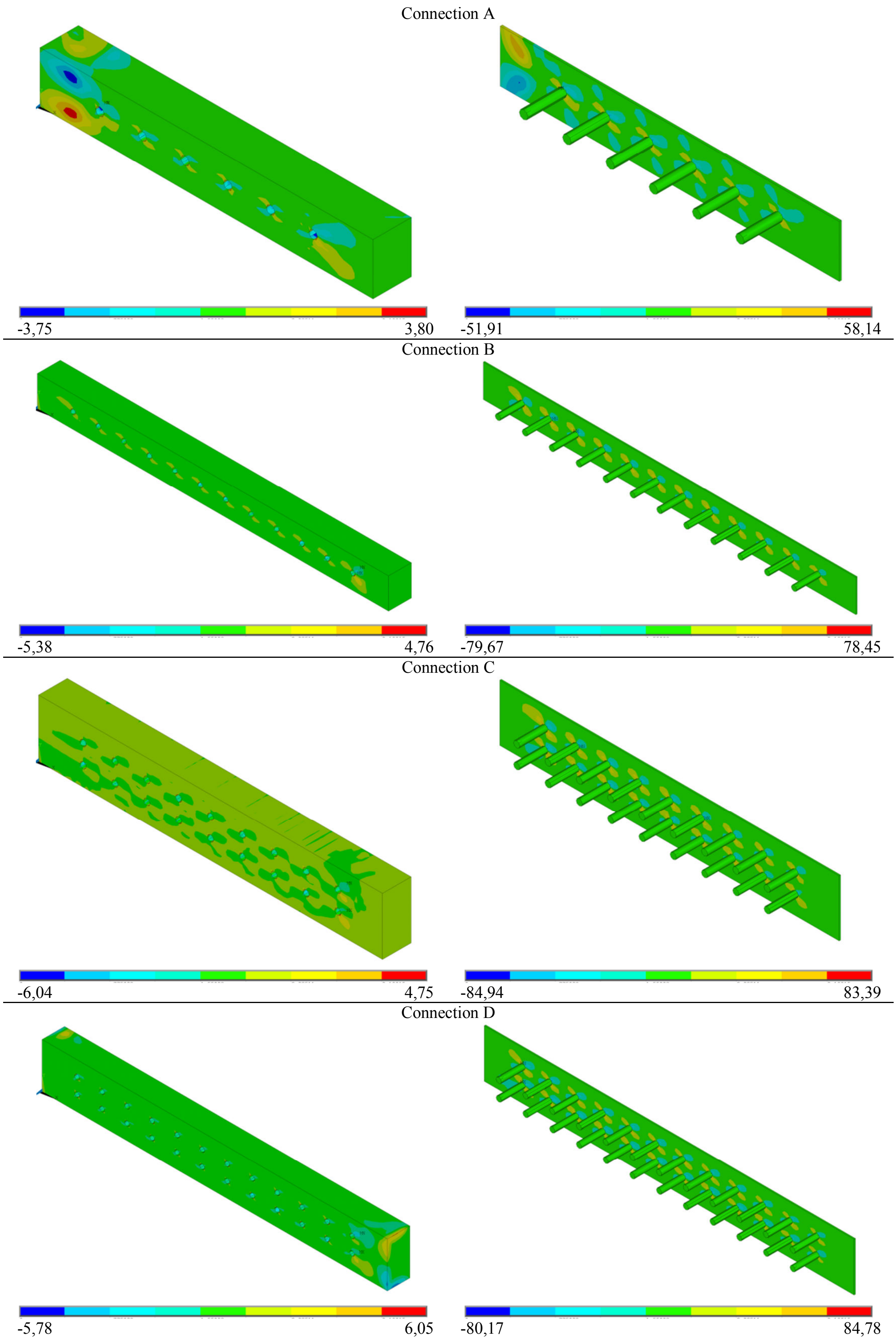

Fig. 3 - On the left, shear stress on wood element. On the right, shear stress on steel plate and dowels, MPa.

CONCLUSIONS

This work present different methodologies applied to the design of a typical W-S-W connection used in building construction. A procedure with all analytical and simplified equations were presented to assess the cross-section and all dimensions for an applied tensile load. In addition, a numerical program using the finite element method was implemented to produce different simulations focused on mechanical analysis, in order to obtain the maximum critical load and to determine the maximum load capacity of each fastener. The comparison of results showed a good agreement with the analytical calculations from standards. These numerical simulations are very relevant; the models can be used for verification in other type of W-S-W connections.

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