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INCLINED SCREW CONNECTIONS WITH INTERLAYERS: BEAM ON FOUNDATION NON-LINEAR MODELLING

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ABSTRACT: Self-tapping screws, thanks to the speed and ease of installation have become more and more popular in the last 25 years. Slip modulus and strength increase when the screw axis is inclined with respect to the normal to the sliding plane, however, in this configuration screw is subjected to axial and shear force, together with bending moment. Moreover, interlayers having poor mechanical properties are often inserted between main connected members to ensure human comfort in the buildings or because it is required by the structural system. The complex interaction between axial and transversal behaviour of inclined screws may not be fully considered by some of the simplified models in literature and codes, in this paper the behaviour of steel-to-timber connection is experimentally assessed and a finite element model of non-linear beam on foundation is validated. Experimental results are compared with the results of finite element analysis and the with Eurocode 5 model results.

KEYWORDS: Inclined screws, Load-bearing capacity, Timber-to-timber connection, Eurocode 5, Friction.

1 INTRODUCTION

Self-tapping screws are commonly used in timber-to-timber, timber-to-concrete, and timber-to-steel connections and are well suited for use in composite floors and beams. They can be easily inserted at an angle with respect to the normal to the sliding plane. In this configuration their axial resisting mechanisms can be exploited. Stiffness and strength of inclined screws can be 5 to 10 times the stiffness and strength of screws perpendicular to the sliding plane. While for screws perpendicular to the sliding plane the ultimate force is usually reached at the conventional displacement of 15 mm with a ductile behaviour, for inclined screws the failure displacement is between 1 mm and 5 mm depending mainly on the inclination angle of the screw and the connection fails mainly due to screw withdrawal or due to screw failure. However, when the screw is inclined, it is simultaneously subjected to axial force, shear force and bending moment. This strong coupling between the axial and the transversal behaviour of the screw makes difficult to predict the actual connection behaviour by means of simplified models.

The connection mechanical behaviour becomes even more difficult to model when an interlayer having structural or non-structural role is present. Often polyurethane interlayers are used for soundproofing and OSB interlayers are common in light-frame buildings.

The interlayer can be considered rigidly connected when it is glued to the main timber member. The interlayer is weakly connected when the secondary connection between the interlayer and the main timber member has negligible strength and stiffness compared to the main connection. It is the case of staples, nails and small diameter and length screws. Examples of interlayers not connected are soundproofing interlayers.

It is known that the interlayer affects the slip modulus of connections as highlighted in [1], however less studies have been conducted on the capacity of connections with interlayers.

Eurocode 5 design method for strength calculation of dowel type fastener connections is based on the Johansen's work [2]. According to European standards, the load-bearing capacity of a screw simultaneously subjected to shear and axial stress, as in the case of inclined screws connections, is given by a quadratic combination of the stress-strengths ratios for transversal and axial directions [3]. This design model might highly underestimate the strength of connections with inclined screws as highlighted by Tomasi et al. in [4].

Bejtka I. and Blaß H.J. in [5] extended the Johansen's yield theory accounting for the withdrawal behaviour of the screws. However, the complex interaction between axial and transversal stresses of inclined screws may not be fully considered in determining the plastic properties of the screws.

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In recent years, several advanced three-dimensional numerical models have been proposed to study the behaviour of connections made of threaded fasteners embedded in timber. The complex screw-timber interaction, due to the presence of thread, has been modelled using various techniques ranging from the reproduction of the actual thread geometry [6] to the use of cohesive contact with damage evolution in conjunction with a fictitious material that wraps the screw and models a complex medium where steel and timber interact [7].
In order to avoid the detailed three-dimensional modelling of the screw using solid elements, some authors developed an approach based on beam to-solid coupling [8].
Also, empirical models for capturing load-slip behaviour joints with dowel-type fasteners were proposed [9, 10].
Another approach to the problem is represented by Beam-On-Foundation (BOF) modelling. According to this method, fasteners are numerically modelled as elastoplastic beams on a nonlinear foundation. BOF modelling has been used to reproduce the hysteretic behaviour and failure mechanisms of timber joints with dowel-type fasteners perpendicular to the sliding plane [11, 12].
In this paper, a BOF model capable of taking into account of the interaction between moment, shear and normal force which may lead to metal fastener yielding at loads below those predicted by the EYM is proposed. The model is able to reproduce the following mode of failure: timber crushing, screw withdrawal and screw yielding. The model also accounts for friction on the sliding plane and interlayer.
The outcomes of an experimental investigation conducted on various inclined screws timber-to-steel connection configurations with or without soundproofing and OSB interlayers are herein described and discussed. These results have been used to validate a finite element modelling approach suitable for describing the ultimate conditions.
The experimental results are also compared with the Eurocode 5 model results.

2 EXPERIMENTAL INVESTIGATION

The experimental campaign involves timber-to-steel connections with screw inclined at 45° inserted in glue laminated timber of strength class GL24h and UPN 100 steel profiles (Figure 1). The screws are self-tapping fully-threaded screws with a diameter of 9 mm and length of 240 mm or 140 mm. The characteristic ultimate stress of the screw is $f_{u,k}$ = 1000 N/mm^2. A special washer is used to restrain the screw head in the tight-fitting oval shape hole in the UPN 100 profile (Figure 2). Washers with an insertion angle α = 45° are common for inclined positioned screws in steel-to-timber joints. In this case the washer has the role of replacing the countersunk drill holes in the steel plate by more economically producible slots. However, due to their particular geometry, a part of the screw near the sliding plane is left free of bending. The soundproofing interlayers are made of polyurethane and are 6 mm thick and 100 mm wide whilst OSB interlayers are 22 mm thick.
Four different configurations have been considered:

- C-45-R: reference configuration
- C-45-S35: with soundproofing interlayer
- C-45-O: with OSB interlayer
- C-45-RL: reduced length of the screw

The materials and the geometries of the configurations are summarised in Table 1.

Table 1: *Configurations details*

Configuration	Interlayer	Thickness (mm)
C-45-R	-	-
C-45-S35	Polyurethane	6
C-45-O	OSB	22
C-45-RL	-	-

A detail of sliding plane between the UPN profile and the glulam member with a soundproofing intermediate layer is showed in Figure 1.

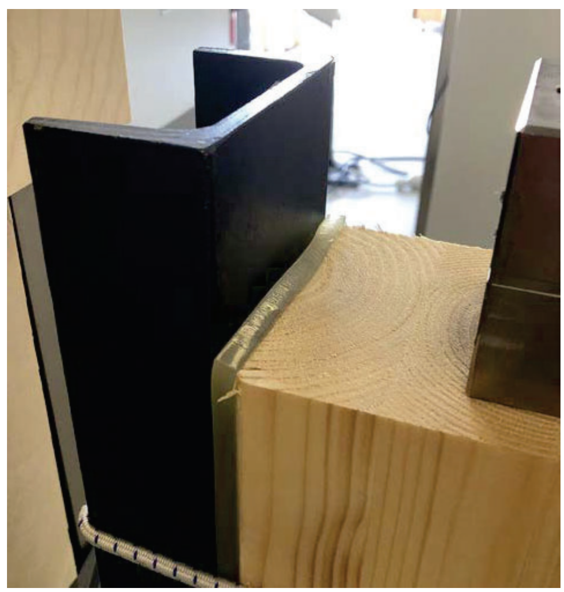

Figure 1: *Test setup detail: shear plane with soundproofing interlayer*

2.1 TEST METHODS

The typical test consisted in a standard symmetric push-out test. The specimen, consisting of 3 members and therefore 2 shear planes with a single screw per shear plane, is brought to failure by pushing the central member. The relative displacement between members has been measured through a LVDT (Linear Variable Differential Transformer). Due to the eccentricity between the load applied to the central member and the reaction that the test plane exerts on the lateral members, in the standard configuration for push-out tests the members tend to

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separate during the test. For this reason, side members were clamped with support not able to induce pre-stress. No predrilling was applied.

The general principles for the determination of strength and deformation characteristics of joints made with mechanical fasteners are described in the European standard EN-26891 [13]. The procedure requires the knowledge of an estimated maximum load F_{est} to be determined on the basis of experience, calculation or preliminary tests, and should be adjusted if, during the execution of the tests, the mean value of the maximum load of the tests already carried out deviates by more than 20% from the estimated value.

The chosen loading procedure is divided into the following phases:

- force controlled loading from 0.0 F_{est} to 0.4 F_{est};
- force controlled holding at 0.4 F_{est} for 30 s;
- force controlled unloading from 0.4 F_{est} to 0.1 F_{est};
- force controlled holding at 0.1 F_{est} for 30 s;
- force controlled loading from 0.1 F_{est} to 0.7 F_{est};
- displacement controlled until failure or 15 mm.

The speed in the displacement-controlled phase has been set equal to 0.06 mm/s and the loading speed in all other phases has been calculated to achieve 15 mm of relative displacement in 12 min resulting in a loading speed comprised between 0.03 kN/s and 0.20 kN/s depending on the estimated maximum load.

Figure 2: *Washer for timber-to-steel connections*

2.2 RESULTS AND DISCUSSION

From the recorded measurements, the initial slip modulus, the slip modulus, the ultimate slip modulus and the maximum load have been determined.

To calculate the stiffness and ultimate displacement values net of displacement components related to local crushing at the member ends, the LVDT displacement measurements were used.

The initial slip modulus has been determined with the following definition:

$$k_i = \frac{0.4F_{max}}{\nu_{04}} \tag{1}$$

Where F_{max} is the maximum force measured up to a relative slip of 15 mm and ν_{04} is the relative slip in the first loading phase corresponding to the considered load.

The slip modulus has been determined with the following definition:

$$k_s = \frac{0.4F_{max} - 0.1F_{max}}{\nu_{04} - \nu_{01}} \tag{2}$$

Where ν_{04} and ν_{01} are the relative slip in the loading phase corresponding to the considered loads.

Figure 3: *Experimental failure modes: tensile-bending combined failure and withdrawal failure.*

The initial slip modulus and the slip modulus are summarized in Table 2. Significant reductions in slip modulus were observed for both the soundproofing interlayer and OSB interlayer.

The reference configuration C-45-R, the configuration with soundproofing interlayer C-45-S35 and the configuration with the OSB interlayer C-45-O showed a failure due to the screw failure (Figure 3) or due to screw withdrawal. The configuration with reduced length screws showed failure due to the screw withdrawal.

The average of the maximum load registered for each configuration are showed in the plot of Figure 5.

The insertion of the interlayer led to a reduction of 10% and 17% in strength in the cases of soundproofing interlayer and OSB respectively (Figure 5).

The configuration with screws with reduced length has 51% less strength than the reference connection (Figure 5).

Table 2: *Results in terms of stiffness referred to a single screw.*

Configuration	$k_{i,m}$ (kN/mm)	$k_{s,m}$ (kN/mm)
C-45-R	9,1	10,5
C-45-S35	9,1	8,1
C-45-O	4,6	5,8
C-45-RL	10,6	14,5

3 FINITE ELEMENT MODEL

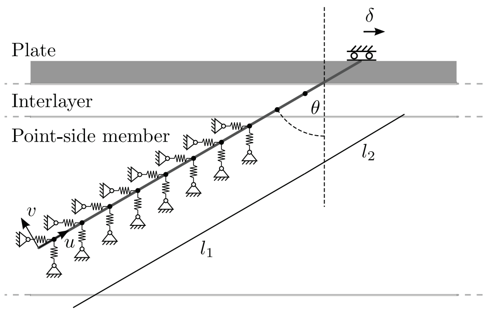

Figure 4: *Finite element model*

3.1 DESCRIPTION

The problem of the determination of the capacity of connections with inclined screws is reduced assuming a beam behaviour for the screw and describing its interaction with timber by 2-node connector elements (Figure 4).

Common screw types have negligible section variations over the screw length. Small section increments are usually made in areas without threads thus causing a partial compensation of the geometric properties. In determining the section properties, the circular section is assumed of diameter equal to 1.1 times the screw core diameter d_c as suggested for transversal capacity calculation in Eurocode 5 [3].

The beam elements used to model the screw are mono-dimensional and linear with section properties integrated during the analysis to account for the steel non-linear behaviour. An elastic-perfectly plastic isotropic behaviour is assumed for the screw steel. The Young's elasticity modulus is E_s = 210000 N/mm^2 and the mean yielding strength is f_y = 1200 N/mm^2. The reaching of high failure stress is granted by the cold forming during the production process.

The interaction between the screw and the surrounding timber along l_1 is modelled through a system of discrete connectors:

- A series of springs parallel to the sliding plane having elastic-perfectly plastic behaviour [14, 15];
- A series of springs perpendicular to the sliding plane having elastic-hardening behaviour and friction parallel to the sliding plane [14, 15];
- A rigid contact with damage between the common node between parallel and perpendicular springs and the node on the beam schematizing the screw (black dots in Figure 4).

The series of springs parallel and perpendicular are non-linear springs which schematize the embedment interaction in the grain direction and in the perpendicular to the grain direction.

Embedment is one of the fundamental load transfer mechanisms in a dowel-type connection. Due to the scale effect, the timber mechanical properties in embedment are significantly different from the mechanical properties that describe the macroscopic behaviour of a timber element. Therefore, proper tests had to be defined in order to provide suitable parameters for mechanical modelling. For a dowel-type fastener, the foundation modulus and the embedment strength can be experimentally determined via test according to EN 383.

In the model, the stiffness of each connector element parallel and perpendicular to the sliding plane has been assumed as:

$$\mathrm{K_{pa}} = \mathrm{k_h} \mathrm{d} \mathrm{l_m} \cos\theta \tag{3}$$

$$\mathrm{K_{pe}} = \beta \mathrm{k_h} \mathrm{d} \mathrm{l_m} \sin\theta \tag{4}$$

where $\mathrm{k_h}$ is the stiffness per unit of length of the beam and have been assumed as for the regression formula provided in [1] derived by interpolation of embedment test:

$$\mathrm{k_h} = (-147.8 + 30.9\rho^{0.46}\mathrm{d}^{-0.32})d \tag{5}$$

$\beta = 0.5$, ρ is the timber density, d is the screw thread outer diameter and $\mathrm{l_m}$ the length of the element between two connectors.

The yielding force of parallel to grain connector has been assumed as:

$$\mathrm{F_{y,pa}} = \mathrm{f_{h,0}} \mathrm{d} \mathrm{l_m} \cos\theta \tag{6}$$

$$\mathrm{F_{y,pe}} = \mathrm{f_{h,90}} \mathrm{d} \mathrm{l_m} \sin\theta \tag{7}$$

and the ultimate force in the direction perpendicular to the grain at a displacement equal to 2d has been assumed as:

$$\mathrm{F_{u,pe}} = \Omega \mathrm{F_{y,pe}} \tag{8}$$

where Ω has been assumed 1.72 as found by Schweigler et al. in [14, 15] where a strong hardening behaviour in the direction perpendicular to the grain is observed.

In connections with inclined screws in tension, a compression in the direction perpendicular to the sliding plane develops. This compression force generates a friction force parallel to the sliding surface. According to literature this contribution leads to an increase in slip

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modulus and strength. To account for this effect connectors perpendicular to the sliding plane are defined as to develop a transversal force proportional to the axial force by means of the friction coefficient. The friction coefficient has been set to $\mu = 0.5$ for connections without interlayer or with OSB interlayer, while $\mu = 0.7$ has been chosen to reproduce the timber-polyurethane frictional behaviour.

The embedment strengths have been assumed as in the Eurocode 5 [3]:

$$f_{h,\alpha} = \frac{f_{h,0}}{k_{90,e} \sin^2 \alpha + \cos^2 \alpha} \tag{9}$$

where $f_{h,0}$:

$$f_{h,0} = 0.082(1 - 0.01 d_{ef}) \tag{10}$$

and where d_{ef} is the effective screw diameter and according to Eurocode 5 [3] can be assumed as 1.1 the screw core diameter d_c. α is the force to the grain angle and $k_{90,e}$ can be assumed as $1.35+0.015d_{ef}$.

The mechanical behaviour of axially loaded screws, and specifically the withdrawal behaviour depends on the interaction along the axial screw direction between the screw thread and the surrounding timber. The withdrawal failure has to be regarded as a local failure of the timber surrounding the screw.

The withdrawal behaviour is modelled through rigid-plastic connectors whose properties are defined according to the findings of Blaß et al. [16] and [17]. According to the formulation proposed by Blaß et al., the withdrawal failure stress can be estimated as follows:

$$f_{w,\alpha} = \frac{f_{w,0}}{k_{90,w} \sin^2 \alpha + \cos^2 \alpha} \tag{11}$$

where $f_{w,0}$:

$$f_{w,0} = 0.6 d^{-0.5} l_{ef}^{-0.1} \rho_m^{0.8} \tag{12}$$

and where d is the screw thread outer diameter, α is the force to the grain angle and $k_{90,w}$ is 1.2.

The associated withdrawal failure force per-connector is:

$$F_{u,E_{tr}} = f_{w,\alpha} \pi d l_m \tag{13}$$

A linear damage evolution with ultimate displacement of 4 mm is assumed to reproduce the withdrawal failure according to the findings of Bedon et al. [7] based on detailed three-dimensional finite element models and experimental outcomes of [17].

The connectors are restrained to external hinges capable of preventing translations only.

Along l_2, that is the length of the part of the screw embedded into the interlayer and the part of the screw free of bending near the sliding plane, no connectors has been considered. The part of the screw free of bending is the section comprised in the UPN web thickness. Therefore, the l_2 of the experimental case C-45-R is greater than zero, despite the absence of interlayer.

The translation perpendicular to the sliding plane and the rotation of the head-end of the screw are restrained to reproduce the clamping effect of the washer (Figure 2). At failure, contact between components is established and the washer behaves as a rotation restraint.

The relative displacement between the UPN profile and the timber members is reproduced by an imposed displacement applied to the screw head, parallel to the sliding plane (Figure 4). Therefore, a typical simulation consisted of a static incremental, displacement-controlled analysis.

3.2 VALIDATION

As highlighted in Figure 5 the finite element model tends to slightly underestimate the failure load, but it is overall quantitatively accurate. Percentage scatters are between -17% and -3%.

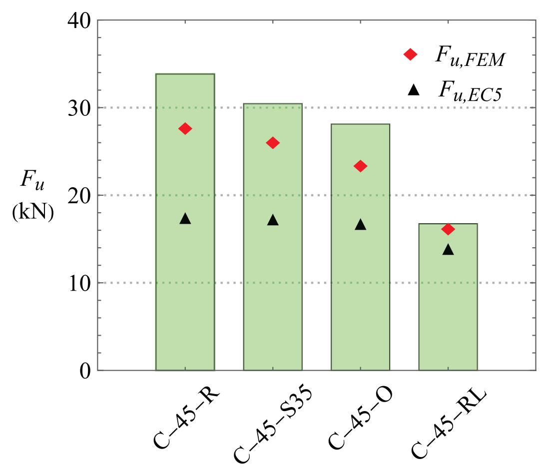

Figure 5: *Experimental (bars) and predicted failure loads with finite element model and Eurocode 5 model (markers).*

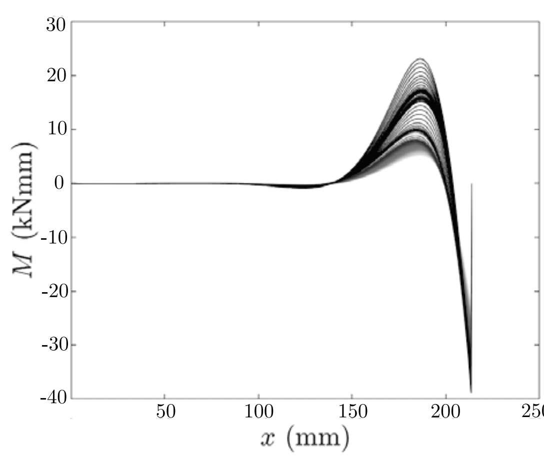

Figure 6: *Bending moment evolution in configuration C-45-R. Darker colour for higher connection slip.*

The plot in Figure 6 shows the bending moment diagram evolution for increasing applied displacement. When the maximum load is achieved, a plastic hinge forms in the head-end of the screw. The bending moment becomes null due to full plasticization of the section caused by the combination of axial force and bending moment.

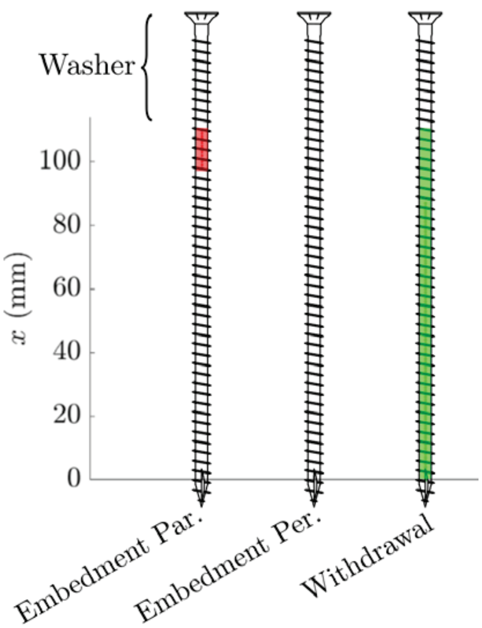

Figure 7: *Failure mode of configuration C-45-RL. Connectors in plastic range position.*

In Figure 7 the connector elements parallel to the sliding plane and the withdrawal connectors that reached plasticization at connection failure are highlighted. No connectors perpendicular to the sliding plane are found to be in plastic range at failure. For the reduced length configuration, a clear withdrawal failure is observed in the finite element model as well as in the experimental investigation. Embedment failure is confined to a zone of negligible extent.

3.3 PARAMETRIC STUDIES

The finite element model has been used to perform parametric studies. The influence of soundproofing interlayer is investigated (μ = 0.7).

The first parametric study is conducted by varying l_2, the length of penetration of the screw into the interlayer plus the part of the screw free of bending, while maintaining the screw length constant (l = 200 mm and l = 100 mm). It can be observed from the plot in Figure 8 that the strength of the connection remains almost unvaried until l_2 reaches 20 mm and 10 mm in the case of 200 mm and 100 mm screw respectively. A small increase in strength is registered between the case of no-interlayer and interlayer length of penetration equal to 5 mm. This is due to the increased friction coefficient granted by the soundproofing interlayer. Moreover, the reduction in strength is more pronounced for shorter screw than for longer screw (-59% and -31% respectively).

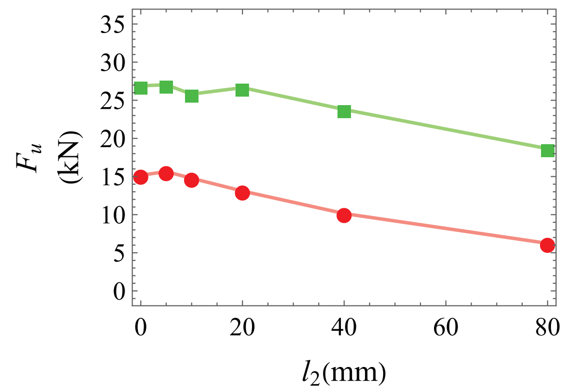

Figure 8: *Interlayer influence on FEM predicted strength for constant screw length: l = 200 mm (green) and l = 100 mm (red).*

The second parametric study is conducted varying the length l_2 while maintaining the screw length constant (l_1 = 200 mm and l_1 = 100 mm). It can be observed from the plot in Figure 9 that the strength of the connection remains almost constant. A small increase in the ultimate force can be observed for increasing l_2. This increase is caused by the increase of the friction component.

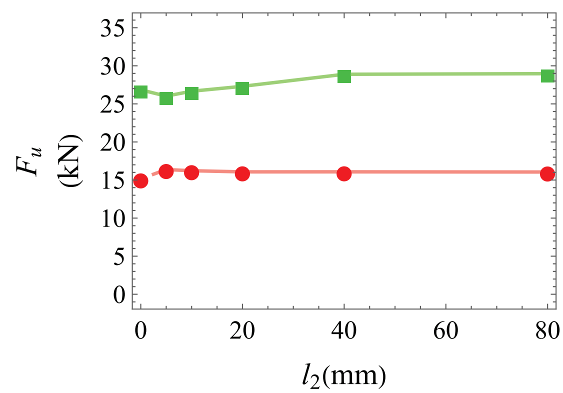

Figure 9: *Interlayer influence on FEM predicted strength for constant length of penetration into the main timber member: l_1 = 200 mm (green) and l_1 = 100 mm (red).*

4 EUROCODE 5 MODEL

The European Yield Model (EYM) is a commonly accepted procedure to calculate the capacity of laterally loaded connections with dowel type fasteners. The EYM is described in the Eurocode 5 [3] and it is based on the Johansen yield theory [2]. According to Johansen yield theory it is assumed that steel and timber exhibit a rigid-plastic behaviour. Different failure modes are identified depending on the degree of restraint that the steel plate has

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on the fastener. According to Johansen theory [2] the transversal strength of dowel-type fastener connecting a thick plate to a timber member is given by:

$$R_{tr} = \min \begin{cases} f_h\, l_1\, d_{ef} \ \text{Embedment} \\ f_h l_1 d_{ef}\left(\sqrt{2 + \dfrac{M_y}{f_h d_{ef} l_1^2}} - 1\right) \ 1\ hin. \\ 2.3\sqrt{M_y f_h d_{ef}}\ 2\ hin. \end{cases} \tag{14}$$

In the EYM the rope effect can also be considered to account for the friction contribution induced by the force normal to the sliding plane generated by the deformation of the fastener.

Regarding the axial behaviour, two more failure mechanisms must be considered:

$$R_{ax} = \min \begin{cases} f_w l_1 d \min\left(\dfrac{d}{8}, 1\right) \ \mathit{Withdrawal} \\ f_u \pi \dfrac{d_{ef}^2}{4} \ \mathit{Tensile} \end{cases} \tag{15}$$

According to the current Eurocode 5 [3], a quadratic interaction between transversal and axial capacity should be considered irrespective to the combined failure modes:

$$\left(\frac{F_{tr}}{R_{tr}}\right)^2 + \left(\frac{F_{ax}}{R_{ax}}\right)^2 \le 1 \tag{16}$$

4.1 RESULTS COMPARISON

Eurocode 5 model underestimates the capacity of all experimental configuration, despite the mean values of input parameters has been considered (Figure 5). EYM shows slightly more accurate in the configuration characterized by a lower penetration length. The scatters between EYM prediction and experimental results are between -48% and -16%.

5 CONCLUSIONS

The connection with inclined screws and interlayer exhibits a more pronounced reduction in stiffness (23% to 45%) than in strength (10% to 17%).

The quadratic combination approach prescribed by Eurocode 5 proved to be too conservative leading to an underestimation of the strength up to 48% while the proposed numerical model can predict the failure load considerably more accurately for the tested configurations (percentage scatters between 17% and -3%).

The proposed finite element model represents a valid alternative to complex three-dimensional models for the study of connections with inclined screws as it accurately describes the experimentally assessed behaviour in terms of both failure mode and failure loads. The reduced computational cost, which is associated with the reduced number of degrees of freedom, makes it suitable for carrying out comparisons and parametric analyses.

Sensitivity studies had demonstrated that the insertion of an interlayer can appreciably affect the failure load of the connection only if the sum of the length of penetration of the screw into the interlayer and the length of the screw free of bending is at least 1/10 of the screw length. Increasing the screw length to compensate for the loss of effective length into the timber member can completely compensate for the interlayer presence.

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