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PUSH-OUT TESTS ON TIMBER-TO-TIMBER COMPOSITE (TTC) SYSTEMS MADE OF HARDWOOD

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ABSTRACT: This paper presents the experimental results of mechanical test on fully threaded inclined screws when combined with different types of hardwood. Push-out specimens with symmetrical configuration were realized using glulam beams and boards made of three different species of Italian hardwood such beech, chestnut and beech-silver fir which constituted respectively the central and side members of the samples. Short term tested under quasi-static monotonic loading were carried out according to EN 26891. The main aim was to define the fasteners' stiffness, strength, static ductility and failure modes and so, to assess their goodness for the timber-to-timber composite (TTC) floor use. Outcomes are presented and discussed. Theoretical models proposed in literature were adopted to estimate the ultimate force and slip modulus to be compared with experimental results. Screws in hybrid beech-silver fir demonstrated significantly higher ultimate load, stiffness, and yield force than those in homogeneous beech and chestnut. The comparison with theoretical models highlighted an overall underestimation of load bearing forces and an overestimate of the slip modulus for fully hardwood components.

KEYWORDS: timber, timber-to-timber composite (TTC) floor, hardwood, inclined screws, push-out test

1 – INTRODUCTION

The use of timber as building material has become extremely widespread in the last years due to its excellent structural properties, environmental sustainability, high prefabrication with consequent reduction in cost and construction time and the light weight compared with masonry and concrete, which allows a significant decrease of seismic actions[1]. Nevertheless, not all the timber species are equally used for structural purposes, since most of the engineered wood products (EWPs) are made of fir and/or spruce. Other species, in particular hardwoods, are underutilized or neglected. The reasons are multifactorial, but they are not due to lower mechanical performances or durability features. Luckily, this trend is destined to change in the coming years since the use of local timber has been recognized and encouraged all over the Europe to reduce the CO_2 emitted during the transportations, to improve local economies and to provide alternative supply sources. Many researches have been carried out to investigate the mechanical properties of timber species different from the commercial ones as beech, birch, and bamboo, highlighting excellent load-bearing properties. Glulam beams made of beech demonstrated to have excellent strength and stiffness properties with consequent smaller deflections compared with the corresponding spruce ones. Chestnut, which is one of the most popular and appreciated species in the Mediterreanean areas, is a well-promising species for structural applications. It has been exposed to a qualification process: European Technical Approval (ETA)

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for the "Uso Fiume" beams [2] and machine strength grading implementation and it is currently under investigation for the production of EWPs. In this framework, the use of glulam beams made of hardwood to realize timber-timber composite (TTC) floors would represent a valuable choice.

2 – BACKGROUND

The solution of TTC floors represents a well-established construction technique, which is consistently used for both the retrofitting of existing timber floors and the realization of new diaphragms. For TTC floors, the connection system is a fundamental part, and thus different types of connectors have been proposed and studied in recent years. Most of the available research carried out to investigate the fasteners 'performance for TTC systems implied the use of commercial EWPs, which are mostly made of softwood. Nevertheless, due to the great differences in terms of mechanical and physical properties among hardwoods and softwoods, it is necessary to perform further analyses to define the fasteners' performances in TTC made with hardwoods. Push-out tests are usually performed to determine strength and deformation characteristics of joints made with mechanical fasteners and the reference standard is EN 26891[3]. In this paper, the mechanical behaviour of screws for TTC systems loaded in shear-tension was investigated for the use on glulam beech, chestnut and hybrid beech-Silver fir, according to the aforementioned standard EN 26891[3].

3 – PROJECT DESCRIPTION

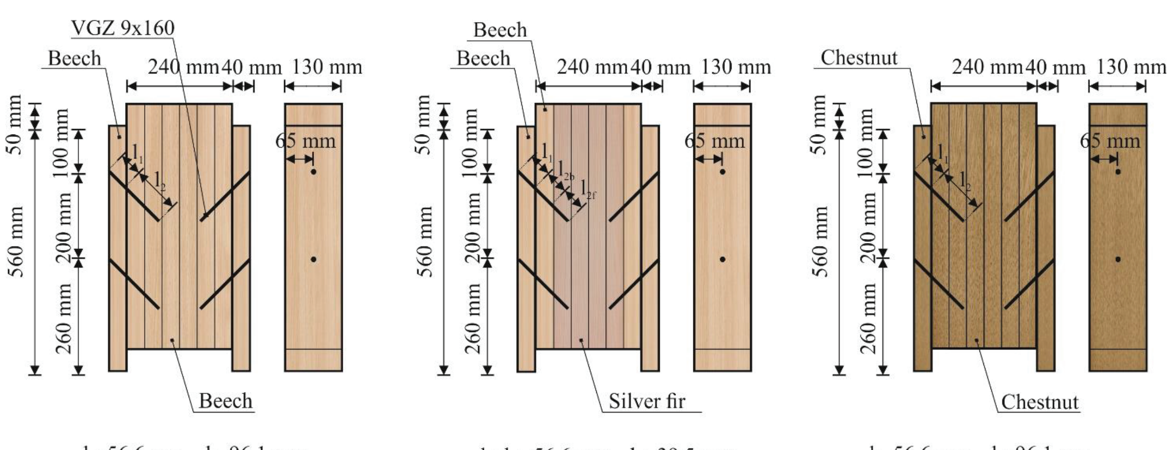
The experimental campaign was carried out at the laboratory of the Department of Civil, Construction-Architectural and Environmental Engineering (DICEAA) of the University of L'Aquila and consisted of push-out tests. The double-shear layout, which is the most widespread employed in push-out tests, was chosen for the specimens and consists of a central timber element flanked by two side elements symmetrically disposed. In our case, the central elements of push-out specimens were realized by using glulam beam portions achieved by cutting beech, beech-Silver fir and chestnut beams manufactured in the framework of a wider experimental campaign aimed at mechanically characterize them in bending and shear. The specimens 'side elements were boards made of beech and chestnut coming from the same batch of boards classified and employed to manufacture the beams. Fully threated VGZ 9 x 160 mm screws [4,5] supplied by Rothoblaas were investigated in 45° shear-tension configuration (rather than in X-formation) to enable exploitation of the beneficial orientation of the screws.

Fig.1 summarizes the main geometrical features of both the screw and three series of specimens, designated with the name: "HOM", "HYB", and "CHES" respectively for homogeneous beech, hybrid beech-Silver fir and homogeneous chestnut configuration. Each series consists of five repeated samples. Table 1 presents the measured densities of the three species, which are used in the subsequent calculations.

Table 1 Density of timber species

Mechanical features		Beech	Silver fir	Chestnut
ρ_m	*[kg/m³]*	704	442	547
St. dev	*[-]*	39	22	37
ρ_K	*[kg/m³]*	621	395	469

ρ_m is the mean density, ρ_k is the characteristic density evaluated according to EN 14358 [6]



a) HOM Series **b) HYB Series** **c) CHES Series**

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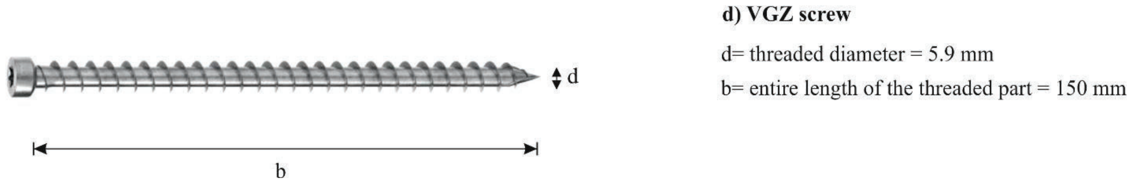

Figure 1. Schematic representation of specimen series and geometrical features

4 – EXPERIMENTAL SETUP

The test procedure was developed in accordance with the EN 26891 [3]. As required, an estimated maximum load F_{est} was determined for each of the three configurations. Then, the load was applied up to $0.4F_{est}$ and maintained for 30 s. The load was then reduced to $0.1F_{est}$ and maintained for 30 s. Thereafter the load was increased until the slip of 30 mm was reached in accordance with the EN 12512 [7] but the setup was designed to reach a maximum displacement of 30 mm.

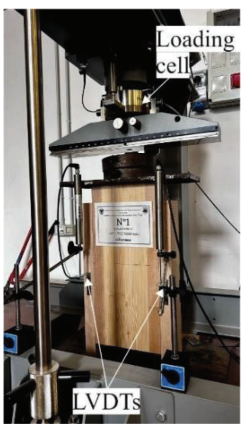

Figure 2. Experimental setup and instrumentation

The load was introduced by a Controls Uniflex 300 flexural frame (300 kN cap.) through a vertical rod hydraulically controlled and measured by a high precision strain gauge load cell (Fig.2). A constant slip rate of 0.06 mm/s was adopted (it was kept in the range between 0.02 mm/s and 0.2 mm/s recommended by the Eurocode 5 [8]). The specimen is equipped with two 100 mm travel LVDTs displacement transducers to measure the vertical slip between the central element and the sides (Fig. 2). Furthermore, the cross-head displacement was recorded with another 100 mm LVDT. The recording was done continuously with a frequency rate of 20 Hz via a multi-channel data recording and control device (Controls Automax Multitest).

4.1 CALCULATION METHODS OF THE MECHANICAL PARAMETERS OF CONNECTIONS

The standards adopted as reference for the evaluation of the connection performance parameters (yield point, secant stiffness, ultimate conditions and static ductility) were EN 12512 [7] and EN 26891[3]. The slip modulus K_s of the connections (corresponding to the slip modulus K_{ser} provided by EN 1995-1-1 [8]) was calculated by means of the following equation (1):

$$K_s = \frac{0.4F'_{max} - 0.1F'_{max}}{v_{0.4} - v_{0.1}} \quad (1)$$

Where $v_{0.1}$ and $v_{0.4}$ are the connection slips (evaluated for each specimen) corresponding to the load levels of $0.1F'_{max}$ and $0.4F'_{max}$ respectively; F'_{max} is the mean value of the maximum load recorded for each specimen of the same series: $F'_{max,i}$ (consistently with EN 26891 [3] excluding values that deviated by more than 20% from the mean). For each testes sample, $F'_{max,i}$ is equal to the actual maximum load $F'_{max,R}$ when the corresponding slip value was less than 15 mm, otherwise the load corresponding to a 15 mm slip F_{15} was used [3]. According to EN 12512 [7], the yield point (F_y, v_y) was determined, taking into account the pronounced non-linear behaviour of the load-slip curves. The ultimate slip v_u corresponds to the attainment of the first of the following conditions: *i)* failure of the specimen, *ii)* slip at 0.8 $F'_{max,R}$ times on the descending branch, and *iii)* a slip value of 30 mm [7]. The ductility D is calculated as the ratio between ultimate slip and yield slip according to [7].

5 – THEORETICAL CALCULATIONS

5.1 LOAD-BEARING CAPACITY

The inclined screws load transfer relies not only on the bending capacity of the screw and the resistance of the wood to joint, but also on the extraction capacity of the fasteners and the friction between the wooden elements induced by the geometrical configuration [9]. The failure modes expected for inclined screws could involve the embedment of the lateral or central timber member or both (named as “a”, “b” and “c” respectively). The formation of one plastic hinge on the screw within the central member (“d” mode) or the lateral member side (“e” mode). The formation of two plastic hinges on the screw (both on the lateral and central member, named “f” mode).

A theoretical model for the estimation of the screw capacity inserted at an angle α to the shear plane (0°≤ α ≤90°) was proposed by Bejtka and Blaß [10]. This model was adopted to theoretically estimate the connection capacity and slip modulus under the following assumptions: for those modes where the failure mechanism is mainly governed by the strength properties of just one of the two timber elements (i.e. modes “a”, “b”, “d”, “e”), the axial capacity of the fastener was calculated by considering only the screw-portion within the involved element.

For failure modes “a” and “d”, the axial capacity is the minimum between the tensile strength of the shank and the head pull-through capacity. For mode “b” and “e”, the axial capacity is the minimum between characteristic tensile strength of the screw ($R_{tens,k}$) and the characteristic thread withdrawal resistance ($R_{thread,k}$). Since for fully threated screws, the pull-through capacity of the head is less relevant than the withdrawal capacity also for failure modes “a” and “d”, the axial capacity is estimated ad for mode “b” and “e”.

The characteristic load-carrying capacity $F_{max,k,th}$ was calculated as the minimum value obtained from the following expression (2) to (7):

$$R_a = R_{ax,k,1} \cdot \cos\alpha + f_{h,1,k} \cdot l_1 \cdot d_1 \cdot \sin\alpha \quad (2)$$

$$R_b = R_{ax,k,2} \cdot \cos\alpha + f_{h,2,k} \cdot l_2 \cdot d_2 \cdot \sin\alpha \quad (3)$$

$$R_c = R_{ax,k}\,(\mu \cdot \sin\alpha + \cos\alpha) + \frac{f_{h,1,k} \cdot l_1 \cdot d_1}{1+\beta} \cdot \left(1 - \frac{\mu}{\tan\alpha}\right) \cdot \left[\sqrt{\beta + 2\beta^2\left[1 + \frac{l_2}{l_1} + \left(\frac{l_2}{l_1}\right)^2\right] + \beta^3\left(\frac{l_2}{l_1}\right)^2} - \beta\left(1 + \frac{l_2}{l_1}\right)\right] \quad (4)$$

$$R_d = R_{ax,k,1}\,(\mu \cdot \sin\alpha + \cos\alpha) + \frac{f_{h,1,k} \cdot l_1 \cdot d_1}{2+\beta}\left(1 - \frac{\mu}{\tan\alpha}\right)\left[\sqrt{2\beta(1+\beta) + \frac{4\beta \cdot (2+\beta) \cdot M_{y,k} \cdot (\sin\alpha)^2}{f_{h,1,k} \cdot d_1 \cdot l_1^2}} - \beta\right] \quad (5)$$

$$R_e = R_{ax,k,2}\,(\mu \cdot \sin\alpha + \cos\alpha) + \frac{f_{h,1,k} \cdot l_2 \cdot d_2}{1+2\beta}\left(1 - \frac{\mu}{\tan\alpha}\right) \cdot \left[\sqrt{2\beta^2(1+\beta) + \frac{4\beta \cdot (1+2\beta) \cdot M_{y,k} \cdot (\sin\alpha)^2}{f_{h,1,k} \cdot d_2 \cdot l_2^2}} - \beta\right] \quad (6)$$

$$R_f = R_{ax,k}\,(\mu \cdot \sin\alpha + \cos\alpha) + \left(1 - \frac{\mu}{\tan\alpha}\right) \cdot \sqrt{\frac{2\beta}{1+\beta}}\,\sqrt{2 \cdot M_{y,k} \cdot f_{h,1,k} \cdot d_1 \cdot (\sin\alpha)^2} \quad (7)$$

Being

- α the fastener-to-shear plane angle;
- μ the friction coefficient for timber-to-timber surfaces assumed as equal to 0.25;
- l_i the penetration length of the screw inserted into element;
- d_i the effective diameter of the screw part inserted into timber element;
- $f_{h,i,k}$ the characteristic embedment strength of the relative timber element;
- $\beta = f_{h,2,k}/f_{h,1,k}$
- $M_{y,k}$ the characteristic yield moment of the screw
- $R_{ax,k,1}$= min{$R_{thread,k}$; $R_{tens,k}$} the axial resistance of the screw part inserted in the lateral timber element;
- $R_{ax,k,2}$= min{$R_{thread,k}$; $R_{tens,k}$} the axial resistance of the screw part inserted in the central timber element

In (4) and (7), $R_{ax,k}$=min{$R_{ax,k,1}$;$R_{ax,k,2}$}. Every term in (2), to (7) was determined according to the provisions contained in the product ETA[5].

5.2 SLIP MODULUS

Calculation according to Tomasi et al. formulation

The theoretical slip modulus $K_{ser,th}$ was calculated by using the formulation (8) proposed by Tomasi et al. [11]. It was calculated by accounting both the contribution of axial slip modulus and lateral slip modulus. The axial slip modulus was calculated considering the pull-out of the both threaded parts of the connector [12].

$$K_{ser,th} = K_{lat} \cdot \sin\alpha\,(\sin\alpha - \mu\cos\alpha) + K_{ax} \cdot \cos\alpha\,(\cos\alpha - \mu\sin\alpha) \quad (8)$$

Being K_{lat} and K_{ax}, respectively, the axial and lateral slip moduli of the screw connection and μ is the friction coefficient. The axial slip modulus K_{ax} was calculated as in the following (9):

$$K_{ax} = 30 \cdot d \cdot l_{eff} \quad (9)$$

Where d is the diameter of the thread and l_{eff} is the length of penetration of the screw inside the specimen.

The lateral slip modulus K_{lat} was evaluated by considering the deformation occurring in both timber elements. By

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analogy with the behaviour of two springs placed in series, the lateral slip modulus can be calculated as followed (10):

$$K_{lat}=\frac{1}{\frac{1}{k_{lat,1}}+\frac{1}{k_{lat,2}}} \tag{10}$$

Where $k_{lat,1}$ and $k_{lat,2}$ are the lateral slip moduli (perpendicular to the screw shank) relative to the deformation of the single timber components. The lateral slip modulus was calculated in according to [5,8] as (11):

$$k_{lat,i}=\rho_m^{1.5}\cdot\frac{d}{23} \tag{11}$$

Where ρ_m is the average density of the element under consideration and d is the diameter of the thread.

Calculation according to De Santis and Fragiacomo formulation

The slip modulus was calculated also by using the formulations proposed by De Santis and Fragiacomo formulation [13] for inclined screws. This formulation is based on the beam on elastic foundation model. One of the two proposed closed form expressions (12) for the prediction of the slip modulus was adopted for our case of interest as the inclination of 45°.

$$K_s=\frac{ee\,\phi^{cc}}{\frac{1}{\rho_1^{aa}\,l_1^{bb}}+\frac{1}{\rho_3^{aa}\,l_2^{bb}}}\,dd^{\left(\frac{l_{inter}}{\phi^{0.5}}\right)} \tag{12}$$

Where ρ_i is the medium density of wood considered in each layer measured in kg/m^3, l_1 is the screw penetration in the lateral timber element in mm, l_2 is the screw penetration length in the central timber element in mm, l_{inter} is the screw penetration length in the interlayer, placed between the first and second layer expressed in mm, ϕ is threaded screw diameter measured in mm and *aa, bb, cc, dd, ee* are coefficients as a function of the inclination of the screw; in our case the inclination is 45° and the coefficients are summarized in Table 2. In our case no interlayer exists so l_{inter}=0. It is worth to mention that, for hybrid specimen, due to the experimental evidence in terms of stiffness and failure, l_2= l_{2b} (see Fig.1b), as a first attempt the remaining l_{2f} length into the Silver-fir was neglected.

Table 2 Coefficients for inclination angle of 45°[13]

aa	*bb*	*cc*	*dd*	*ee*
1.05	0,695	0,657	0,988	0,325

6 – RESULTS

6.1 EXPERIMENTAL RESULTS

The force-displacements curves in terms of shear force versus slip of the entire specimen for all the configurations and screwed connections are plotted in Fig.3. The experimental results in terms of ultimate force F'_{max}, slip modulus K_s (assessed according to EN 1995-1-1 [8]), yielding force F_y (evaluated according to EN 12512 case B [7]), yielding displacement v_y, ultimate displacement v_u and ductility D (calculated according to EN 12512 [7]) of the entire connection system for each specimen are given in Table 3 to 5.

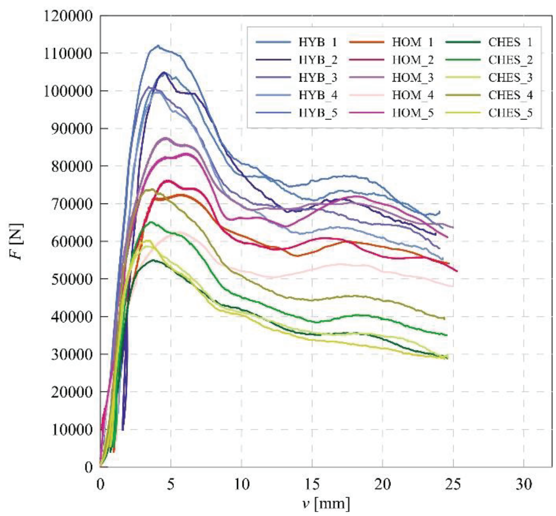

Figure 3. Experimental results

Table 3 The results of Series Homogeneous Beech with 9 mm × 160 mm screws

HOM Series		Mean	St. Dev	CoV
F'_{max}	*[kN]*	76.43	8.75	11%
K_s	*[N/mm]*	25814	3.72	14%
F_y	*[kN]*	68.51	9.16	13%
v_y	*[mm]*	2.64	0.21	8%
D	*[-]*	11.45	0.89	8%

Table 4 The results of Series Hybrid Beech – Silver Fir with 9 mm × 160 mm screws

HYB Series		Mean	St. Dev	CoV
F'_{max}	*[kN]*	104.46	4.30	4%
K_s	*[N/mm]*	36205	3.34	9%

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F_y	*[kN]*	99.28	3.81	4%
v_y	*[mm]*	3.06	0.47	15%
D	*[-]*	9.99	1.29	13%

Table 5 The results of Series Glulam Chestnut with 9 mm × 160 mm screw

CHES Series		Mean	St. Dev	CoV
F'_{max}	*[kN]*	62.57	6.51	10%
K_s	*[N/mm]*	29090	3.75	13%
F_y	*[kN]*	58.50	5.29	9%
v_y	*[mm]*	2.33	0.34	14%
D	*[-]*	13.14	1.97	15%

Using the homogeneous beech series as a reference (Fig. 4), the hybrid beech-Silver fir configuration achieves the highest ultimate force F'_{max}, surpassing it by 36.7% while the chestnut series achieves an ultimate force 18% lower than the reference configuration. In terms of slip modulus, K_s, the screws in hybrid configuration were characterized for an increased stiffness (40.3% higher than these in homogeneous configuration), the values achieved with chestnut configuration is slightly higher (12.7%) compared to the slip modulus achieved by screws in homogeneous beech. The ductility of fasteners in hybrid configuration in 12.7% lower than the one in homogeneous configuration, contrarily, on chestnut their ductility increases of 14.7%.

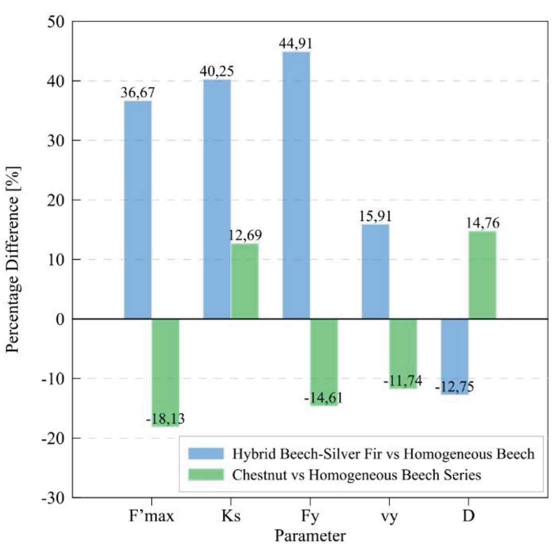

Figure 4. Comparison of experimental evidence among the series

a) HYB Series **b) HOM Series**

Figure 5. Failure modes of HYB and HOM series

Failure modes within the central glulam member are highlighted in Fig.5. It is evident that in HYB (Fig.5a) the thread on the final part caused a marked embedment within the Silver-fir lamella; this effect didn't arise in HOM series (Fig.5b).

6.2 COMPARISON OF EXPERIMENTAL EVIDENCE WITH THEORETICAL RESULTS

The ultimate forces F'_{max} achieved via test were compared with those obtained by using the theoretical calculations stated in Section 5.1. The results are summarized in Fig.6. It is evident that the available formulations severely underestimate the load carrying capacity It is worth noting that the formulations available in literature for determining the input parameter required by the theoretical model (e.g. embedment strength, screw withdrawal capacity, screw head pull through resistance), have been calibrated on wood species characterized by density values not exceeding 650 kg/m^3. Consequently, further studies are highly recommended to improve the calibration of the theoretical model.

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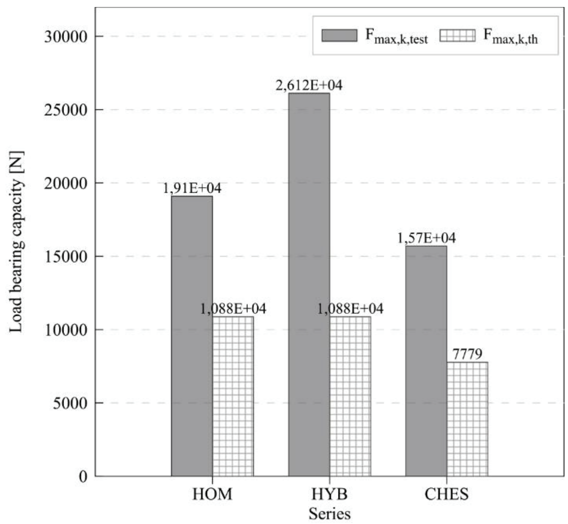

Figure 6. Load bearing comparison between test evidence and the Bejtka and Blaß [10] *theoretical model*

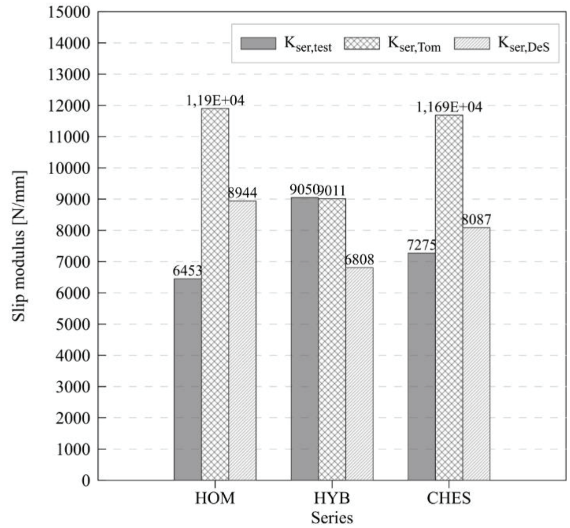

Figure 7. Slip modulus comparison between test evidence and the theoretical models proposed by Tomasi et al. [11] *and De Santis & Fragiacomo* [13]

In Fig.7 the comparison between the experimental and theoretical slip modulus estimated with the models proposed by Tomasi et al. [11] and De Santis & Fragiacomo [13] is showed. Overall, models overestimated the stiffness values of homogeneous configurations HOM and CHES. The model proposed by Tomasi et al. [11] overestimates (84%) the stiffness of screws in homogeneous beech and (61%) in chestnut. The overestimation of slip modulus is lower (39% for screws in homogeneous beech and 11% in chestnut) by using the model proposed by De Santis & Fragiacomo [13]. Concerning the slip modulus of screws in hybrid configuration, the model of Tomasi et al. [11] fit accurately (1% of scatter), while the model from De Santis & Fragiacomo [13] underestimate the slip modulus of 25%. For HYB series it is worth noting that the calculations were carried out by adopting a reduced penetration length of the screw into the glulam member, accounting as "effectively involved" just the outer beech lamella and neglecting the penetration length into the Silver-fir. It was considered as a first calculation attempt due to the experimental evidence in terms of achieved failure modes and slip modulus of screws in HYB series (40% higher than the one in HOM). The overestimation of theoretical models, especially for fully threaded screws could depends on the uncertainties associated with the axial stiffness related to the pull-out of the threaded part of screws. This latter in turns depends on the timber density which is strongly variable.

6.3 COMPARISON OF EXPERIMENTAL EVIDENCE WITH LITERATURE FINDINGS

The experimental evidence is compared also with literature findings of Schiro et al. [9] that tested double threaded 45° inclined screws in specimens entirely made of beech LVL (LVL beam as central element and LVL panel as side) as in combination with spruce solid wood used as central element. In this work hardwood-based configurations showed significantly higher load capacities compared to softwood, which aligns with our findings that hybrid and hardwood materials offer better strength. Additionally, the authors emphasized that "hybrid" configurations increase stiffness, particularly when hardwood elements are used as the central load-bearing component. Concerning the ductility, Schiro et al. [9] reported that screws in hardwood-based systems tend to have lower ductility, while, when placed in softwood components the increase the energy absorption, becoming more suitable for dynamic loads. It aligns with the evidence from screws in CHES series due to the unique mechanical features of chestnut, which doesn't properly act as a hardwood. Schiro et al. [9] carried out experimental/theoretical comparisons in terms of ultimate load bearing forces and slip modulus with the models of Bejtka and Blaß [10] and Tomasi et al. [11] respectively. The theoretical calculations underestimate the load bearing forces and overestimate the slip modulus for fully hardwood components. It aligns with our evidence.

6 – CONCLUSION

This study investigated the mechanical performance of timber-to-timber screw connections in three different configurations: Homogeneous Beech (HOM), Hybrid Beech-Silver Fir (HYB), and Glulam Chestnut (CHES). The results highlight how material composition influences key mechanical properties, including ultimate load (F'_{max}), slip modulus (K_s), yield force (F_y), yield displacement (v_y), and ductility (D).

- Screws in hybrid beech-silver fir had significantly higher ultimate load, stiffness, and yield force than those in homogeneous beech.
- Screws in glulam chestnut had a lower ultimate load and yield force but showed higher ductility (meaning better deformation capacity before failure).
- Screws in hybrid configuration sacrifices ductility for increased strength and stiffness, whereas screws in chestnut provides more flexibility

The evidence in terms of slip modulus and ultimate force were compared with those achieved by adopting suitable theoretical models for inclined screws proposed in literature. The comparison highlighted an overall underestimation of load bearing forces and an overestimate of the slip modulus for fully hardwood components. This is confirmed by the comparison with other works on push-out tests of screws in hardwood components. Additionally, the use of hybrid elements with inner layers made of conifers within this work, highlighted a gap in the proposed theoretical models which have been formulated for homogeneous central elements.

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