BEHAVIOUR OF TIMBER-TO-TIMBER CONNECTIONS WITH INTERPOSED RESILIENT SOUNDPROOFING PROFILE

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ABSTRACT: This paper reports the main outcomes of an ongoing research, supported by ROTHO BLAAS S.r.l. company, aimed at the experimental and theoretical characterization of timber-to-timber screwed connections with interposed an acoustic resilient profile for flanking noise reduction. The research is developed on two levels: experimental and analytical. An extended experimental campaign conducted on timber-to-timber screwed connections loaded in shear is presented. Obtained result are critically discussed in terms of observed failure mode, yielding condition and ductility. Experimental results are finally used to validate analytical models available in literature and specialized to account for the effect of acoustic interlayer on stiffness and load-carrying capacity.

KEYWORDS: Load-Carrying capacity, Resilient soundproofing interlayer, Timber-to timber screwed connections

1 – INTRODUCTION

Timber structures are particularly sensitive to low frequencies and require appropriate sound insulation strategies to comply with critical acoustic performance levels. This problem is significant in light structures such as traditional ceilings or frame walls because of reduced mass and acoustic damping. Joints appear to be the most critical points for both acoustical and structural aspects [1]: a valid constructive strategy to limit the acoustic transmission through the connections consists in the insertion of resilient strips between the connected elements (Figure 1). The effects of the interposed resilient strip on the stiffness and load-carrying capacity of connection have not yet been studied adequately from experimental and theoretical point of view.

Indeed, in literature the effect of a timber-based interlayer on the behaviour of timber-concrete composite beam is widely investigated from experimental and theoretical point of view ([2] [3] [4]) while few researches investigate connections with interposed resilient profiles. Some preliminary studies on this topic are reported in [5] and [6] for timber-to-steel connections.

This work summarizes the results of an extended experimental campaign specifically designed to assess the effects of an interposed resilient strip on the mechanical behaviour of timber-to-timber screwed connections. Experimental results are used to propose some improvements to analytical models available in literature ([7] [8][9]) to account for the effect of resilient strip on the mechanical response of timber connections.

Figure 1. Example of typical structural joints with interposed acoustic layer (Rothoblaas archive).

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2 – EXPERIMENTAL CAMPAIGN

The experimental campaign was conducted according to the UNI EN 408 [10]. Fifteen different configurations were tested, varying the nominal diameter of the screws (HBS6-HBS8-HBS10 [11]) and the resilient thickness (6-12-18mm) of the Xylofon 35 [12] soundproof layer. For each diameter, two reference configurations characterized by absence of interlayer and air gap plus Teflon spacer respectively were analysed. Table 1 summarizes the experimental campaign carried out at the internal laboratory of ROTHO BLAAS. Nr. 3 repetitions of the monotonic test were performed for each examined configuration.

2.1 SAMPLE DESCRIPTION

Table 1. Details of the tested configurations.

Test ID	Nominal diameter *[mm]*	Screw type	interlayer type	Layer thickness *[mm]*
NX_6	6	HBS6180	None	0
AIR_6_6			Air + teflon	6
X35_6_6			XYLOFON 35	6
X35_6_12			XYLOFON 35	12
X35_6_18			XYLOFON 35	18
NX_8	8	HBS8180	None	0
AIR_8_6			Air + teflon	6
X35_8_6			XYLOFON 35	6
X35_8_12			XYLOFON 35	12
X35_8_18			XYLOFON 35	18
NX_10	10	HBS10180	None	0
AIR_10_6			Air + teflon	6
X35_10_6			XYLOFON 35	6
X35_10_12			XYLOFON 35	12
X35_10_18			XYLOFON 35	18

Each sample was made of a two-piece GL24h glue laminated timber according to EN 14080 [13]. Sample dimensions were the same for the cases of Ø6 and Ø8, but they were increased for Ø10 (Figure 2).

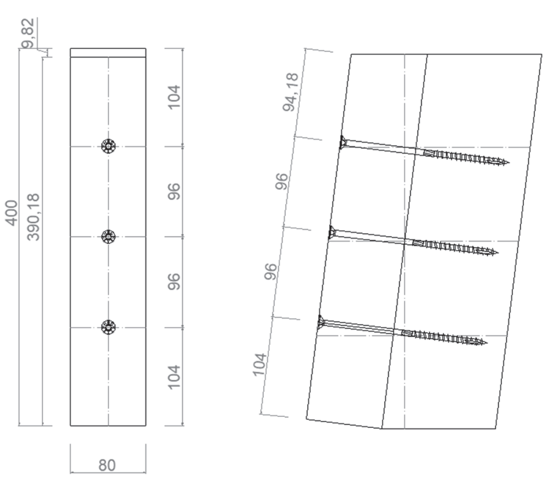
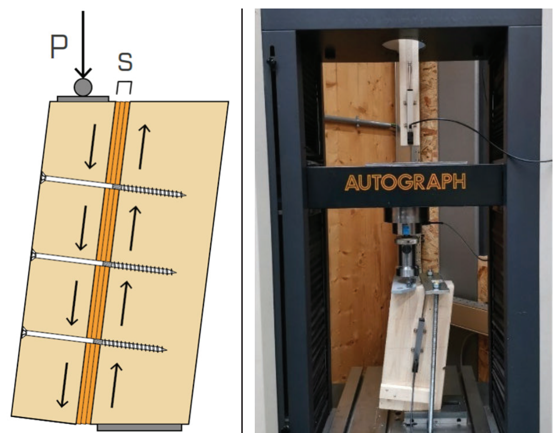


Figure 2. Sample geometry – NX_8_0 configuration.

The samples were assembled using three 180mm long screws fastened perpendicular to the wood fibres. The edge spacing provided by the technical data-sheets was considered both in the longitudinal and transversal directions. As prescribed by EN 1380 [13], samples were conditioned at (20 ± 2) °C temperature and (65 ± 5) % humidity before performing the tests until a wood relative humidity of 12% was reached.

2.2 TEST SETUP AND INSTRUMENTS

A servo-hydraulic testing machine with a maximum capacity of 50 kN equipped with a load cell and an integrated displacement transducer was used to carry out the experimental tests. A Linear Variable Differential Transformer (LVDT) that registers the displacements along the shear plane inclined by 7° with respect of the vertical direction was also installed. Figure 3a depicts the test layout according to EN 408 [10] while figure 3b reports a photo of the adopted setup.



a) *b)*

Figure 3. a) Scheme of test layout; b) Photo of adopted setup.

2.3 LOADING PROTOCOL

The monotonic tests were conducted according to the EN UNI EN 26891 [15] loading protocol. The ultimate conditions were considered as reaching a displacement of 30 mm along the shear plane or alternatively as reaching a decreasing of the force of 20% with respect the maximum achieved.

3 – EXPERIMENTAL RESULTS

In this section, the main results of the experimental campaign are reported in terms of observed failure modes and force-displacement curves.

3.1 OBSERVED FAILURE MODE

All the specimens subject to monotonic load, at the end of the test, show the localized embedment of the wood and a S-shape deformation of the screws with double hinge (Figure 4).

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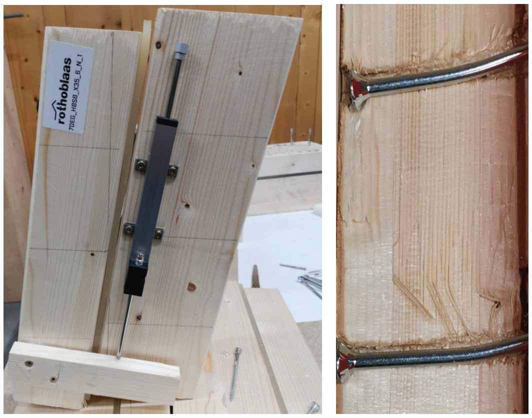

Figure 4. Observed failure mode at the end of the test.

Failure modes are not affected by the presence of the interlayer for all the interlayer thicknesses and screws diameters.

3.2 LOAD-DISPLACEMENT CURVES

The experimental load displacement curves show, for all the examined configuration, a non-linear behaviour without a clear yielding condition. Analysing the experimental load-displacement curves of HBS8 configurations, plotted in Figure 4 for the individual screw, it is possible to observe a clear a modification of the response of the connections due the thickness of interposed resilient profile both in terms of initial stuffiness and peak force.

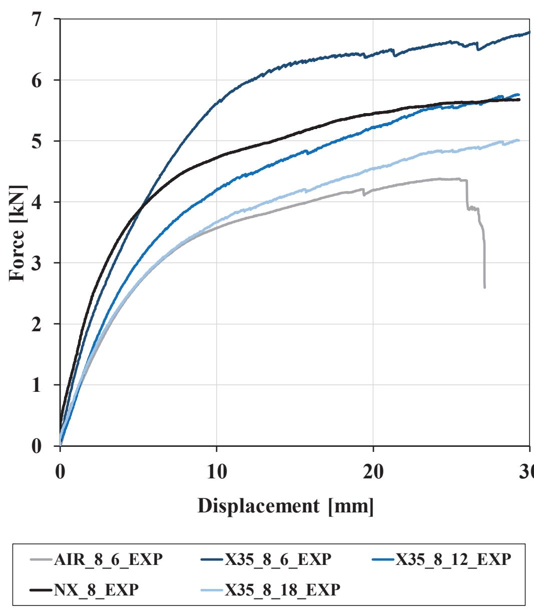

Figure 4. Experimental load-displacement curve - HBS8 configurations.

In detail, configurations with a 6mm thick profile are characterized by an overstrength compared to the reference configuration (absence of interlayer) probably due to the surface property of the XYLOFN 35 inducing interlocking effects between the timber elements. The displacement capacity of the tested configuration seems not affected by the interlayer.

3 – ANALYSES OF TEST RESULTS

The experimental load-displacement curves were truncated at 15mm and linearized according to the "method b" of EN 12512 [16]. Figure 5 reports, for the individual screw, the mean linearized force-displacement curves obtained from the three repetitions of the monotonic test carried out for the HBS8 configuration.

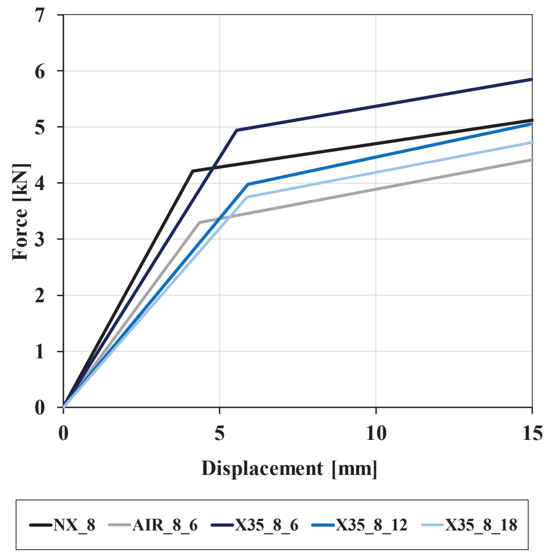

Figure 5. Linearized force-displacement curves. - HBS8 configurations.

Linearized force-displacement curves highlight a modification of the mechanical response of the connections due to both the screw diameters and the thickness of interposed resilient profile.

Table 2. Parameters evaluated according to method b" of EN 12512 [16].

ID	F_{15mm} *[kN]*	F_{v_prEN} *[kN]*	μ_s *[-]*	F_{ax} *[kN]*	F_v *[kN]*
NX_6	3.47	1.93	0.25	1.93	2.41
AIR_6_6	2.95	1.58	0.00	1.93	1.58
X35_6_6	3.92	1.60	0.50	1.93	2.57
X35_6_12	3.04	1.34	0.50	1.93	2.31
X35_6_18	3.05	1.14	0.50	1.93	2.11
NX_8	5.12	3.07	0.25	2.56	3.71
AIR_8_6	4.42	2.64	0.00	2.56	2.64
X35_8_6	5.84	2.65	0.50	2.56	3.93
X35_8_12	5.05	2.30	0.50	2.56	3.58
X35_8_18	4.74	2.01	0.50	2.56	3.29
NX_10	7.04	4.20	0.25	4.25	5.26
AIR_10_6	5.30	3.69	0.00	4.25	3.69
X35_10_6	7.06	3.70	0.50	4.25	5.83
X35_10_12	5.98	3.27	0.50	4.25	5.40
X35_10_18	5.57	2.91	0.50	4.25	5.04

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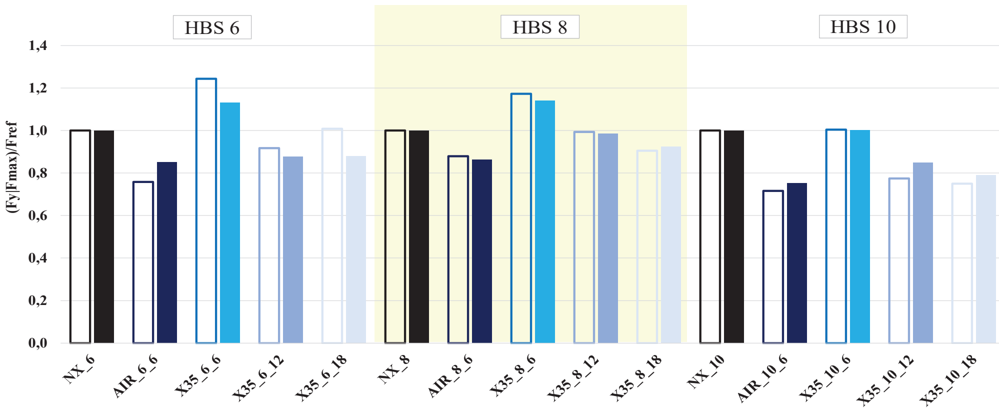

Figure 5. Dimensionless values of yielding and peak force (empty bars correspond to the yielding).

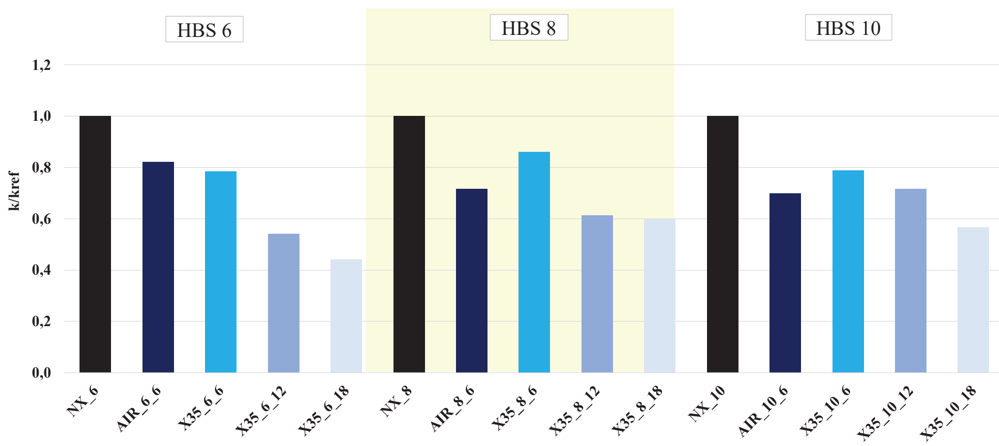

Figure 6. Dimensionless values of elastic stiffness.

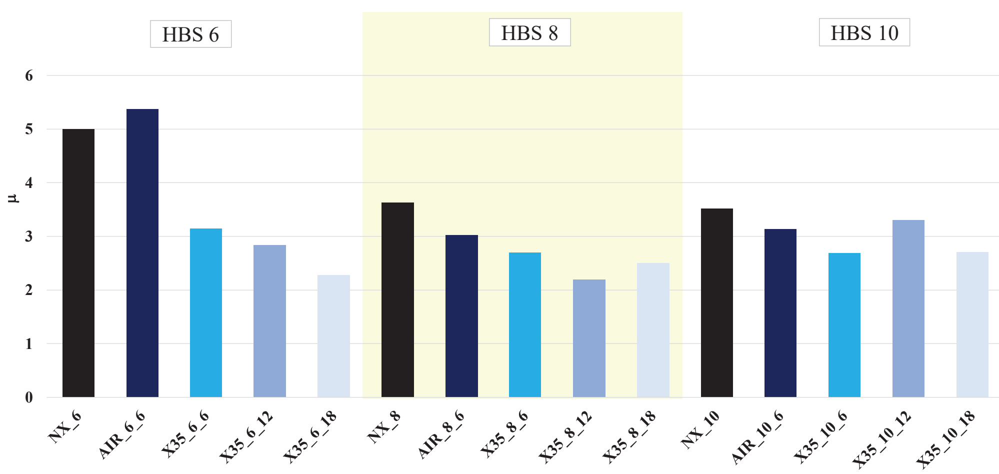

Figure 7. Ductility values of analysed configurations.

As expected, the increase in the diameter of the screw induces an increase in load carrying capacity and a lower susceptibility to the increase in thickness of the interposed resilient profile. Table 2 summarizes the mean values of parameter obtained from the linearization procedure applied to all the samples of the tested configurations. It is worth nothing that the values are referred to the individual screws. All configurations with interposed resilient profile show a significant stiffness reduction compared to the reference configuration (absence of interlayer).

Effects of interlayer on the load-carrying capacity

The dimensionless force values (current values divided by the reference NX value) of Figure 5 highlight that HBS6 and HBS8 screw configurations with a 6mm thick profile are characterized by an overstrength compared to the reference configuration (absence of interlayer). Moreover, for all screw diameters, as the thickness of the resilient profile increases there is a reduction in yield and peak strengths which settle on the values of the limit configuration of connections with detached elements (air gap and Teflon spacer).

Effects of interlayer on the elastic stiffness

Stiffness values of Figure 6 show that all configurations with interposed resilient profile present a significant stiffness reduction compared to the reference configuration (absence of interlayer). The stiffness reduction ranges from approximatively 15% to 60%. Moreover, configurations with small screw diameters are susceptible to a significant stiffness reduction as the interposed resilient profile thickness increases. Otherwise, the configurations characterized by a screw diameter to interlayer thickness ratio greater than 1 show stiffness values greater than the limit configuration with detached elements (air gap and Teflon spacer).

Effects of interlayer on the ductility

The ductility values of the different type of analysed configurations are plotted in Figure 7. It is possible to observe that configurations with small screw diameters are susceptible to a significant ductility reduction as the interposed resilient profile thickness increases. Only the configurations characterized by a large diameter show limited reduction of the ductility values.

4 – ANALYTICAL MODEL

4.1 LOAD-CARRYING CAPACITY MODEL

The upgraded Johansen theory provided by Blaß et al. [7] to account for the interposition of a OSB interlayer in timber-to-timber connections has been implemented in the Annex K of prEN 1995-1 [9]. In this work, such formulation is adopted to compute the basic shear contribution F_{v_prEN} of the tested configurations adopting K_{mod} and γ_M factors equal to 1.0. The strength increases due to the so called "rope effect" that involves the axial capacity of the screws (μ_s Fax) should be added to the basic shear contribution to obtain a reliable estimation of the total load carrying capacity of the connections (F_v). The following expression is used to evaluate the load-carrying capacity:

$$F_v = F_{v\_prEN} + \mu_s F_{ax} \qquad \text{Eq. (1)}$$

Where:

F_v is the load bearing capacity of the connection

F_{v_prEN} is the shear capacity of the connection computed according to expression K10 of Annex K of prEN 1995-1

μ_s static friction coefficient responsible for the "rope effect" strength increases

F_{ax} is the axial capacity of the connection

It is worth nothing that for timber-to-timber connection the friction coefficient is set equal to μ_s =0.25 [8] and for timber-to-Teflon connection the friction coefficient is negligible (i.e. μ_s = 0.00). Otherwise, experimental tests carried out to characterize the frictional behaviour of timber-to-XYLOFON 35 resilient profile according to ISO 15113-2005 test protocol [17] demonstrated that a reliable estimation of the friction coefficient is μ_s =0.5.

In order to compare the mean experimental outcomes with the analytical predictions of load-carrying capacity, the mean values of the required mechanical parameters were evaluated by specific experimental tests ([18][19]) and listed in Table 3.

The load-carrying capacity of the studied timber-to-timber connection with interposed resilient profile are therefore evaluated adopting the formulations provided by the prEN for connected interlayer considering the two limit conditions characterized by presence and absence of the strength increase due to "rope effect". Results are plotted in Table 4.

Table 3. Mean values of parameters used in the model.

ID		HBS 6	HBS8	HBS10
Embedment strength of Glulam elements	f_{hm} [MPa]	21.41	19.64	18.37
Embedment strength of resilient profiles	$f_{h,int,m}$ [MPa]	0.90	0.67	0.55
Yielding moment	M_{ym} [Nmm]	14500	30000	48000
Pull-through resistance	$F_{head,m}$ [kN]	1.93	2.56	4.25
Timber-to-Teflon friction coefficient	μ_s	0.00	0.00	0.00
Timber-to-Timber friction coefficient	μ_s	0.25	0.25	0.25
Timber-to-XYLOFON 35 friction coefficient	μ_s	0.50	0.50	0.50

Table 4. Analytical prediction vs experimental results

ID	F_{15mm} *[kN]*	F_{v_prEN} *[kN]*	μ_s *[-]*	F_{ax} *[kN]*	F_v *[kN]*
NX_6	3.47	1.93	0.25	1.93	2.41
AIR_6_6	2.95	1.58	0.00	1.93	1.58
X35_6_6	3.92	1.60	0.50	1.93	2.74
X35_6_12	3.04	1.34	0.50	1.93	2.48
X35_6_18	3.05	1.14	0.50	1.93	2.28
NX_8	5.12	3.07	0.25	2.56	3.71
AIR_8_6	4.42	2.64	0.00	2.56	2.64
X35_8_6	5.84	2.65	0.50	2.56	4.16
X35_8_12	5.05	2.30	0.50	2.56	3.81
X35_8_18	4.74	1.14	0.50	2.56	3.52
NX_10	7.04	4.20	0.25	4.25	5.26
AIR_10_6	5.30	3.69	0.00	4.25	3.69
X35_10_6	7.06	3.70	0.50	4.25	6.21
X35_10_12	5.98	3.27	0.50	4.25	5.78
X35_10_18	5.57	2.91	0.50	4.25	5.42

In the graphs of Figure 8 and Figure 9 mean values of experimental strengths (F=15mm) are compared with analytical prediction obtained adopting the selected values

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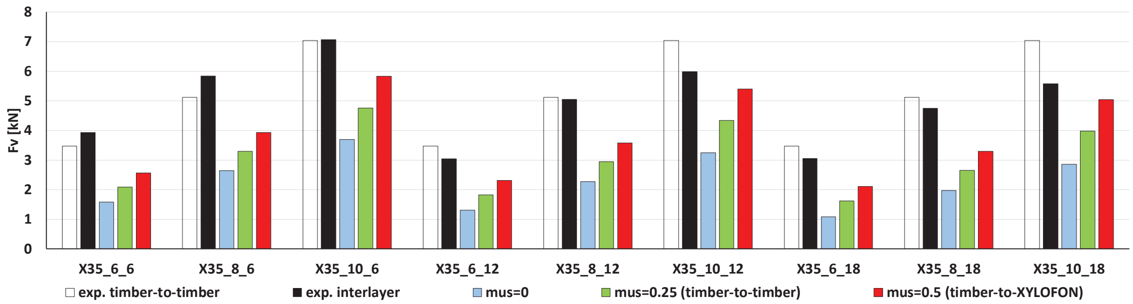

Figure 8. Analytical prediction vs experimental values of connection load-carrying capacity considering alternative interface frictional properties.

of the friction coefficient to account for the so called "rope effect" strength contribution.

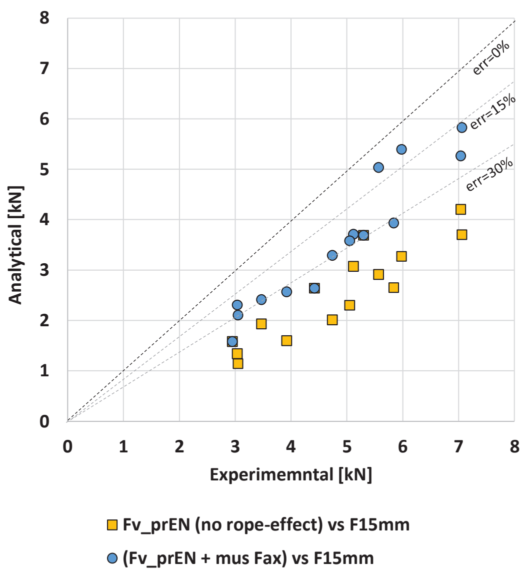

Figure 9. Analytical prediction vs experimental values of connection load-carrying capacity.

Values plotted in the graph of Figure 9 demonstrate that neglecting of the rope effect contribution (i.e. $\mu_s = 0$) leads to an unacceptable underestimation of the connection resistance. Otherwise, mean experimental strengths (F=15mm) obtained for the configurations with interlayer are always higher than the model prediction carried out for the reference configuration of a timber-to-timber connection without interlayer (timber elements in contact) using a friction value equal to 0.25. Figure 8 shows that for XYLOFON 35 configurations, predictions obtained using friction values from experimental tests seems to be more reliable than the ones carried out using the reference friction value equal to 0.25. In addition, it can be observed that analytical strength prediction of connections assembled using large screws diameter (i.e. HBS10) provides a value very close to the experimental evidence while for small screws diameter (i.e. HBS6 and 8) the analytical estimation in general underestimates the experimental resistance. Moreover, analytical predictions obtained for small interlayer thicknesses are more conservative (i.e. in favour of safety) than those obtained for large interlayer thicknesses.

4.2 STIFFNESS MODEL

Expression K8 of Annex K of prEN 1995-1 [9] provides an analytical formulation to predict the elastic stiffness $K_{SLS,mean}$ of the connections with interposed layer. It is worth nothing that K8 expression disregards the properties of the interlayer and the interlocking effects between the interlayer itself and the timber member.

Estimation of the mean elastic stiffness according to prEN formulation is plotted in the graph of Figure 10 vs the experimental values obtained from linearization procedure.

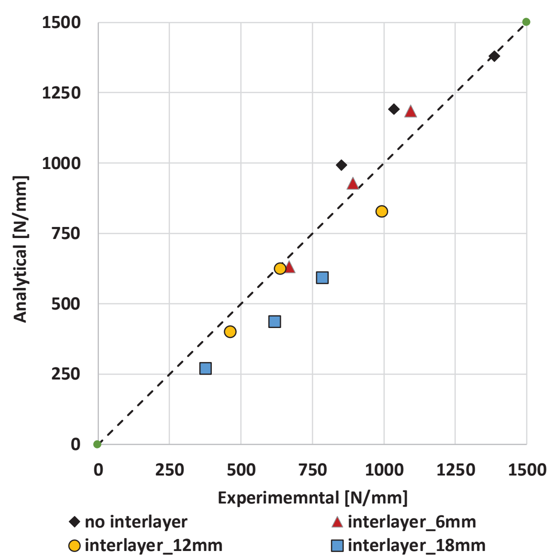

Figure 8. Analytical prediction vs experimental values of connection elastic stiffness.

Results plotted in the graph of Figure 10 demonstrate a good capability of the prEN formulation to predict the elastic stiffness of the examined connection with interposed interlayer.

5 – CONCLUSIONS

Results obtained in this work demonstrate that the mechanical behaviour of a screwed timber-to-timber connections is affected by the interposed resilient soundproof profiles. Experimental tests conducted on different connection configurations highlight a quite relevant stiffness reduction due to the resilient strip interposition. Otherwise, the strength seems less affected by the presence of the interlayer especially for 6mm thick interlayer and for large diameter screws (i.e. HBS10). Failure modes observed during experimental test result are not affected by the presence of the interlayer.

The estimation of the load carrying capacity of timber-to-timber connections with interposed soundproof resilient profile could be carried out referring to the approach implemented in the Annex K of prEN 1995-1 [9]. However, an accurate estimation of the so called "rope-effect" contribution, to be added to the shear strength estimated with the prEN formulas, is necessary to provide a reliable estimation of the load-carrying capacity of a timber-to-timber screwed connection with interposed resilient profile. Indeed, both the interlocking effects and the frictional interface properties, provided by the interlayer itself, provide a significant strength contribution.

Proposed predictive model result consistent with experimental results confirming that it is preferable to have interlayers of small thickness since they do not negatively affect the connection strength.

Model outcomes shows that adoption of the reference model for timber-to-timber connection (i.e. neglection of the interspace and adoption of a friction coefficient equal to $\mu_s = 0.25$ for the rope effect contribution) ensure an acceptable and in favour of safety estimation of the load bearing capacity of a screwed timber-to-timber connection with interposed XYLOFON 35 profiles.

Model calibration finally demonstrates that a reliable friction coefficient values to be assumed for screwed timber-to-timber connection with interposed XYLOFON 35 profiles is $\mu_s = 0.5$.

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