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EXPERIMENTAL AND ANALYTICAL ANALYSIS OF TIMBER CONNECTIONS WITH INTERPOSED ACOUSTIC RESILIENT STRIP

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ABSTRACT: The load-carrying capacity and stiffness of timber-to-timber or steel-to-timber connections with an interlayer is a topic of great interest, as it is increasingly required to acoustically insulate, by means of resilient strip, the connections used to assemble timber buildings. The effects of the interposed resilient strip on the stiffness and load-carrying capacity of connections have not yet been studied effectively from experimental and theoretical point of view. This paper reports the main outcomes of an ongoing research, supported by Rotho Blaas S.r.l. company, aimed at the characterization of timber connections with interposed an acoustic resilient strip for flanking noise reduction. The research is developed on two levels: experimental and analytical. An experimental campaign conducted on steel-to-timber nailed connections was carried out and analysed. Experimental results were used to validate analytical models available in literature and specialized to account for the effect of acoustic interlayer on both elastic behaviour and failure mechanism.

KEYWORDS: Acoustic layer, Load-carrying capacity, Resilient soundproofing, Sound insulation, Timber joints

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. Cross Laminated Timber (CLT) structures are more soundproof performing thanks to their massiveness and the continuity of the panels. However, the structural connections can cause acoustic bridges which negatively affect the acoustic performance of the system [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. Calculation is therefore approximatively based on the models developed for standard connections without considering accurately the effects of the interposed layer or gap.
In this work results of an experimental campaign are used to assess the effects of an interposed resilient strip on the mechanical behaviour of timber-to-steel nailed connections. Experimental results are finally used to validate robust analytical models, available in literature and developed for different applications [2-3], to account for the effect of resilient strip on the mechanical response of timber connections.

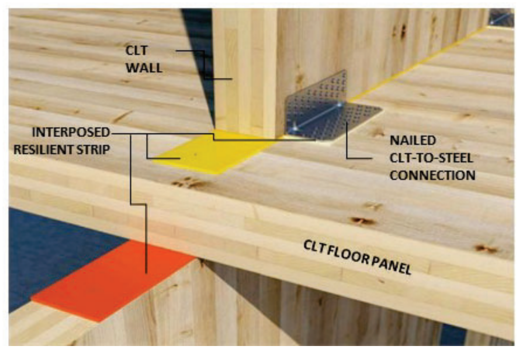

Figure 1: *Example of wall-to-floor CLT joint with interposed acoustic layer.*

2 EXPERIMENTAL CAMPAIGN

The experimental campaign was aimed to investigate the effects of the interposition of a resilient acoustic strip on the mechanical response of a timber-to-steel nailed connections. Four types of timber-to-steel connection were tested varying: the type of timber elements (GluLam or CLT) and the gap between the timber elements (in contact or with 6mm thick resilient acoustic strip). The tested nails are "LBA" type according to ETA-22/0002 [4] while the resilient acoustic strip is "XYLOFON 35" type according to ETA-23/0061 [5]. The experimental program, carried out according to EN 1380 [6] provisions, is summarized in Table 1.

Table 1: *Detail of the experimental campaign*

Sample ID	*Timber element*	*Interposed strip*	*N. of test*
GL-NX	GluLam	*none*	3
GL-X35	GluLam	*Xylofon 35*	3
CLT-NX	CLT	*none*	3
CLT-X35	CLT	*Xylofon 35*	3

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The tested sample is geometrically represented in Figure 2 and is composed by the following components:

(a) timber element (GluLam or CLT). The rectangular cross section dimension is 120x80mm while the length is 200mm;
(b) couple of U-shaped 4mm thick steel profiles;
(c) 2 x 5 nails LBA type with a diameter of 4mm and length of 60mm;
(d) 6mm thick XYLOFON 35 resilient acoustic strip (only for X35 configuration).

As prescribed by EN 1380 [6], the timber specimens were conditioned at (20 ± 2)°C temperature and (65 ± 5)% relative humidity for 15 days before performing the tests. The resulting mean density of the samples was equal to 458kg/m^3 for GluLam specimens and to 472 kg/m^3 for CLT specimens.

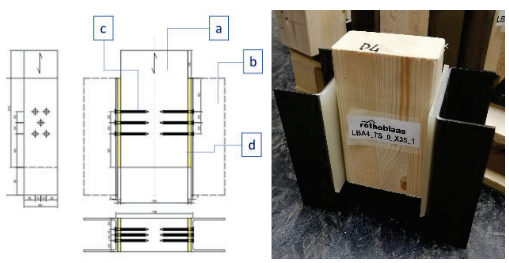


__Figure 2:__ Geometry of the tested samples

The samples were tested using a universal testing machine in displacement control. The upper face of the timber element was loaded while the U-shaped steel profiles contrasted against the basement. The nailed connections were therefore monotonically loaded parallel to grain direction. Figure 3 reports a photo of the adopted setup.

During the test the applied force and the timber-to-steel relative displacement were recorded.

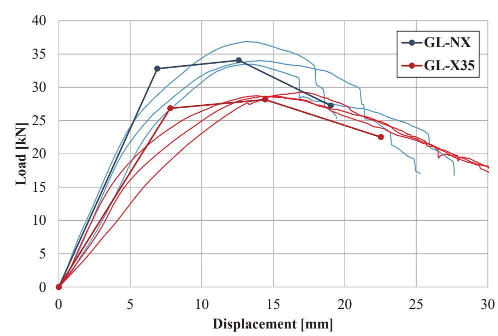
__Figure 3:__ View of the experimental setup.

3 EXPERIMENTAL RESULTS

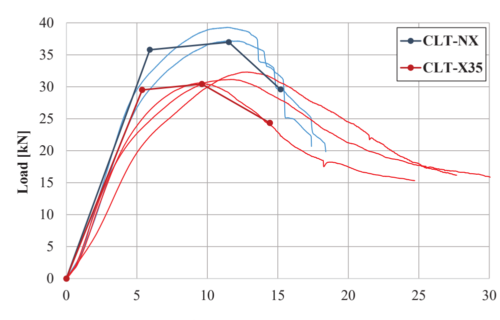
This section reports the test results in terms of load-displacement curves and observed failure modes.

It is worth noting that the experimental capacity curve of a steel-to-timber connection generally does not show a well-defined yielding limit [7-10]. Two different criteria can then be adopted for the definition of the yielding condition starting from experimental results [11]: the first one is based on EN 12512 [12] provisions, while the second one is based on an energetic approach (the so-called Equivalent Energy Hardening method [13]).

For traditional steel-to-timber connections, the well know Method "b" of EN 12512 is typically adopted since load-displacement curves are not characterized by a marked variation of the gradient at the level of yielding condition. In this work, in order to better capture the features of the experimental curves, an alternative approach for the definition of the yielding point was adopted referring to the Equivalent Energy Hardening method [12]: the slope of the second branch of the bi-linear curve is defined by forcing the passage through the peak force point and the equivalence of strain energy between the experimental envelope curve and the piecewise linear approximation. In the following, Method "b" of EN 12512 will be labelled as EN12512-b, whereas the Equivalent Energy Hardening method as EEH. Experimental load-displacement curves superimposed to the mean tri-linear backbone curve obtained according to the EN12512-b and EEH methods are reported in Figure 4 and Figure 5 respectively.



a)



b)

__Figure 4:__ Experimental load displacement curves superimposed on mean trilinear backbone curve obtained applying the EN12512-b method: a) GluLam and b) CLT configurations.

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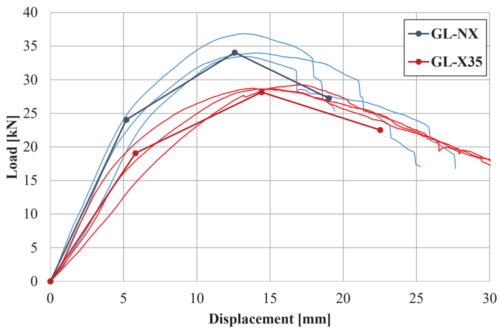
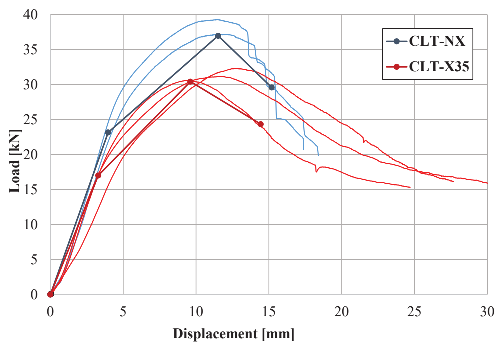


a)



b)

Figure 5: *Experimental load displacement curves superimposed on mean trilinear backbone curve obtained applying the EEH method: a) GluLam and b) CLT configurations.*

The failure mode observed at the end of all experimental tests principally involved the nails used to connect the steel plate to the timber element. Two plastic hinges can be typically recognized in the nails, one under the cap and another one in the shank (about 20–25 mm below the cap). In addition, localized crushing of wood around the nail shank, oriented in the axial load direction, can be observed, see Figure 6-a. For large displacement, the failure of the head of the nails occurred, see Figure 6-b.

a)

b)

Figure 6: *Samples GL-X35_02 at the end of test: a) local crashing of the timber along the grain direction and b) failure of the head of nails.*

The detailed analyses of the experimental results conducted according to method EN12512-b and EEH are reported in Table 2 and Table 3 respectively. More specifically, the tables report: the yielding and peak point parameters; the elastic and post elastic stiffnesses. Analyses were performed separately for each sample and then the averaged values were computed in order to perform a direct comparison between the configuration without and with interlayer.

Table 2: *Analyses of experimental results according to EN12512b method. Label "A" stands for averaged values.*

EN 12512-b GLULAM		GL-NX_1	GL-NX_2	GL-NX_3	**GL-NX_A**	GL-X35_1	GL-X35_2	GL-X35_3	**GL-X35_A**
k1	[kN/m]	3.62	4.73	5.07	**4.47**	4.50	3.28	2.52	**3.43**
k_ult	[kN/m]	0.20	0.21	0.23	**0.22**	0.22	0.17	0.19	**0.19**
dy	[mm]	9.01	6.87	6.98	**7.62**	6.00	8.40	11.17	**8.52**
dFmax	[mm]	13.49	13.94	13.15	**13.52**	13.79	15.21	17.07	**15.36**
du	[mm]	26.77	25.27	19.41	**23.82**	22.97	22.92	23.40	**23.82**
Fy	[kN]	32.60	32.50	35.43	**33.51**	26.98	27.52	28.16	**27.55**
Fmax	[kN]	33.48	34.01	36.87	**34.79**	28.74	28.68	29.26	**28.89**
Fu (0.8 Fmax)	[kN]	26.79	27.21	29.50	**27.83**	22.99	22.94	23.41	**23.11**

EN 12512-b CLT		CLT-NX_1	CLT-NX_2	CLT-NX_3	**CLT-NX_A**	CLT-X35_1	CLT-X35_2	CLT-X35_3	**CLT-X35_A**
k1	[kN/m]	5.94	6.53	5.70	**6.06**	3.96	5.79	5.60	**5.12**
k_ult	[kN/m]	0.19	0.23	0.22	**0.21**	0.21	0.23	0.23	**0.22**
dy	[mm]	6.05	5.82	6.32	**6.06**	7.89	5.13	5.30	**6.11**
dFmax	[mm]	12.25	11.45	11.69	**11.80**	12.84	9.40	9.40	**10.55**
du	[mm]	19.26	18.40	17.39	**18.35**	25.84	24.46	24.47	**23.82**
Fy	[kN]	35.94	38.02	36.01	**36.66**	31.28	29.73	29.67	**30.23**
Fmax	[kN]	37.15	39.30	37.18	**37.88**	32.30	30.59	30.59	**31.16**
Fu (0.8 Fmax)	[kN]	29.72	31.44	29.75	**30.30**	25.84	24.47	24.47	**24.93**

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Table 3: Analyses of experimental results according to EEH method. Label "A" stands for averaged values.

EEH GLULAM		GL-NX_1	GL-NX_2	GL-NX_3	**GL-NX_A**	GL-X35_1	GL-X35_2	GL-X35_3	**GL-X35_A**
k1	[kN/m]	3.62	4.73	5.07	**4.47**	4.50	3.28	2.52	**3.43**
k_ult	[kN/m]	2.48	2.44	2.80	**2.58**	1.71	2.08	1.88	**1.89**
dy	[mm]	6.88	4.94	5.54	**5.79**	4.15	6.16	8.92	**6.41**
dFmax	[mm]	13.49	13.94	13.15	**13.52**	13.79	15.21	17.07	**15.36**
du	[mm]	26.77	25.27	19.41	**23.82**	22.97	22.92	23.40	**23.82**
Fy	[kN]	24.61	23.01	28.11	**25.24**	18.36	20.03	22.44	**20.28**
Fmax	[kN]	33.48	34.01	36.87	**34.79**	28.74	28.68	29.26	**28.89**
Fu (0.8 Fmax)	[kN]	26.79	27.21	29.50	**27.83**	22.99	22.94	23.41	**23.11**

EEH CLT		CLT-NX_1	CLT-NX_2	CLT-NX_3	**CLT-NX_A**	CLT-X35_1	CLT-X35_2	CLT-X35_3	**CLT-X35_A**
k1	[kN/m]	5.94	6.53	5.70	**6.06**	3.96	5.79	5.60	**5.12**
k_ult	[kN/m]	3.03	3.43	3.18	**3.22**	2.52	2.66	3.25	**2.81**
dy	[mm]	4.89	3.62	4.26	**4.26**	5.35	3.27	3.02	**3.88**
dFmax	[mm]	12.25	11.45	11.69	**11.80**	12.84	9.40	9.40	**10.55**
du	[mm]	19.26	18.40	17.39	**18.35**	25.84	24.46	24.47	**23.82**
Fy	[kN]	28.99	22.15	23.48	**24.87**	20.83	18.12	15.70	**18.22**
Fmax	[kN]	37.15	39.30	37.18	**37.88**	32.30	30.59	30.59	**31.16**
Fu (0.8 Fmax)	[kN]	29.72	31.44	29.75	**30.30**	25.84	24.47	24.47	**24.93**

Data reported in Table 2 and Table 3 are plotted in the graph of Figure 7-9 and Figure 10-12 for GluLam and CLT specimens respectively.

Analysing the results, it is possible to observe that the interposition of a resilient layer strongly affects the global response of the connection. In detail obtained results demonstrate that, regardless of the linearization criterion used, the interposed resilient layer induces:

i) a negligible effect on the yielding and peak displacements and therefore on the ductility values;

ii) a reduction of the yielding force of about 20% for GluLam samples and of about 25% for CLT samples and a reduction of the peak force of about 15% for both Glulam and CLT samples;

iii) a reduction of the elastic stiffness of about 28% for GluLam samples and of about 17% for CLT samples;

vi) a negligible effect on post elastic and ultimate stiffness.

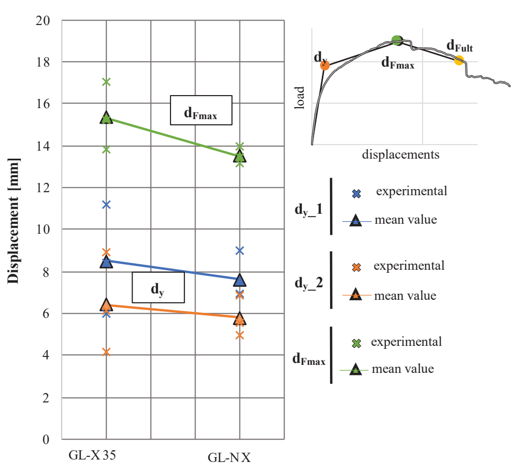

Figure 7: *Effects of interposition of a resilient acoustic strip on the yielding and peak displacement of GluLam samples.*

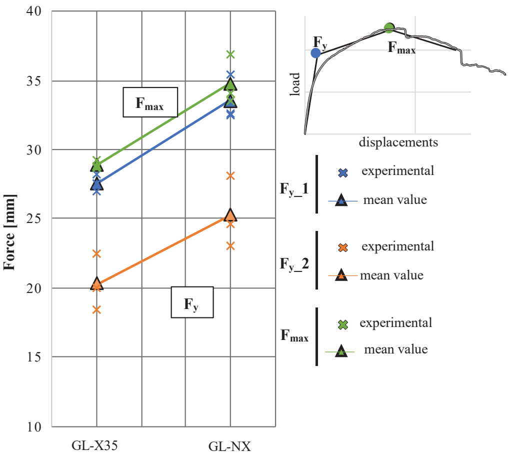

Figure 8: *Effects of interposition of a resilient acoustic strip on the yielding and peak force of GluLam samples.*

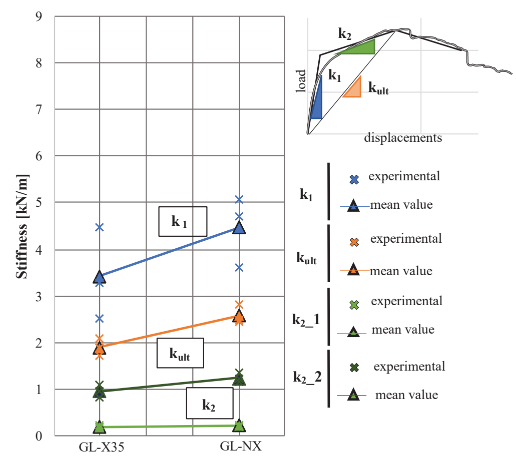

Figure 9: *Effects of interposition of a resilient acoustic strip on the elastic and post-elastic stiffness of GluLam samples.*

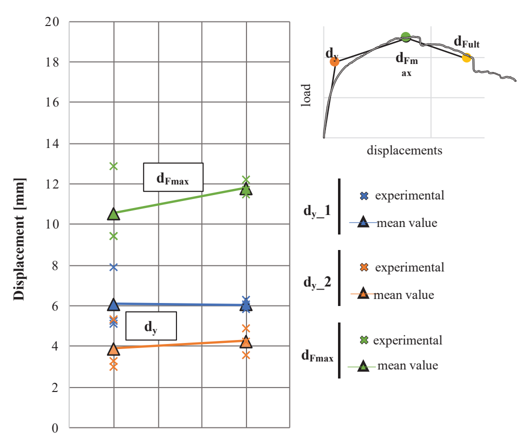

Figure 10: *Effects of interposition of a resilient acoustic strip on the yielding and peak displacement of CLT samples.*

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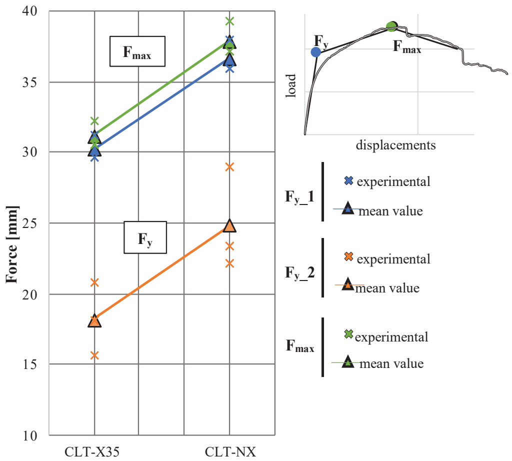

Figure 11: *Effects of interposition of a resilient acoustic strip on the yielding and peak force of CLT samples.*

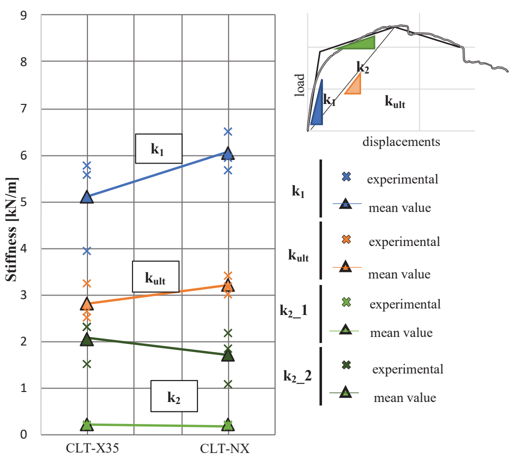

Figure 12: *Effects of interposition of a resilient acoustic strip on the elastic and post-elastic stiffness of CLT samples.*

It is worth noting that the above-described effects of the interlayer on the strength and stiffness of the nailed steel-to-timber connection is relative to the case of an infinitely stiff metal plate.

In the case of connections typically used to transfer shear forces in real GluLam or CLT structures, the geometry of the brackets is three-dimensional with a consequent significant deformative contribution of the steel plates.

When the bracket is used with an acoustic interlayer, the strength and stiffens reduction of the nailing system might not be significant as recorded in the tests exposed in this work as the deformability of the bracket itself could prevail (see for example [13]).

4 ANALYTICAL MODELS

The general formulations proposed in Johansen's theory and reported in the codes [15-16] or product technical sheet [4] are not applicable in the case of an interposed layer in the shear plane. Alternative methods accounting for the gap due to the interlayer are therefore necessary to define the strength and stiffness of the connection.

In this work, two different literature models were analysed and applied to account for the effects of an acoustic interlayer on the behaviour of a timber-to-steel connection.

The first model is based on the universally recognized Johansen theory as specified by Blass et al. [2] to account for the effects of an interlayer on the load-carrying capacity of the timber connection. This model was firstly developed to account for the effects of a OSB panel interposed into single shear timber-to-timber and timber-to-steel joint considering also the interlocking effect due to the stapled OSB-stud connection. This method provides the estimation of the connection strength while does not deal with the aspects related to connection stiffness.

An alternative model, developed for timber-to-concrete connection of composite floor beam, is the one proposed by Gelfi et al. [3]. This model assimilates the connector to a beam on an elastic support considering the connector free to deform in the interlayer. Hence, the effect of the interlayer is accounted both in terms of elastic stiffness and load-carrying capacity.

Despite the different basic formulations, for both models the key parameter governing the effect of the interlayer on the stiffness and strength is the ratio between the thickness of the interlayer and the diameter of the connector.

For the sake of brevity, only the results obtained with the two considered models are reported below; for the complete formulations, see the cited literature.

The geometric parameters of the specimens and the average density values were considered in the calculations. The cases without interlayer were considered as limit condition of zero gap.

The results obtained with the two models are reported in Table 4 and Table 5 for the strength and stiffens respectively.

Table 4: *Strength estimation obtained with the Blaas and Gelfi-Giurinai analytical models. Analytical values include the rope-effect contribution according to ETA-22/0002 [4].*

	F_{y_Enb} [kN]	F_{y_EEH} [kN]	F_{max} [kN]	F_{v_Blass} [kN]	$F_{v\_Gelfi-Giuriani}$ [kN]
GL-NX	33.51	25.24	34.79	28.66	28.66
CLT-NX	36.66	24.87	37.88	28.92	28.92
GL-X35	27.55	20.28	28.89	24.00	22.48
CLT-X35	30.23	18.22	31.16	24.1	22.6

Table 5: *Stiffness estimation obtained with the EC5 and Gelfi-Giuriani models.*

	$K_{1\_exp.}$ [kN/m]	$K_{ser\ (EC5)}$ [kN/m]	$K_{1\_Gelfi-Giuriani}$ [kN/m]
GL-NX	6.06	9.9	5.67
CLT-NX	4.47	10.36	5.79
GL-X35	5.12	-	4.31
CLT-X35	3.43	-	4.4

Results shows that both the analytical models capture the strength reduction due to the interlayer. Analytical strength values are in the range F_{y_EEH} and F_{max} providing a good estimation of the expected load bearing capacity.

As far as stiffness is concerned, it can be observed that the Gelfi-Giuriani model is able to capture, with excellent approximation, the stiffness reduction due to the interlayer.

5 CONCLUSIONS

Results obtained in this work demonstrate that the mechanical behaviour of a nailed timber-to-steel connections is strongly affected by the interposition of a resilient acoustic strip. 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. Failure modes are not affected by the presence of the interlayer.

Analytical models provide an accurate estimation of the stiffens and strength reduction due to the interposition of resilient strip even if, as far as strength is concerned, they seem to be calibrated on the yield condition and not on the peak force.

Finally, in the case of tri-dimensional bracket used with an acoustic interlayer, the strength and stiffens reduction of the nailing system might not be significant as recorded in this work as the deformability of the bracket itself could prevail.

An extension of the experimental campaign is ongoing with the aim of characterizing the effects of the interposition of an interlayer for the different types of connection typically used in Glulam and CLT structures.

ACKNOWLEDGEMENTS

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REFERENCES

[1] A. Speranza, L. Barbaresi and F. Morandi, «Experimental analysis of flanking transmission of different connection systems for CLT panels,» in World Conference on Timber Engineering, Vienna, Austria, 2016.

[2] H. J. Blaß e B. Laskewitz, «Load-carryiing capacity of joints with dowel-type fasteners and interlayers,» in International Council for Research and Innovation in Building and Construction, Delft , Olanda, 2000.

[3] P. Gelfi, E. Giuriani e A. Marini, «Comportamento della connessione a piolo nelle travi miste in legno e calcestruzzo: modellazione teorica e confronti sperimentali,» in III Workshop Italiano sulle Costruzioni Composte, Ancona, Italia, 1998.

[4] European Technical Assessment ETA-22/0002 of 2022/01/24 - Nails and screws for use in nailing plates in timber structures

[5] European Technical Assessment ETA-23/0061 of 2023/02/24 - Flexible interlayer to be used for the reduction of flanking sound transmission and/or vibration transmission in construction works

[6] UNI EN 1380, Timber structures - Test methods - Load bearing nails, screws, dowels and bolts, 2009.

[7] Trutalli D, Marchi L, Scotta R, Pozza L. Capacity design of traditional and innovative ductile connections for earthquake-resistant CLT structures. Bull Earthq Eng 2019;17:2115–36. https://doi.org/10.1007/s10518-018-00536-6.

[8] Gavric I, Fragiacomo M, Ceccotti A. Cyclic behaviour of typical metal connectors for cross-laminated (CLT) structures. Mater Struct 2014:1–17.

[9] Pozza L, Saetta A, Savoia M, Talledo D. Coupled axial-shear numerical model for CLT connections. Constr Build Mater 2017;150:568–82. https://doi.org/10.1016/j. conbuildmat.2017.05.141.

[10] Piazza M, Polastri A, Tomasi R. Ductility of timber joints under static and cyclic loads. Proc Inst Civ Eng – Struct Build 2011;164:79–90. http://dx.doi.org/10.1680/ stbu.10.00017.

[11] Muñoz PQW, Salenikovich A, Mohammad M. Determination of yield point and ductility of timber assemblies: in search for a harmonised approach. In: Int. counc. res. innov. build. constr., CIB; 2008. p. W18/42–12–2.

[12] EN 12512. Timber structures. Test methods. Cyclic testing of joints made with mechanical fasteners. Brussels, Belgium: CEN; 2011.

[13] Pozza L, Scotta R, Trutalli D, Polastri A, Ceccotti A. Concrete-plated wooden shear walls: structural details, testing, and seismic characterization. J Struct Eng 2016;142:E4015003.

[14] European Technical Assessment ETA-22/0089 of 2022/08/25 - Three-dimensional nailing plate (Angle Bracket or Hold Down for timber-to-timber or timber-to-concrete or steel connections)

[15] CEN European Committee for Standardization. (2009) Design of timber structures—Part 1-1: General—Common rules and rules for buildings. Eurocode 5, CEN, Brussels, Belgium, 2009.

[16] CEN European Committee for Standardization. (2013). "Design of structures for earthquake resistance—Part 1: General rules, seismic actions and rules for buildings." Eurocode 8, CEN, Brussels, Belgium.

 https://doi.org/10.52202/069179-0181