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CIRI EDILIZIA E COSTRUZIONI
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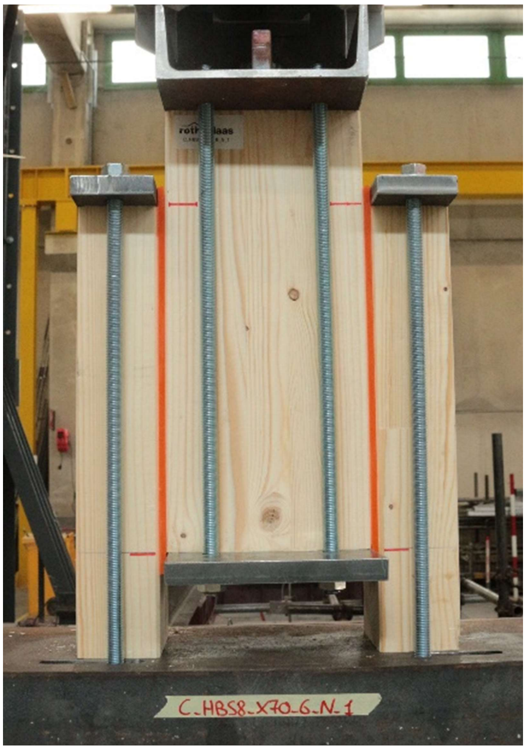
ROTHOBLAAS SRL

Experimental and analytical analysis of timber connections with interposed resilient soundproofing profile.

SHORT REPORT



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Summary

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 affect negatively the acoustic performance of the system [R.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).

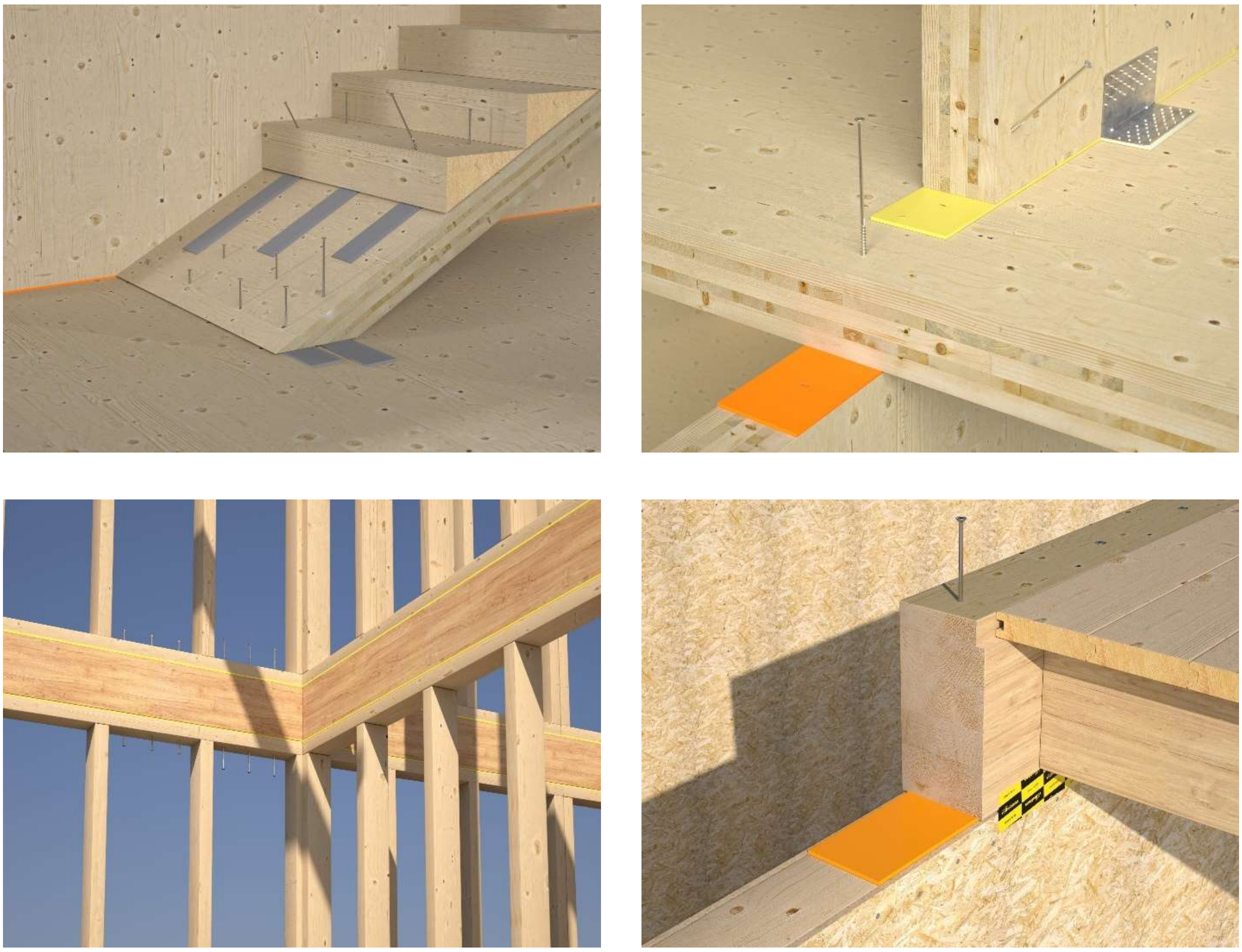


***Figure 1** Example of typical structural joints with interposed acoustic layer (Rothoblaas archive).*

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 standard connection models without considering accurately the effects of the interposed layer or gap.

2. *Research objective*

This Short Technical Report (STR) has been produced by CIRI Buildings and Construction according to the research agreement *Rep. 28/2021 - Protocol n. 1080 del 15/12/2021* commissioned by Rothoblaas S.r.l. within the project ID: PRP2183.

This STR summarizes the main outcomes of the research aimed at the characterization of screwed timber-to-timber connections with interposed an acoustic resilient strip for flanking noise reduction. The research is developed on two levels: experimental and analytical.

EXPERIMENTAL - results of two extended experimental campaigns, carried out in the company headquarters laboratory [R.2] and at the CIRI Buildings and Construction laboratory of university of Bologna [R.3] respectively, are used to assess the effects of an interposed resilient strip on the mechanical behavior of timber-to-timber screwed connections.

ANALITICAL - test results are used to verify the capability of analytical literature models to account for the effect of resilient strip on the mechanical response of timber connections.

The STR firstly reports a summary of the experimental campaigns carried out at Rothoblaas and CIRI Buildings and Construction laboratories. Experimental results are then analyzed adopting suitable linearization procedure [R.4] and then used to assess the effects of an interposed resilient strip on the mechanical behavior of timber-to-timber screwed connections. A study regarding the applicability of analytical models is also reported. An analytical method providing the best prediction of the load carrying capacity of the different tested configurations was finally selected.

3. *Experimental campaigns*

Two complementary experimental campaigns were carried out to characterize the mechanical behavior and failure mode of different types of screwed timber-to-timber connections with interposed resilient soundproofing profile.

A preliminary experimental campaign was carried out at the internal laboratory of Rothoblaas facility and was aimed to investigate the monotonic behavior of the connections with alternative configurations of resilient soundproof profile. An additional experimental campaign was subsequentially carried out at the CIRI-EC laboratory of university of Bologna to investigate the cyclic behavior of selected types of connections monotonically tested in the previous campaign.

A brief description of the two experimental campaigns is reported below, detailing: setups, loading protocols and observed failure modes.

3.1. *Rothoblaas laboratory tests*

The experimental campaign carried out at the internal laboratory of Rothoblaas facility, investigated 43 different configurations, varying the diameter of the screws and the resilient soundproof layers. For each configuration, nr. 3 repetitions of the test were performed for a total of 129 tests. The full description of the experimental results is reported in the test report "*Experimental characterization of monotonic behavior of screwed timber-to-timber joint (one shear plane setup) with interposed resilient soundproofing profile*" available in the company's internal archives [R.2].

Setup: the experimental campaign was conducted according to the EN 1380 [R.5] and consists of monotonic test on timber-to timber connection with a shear plane inclined of 7° and assembled using three HBS screws [R.6] interposing a resilient soundproof layer (e.g.). Figure 2 reports the adopted setup, the geometry, and the components of the samples.

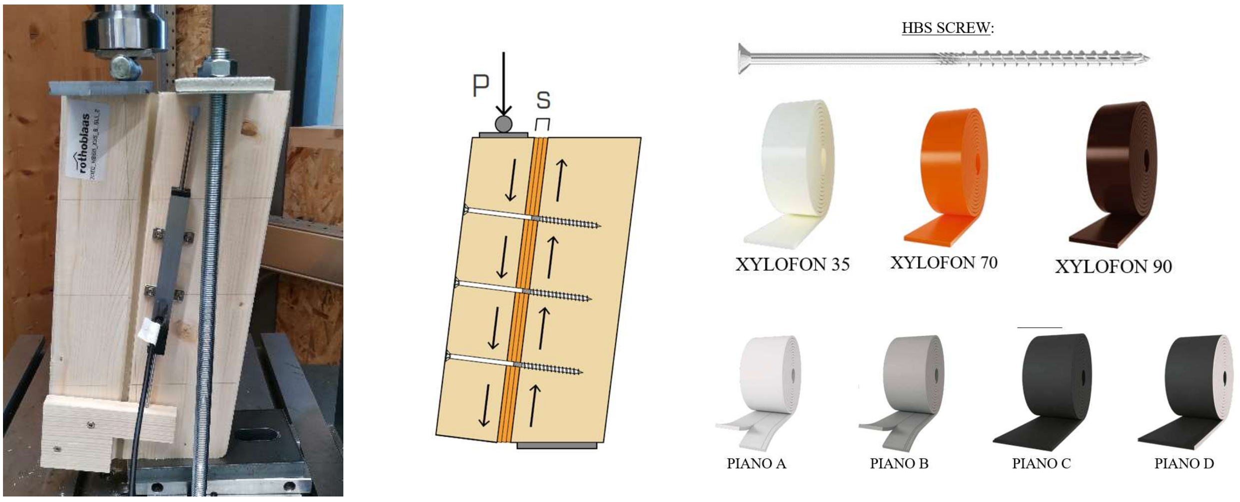


Figure 2 *Setup, sample geometry and components used for monotonic tests.*

Experimental campaign was focused on HBS Ø8 screws, while the cases of HBS Ø6 and HBS Ø10 were introduced to study possible size-effects. Moreover, several parameters that can influence the mechanical response of the connection were investigated, such as: the nature and thickness of the soundproof layer interposed (XYLOFON [R.7] or PIANO [R.8]) and the relative *shore*.

Loading protocol: Monotonic tests were carried out according to the loading protocol prescribed by EN 26891 [R.9] and schematically depicted in Figure 3. The loading/unloading cycle in the range 0.1-0.4 Fmax was not performed.

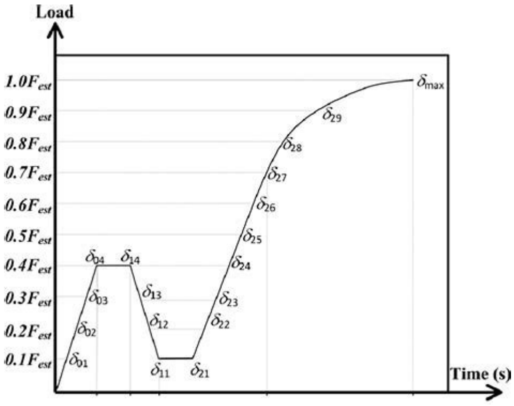


Figure 3 *Load steps adopted for monotonic tests*

Failure mode: all the specimens show the localized embedment of the wood without any failure of the screws which were characterized by a S-shape deformation with double hinge. For large slip values, the timber elements were subjected to longitudinal splitting of the portion enclosed between the heads of the screws. Figure 4 reports an example of the deformed configuration of the sample and of the screws at the end of the tests.

Figure 4 *Observed failure mode at the end of the monotonic tests.*

Mechanical parameters: the experimental load-displacement curves were linearized according to the "method b" of EN 12512 [R.10] defining the yielding condition and the peak force. In this TR, results refer to the individual screws and consider the load-slip curves truncated at 15mm.

3.2. CIRI-EC laboratory tests

The experimental campaign carried out at CIRI-EC laboratory investigated 13 different configurations, varying the diameter of the screws and the resilient soundproof layers. For each configuration, nr.3 repetitions of the test were performed for a total of 39 cyclic tests. The full description of the experimental results is reported in the test report "*Experimental characterization of monotonic and cyclic behavior of screwed timber-to-timber joint with interposed resilient soundproofing profile*" *[R.3]*.

Setup: the experimental campaign was conducted according to the UNI EN 12512 [R.10] and consists of cyclic test on timber-to-timber connection with double shear plane interposing a resilient soundproof layer and assembled using n.4 HBS screws [R.6]. Figure 5 reports the adopted setup, geometry, and components of the samples.

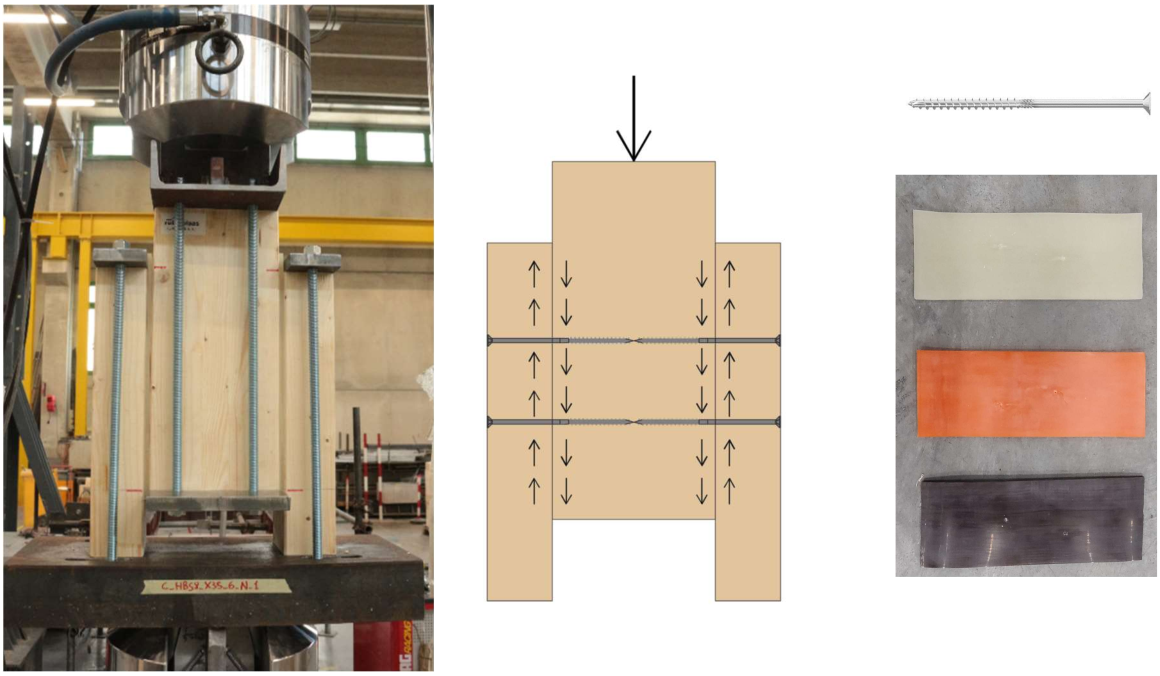


Figure 5 *Setup, sample geometry and components used for cyclic tests.*

As for monotonic test, the experimental campaign was focused on HBS Ø8 screws, while the cases of HBS Ø6 and HBS Ø10 were introduced to study possible size-effects. The significant parameters that can influence the mechanic response of the connection were investigated, such as: the nature and thickness of the soundproof XYLOFON [R.7] profile.

Loading protocol: Cyclic tests were performed according to the loading protocol prescribed by EN 12512 [R.10] and schematically depicted in Figure 6. The yielding displacement V_y was set to 5 mm for all the analysed configurations. The maximum cyclic displacement achieved during the tests was equal to 40mm.

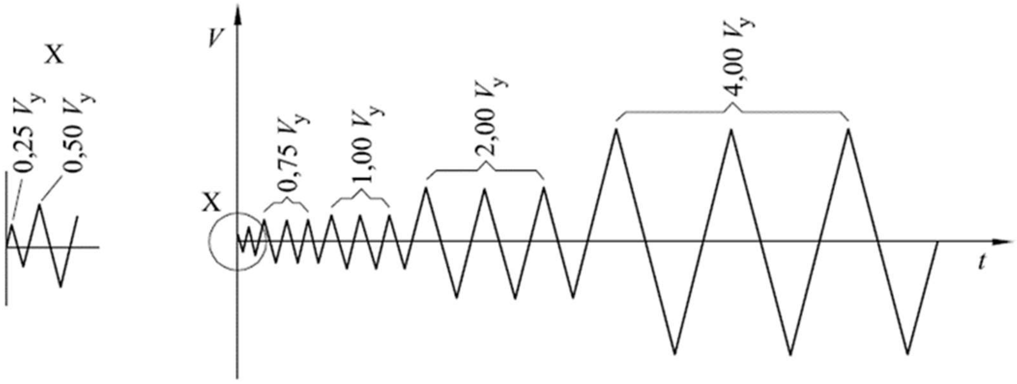


Figure 6. *Load steps adopted for the cyclic tests.*

<u>Failure mode</u>: all specimens subjected to cyclic load show the localized embedment of the wood at the end of the test and failure of all four screws at the interface of the timber elements, as shown in Figure 7.

Figure 7 *Observed failure mode at the end of the cyclic test.*

<u>Mechanical parameters</u>: the envelope load-displacement curves were linearized according to the "method b" of EN 12512 [R.10] defining the yielding condition and the peak force. In this STR, results from linearization of curves truncated at 20mm of slip were used. The cyclic parameters (strength degradation and equivalent viscous damping) were also computed according to EN 12512 [R.10] prescriptions. Results refer to <u>individual screw</u> (total strength divided by n.4 screws).

4. *Analysis of monotonic test results*

This section reports the analysis of some test configurations specifically selected to define the effect of an interposed resilient soundproofing profile on the monotonic response of the connection.

The studied configurations are listed in Table 1 (divided by increasing values of the screw diameter). The selection includes: three different diameters of the HBS screws (6mm, 8mm, 10mm) [R.6], and two different type of resilient soundproofing profile (XYLOFON [R.7] and PIANO [R.8]). To univocally define the effect of a specific resilient soundproofing profile on the connection response, for each set of tests with the same screw diameter two reference limit configurations were considered. The first one had the timber elements in contact (absence of interlayer) while the second one had the timber elements detached (air gap and Teflon spacer).

Table 1 *List of the selected configuration monotonically tested.*

ID	Screw nominal diameter [mm]	Screw length [mm]	Screw type	Force-Fiber Angle	Layer Type	Layer thickness [mm]
NX_6	6	180	HBS6180	0°	None	0
AIR_6_6	6	180	HBS6180	0°	Air + teflon	6
X35_6_6	6	180	HBS6180	0°	XYLOFON 35	6
X35_6_12	6	180	HBS6180	0°	XYLOFON 35	12
X35_6_18	6	180	HBS6180	0°	XYLOFON 35	18
NX_8	8	180	HBS8180	0°	None	0
AIR_8_6	8	180	HBS8180	0°	Air + teflon	6
X35_8_6	8	180	HBS8180	0°	XYLOFON 35	6
X35_8L_6	8	180	HBS8360*	0°	XYLOFON 35	6
X35_8_12	8	180	HBS8180	0°	XYLOFON 35	12
X35_8_18	8	180	HBS8180	0°	XYLOFON 35	18
X70_8_6	8	180	HBS8180	0°	XYLOFON 70	6
X90_8_6	8	180	HBS8180	0°	XYLOFON 90	6
PA_8_6	8	180	HBS8180	0°	PIANO A	6
PB _8_6	8	180	HBS8180	0°	PIANO B	6
PC_8_6	8	180	HBS8180	0°	PIANO C	6
PD _8_6	8	180	HBS8180	0°	PIANO D	6
NX_10	10	180	HBS10180	0°	None	0
AIR_10_6	10	180	HBS10180	0°	Air + teflon	6
X35_10_6	10	180	HBS10180	0°	XYLOFON 35	6
X35_10_12	10	180	HBS10180	0°	XYLOFON 35	12
X35_10_18	10	180	HBS10180	0°	XYLOFON 35	18

Results from experimental test carried out in the configurations reported in Table 1 were critically analyzed. Three significant comparison groups were selected in order to emphasize the effect of the interposed resilient soundproof profile on the connection response. More in detail, the mechanical parameters extracted from the linearized load-displacement curves (i.e. load carrying capacity, stiffness and ductility) were investigated and compared.

4.1. Timber-to-timber connections with interposed "XYLOFON" resilient profiles

This section provides a comparison between connections assembled using HBS8 screws and interposing different types of XYLOFON resilient profiles. Three different profiles with decreasing levels of compressibility are considered: XYLOFON 35, XYLOFON 70, and XYLOFON 90. In addition, two reference configurations characterized by absence of interlayer and air gap with Teflon spacer respectively, were analyzed. Details of the considered configurations are listed in Table 1. For each of the 6 configurations examined, three repetitions of the monotonic test were carried out and then analysed.

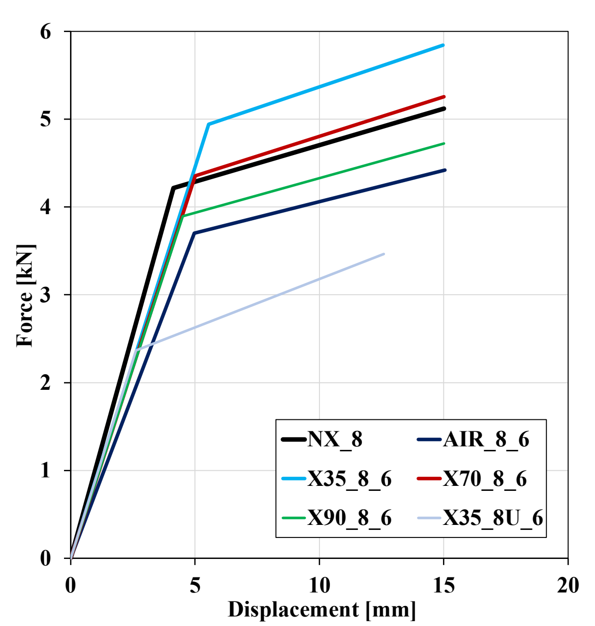
***Table 2** Details of timber-to-timber connections with interposed "XYLOFON" resilient profiles.*

ID	Screw nominal diameter [mm]	Screw length [mm]	Screw type	Force-Fiber Angle	Layer Type	Layer thickness [mm]
NX_8	8	180	HBS8180	0°	None	0
AIR_8_6	8	180	HBS8180	0°	Air + teflon	6
X35_8_6	8	180	HBS8180	0°	XYLOFON 35	6
X70_8_6	8	180	HBS8180	0°	XYLOFON 70	6
X90_8_6	8	180	HBS8180	0°	XYLOFON 90	6
X35_8U_6	8	180	HBS8360*	0°	XYLOFON 35	6

* Used only the untreated portion of the screw in order to nullify the withdrawal capacity.

<u>Linearized force-displacement curves</u>

The experimental load-displacement curves were linearized according to the "method b" of EN 12512 [R.10]. Figure 8 reports the mean linearized force-displacement curves and the corresponding mean values of the mechanical parameters obtained from the three repetitions of the monotonic test carried out for each configuration. Results refer to the individual screw.



ID	K [kN/mm]	dy [mm]	Fy [kN]	F_{15mm} [kN]	μ [–]
NX_8	1.04	4.14	4.22	5.12	3.73
AIR_8_6	0.74	4.98	3.70	4.42	6.70
X35_8_6	0.89	5.54	4.94	5.84	2.71
X70_8_6	0.88	5.00	4.36	5.26	3.04
X90_8_6	0.86	4.51	3.90	4.72	3.22
X35_8U_6	0.90	2.64	2.37	3.46	5.75

***Figure 8** Linearized force displacement-curves and corresponding mean mechanical parameters.*

Linearized force-displacement curves highlight a modification of the mechanical response of the connections due to the type of interposed resilient profile. A detailed analysis of the effects in terms of strength, stiffness and ductility is reported in the following paragraphs.

Effects of interposed resilient profile on the load carrying capacity

Analyzing the linearized curves and the force values of Figure 9 it is possible to observe that:

- The configuration with the detached elements (air gap and Teflon spacer) has the smallest yield force and peak strength values. According to the dimensionless values depicted in Figure 9, the air gap induces a 15% reduction of the force values compared to the reference configuration (absence of interlayer).
- The increase in compressibility of the resilient profile leads to an increase in both yield force and peak load-carrying capacity. As depicted in the graph of Figure 9, the strength increase is approximately 10% between XYLOFON 90 and XYLOFON 70 and 20% between XYLOFON 70 and XYLOFON 35. Such strength increase is probably due to the interface properties of the more compressible profiles as confirmed by the research conducted at TU-Graz entitled "Einflussparameter auf die Reibungskenngrößen von XYLOFON-Schalldämmstreifen zwischen BSP-Raumzellen" [R.11] investigating the friction behavior of the XYLOFON resilient profile.
- All connections assembled with XYLOFON resilient profiles show higher yield force and peak load-carrying capacity values than those of the connections with detached elements (air gap and Teflon spacer).
- Connections assembled using XYLOFON 35 profile provide strength values approximately 15-20% higher than the reference configuration. Connections assembled using XYLOFON 70 profile provide strength values approximately equal to the reference configuration. Connections assembled using XYLOFON 90 profile provide strength values approximately 5-10% lower than the reference configuration.
- The configuration assembled using XYLOFON 35 with the untreated portion of the screw shows atypical behaviour compared to the counterpart assembled with threaded screws. The strength values are approximatively reduced by half because of the so called "rope effect", provided by the axial capacity of the connector that cannot be activated as well as the frictional phenomenon.

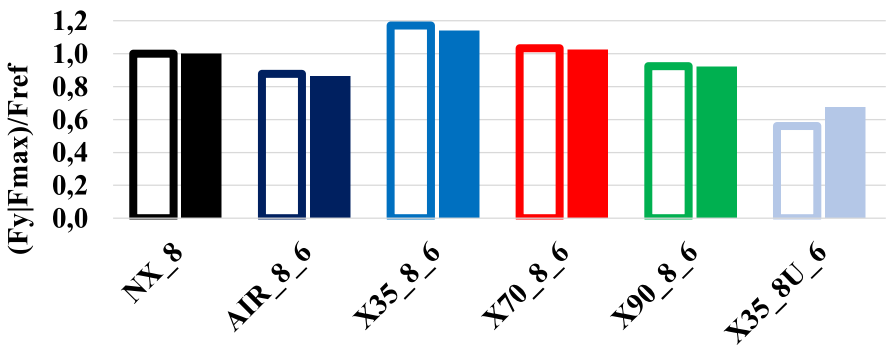


Figure 9 *Dimensionless values of yielding force and peak load-carrying capacity (empty bars correspond to the yield force).*

Effects of interposed resilient profile on the elastic stiffness

Analyzing the linearized curves and the stiffness values of Figure 10 it is possible to observe that:

- The configuration with the detached elements (air gap and Teflon spacer) has the smallest stiffness. According to the dimensionless values depicted in Figure 10, air gap induces a 30% reduction of the stiffness values compared to the reference configuration one (absence of interlayer).
- All connections assembled with XYLOFON resilient profiles are characterized by approximately equivalent stiffness values regardless the compressibility of the profile.
- All connections assembled with XYLOFON resilient profiles show higher stiffness values than those of the connections with detached elements (air gap and Teflon spacer). According to Figure 10, the resilient profiles ensure stiffness values approximatively 15% greater than the configuration with the detached elements (air gap and Teflon spacer).
- All connections assembled with XYLOFON resilient profiles show lower stiffness values than the reference configuration one (absence of interlayer). The interposition of the XYLOFON resilient profiles induce 15% reduction of the stiffness values.

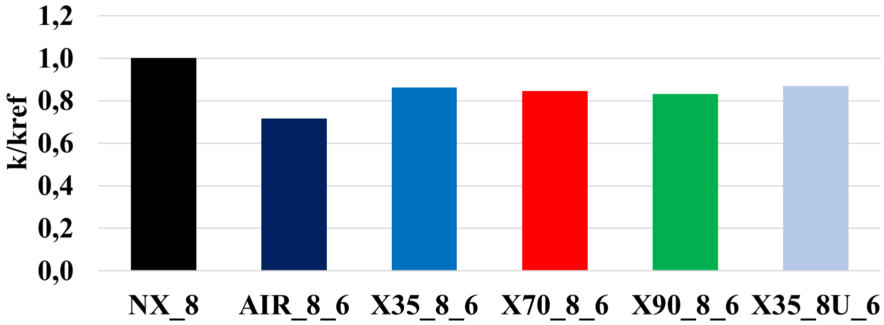


Figure 10 *Dimensionless values of elastic stiffness.*

Effects of interposed resilient profile on ductility

The ductility value is defined as the ratio between the ultimate displacement (in this study fixed to 15mm) and the yielding displacement; ductility ratio of different analysed configurations are plotted in Figure 11. For all the configurations, the ductility values are approximately equal to 3. The reference configuration (absence of interlayer) shows a slightly higher value but still lower than 4. It means that the post-elastic behaviour of the connection is moderately influenced by the interposition of a XYLOFON resilient profile.

It is worth nothing that the configuration assembled using XYLOFON35 resilient profile with the untreated portion of the screw shows a very high ductility values because of the anticipated yielding of the connections.

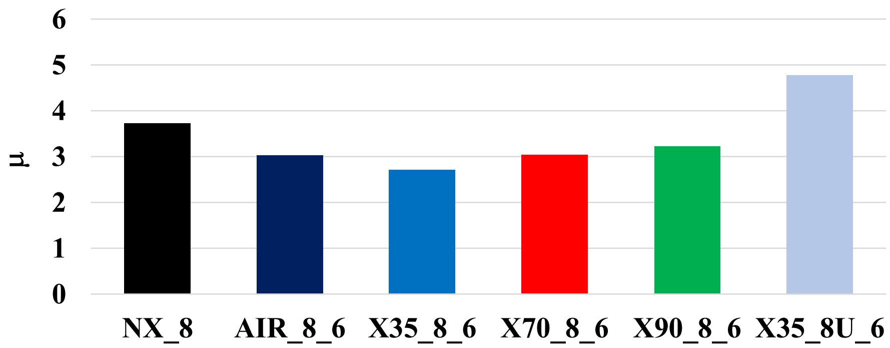


Figure 11 *Ductility values of analyzed configurations.*

4.2. *Timber-to-timber connections with interposed "XYLOFON" or "PIANO" resilient profiles*

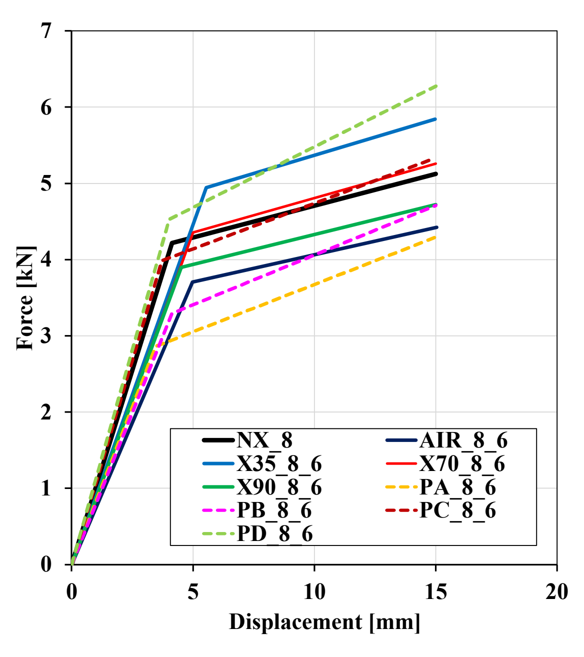
This section provides a comparison between connections assembled using HBS8 screws and interposing two different types of resilient profiles: XYLOFON and PIANO. For both type of resilient profiles, decreasing levels of compressibility are considered: XYLOFON 35-70-90 and PIANO A-B-C-D respectively. Two configurations characterized by absence of interlayer and air gap + Teflon spacer are used as reference for the comparison. Details of the 9 configurations considered in this comparative study are listed in Table 3. For each of the 9 configurations three repetitions of the monotonic test were carried out and then analysed.

Table 3 *Details of timber-to-timber connections with interposed "XYLOFON" and "PIANO" profiles.*

ID	Screw nominal diameter [mm]	Screw length [mm]	Screw type	Force-Fiber Angle	Layer Type	Layer thickness [mm]
NX_8	8	180	HBS8180	0°	None	0
AIR_8_6	8	180	HBS8180	0°	Air + teflon	6
X35_8_6	8	180	HBS8180	0°	XYLOFON 35	6
X70_8_6	8	180	HBS8180	0°	XYLOFON 70	6
X90_8_6	8	180	HBS8180	0°	XYLOFON 90	6
PA _8_6	8	180	HBS8180	0°	PIANO A	6
PB _8_6	8	180	HBS8180	0°	PIANO B	6
PC_8_6	8	180	HBS8180	0°	PIANO C	6
PD_8_6	8	180	HBS8180	0°	PIANO D	6

Linearized force-displacement curves

The experimental load-displacement curves were linearized according to the "method b" of EN 12512 [R.10]. Figure 12 reports the mean linearized force-displacement curves and the corresponding mean values of the mechanical parameters obtained from the three repetitions of the monotonic test carried out for each configuration. Results refer to the individual screw.



ID	K [kN/mm]	dy [mm]	Fy [kN]	F_{15mm} [kN]	μ [–]
NX_8	1.04	4.14	4.22	5.12	3.73
AIR_8_6	0.74	4.98	3.70	4.42	6.70
X35_8_6	0.89	5.54	4.94	5.84	2.71
X70_8_6	0.88	5.00	4.36	5.26	3.04
X90_8_6	0.86	4.51	3.90	4.72	3.22
PA _8_6	0.83	3.46	2.86	4.29	4.35
PB _8_6	0.80	4.13	3.29	4.71	3.63
PC_8_6	1.08	3.73	3.99	5.33	4.04
PD_8_6	1.14	4.02	4.53	6.28	3.80

***Figure 12** Linearized force displacement-curves and corresponding mean mechanical parameters.*

Linearized force-displacement curves highlight a modification of the mechanical response of the connections due to the type of interposed resilient profile. In general, it can be observed that the type of interposed resilient profiles modifies both the elastic and post-elastic branches of the linearized load-displacement curves. A detailed analysis of the effects in terms of strength, stiffness and ductility is reported in the following sections.

Effects of interposed resilient profile on the load-carrying capacity

Analyzing the linearized curves and the force values of Figure 13 it is possible to observe that:

- The reduction in compressibility of the resilient profile induces an opposite trend between XYLOFON and PIANO. For XYLOFON profile the yielding and peak forces decrease as the compressibility decrease, while for PIANO profile they increase.
- XYLOFON 35 and PIANO D show strength values greater than the reference configuration (absence of interlayer).
- XYLOFON 70 and PIANO C show strength values approximately equal to the reference configuration (absence of interlayer).
- XYLOFON 90 and PIANO B show strength values approximately equal to the connections with detached elements (air gap and Teflon spacer) while PIANO A configuration is characterized by the lowest values of yielding and peak strength.

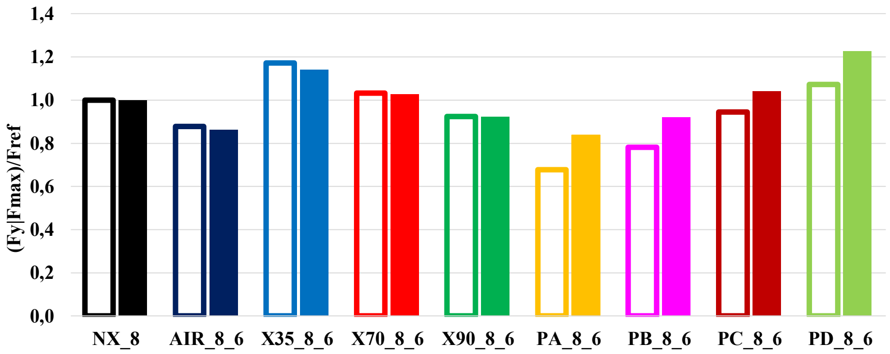


Figure 13 *Dimensionless values of yielding force and peak load-carrying capacity (empty bars correspond to the yield force)*

Effects of interposed resilient profile on elastic stiffness

Analyzing the linearized curves and the stiffness values of Figure 14 it is possible to observe that:

- All profiles show a greater stiffness than the limit configuration with detached elements one (air gap and Teflon spacer).
- PIANO C and D configurations show a stiffness approximately equal to the reference configuration (absence of interlayer) while all other configurations with interposed resilient profiles show a stiffness reduction of approximately 20%.

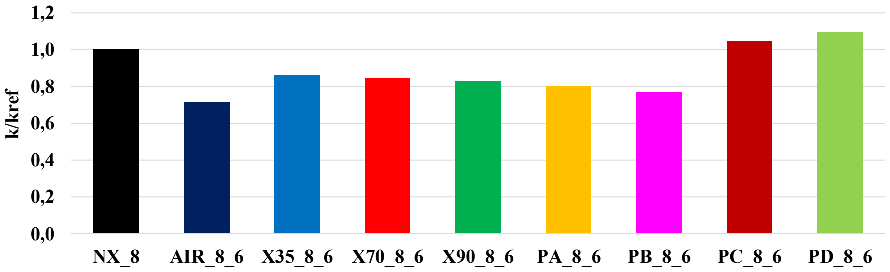


Figure 14 *Dimensionless values of elastic stiffness.*

Effects of interposed resilient profile on ductility

Ductility values of the different type of analysed configurations are plotted in Figure 15. It is possible to observe that:

- the configurations assembled using XYLOFON resilient profile are characterized by ductility value approximately equal to the limit configuration with detached elements one (air gap and Teflon spacer).
- the configurations assembled using PIANO resilient profile are characterized by ductility value approximately equal to the reference configuration one (absence of interlayer).

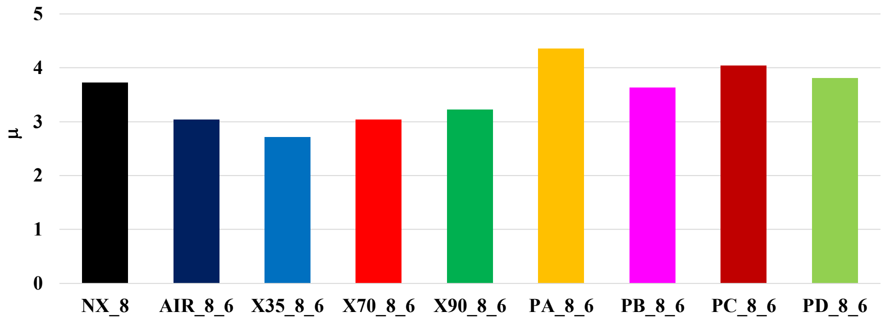


Figure 15 *Ductility values of analyzed configurations.*

4.3. Timber-to-timber connections with interposed "XYLOFON" and different screw diameters

This section provides a comparison between connections assembled using different HBS screw diameters and interposing different thicknesses of XYLOFON 35 resilient profiles. For each diameter, two reference configurations characterized by absence of interlayer and air gap and Teflon spacer respectively are analyzed. Details of the considered configurations are listed in Table 4. Three repetitions of the monotonic test were carried out for each of the n.15 examined configurations and then the results were analysed.

Table 4 *Details of timber-to-timber connections with interposed "XYLOFON" and different screw diameters.*

ID	Screw nominal diameter [mm]	Screw length [mm]	Screw type	Force-Fiber Angle	Layer Type	Layer thickness [mm]
NX_6	6	180	HBS6180	0°	None	0
AIR_6_6	6	180	HBS6180	0°	Air + teflon	6
X35_6_6	6	180	HBS6180	0°	XYLOFON 35	6
X35_6_12	6	180	HBS6180	0°	XYLOFON 35	12
X35_6_18	6	180	HBS6180	0°	XYLOFON 35	18
NX_8	8	180	HBS8180	0°	None	0
AIR_8_6	8	180	HBS8180	0°	Air + teflon	6
X35_8_6	8	180	HBS8180	0°	XYLOFON 35	6
X35_8_12	8	180	HBS8180	0°	XYLOFON 35	12
X35_8_18	8	180	HBS8180	0°	XYLOFON 35	18
NX_10	10	180	HBS10180	0°	None	0
AIR_10_6	10	180	HBS10180	0°	Air + teflon	6
X35_10_6	10	180	HBS10180	0°	XYLOFON 35	6
X35_10_12	10	180	HBS10180	0°	XYLOFON 35	12
X35_10_18	10	180	HBS10180	0°	XYLOFON 35	18

Linearized force-displacement curves

The experimental load-displacement curves were linearized according to the "method b" of EN 12512 [R.10].

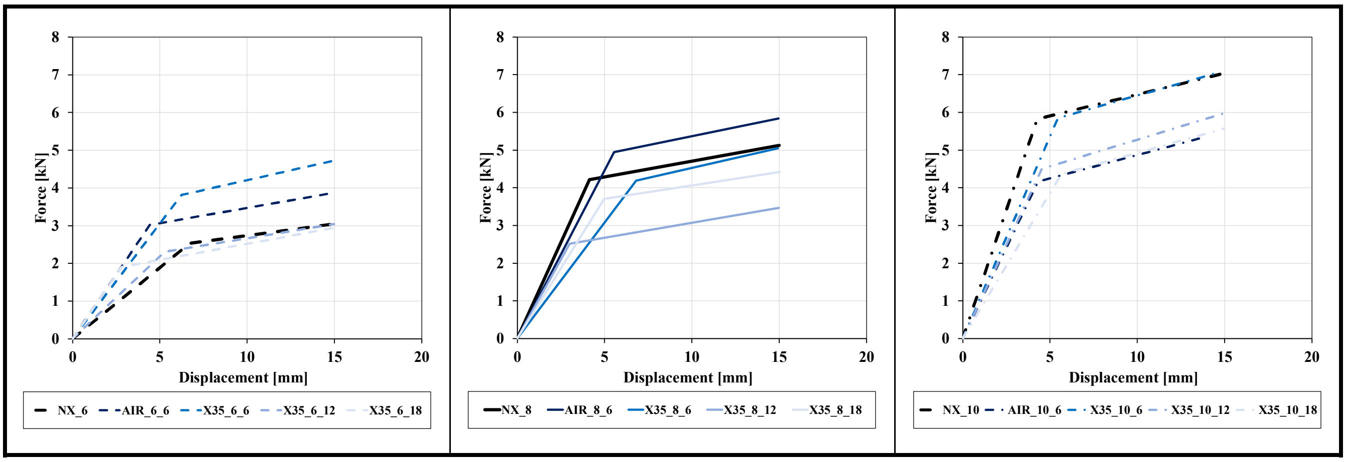
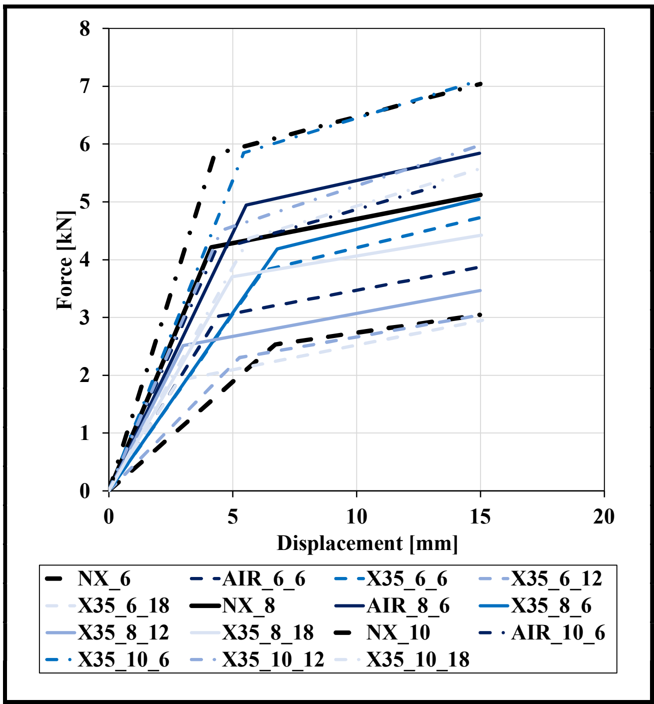


Figure 16 reports the mean linearized force-displacement curves and the corresponding mean values of the mechanical parameters obtained from the three repetitions of the monotonic test carried out for each configuration. Results refer to the individual screw.



ID	K [kN/mm]	dy [mm]	Fy [kN]	F_{15mm} [kN]	μ [–]
NX_6	0.85	3.00	2.51	3.47	5.00
AIR_6_6	0.70	2.81	1.91	2.95	5.37
X35_6_6	0.67	4.76	3.13	3.92	3.15
X35_6_12	0.46	5.28	2.31	3.04	2.84
X35_6_18	0.38	6.71	2.53	3.05	2.28
NX_8	1.04	4.14	4.22	5.12	3.63
AIR_8_6	0.74	4.98	3.70	4.42	3.02
X35_8_6	0.89	5.54	4.94	5.84	2.70
X35_8_12	0.64	6.80	4.19	5.05	2.19
X35_8_18	0.62	6.24	3.81	4.74	2.50
NX_10	1.39	4.27	5.82	7.04	3.52
AIR_10_6	0.97	4.32	4.17	5.30	3.13
X35_10_6	1.09	5.45	5.85	7.06	2.69
X35_10_12	0.99	4.54	4.51	5.98	3.30
X35_10_18	0.78	5.66	4.37	5.57	2.71

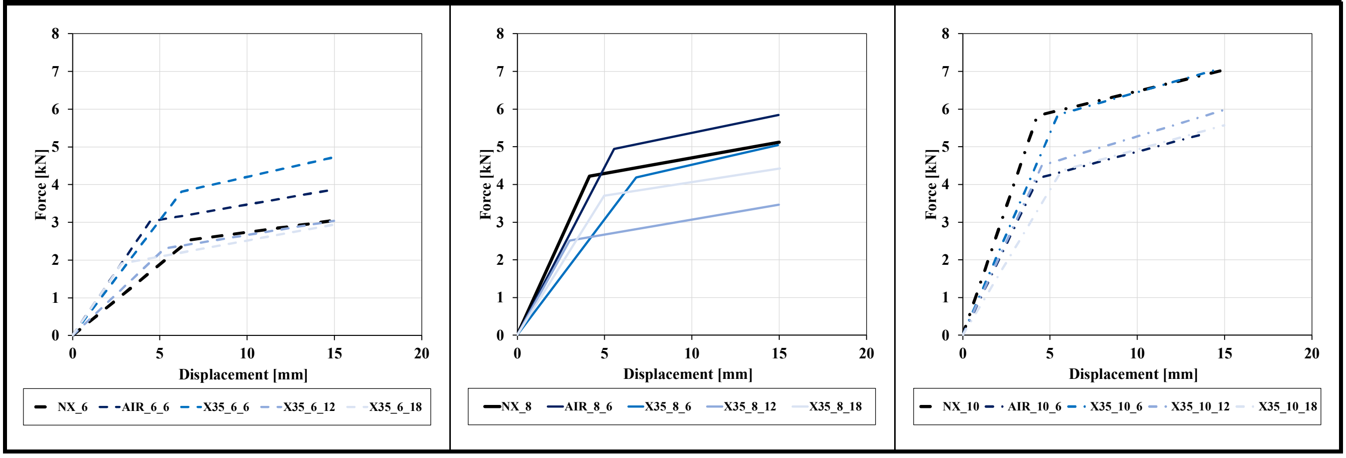


Figure 16 *Linearized force displacement-curves and corresponding mean mechanical parameters.*

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. 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.

Effects of interposed resilient profile and screw diameter on the load carrying capacity

Analyzing the linearized curves and the force values of Figure 17 it is possible to observe that:

- HBS6 and HBS8 screw configurations with a 6mm thick profile are characterized by an overstrength compared to the reference configuration (absence of interlayer). Otherwise, HBS10 screw configurations with a 6mm thick profile does not provide overstrength but show values approximately equal to the reference configuration.
- 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).

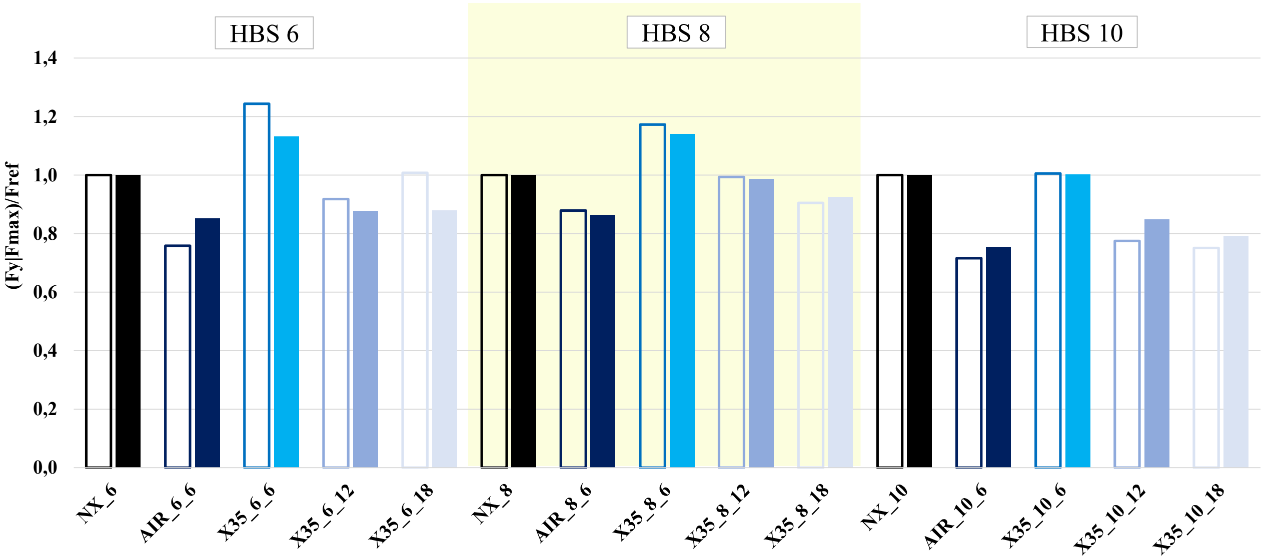


Figure 17 *Dimensionless values of yielding force and peak load-carrying capacity (empty bars correspond to the yield force)*

Effects of interlayer on the elastic stiffness

Analyzing the linearized curves and the stiffness values of Figure 18 it is possible to observe that:

- All configurations with interposed resilient profile show a significant stiffness reduction compared to the reference configuration (absence of interlayer). The stiffness reduction ranges from approximatively 15% to 60%.
- Configurations with small screw diameters are susceptible to a significant stiffness reduction as the interposed resilient profile thickness increases.
- Only 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).

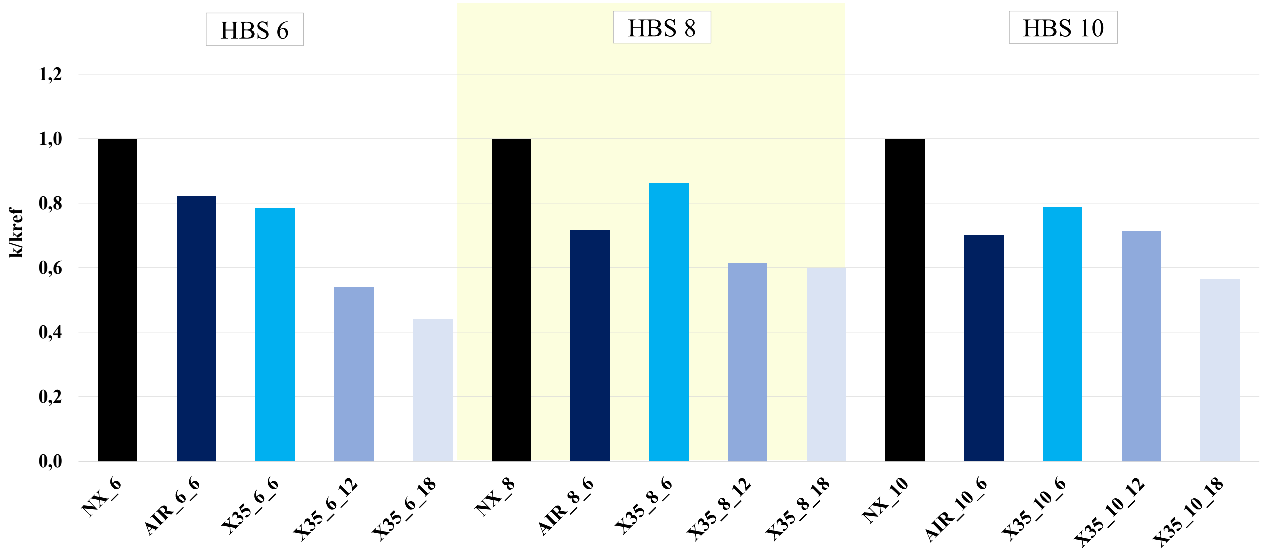


Figure 18 *Dimensionless values of elastic stiffness.*

Effects of interlayer on the ductility

The ductility values of the different type of analysed configurations are plotted in Figure 19. It is possible to observe that:

- All the configurations with interposed resilient profile show a significant stiffness reduction compared to the reference configuration (absence of interlayer). The stiffness reduction ranges from approximatively 15% to 60%.
- 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.

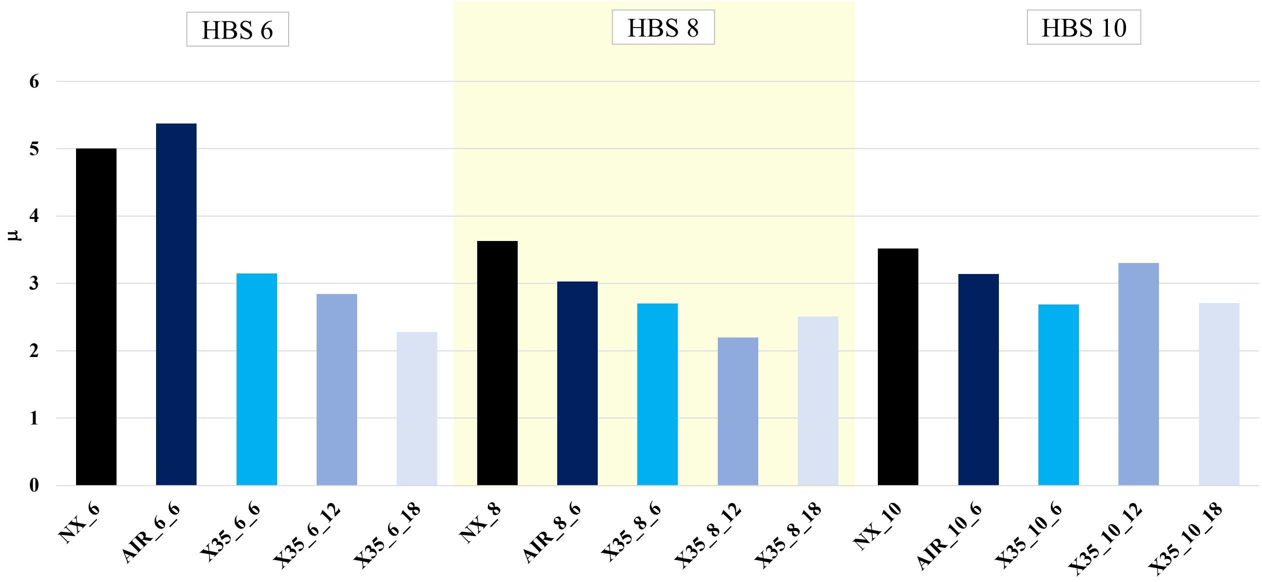


Figure 19 *Ductility values of analyzed configurations.*

5. *Analysis of cyclic test results*

This section analysed the results from the cyclic test carried out on connections assembled using different HBS screw diameters and interposing XYLOFON 35 resilient profiles. For each diameter, the two reference configurations, characterized by absence of interlayer and air gap and Teflon spacer respectively, are analyzed and compared. Details of the considered configurations are listed in Table 5. For each of the 9 configurations examined, three repetitions of the cyclic test were carried out and then the results were analysed.

***Table 5** Details of timber-to-timber connections with interposed "XYLOFON 35" resilient profiles.*

Test ID	**Nominal diameter**	**Length**	**Screw type**	**Force-Fiber Angle**	**Layer**	**Layer thickness**
NX_6	6	180	HBS6180	0°	None	0
AIR_6_6	6	180	HBS6180	0°	Air	6
X35_6_6	6	180	HBS6180	0°	XYL 35	6
NX_8	8	180	HBS8180	0°	None	0
AIR_8_6	8	180	HBS8180	0°	Air	6
X35_8_6	8	180	HBS8180	0°	XYL 35	6
NX_10	10	180	HBS10180	0°	None	0
AIR_10_6	10	180	HBS10180	0°	Air	6
X35_10_6	10	180	HBS10180	0°	XYL 35	6

5.1. *Force vs displacement curves*

The experimental load-displacement curves were analysed defining the first-cycle envelope curves and then linearized according to the "method b" of EN 12512 [R.10]. Figure 20, Figure 21 and Figure 22 report a selection of the experimental cyclic curves with a zoom of the experimental cycles (in the range 0-20mm) superimposed to the linearized curves. Results refer to the individual screw.

Linearized force-displacement curves highlight a modification of the mechanical response of the connections due to both the screw diameters and the interposed resilient profile. Cyclic results are consistent with the monotonic ones and show that the increase in the diameter of the screw induces an increase in load carrying capacity. Moreover, configurations with large diameters show a lower susceptibility to the interposition of the XYLOFON 35 resilient profile.

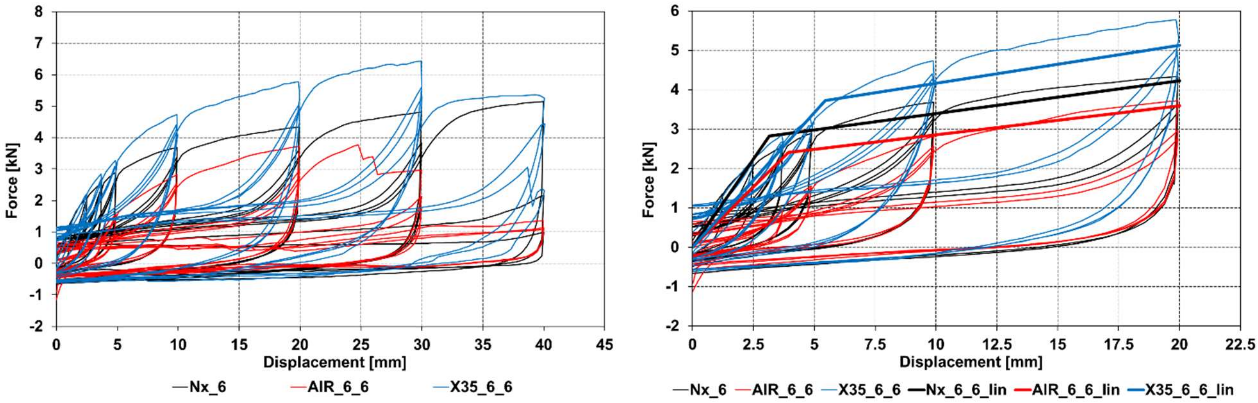


***Figure 20 .** HBS6 cyclic force displacement-curves with superimposed linearized backbone curves.*

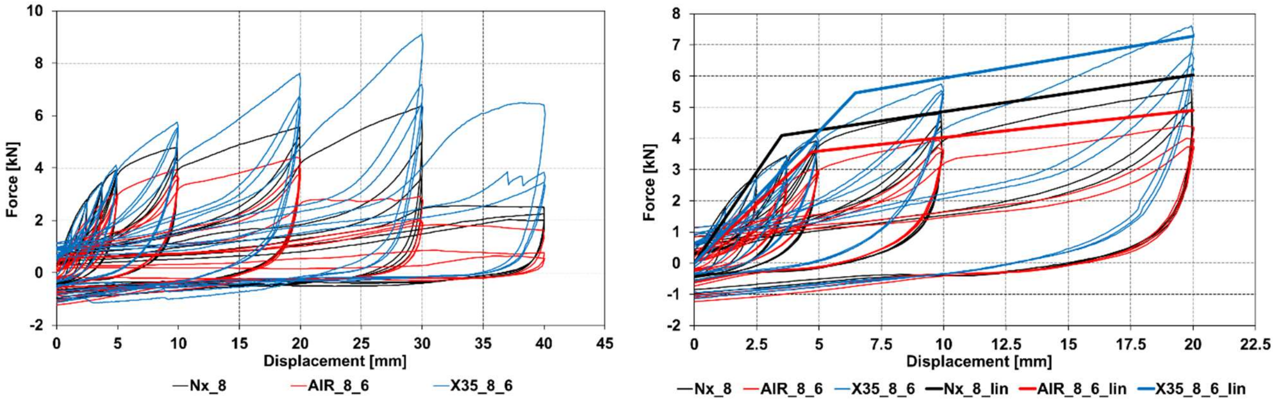


Figure 21 *HBS8 cyclic force displacement-curves with superimposed linearized backbone curves.*

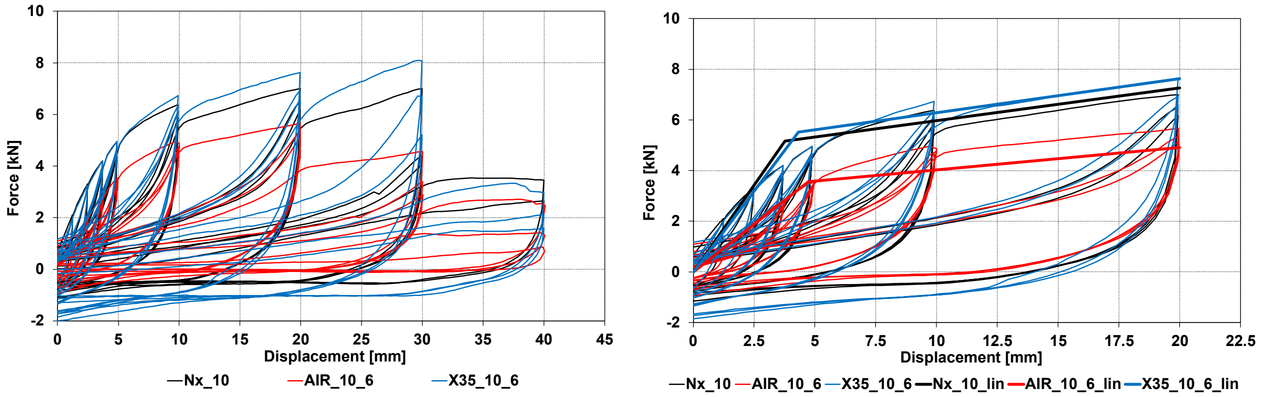


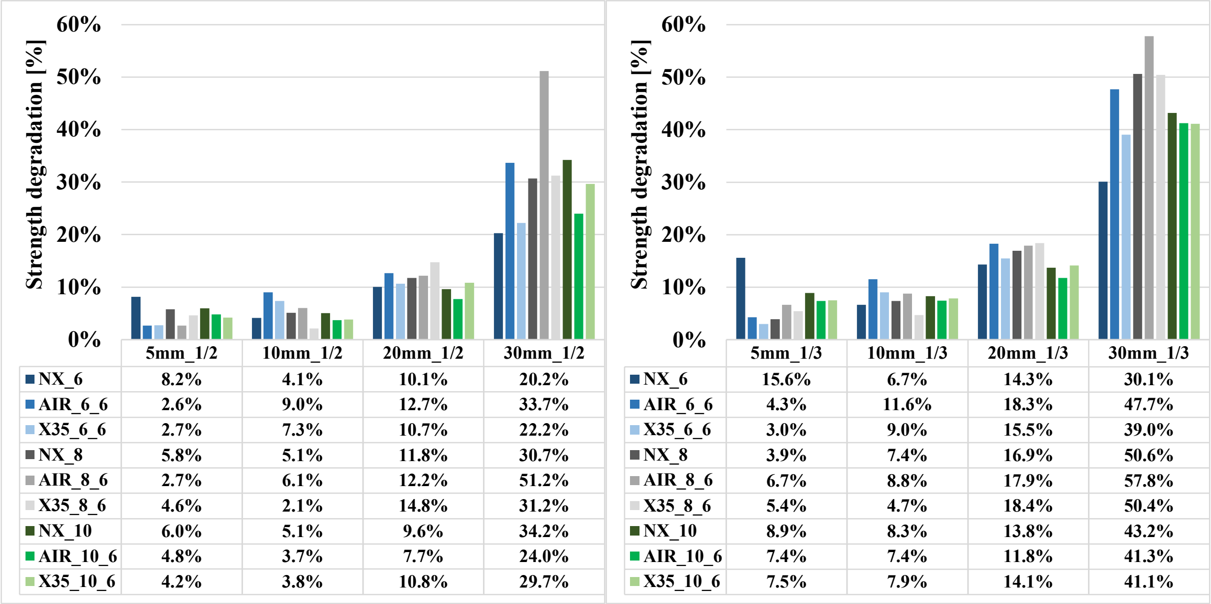
Figure 22 *HBS10 cyclic force displacement-curves with superimposed linearized backbone curves.*

5.2. Strength degradation

The strength degradation was evaluated for each cycle amplitude according to the procedure defined by EN 12512 [R.10]. Two evaluations were carried out referring to the different strength values recorded at the 1st and 2nd cycles and at the 1st and 3rd cycles respectively (Figure 23).

Analyzing the strength degradation values it is possible to observe that:

- Up to 20mm amplitude the greatest degradation rate occurs with the 1st cycle repetition while for larger amplitudes even the 2nd cycle repetition significantly affects the strength degradation.
- For small amplitude cycles, configurations assembled using large diameter screws are less affected by the interlayer than small diameter ones, showing similar strength degradation values to the reference configuration one (absence of interlayer).
- For small amplitude cycles, the interposition of the XYLOFON 35 resilient profile generally induces lower strength degradation values than the ones of the limit configuration of connections with detached elements (air gap and Teflon spacer).



	5mm_1/2	10mm_1/2	20mm_1/2	30mm_1/2
NX_6	8.2%	4.1%	10.1%	20.2%
AIR_6_6	2.6%	9.0%	12.7%	33.7%
X35_6_6	2.7%	7.3%	10.7%	22.2%
NX_8	5.8%	5.1%	11.8%	30.7%
AIR_8_6	2.7%	6.1%	12.2%	51.2%
X35_8_6	4.6%	2.1%	14.8%	31.2%
NX_10	6.0%	5.1%	9.6%	34.2%
AIR_10_6	4.8%	3.7%	7.7%	24.0%
X35_10_6	4.2%	3.8%	10.8%	29.7%

a)

	5mm_1/3	10mm_1/3	20mm_1/3	30mm_1/3
NX_6	15.6%	6.7%	14.3%	30.1%
AIR_6_6	4.3%	11.6%	18.3%	47.7%
X35_6_6	3.0%	9.0%	15.5%	39.0%
NX_8	3.9%	7.4%	16.9%	50.6%
AIR_8_6	6.7%	8.8%	17.9%	57.8%
X35_8_6	5.4%	4.7%	18.4%	50.4%
NX_10	8.9%	8.3%	13.8%	43.2%
AIR_10_6	7.4%	7.4%	11.8%	41.3%
X35_10_6	7.5%	7.9%	14.1%	41.1%

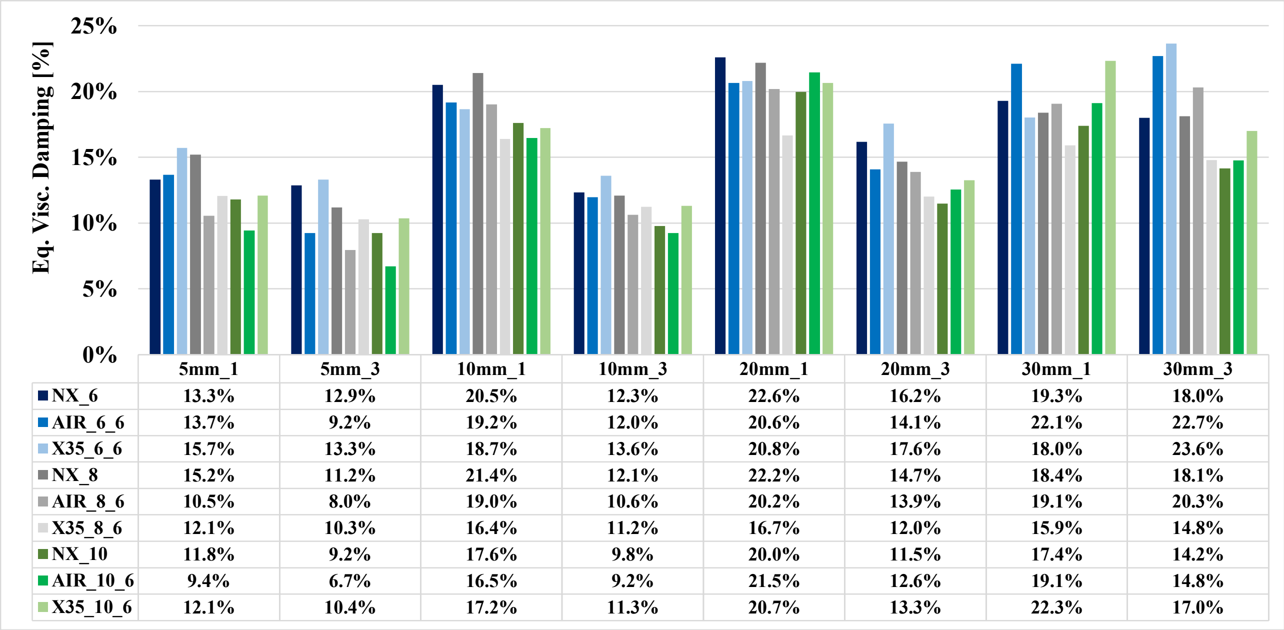
b)

Figure 23 *Percentual strength degradation values of the different configurations: a) 1st-2nd cycles and b) 1st-3rd cycles.*

5.3. Equivalent viscous damping

The equivalent viscous damping ratio was evaluated, for each cycle amplitude, according to the procedure defined by EN 12512 [R.10]. Two evaluations were carried out referring to 1st and 3rd cycles respectively (Figure 24). Analyzing the equivalent viscous damping values, it is possible to observe that:

- For all configurations, the equivalent viscous damping values computed referring to the 3rd cycles are lower than the ones computed referring to the 1st cycles meaning that the strength degradation affects negatively the dissipative capacity of the connections.
- For all the configurations, the interposition of the XYLOFON 35 resilient profile generally induces higher values of equivalent viscous damping than the ones of both reference configuration (absence of interlayer) and limit configuration of connections with detached elements (air gap and Teflon spacer).
- Configurations assembled using large diameter screws are characterized by lower equivalent viscous damping values than configurations assembled using small diameter screws.



	5mm_1	5mm_3	10mm_1	10mm_3	20mm_1	20mm_3	30mm_1	30mm_3
■ NX_6	13.3%	12.9%	20.5%	12.3%	22.6%	16.2%	19.3%	18.0%
■ AIR_6_6	13.7%	9.2%	19.2%	12.0%	20.6%	14.1%	22.1%	22.7%
■ X35_6_6	15.7%	13.3%	18.7%	13.6%	20.8%	17.6%	18.0%	23.6%
■ NX_8	15.2%	11.2%	21.4%	12.1%	22.2%	14.7%	18.4%	18.1%
■ AIR_8_6	10.5%	8.0%	19.0%	10.6%	20.2%	13.9%	19.1%	20.3%
■ X35_8_6	12.1%	10.3%	16.4%	11.2%	16.7%	12.0%	15.9%	14.8%
■ NX_10	11.8%	9.2%	17.6%	9.8%	20.0%	11.5%	17.4%	14.2%
■ AIR_10_6	9.4%	6.7%	16.5%	9.2%	21.5%	12.6%	19.1%	14.8%
■ X35_10_6	12.1%	10.4%	17.2%	11.3%	20.7%	13.3%	22.3%	17.0%

Figure 24 *Equivalent viscous damping values of the different configurations.*

6. Analytical models

Two alternative analytical models are used to predict the load carrying capacity of the timber-to-timber connections with interposed different types of soundproof resilient profile. The first method is the standard one based on the well know Johansen theory [R.12] (J) while the second one consists in the upgrading of the basic Johansen theory provided by Blaß et al. [R.13] (B) to account for the interposition of a OSB interlayer in timber-to-timber connections.

Table 6 reports a comparison between the experimental monotonic results and the analytical prediction carried out adopting the two different models. The mean mechanical parameters of the materials (timber density ρ, screw yielding moment M_y etc..) were implemented in the analytical models in order to provide an estimation of the load carrying capacity coherent with the mean strength values extracted from the linearization of the experimental load-displacement curves in terms of both yielding force (F_y) and strength at a15mm displacement (F_{max}). For each configuration, the best prediction was selected as the value, provided by the two alternative models, that minimizes the difference with the yielding experimental force. It is reported in Table 1 highlighting the selected model.

***Table 6** Experimental force values and analytical predictions of examined configurations.*

ID	Experimental		Analitical			
	Yielding	Peak (15mm)	Johansen model	BlaB model	Best Prediction	
	Fexp_y [kN]	Fexp_max [kN]	F_J [KN]	F_B [kN]	Fan [kN]	
NX_6	2,51	3,47	2,78	2,09	2,78	J
NX_8	4,22	5,12	4,41	3,36	4,41	J
NX_10	5,82	7,04	6,13	4,73	6,13	J
AIR_6_6	**1,91**	**2,95**	**2,78**	**2,09**	**2,09**	**B**
AIR_8_6	**3,70**	**4,42**	**4,41**	**3,36**	**3,36**	**B**
AIR_10_6	**4,17**	**5,30**	**6,13**	**4,73**	**4,73**	**B**
X35_6_6	3,13	3,92	2,78	2,09	2,78	J
X35_8_6	4,94	5,84	4,41	3,36	4,41	J
X35_10_6	5,85	7,06	6,13	4,73	6,13	J
X70_8_6	4,36	5,26	4,41	3,36	4,41	J
X90_8_6	3,90	4,72	4,41	3,36	4,41	J
PA _8_6	**2,86**	**4,29**	**4,41**	**3,36**	**3,36**	**B**
PB _8_6	**3,29**	**4,71**	**4,41**	**3,36**	**3,36**	**B**
PC_8_6	3,99	5,33	4,41	3,36	4,41	J
PD_8_6	4,53	6,28	4,41	3,36	4,41	J

Figure 25 reports the percentage difference between the analytical prediction and the experimental values of both yielding force and strength at a15mm displacement.

Analysing the percentage differences, it is possible to observe that:

- The analytical model seems to be calibrated to capture the experimental yielding condition but the analytical prediction strongly underestimates the correspondent value of strength at a15mm displacement.
- As expected, the analytical prediction provided by the Johansen model results consistent for the reference configuration (absence of interlayer) while the prediction provided by the Blass model fits well with configurations with detached elements (air gap and Teflon spacer).
- XYLOFON configurations are adequately approximated by the Johansen model even if it slightly underestimates the yielding condition of the XYLOFON 35 configurations.
- PIANO A and PIANO B configurations are correctly approximated by the Blass model.
- PIANO C and PIANO D configurations are correctly approximated by the Johansen model.

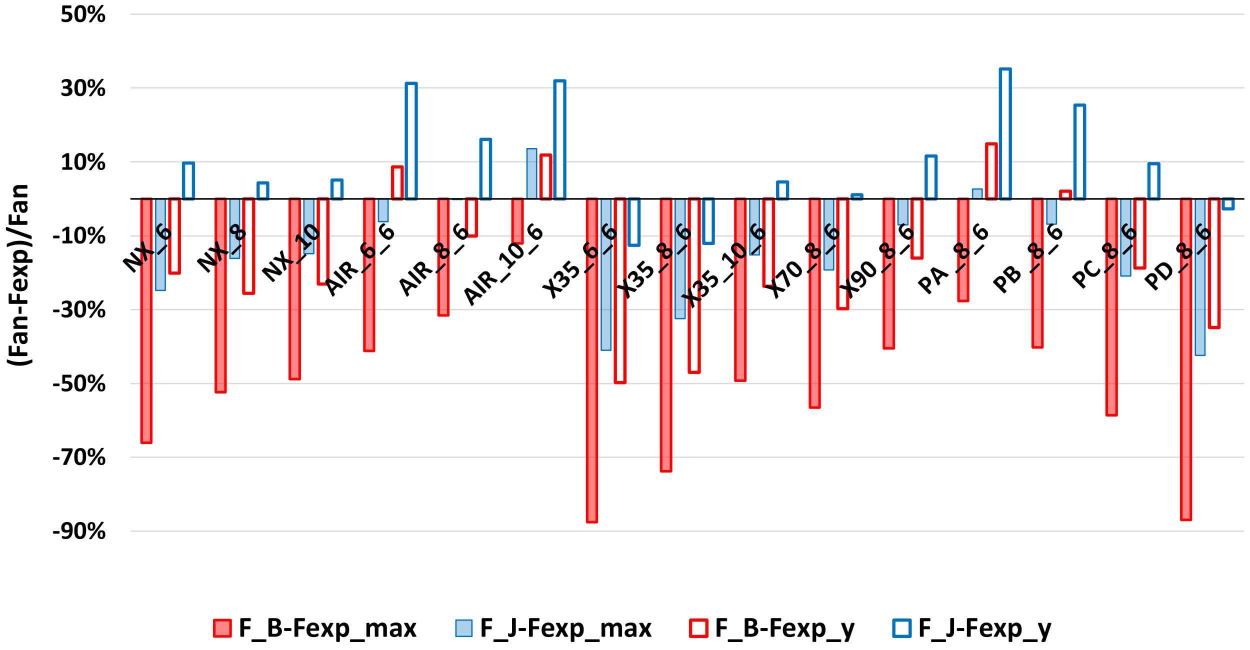


Figure 25 *Percentage differences between analytical prediction and experimental yielding force and strength at a15mm displacement (empty bars correspond to the yield force).*

The graph of Figure 26 reports the best analytical prediction vs both the experimental yielding force and strength at a15mm displacement.

Analysing the graph, it is possible to observe that:

- the selected analytical predictions never overestimate the experimental strength values at a 15mm displacement;
- the analytical predictions closely approximate the experimental yielding condition ensuring a maximum overestimation of the yielding force of approximately 15%.

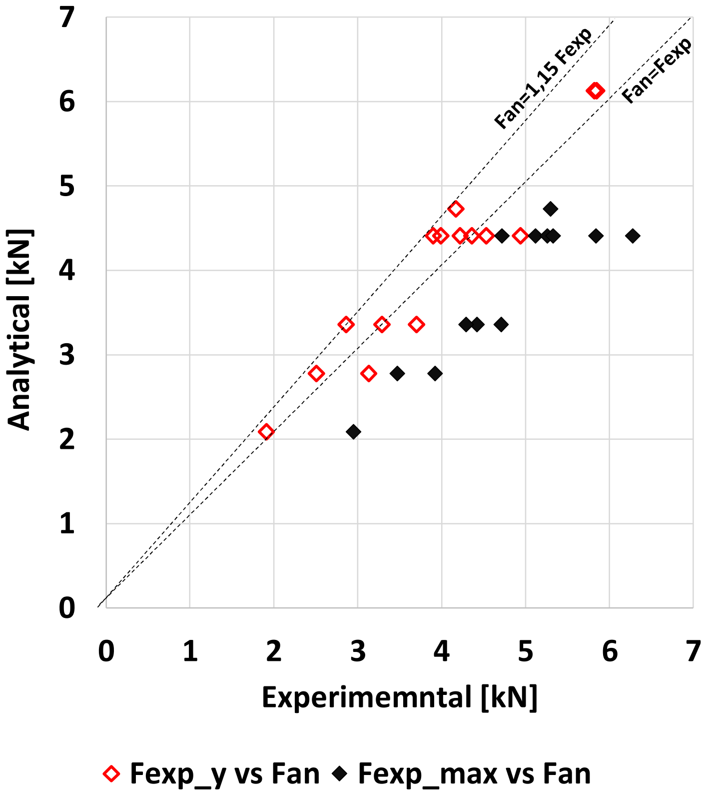


Figure 26 *Percentage differences between analytical prediction and experimental results of examined configurations.*

It is worth nothing that a more reliable prediction of the experiment results could be reached enhancing the reference models in order to account for both the interlocking effects and the frictional interface properties provided by the interposed resilient soundproof profiles.

7. Conclusions

Results obtained in this work demonstrate that the mechanical behavior of a screwed timber-to-timber connections is strongly affected by the type of 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 the XYLOFON-type profiles and thicknesses of the resilient layer up to 6mm. Only PIANO A and PIANO B interposed profiles affect negatively the load carrying capacity of the connections.

Failure modes are not affected by the presence of the interlayer as well as the cyclic behavior.

A preliminary estimation of the load carrying capacity of timber-to-timber connections with interposed soundproof resilient profile was carried out referring to the literature models. Performed estimations demonstrate that the load carrying capacity of connection with XYLOFON 35-70-90, PIANO C-D interposed profiles can be faithfully predicted referring to the standard Johansen theory. Otherwise, for PIANO A and B the Blass models seems to be more adequate.

8. References

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