Proceedings of the 3rd Croatian Conference on Earthquake Engineering - 3CroCEE
19–22 March 2025, Split, Croatia

DOI: https://doi.org/10.5592/CO/3CroCEE.2025.77

PUSH-OUT TESTS ON TIMBER-STEEL HYBRID JOINT WITH SCREWS CONNECTIONS. NUMERICAL AND EXPERIMENTAL INVESTIGATIONS

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Abstract

The increasing spread of timber as structural material strongly seeks for deeper investigations concerning its behaviour, in static and, even more, in cyclic conditions. It is well known that timber is characterised by several favourable properties, as lightness (significantly lower than e.g., concrete and steel), high strength-to-weight ratio, proneness to reusability and recyclability (under certain conditions taken into account since the early design phases), but some other properties are detrimental and should be handled. One of the main unfavourable characteristics that is source of several issues in timber structures is the material low ductility, especially in tension and shear where brittle behaviour is acknowledged. In order to provide adequate ductility, avoiding significant unexpected strength loss, proper design of connections is the key to guarantee ductile structural behaviour; moreover, it is very common to combine timber with steel, giving rise to timber-steel composite (STC) assemblies, where desirable properties of both materials are highlighted. This solution allows for significant environmental advantages with comparable structural performance in terms of static loading with reference to traditional solutions, according to available literature findings; on the other hand, very few experimental campaigns with cyclic loading conditions were encountered and this issue was the reason behind the motivation of this research: timber structures are now spreading in areas, as southern Europe, where seismicity is generally significantly higher than e.g., northern Europe where timber is very common but seismicity is low. This paper presents the outcomes of both static and cyclic push-out tests, carried out according to European Standard EN 12512. The results are compared with the predictions of numerical investigations, carried out in advance such to select optimal conditions for experimental activities. Screw shear connectors with two diameters (8 mm and 12 mm) are considered. On the basis of results, equivalent viscous damping is calculated, acknowledging effects of screw diameter.

Keywords: ***Timber-steel hybrid joint, screw connections, numerical modelling, cyclic tests, ductility, viscous damping, sustainability.***

1. Introduction

Timber is experiencing an outstanding popularity as an environmentally sustainable material, due to its carbon sequestration capacity [1]. When an engineered timber product (ETP) like Cross-Laminated Timber (CLT) or Glued-Laminated Timber (Glulam) is manufactured, carbon naturally contained in wood is preserved from emission in the atmosphere and it is stored at least up to building End-of-Life (EOL). From this point on, different scenarios may be practicable; in case the timber member is reused or recycled the carbon is maintained stored, while if it incinerated (with or without energy recovery) or landfilled carbon is released in the atmosphere with different timing and modalities [2].

However, timber EOL scenario cannot be merely chosen according to environmental considerations, but awareness on structural conditions is needed [3]; in case a total reuse of the structural member is foreseen, no damage should be present, and no extraordinary load or excessive deflections should have been experienced. Clear understanding of structural behaviour is the key to allow for a sustainable choice in the EOL phase. In particular, it is worth considering nowadays trends for timber buildings, as they broadly are hybrid; it is common to observe timber-concrete and timber-steel hybrid buildings [4, 5], in order to take advantage of every possible favourable properties of each material. Moreover, some unfavourable characteristics of each material are minimized, e.g., timber brittleness

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and low ductility, concrete high environmental impact and high specific weight, steel high initial cost. The hybridization concept is quite a novelty in the building sector, such that existing heritage is limited with respect to pure timber one and even more compared to traditional reinforced concrete (RC) or steel buildings.

It is also worth considering that timber buildings are traditionally widespread – in the European context – in regions characterised by low seismicity levels, such that lateral stability is dominated by wind action, while seismic one is generally not addressed [6]. However, timber buildings are becoming more common solutions even in previously unpopular areas, and a proper seismic design is required [7]; this necessity, coupled with limited real case studies, highlights the importance to shed a light on this topic. In particular, some literature on timber-steel hybrid joints tested under static loading conditions is available [8, 9, 10], while a few investigations present tests with cyclic loading conditions [11]. This lack of experience unveils some urgent issues to be faced, such as strength and stiffness degradation, change in the failure mode, energy dissipation, etc.

The systematic literature research developed for this study lead to identification of a representative configuration for a timber-steel hybrid joint [9]; two connectors – screws and bolts – were examined with numerical modelling in previous studies [12, 13], and modelling technique is hereby refined. Thereafter the configuration with screw connectors is tested during an experimental campaign, with two different diameters (12 mm and 16 mm), both in static and cyclic loading conditions. European standards are adopted to define test methods and loading procedures in the planning phase, and relevant parameters calculations during the analysis phase. Considering tests carried out under static and cyclic loads, European standards are adopted [14, 15]. Moreover, new generation of Eurocode 8 [16] includes direct mention to EN 12512:2001 [15], such that harmonization process is encouraged. Finally, observation of specimens after testing enabled considerations in a life cycle thinking perspective; damage extent after load was applied is directly correlated with reuse potential.

The paper is organised as follows: the methodology is explained in Section 2, results are presented in Section 3, and discussion and conclusions are respectively outlined in Section 4 and Section 5.

2. Method

In order to identify a representative configuration for numerical and experimental modelling, a literature review was carried out and one of the investigation examined was selected as reference [9]; however, being such research focused on static loading conditions, some modifications to the setup were introduced to the scope of testing also in cyclic loading conditions, like the position of screws, which are, in the modified test setup, at equal distance from steel beam end to CLT top end (Figure 1). Numerical modelling methodology is mostly described in previous authors' studies [12, 13], but in this case two refinements are developed:

- Specimens tested with numerical analysis are adapted, and they precisely represent those ones designed for experimental tests;
- Cyclic loading procedure is assessed after laboratory statics tests, so that it is accurately established.

Test plan is presented in Table 1. Static and cyclic loading procedures are designed according to European standards, respectively EN 26891:1991 [14], and EN 12512:2001 [15]. According to results obtained from static tests, yield slip is defined (V_y), such that in 1st and 2nd cycles the specimen is loaded until $0.25V_y$ and $0.5V_y$ both in compression and in tension; 3rd cycle (up to $0.75V_y$ slip) is repeated three times, and the same procedure is repeated for the following ones (V_y, $2V_y$, $4V_y$, etc.). The test is finished when either failure or 30 mm slip is reached, according to the standard.

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Table 1. Test plan

Test #	Screw diameter (mm)	Load type
1	12	Static
2	12	Cyclic
3	12	Cyclic
4	12	Cyclic
5	16	Static
6	16	Cyclic
7	16	Cyclic
8	16	Cyclic

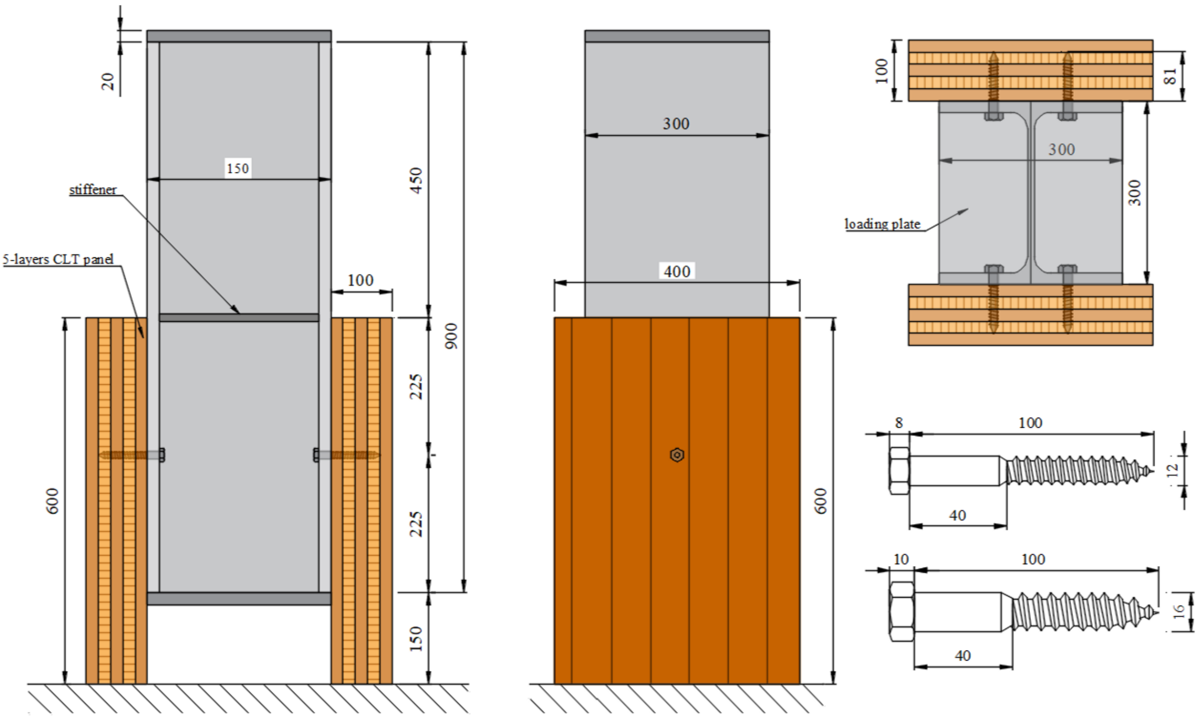

Figure 1. Configuration of specimen for experimental campaign. Screws used as timber-to-steel connections are represented. Picture adapted from a previous study [13].

Numerical analysis is used to estimate specimens' behaviour, especially in cyclic loading conditions, and to easily identify the most damaged regions to monitor during experimental campaign. Considering both EN 12512:2001 [15] and draft of the new Eurocode 8 [16], two parameters are selected to determine joints properties: impairment of strength (IS), equivalent viscous damping at 1st cycle (EVD1), and equivalent viscous damping at 3rd cycle (EVD3). Impairment of strength is referred to the reduction of load capacity of a joint that is undergoing cyclic loading; it is evaluated calculating the ratio between measured capacities of the first and third cycles, each time at the maximum reached amplitude. Equivalent viscous damping measures the hysteresis properties of a joint subjected to cyclic loading, according to Eq. (1).

$$\mathrm{EVD} = \frac{E_d}{2\pi \cdot E_p} \tag{1}$$

Where:

- E_d is the energy dissipated in one half-cycle
- E_p is the available potential energy

Available potential energy is calculated with a MATLAB code designed on purpose; considering that data do not present relevant noise, an easy numerical integration technique is selected, in particular

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the trapezoidal rule is applied. It is worth mentioning that in the considered standard [15], there is not specific instruction on which cycle has to be used to compute EVD, so that it is calculated at first (EVD1) and third (EVD3) cycles. In this way, EVD1 is a measure of early-stage dissipation properties and EVD3 provides a more stable representation of the dissipation characteristics, since transient effects may affect 1st cycle.

The last step is visual analysis of tested specimens, with identification of the following features:

- Screw failure modes
- CLT panel damage extension
- Possibility to disassemble the specimen without increasing timber damage

3. Results and discussion

Results from both numerical analysis and experimental tests are hereby presented. Load-displacement curves from static tests and backbone curves from cyclic tests are shown in Figure 2.

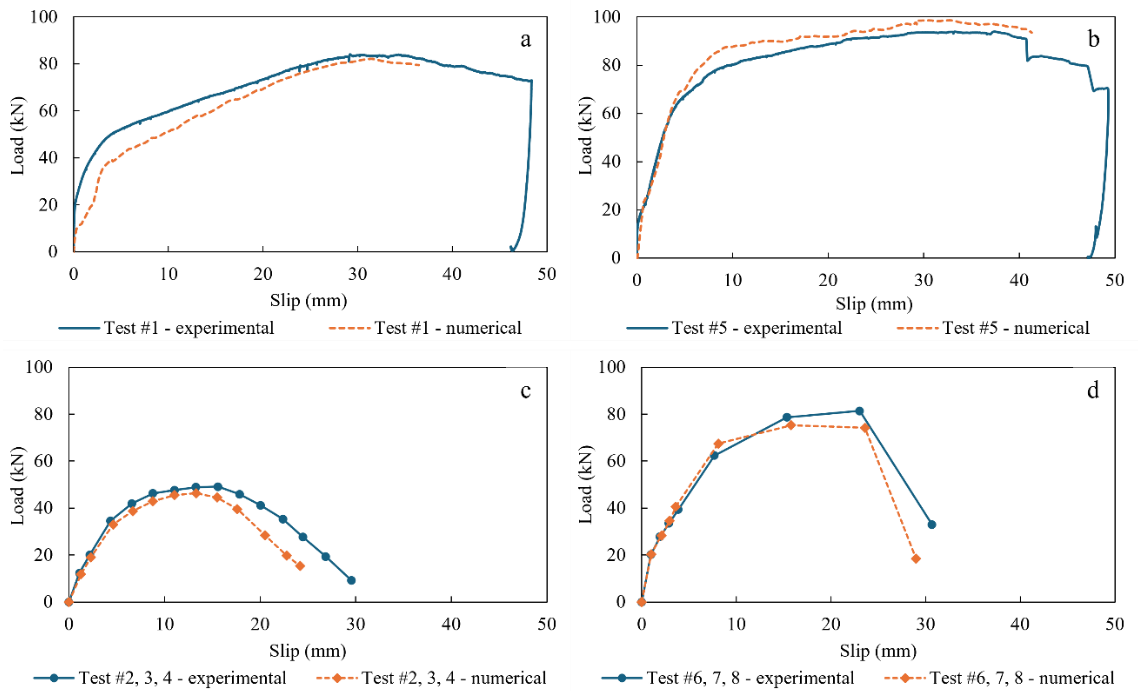

Figure 2. Load-slip results from analytical modelling and experimental tests. Static tests (a, b) and backbone curves from cyclic tests (c, d).

Effects of different screws diameters is evident from comparing Figure 2a and Figure 2b, where maximum capacities in static loading conditions are identified, as they are respectively 82 kN and 93 kN on the other hand ductility of test #1 and test #5 are very similar, given that the peak load is recorded at very similar slips, respectively 30 mm and 35 mm (Table 2). It is worth noticing that numerical modelling correctly represents the specimens load-slip curves detected in the experimental campaign; initial stiffness is correctly caught for test #5, while slightly underestimated for test #1, probably also due to some slackening in the setup.

Focusing on Figure 2c and Figure 2d, effects of cyclic loading conditions can be observed and, moreover, parameters listed in Table 2 provide a clear picture of the situation; impairment of strength (IS) is much more evident in tests #2, 3, 4 for 15 mm slip, while at 30 mm slip strong strength reductions are noticed for every joint, which almost lost almost of their capacities, with very high results variability. Focusing on equivalent viscous damping, significant energy dissipation is calculated for EVD1 at 15 mm for tests #6, 7, 8, while moderate energy dissipation capacity is recorded for tests #2, 3, 4. Considering EVD calculated for 3rd cycle, deterioration of the specimen dissipation capacity is

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acknowledged for tests #6, 7, 8; on the other hand, results obtained for tests #2, 3, 4 are very similar for EVD1 and EVD3, so that deterioration is recorded from low slip values.

Results presented in Table 2 are focused on two specific slip values: 15 mm and 30 mm. The first slip value is useful to compare static and cyclic behaviours, since this is the limit slip suggested by EN 26891:1991 [15]; on the other hand, the second slip value is prescribed in the new Eurocode 8 [16]. However, both these two slip values may also be considered from an environmental perspective:

- Slip=15 mm corresponds to a "sustainability serviceability limit state", given that deterioration resulting from this deformation are still controlled and demountability is not totally compromised;
- Slip=30 mm corresponds to a "sustainability ultimate limit state", since deterioration is extended in the surroundings of the screw holes and easy demountability is not possible.

Table 2. Experimental tests results analysis: peak load, slip at peak load, load at 15 mm, impairment of strength at 15 mm, impairment of strength at 15 mm, impairment of strength at 30 mm, equivalent viscous damping at 1st cycle at 15 mm, equivalent viscous damping at 1st cycle at 30 mm, equivalent viscous damping at 3rd cycle at 15 mm, equivalent viscous damping at 3rd cycle at 30 mm.

Test #	Peak load (kN)	Slip at peak load (mm)	Load at 15 mm (kN)	IS at 15 mm	IS at 30 mm	EVD1 at 15 mm	EVD1 at 30 mm	EVD3 at 15 mm	EVD3 at 30 mm
1	82	30	67	-	-	-	-	-	-
2	49	16	48	85%	59%	10%	8%	8%	7%
3	46	13	43	75%	x	8%	x	8%	x
4	52	13	50	79%	48%	9%	7%	7%	7%
5	93	35	85	-	-	-	-	-	-
6	85	15	85	89%	x	14%	x	8%	x
7	84	23	81	87%	64%	15%	11%	6%	7%
8	82	23	79	89%	35%	15%	9%	7%	x

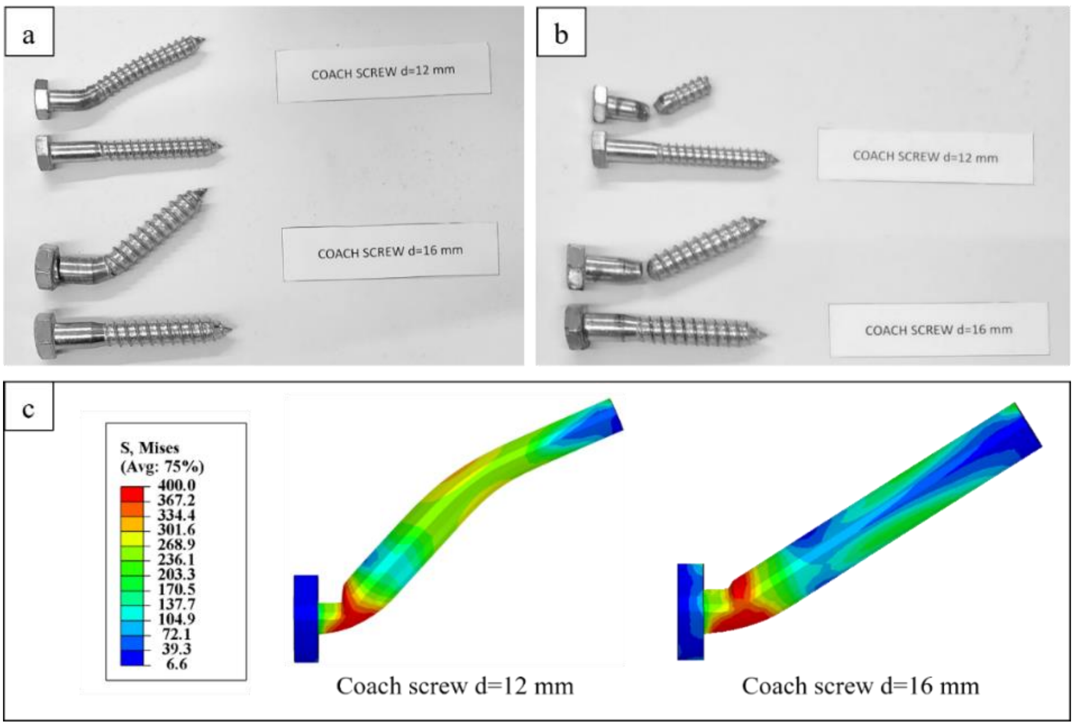

Figure 3. Screws failure modes in static (a) and in cyclic (b) loading conditions. Experimental findings match with results from numerical modelling in static loading conditions (c), refined from a previous study [12].

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In order to properly understand differences arisen from considering screws with 12 mm and 16 mm diameters, failure modes are shown in Figure 3: greater bending deformation as a result of higher slenderness ratio of 12 mm-screws is highlighted; initiation of 2nd plastic hinge is detected in Figure 3a (test #1), while 2 clear plastic hinges are noticed for the same screws used in the specimens tested in cyclic loading conditions (Figure 3b, tests #2, 3, 4), as described in Table 3. On the other hand, greater strength of 16 mm-screws results in a less ductile failure mode, due to higher stress concentration, with 1 plastic hinge.

Moreover, numerical modelling carried out before experimental testing phase correctly predicted screws failure modes (Figure 3), with greater high stress concentration region for 16 mm-screw.

Table 3. Failure modes description

Test #	Failure mode
1	Screws with 1 evident plastic hinge and initiation of 2nd plastic hinge. CLT damage extended for 20 cm along holes direction
2, 3, 4	Screws with 2 plastic hinges and ruptures in their correspondences
5	Screws with 1 plastic hinge. CLT damage extended for 30 cm along holes direction
6, 7, 8	Screws with 1 plastic hinge and rupture in their correspondence

Finally, it is worth focusing on the surroundings of connections locations, in order to explore whether CLT damages (crushing, splitting, delamination, etc.) are correlated with screws failure modes. First of all, focusing on Figure 4a and Figure 4c, it is evident that timber is strongly damaged and splitting failure is detected; damage extent is greater in Figure 4c, as it also reached the CLT end, as an acknowledgement of the fact that a less ductile screw failure mode results into larger panel deterioration. On the other hand, greater screw ductility (12 mm diameter screw) takes advantage of timber embedment strength, resulting in more ductile specimen. Considering Figure 4b and Figure 4d, timber deterioration is noticed to be less extended, confirming the concept previously mentioned of "sustainability ultimate limit state", even though screws failures occur abruptly during testing; post-testing observed failure modes are the same with respect to static ones, except for fully development of both plastic hinges in tests #2, 3, 4.

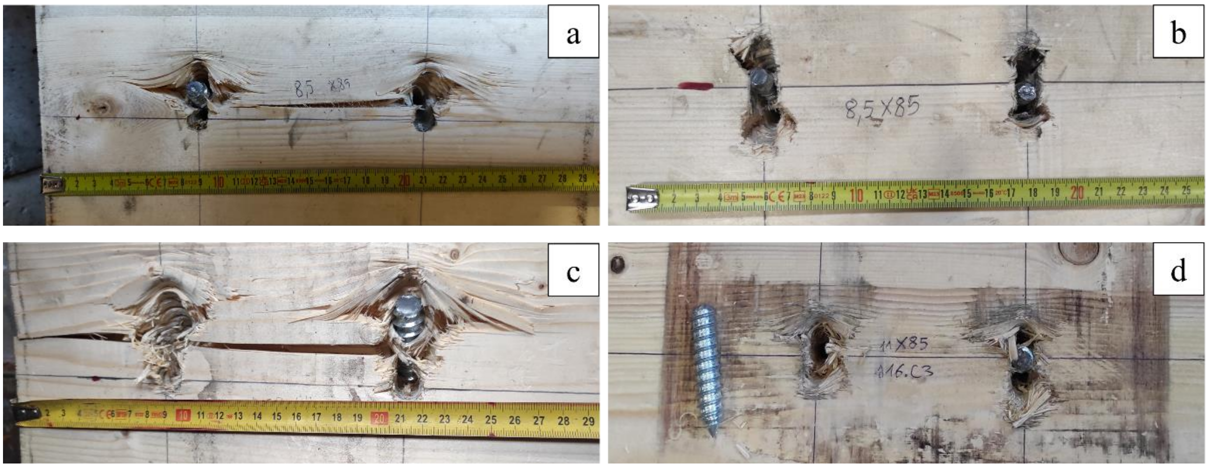

Figure 4. CLT panels in the surroundings of screw holes after testing. Specimen with 12 mm screw tested in static loading conditions (a); specimen with 12 mm screw tested in cyclic loading conditions (b); specimen with 16 mm screw tested in static loading conditions (c); specimen with 16 mm screw tested in cyclic loading conditions (d).

4. Conclusions

This research aims at providing a benchmark for future studies on timber-steel hybrid joints, which are expected to become increasingly widespread. The main focus is understanding of joints behaviour in

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cyclic loading conditions, but remarks and observations towards environmental sustainability are constantly proposed.

Existing literature provides a quite defined frame for timber-steel hybrid joints subjected to static loading conditions, however a few investigations focus on cyclic tests, so that possible issues that may cause sudden strength or stiffness loss can be overlooked with unexpected consequences. This gap should be filled in the next years since timber-hybrid solutions are now becoming of prominent interest, and their popularity now crossed the traditional boundaries. This investigation moves in this direction, since comparison between static and cyclic tests are carried out, with calculation of parameters related to cyclic loading conditions, as impairment of strength and equivalent viscous damping.

The choice of investigating two different diameters for screws was relevant because some differences is noticed between tests #1, 2, 3, 4 (with 12 mm-screw diameter) and tests #5, 6, 7, 8 (with 16 mm-screw diameter); this last set of tests highlighted minor strength loss under repeated loading, but failure mode is less ductile with respect to the other set of tests. It is fundamental to ensure ductile failure modes for connections, since in case the whole ductility is demanded to the timber panel, brittle failures as e.g., splitting, row and/or block shear develop; on the other hand, in case two plastic hinge evolve, overcome of timber embedment strength is facilitated and abrupt cracking is limited. In this context, the abovementioned concept of "sustainability limit states" is the key to read the whole research: this concept involves both structural (serviceability and ultimate limit states) and environmental perspectives, considering that reuse End-of-Life scenario can be foreseen just in case the slip – and consequently joint deterioration – is limited (e.g., for slips lower than 15 mm). Focusing on this serviceability limit state, it is worth mentioning the concept of demountability easiness, which can be applied just in case connectors deformations are small. On the other hand, experience has shown that multiple EOL scenarios are necessary to smooth some of the uncertainties linked to this stage, so that e.g., lower reuse percentages may be planned in case a strong seismic event hit the building and large drifts are experienced.

Future developments include testing on different connections systems – e.g., bolts – to better understand the link between structural performances and environmental sustainability. Moreover, additional tests on similar specimens within "sustainability serviceability limit states" are foreseen, in order to define a limit below that connectors demountability is possible without extending damage in the CLT panel. Considering the possibility of a seismic event, it is also essential to evaluate demountability easiness in the perspective of ready connections substitution, such that not just environmental sustainability is guaranteed, but also social and economic one, given that inconveniences caused to inhabitants are reduced and extended and expensive post-seismic repair are avoided.

Acknowledgements

Authors want to express their gratitude to ROTHOBLAAS SRL for providing steel screws to carry out experimental laboratory tests presented in this study.

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