

1 IN-PLANE STIFFNESS OF TIMBER FLOORS
2 STRENGTHENED WITH CLT

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1 Abstract

2 Five full-scale timber floors were tested in order to analyse the in-plane behaviour of these
3 structural systems. The main objective was an assessment of the effectiveness of in-plane
4 strengthening using cross-laminated timber (CLT). To that end, one unstrengthened
5 specimen (original), one specimen strengthened with a second layer of floorboards, two
6 specimens strengthened with three CLT panels, and one specimen strengthened with two
7 CLT panels, were tested. A numerical analysis was then performed in order to analyse the
8 composite behaviour of the timber floors in more detail. Due to its importance as regards
9 composite behaviour, the first phase of the experimental programme was composed of push-
10 out tests on specimens representing the shear connection between the timber beams and the
11 CLT panels. This paper describes the tests performed and the numerical modelling applied
12 to evaluate the composite behaviour of the strengthened timber floors. The use of CLT panels
13 is revealed to be an effective way to increase the in-plane stiffness of timber floors, through
14 which the behaviour of the composite structure can be significantly changed, depending on
15 the connection applied, or modified as required.

16

17 Keywords

18 *Cross-laminated timber, timber floors, experimental evaluation, in-plane stiffness,*
19 *connection.*

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1. Introduction

In many countries, traditional construction comprises masonry walls with floor and roof systems made of timber. Current approaches assume the need to preserve and to protect existing timber systems as a cultural value. In this context, the strengthening and stiffening of old timber floors is often needed, as they were designed to bear moderate loads and may suffer from excessive deflections with respect to current requirements. It is important to assess the floor diaphragm's in-plane stiffness, as it can affect the structural performance of a traditional masonry building subjected to lateral loads: the common configuration of existing timber floors with a crosswise single layer of wooden planks might need in-plane shear strengthening, in order to ensure the efficient distribution of the lateral seismic load through all bearing walls (Branco et al. 2009; Branco and Tomasi 2013; Appleton 2003).

There are several techniques for strengthening existing timber floors. Their effectiveness in terms of in-plane stiffness differs, depending on the strengthening technique used (Modena et al. 2004; Valluzzi et al. 2008; Piazza et al. 2008; Angeli et al. 2010). The techniques most effective in terms of increasing in-plane stiffness are those which reinforce the compression side of the floor cross-section. The basic idea is to improve the in-plane stiffness of the floor system by implementing stronger behaviour on the part of the T-section. Among the various possibilities, the addition of a concrete layer over the timber structure is common practice and has been studied in depth (Piazza et al. 2008; Tomasi et al. 2009). When the strengthening required for the actual system is not significant, it is possible to use wood-based materials instead of a concrete slab to enhance the in-plane stiffness (Angeli et al. 2010; Branco and Tomasi 2013; Valluzzi et al. 2008). In fact, a old technique for strengthening timber floor systems is the addition of a second layer of wooden boards. This

1 second layer is used to recover part of the existing deformation (as a false floor), to increase
2 the bending stiffness and to contribute to the in-plane stiffness of the floor.

3 Nowadays, special attention is being paid to the use of wood-based solutions for
4 strengthening timber systems. In the case of heritage structures, the use of materials different
5 from the original is often restricted. In this context, the use of cross-laminated timber (CLT)
6 in rehabilitation works has increased. This wood-based material is easy to apply and has
7 mechanical properties with great potential in terms of flexural and in-plane strengthening.
8 In both cases, the connection between the timber beams and the CLT panels is crucial for
9 increasing the load-carrying capacity and for the distribution of stresses along the composite
10 cross-section.

11 Thanks to the enhanced mechanical performances of CLT, namely good in- and out- plane
12 load bearing capacities and two way action capability, it is possible to replace an entire
13 timber floor system composed of beams and boards with CLT panels, but here it will be
14 assumed that the timber beams are kept and the CLT panels are simply placed over the beams
15 and screwed to them. The CLT solution is therefore analysed as an alternative to the
16 traditional technique of adding a second layer of floorboards to strengthen the floor. The aim
17 of the research is to assess the effectiveness of in-plane strengthening with cross-laminated
18 timber. In a first step, an experimental series of push-out tests was devised to study the
19 connection between timber beams and CLT elements, using different screws. The main
20 objective was to assess the load-slip behaviour of the connection to allow a detailed analysis
21 of the results obtained from tests of full-scale timber floors made in the following stage. A
22 total of 20 connections were tested. They were divided into four groups, with five specimens
23 each, according to the screw used (self-tapping fully threaded or not) and their inclination in

1 relation to the shear direction (45° or 90°) Full-scale timber floors were then tested in order
2 to analyse the in-plane behaviour of traditional timber floors and to assess the effectiveness
3 of the CLT in-plane strengthening. Five specimens were tested: one unstrengthened
4 (original), one strengthened with a second floorboard layer, one strengthened with CLT
5 divided into two panels, and two strengthened with CLT divided into three panels. The last
6 three specimens were used to evaluate the effect of the number of CLT panels used in the
7 strengthening.

8

9 2. Experimental procedure

10 2.1. Test procedure and specimens

11 2.1.1. Timber -to-CLT push -out tests

12 A total of 20 timber-to-CLT connections were evaluated through push-out tests divided into
13 four groups of five specimens each, according to the self-tapping screw type used and its
14 inclination in relation to the shear direction, measured by the angle α : HBS 8x140 (half
15 threaded) and VGZ 7x140 (fully threaded) placed as normal (90°) to the shear plane and
16 SFS WT-T-8.2x190 (half threaded) and VGZ 7x180 (fully threaded) placed inclined at 45°
17 to the shear plane. The central element was made of solid wood, of strength class C18
18 according to EN 338, with 100x200mm², and the exterior elements were made of CLT with
19 a thickness of 66mm, i.e. 100x66mm² (Figure 1). Prior to testing, all solid wood and CLT
20 elements were stored in a climatic chamber at 20°C with a relative humidity of 65%, to
21 ensure that they had a moisture content around 12%.

1 The main objective of these tests was to assess the shear stiffness of the connections used in
2 the full-scale timber slabs analysed in the next research step. By using screws with different
3 inclinations in relation to the shear plane, namely 90° and 45°, it was possible to quantify the
4 improvement expected by using screws 45° inclined, enlarged in the case of full threaded
5 screws. Two types of threaded screws (SFS-WT-T and VGZ) were compared in terms of
6 efficiency, as their cost differed.

7 The load-carrying capacity and the deformation behaviour of the connections were
8 determined using push-out tests according to EN 26891:1991. During the test, the load and
9 relative displacements (slip) of the joint members were measured. Load was applied with a
10 hydraulic jack and recorded by means of a load cell. To measure the slip, two transducers
11 were used, one on each side of the specimen, with an accuracy of 0.1mm. Figure 2 shows
12 the set-up and instrumentation used in the push-out tests.

13

14 2.1.2. Tests on full -scale timber floors

15 Five full-scale timber floors were subjected to in-plane monotonic tests: one unstrengthened
16 floor (S), one floor strengthened with a second floorboard (SS), two floors strengthened with
17 three CLT panels (CLT3.1 and CLT3.2, with different screws) and one floor strengthened
18 with two CLT panels (CLT2). The last three specimens were used to assess the effect of the
19 number of CLT panels used in the strengthening, and the type of screws. In specimens S and
20 SS, with one and two layers of floorboards respectively, nails measuring 2.5x60mm were
21 used in the application of the floorboards. In specimens strengthened with CLT (CLT2,
22 CLT3.1 and CLT3.2), screws were used to connect the CLT panels to the timber beams. The

1 CLT2 and CLT3.1 specimens used VGZ 7x180 screws and CLT3.2 used SFS WT-T-
2 8.2x190 screws. In all CLT specimens, screws were inclined by 45° in relation to the shear
3 plane. A total of 60 screws, corresponding to 30 points, with a pair of screws placed in X
4 position (crosswise layout of the screws equal to specimen groups V6-V10 and S1-S5
5 evaluated in the push-out tests – see Figure 1), were used to connect the CLT panels to the
6 timber beams in each specimen. Figure 3 presents the timber floor specimens tested. All
7 timber floors tested were made of C24 solid wood beams measuring 100x160mm² with a
8 length of 2.42m and spaced at 0.50m. The floorboards were made from a Brazilian
9 hardwood, angelim-amargoso (*Andira vemifuga*), with a width of 125mm and thickness of
10 20mm.

11 The test set-up is presented in Figure 4. A hydraulic jack, positioned at a height of 2m above
12 the base of the floor, applied a transversal force, with programmed displacement (or
13 displacement control). In this case, the loading (displacement) was monotonic with a
14 constant rate of 0.05mm/s until a maximum value of 200mm. Three linear variable
15 differential transformers (LVDTs) were used for measuring the shear in-plane deformation
16 of the specimens during the tests. In Figure 4 the measuring positions are marked by numbers
17 1 to 3 and the force (F) applied is identified.

18

19 2.2. Test results and analysis

20 2.2.1. Timber -to-CLT push -out tests

21 The mean experimental load-slip curves of the timber-to-CLT connections tested are
22 presented in Figure 5, and Table 1 reports the average results obtained for the maximum load

1 per specimen (F_{max}), corresponding slip value (S_{max}) and slip modulus (K_{ser}) per screw. The
2 experimental results were analysed according to EN 26891:1991, where the value of F_{est} was
3 assumed to be the average of the maximum load (F_{max}) measured in each particular specimen
4 group. The maximum load (F_{max}) of each test corresponds to the maximum value measured
5 for the load during the slip range from 0 to 15mm.

6 The results obtained using VGZ screws, groups V1-V5 and V6-V10, showed that the use of
7 the screws inclined at 45° corresponds to an increase of the loadcarrying capacity of 200%
8 and 500% in the slip modulus value in comparison with screws placed normally (90°) to the
9 shear plane. As expected, due the greater diameter and angle to the shear direction (45°),the
10 specimen group with SFS screws (S6-S10) presented higher values both for maximum load
11 and for slip modulus. It is important to note, however, that this improved performance could
12 have resulted directly from the higher diameter value (8.2mm) used in comparison with the
13 V6-V10 group with VGZ screws (7mm). When both groups with screws placed normal to
14 the shear plane, H1-H5 and V1-V5, were compared, the group with VGZ screws reached a
15 higher mean value for the maximum load (F_{max}), showing that despite having a smaller
16 diameter the VGZ full threaded screw had a higher load-carrying capacity than the HBS
17 screw. By contrast, the average value obtained for the slip modulus in the case of the VGZ
18 screws was smaller than that calculated for the specimens using HBS screws. It is important,
19 however, to point out the high values of the coefficient of variation (CoV) demonstrated by
20 the test results for this property, slip modulus, which can mitigate the difference between
21 those two specimen groups. Another important property is that the VGZ 7x140 screws are
22 fully threaded, and the HBS 8x140 screws have a threaded shank on approximately half the ir
23 length. Comparing the diameters and the threaded part of the screws indicates that the slip

1 modulus is mostly dependent on screw diameter and the load carrying capacity is
2 considerably influenced by the threaded part of the screws. Such behaviour can be expected
3 as a result of the rope effect, which mostly influences the final loading phase (load carrying
4 capacity) while the slip modulus is derived from the initial elastic loading phase, and screw
5 diameter does have a supposedly dominant effect during this loading phase.

6 All specimens presented a ductile behaviour, making it possible to use the methodology
7 proposed by Eurocode 5 (EC5), EN 1995-1-1:2004, for these types of connections. The
8 failure mode (f) presented by the specimens corresponds to the failure mode defined in EC5
9 for single shear. In the case of specimen groups with inclined screws, however, it was
10 possible to identify a withdrawal movement of the screw for large deformation (slip).

11 Comparison of the values, per fastener, for the maximum load obtained from the tests and
12 those predicted by EC5, applying expression 8.6 of EN 1995:2004 showed that all tests
13 results were higher than those predicted (Table 2). It is important to point out, however, that
14 the values predicted by the EC5 assumed characteristic values while the experimental values
15 were expressed as average. Only the test results obtained for specimen group H1-H5 were
16 slightly higher than predicted. More tests should be performed to allow a statistical
17 comparison but the homogeneity of the tests results (CoV=8%, see Table 1) must be
18 highlighted. In terms of stiffness, the values predicted by EC5 are higher than those obtained
19 in the tests performed (Table 2). It is important to point out that EC5 does not take the case
20 of inclined screws for the slip modulus (K_{ser}) into account. It was therefore decided to apply
21 the methodology proposed by Tomasi et al. (2010) for the slip modulus of timber-to-timber
22 connections with inclined screws.

1 According to Tomasi et al. (2010), the screw axial stiffness assumes two different values
2 according to the failure mode observed: simultaneous pull-out of both threaded segments
3 from the connected elements or pull-out of only one of the two threaded screw segments.
4 The failure modes observed in group specimens V6-V10 and S1-S5 were a combination of
5 failure mode f according to EN 1995-1-1:2004 and failure as a consequence of the pull-out
6 of the threaded part of the screw. However, it is noted that the slip in the axial direction of
7 screws and the related withdrawal/penetration stiffness of the screws were not measured.

8 Although it cannot be assumed that both solid wood and CLT elements equally influenced
9 the stiffness modulus K_{ser} measured in the push-out tests (Tables 1 and 2), in the absence of
10 measurements of the slip in axial direction of the screws, no conclusion can be drawn about
11 the individual contribution of the solid wood and CLT elements for the connection stiffness.

12 It is notable that the stiffness modulus K_{ser} for specimens with screws inclined 45° was
13 significantly higher than the stiffness modulus K_{ser} for specimens with screws placed
14 normally (90°) to the shear plane. This difference proves the presence of the tensile loading
15 of screws and related withdrawal/penetration stiffness that increased the stiffness modulus
16 K_{ser} (Table 1, 2). Given that the shear stiffness of specimen connection consists of stiffness
17 related to the shear slip of screws and withdrawal/penetration stiffness of screws in both
18 timber elements, and the withdrawal/penetration stiffness of the screws was not measured,
19 the shear stiffness of specimen connection – K_{ser} (Table 2, calculated for one screw) obtained
20 during push-out tests and theoretical models described in Tomasi et al. (2010) for both
21 models – was compared in the single stiffness model (SSM) and the double stiffness model
22 (DSM). Equations (1), (2), (4) were used for calculations relating to DSM and Equations (1),
23 (3), (4) for calculations relating to SSM (Tomasi et al. 2010).

1 The following equations derived by Tomasi et al. (2010) were used in the case of specimens
 2 connected with inclined screws.

$$K_{ser} = K_{\perp} \cdot \cos^2 \alpha + K_{\parallel} \sin^2 \alpha \quad (1)$$

$$K_{\parallel} = \frac{1}{1/K_{ser,ax,1} + 1/K_{ser,ax,2}} \quad (2)$$

$$K_{\parallel} = K_{ser,ax,i} \quad (3)$$

$$K_{ser,ax,i} = 30 \cdot s_g \cdot d \quad (4)$$

3 Here, α is the inclination angle of the screw, K_{\perp} is the slip modulus according to Tomasi et
 4 al. (2009) per screw and per shear plane, K_{\parallel} is the axial slip modulus for a screw, in Eq. (2)
 5 for the double stiffness model and in Eq. (3) for the single stiffness model, K_{ser} is the stiffness
 6 for screws crossed in an X position working simultaneously, one under shear-tension stress
 7 **and the other under shear-compression stress**, $K_{ser,ax,i}$ is the instantaneous
 8 withdrawal/penetration stiffness, s_g is the embedment length, in millimetres, of the threaded
 9 segment of the screw and d is the outer diameter of the screw thread.

10 A comparison of the results of the push-out tests and theoretical models (Table 2) shows that
 11 the experimental shear stiffness of specimen connection obtained for one screw in both
 12 specimen groups (V6-10 and S1-S5) is located between the values of stiffness, calculated by
 13 DSM and SSM. The value of shear stiffness K_{ser} for specimen group V6-V10 is almost equal
 14 to the average value of stiffness calculated by DSM and SSM. The value of shear stiffness

1 K_{ser} for specimen group S1-S5 is almost equal to the value of stiffness calculated by SSM.
2 Comparing the test results and considering the failure mode, simultaneous pull-out of both
3 threaded segments from both connected elements, the values predicted using Equations
4 (1),(2) and (4) according to DSM, are lower. The value of stiffness predicted for specimen
5 group V6-V10 is 74% of the experimental value and the value predicted for specimen group
6 S1-S5 is 55% of the experimental value of stiffness.

7 2.2.2. Full -scale timber floors

8 Five full-scale specimens were tested to analyse the in-plane behaviour of timber floors and
9 the effectiveness of the CLT strengthening. The description of each specimen, including the
10 type of connections used to make the floor and the most important test results, are described
11 in Table 3. The maximum load F_{max} of each test corresponds to the maximum load measured
12 during the test phase of displacement within 0-100mm. The stiffness K was evaluated
13 according to EN 26891:1991, where the values $0.4F_{est}$ and $0.1F_{est}$ were assumed to be equal
14 to $0.4F_{max}$ and $0.1F_{max}$, respectively, and the corresponding displacements $v_{0.4}$, $v_{0.1}$ were used
15 in the calculation. For calculation of the stiffness K of the timber floors, the load applied on
16 the upper beam and the displacement on the opposite side of the beam were used.

17 The test results obtained (Table 3 and Figure 6) show that strengthening using a second layer
18 of floorboards (specimen SS) can double the stiffness of a timber floor system (specimen S),
19 and that the maximum load value is almost quadrupled. The specimens strengthened by CLT
20 panels are approximately five to ten times stiffer than the unstrengthened specimen (S), and
21 two to four times stiffer than the specimen strengthened by a second layer of floorboard

1 (specimen SS). The greatest stiffness was observed in Specimen CLT3.2, where the SFS
2 type of screw with a greater diameter was used.

3 3. Numerical modelling

4 3.1. Models

5 After the experimental tests, a numerical analysis was performed in order to analyse in more
6 detail the composite behaviour of the timber floors evaluated. Numerical models were
7 developed using the finite element analysis (FEA) software ANSYS (Ansys 2009).
8 BEAM188 1D beam elements were used for modelling the timber beams and SOLID186
9 volume elements were used for modelling CLT panels. CONTA174/TARGE170 elements
10 were used for modelling the contact interface and related friction between elements
11 representing the CLT panels. The eccentric position of timber beams in relation to CLT
12 panels was neglected and the position of the beam elements was assumed to be in the middle
13 plane of the CLT element. In the model, the system was fixed by three vertical supports and
14 one horizontal support on the bottom beam, and horizontal supports in the out-of-plane
15 direction of the floor in each connection between the beams and CLT panels. An overview
16 of the models is presented in Figure 7.

17 Connections between beam elements and volume elements (timber beam - CLT panel) were
18 modelled through MPC184 elements with linear load-displacement relationships in both in-
19 plane CLT directions, obtained during the push-out tests. The slip modulus K_{ser} in a direction
20 parallel to the axis of horizontal beams was determined during the push-out tests of
21 specimens with screws inclined at a 45° angle. The slip modulus K_{ser} , in a direction
22 perpendicular to the axis of horizontal beams, was determined during the push-out tests of

1 specimens with screws inclined at a 90° angle. Because SFS screws also inclined at a 90°
2 angle were not tested, the slip modulus determined for the screw HBS8x140 inclined at a
3 90° angle was adopted, with a diameter close to the SFS used in the CLT3.2 specimen. To
4 approximate the structural behaviour with a numerical model, the load-displacement
5 behaviour of whole specimens and relative displacements between CLT panels and timber
6 beams observed during the tests were analysed. Relative displacements are described
7 through a simple model visualised in Figure 8, where a rigid connection between the fastener
8 and beam is assumed and the slip of fastener in CLT panel is described. Considering the in-
9 plane shear displacement of the timber floor strengthened with CLT, it can be expected that
10 the stiffness of the connection in the direction perpendicular to the axis of the beam affects
11 the stiffness more strongly than the connection stiffness in the direction parallel to the axis
12 of the beam. To assess this expectation, a parametric study based on finite element modelling
13 was performed. For each specimen modelled (CLT3.1, CLT3.2, CLT2) three groups of
14 numerical models were developed, depending on the stiffness of the connection beam-CLT
15 and friction between the CLT panels. The effect of friction between CLT panels on the
16 stiffness behaviour of the timber floor specimen was analysed by the coefficient of friction
17 μ , ranging from 0.2 to 0.8.

18 Taking into account the anisotropy of wood, a transversely isotropic material model was
19 defined in the three orthogonal directions, where properties in the radial and tangential
20 direction were assumed to be equal because of the reduction of material characteristics. In
21 terms of material properties, the elastic material characteristics of C24 defined in standard
22 EN 338:2003 were adopted for the beam elements. The Poisson's ratios ν_{LT} and ν_{RT} were
23 calculated from Dahl (2009) and missing mechanical parameters were obtained as dependent

1 mechanical properties for the transversely isotropic model. The material characteristics of
2 CLT panels were adopted and modified from EN 338:2003 and European Technical
3 Approval ETA-06/0009 (2011). The boards used in the CLT panels were graded by the
4 manufacturer as strength class C24 (EN 338:2003). As mentioned before, the material
5 characteristics of CLT panels were modified in order to respect and approximate the stiffness
6 behaviour of the CLT panel, influenced by different orientations of timber boards, and in
7 particular layers of CLT. Elastic properties were calculated as the weighted average of the
8 material characteristics of wood for directions parallel and perpendicular to the grain with
9 regard to the thickness of corresponding layers of CLT panels.

10 3.2. Parametric study and discussion

11 Comparison between the tests and numerical modelling results shows a good match in the
12 case of CLT3.1 and CLT3.2 specimens (Table 4). In the case of specimen CLT2, the stiffness
13 behaviour obtained by means of numerical modelling was overestimated. This can be
14 explained by the simplified modelling of the connection, where only a linear load-slip
15 relationship was used in the numerical models. As a result of this simplification, the
16 structural behaviour of the elastic phase was compared. The results of a parametric study
17 showed that the stiffness of the screwed connections in a direction perpendicular to the axis
18 of the beams had its main effect on the in-plane stiffness of the whole timber floor specimens.
19 The effect of the friction between the CLT panels was not observed. As evidenced in the
20 first experimental process, the inclination angle had a major effect on both stiffness and
21 load-carrying capacity of connection beam CLT. It is therefore possible to conclude that the
22 global behaviour of a timber floor composite structure can be significantly changed
23 depending on the connection applied.

4. Conclusions

The results obtained from push-out tests showed that, for the adopted materials and testing conditions (see Figures 1 and 2), the average value of the load-carrying capacity of a screw connection with 45° inclined screws is approximately one and a half times higher than that of a screw connection with screws placed normally (90°). The stiffness of screw connections obtained in push-out tests showed a strong effect of inclination angle on connection stiffness. Connections with screws inclined 45° resulted in a stiffness six and a half times higher than that of connections with screws placed normally. A comparison between results obtained in push-out tests and values calculated according to Eurocode 5 (EN 1995-1-1:2004) showed that load-carrying capacity calculated according to EC5 was lower than that obtained experimentally, for all specimen groups. A comparison of stiffness showed the opposite relationship – the stiffness calculated according to EC5 for screws placed normally (90°) was higher than the stiffness obtained in push-out tests (instantaneous slip modulus at the serviceability limit state K_{ser}). Due to the absence of rules in EC5 for the calculation of stiffness for screw connections with inclined screws, the comparison of experimental connection stiffness was made with stiffness calculated according to Tomasi et al. (2010). The comparison showed a very good match with stiffness calculated according to the single stiffness model (SSM) for one specimen group, and another specimen group had a stiffness corresponding to the average of the SSM and the double stiffness model (DSM). The load-carrying capacity and stiffness of screw connections obtained in the push-out tests showed that the difference caused by inclination angle is ‘great’ and should not be neglected in analysis of this type of connection.

1 Results for the full-scale timber floors showed CLT panels were a potential structural
2 solution for the in-plane strengthening of timber floors. The tests results showed that
3 strengthening using a second layer of floorboards (specimen SS) can double the stiffness of
4 the timber floor system (specimen S), while almost quadrupling the maximum load. The
5 specimens strengthened by CLT panels were approximately five to ten times stiffer than the
6 unstrengthened specimen (S) and two to four times stiffer than the specimen strengthened
7 by a second layer of floorboards (specimen SS). The load-carrying capacity of a timber floor
8 strengthened with CLT panels was approximately eleven times higher than that of the
9 original specimen (S), and approximately three times higher than that of specimen SS.

10 The parametric study performed by means of a numerical modelling showed a good
11 match with experimental results for stiffness in the case of Specimens CLT3.1 and CLT3.2.
12 The stiffness calculated in the numerical model was overestimated compared with the
13 experimental value in the case of Specimen CLT2. The results of the parametric study
14 showed a relationship between screw connection stiffness and the stiffness of the entire
15 timber floor K . In this context, the main effect on in-plane stiffness of whole timber floor
16 specimens was caused by the stiffness behaviour of the screw connections in the direction
17 perpendicular to the axis of the beams.

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1 References

- 2 Angeli, A., Piazza, M., Riggio, M., Tomasi, R. (2010), Refurbishment of traditional timber
3 floors by means of wood-wood composite structures assembled with inclined screw
4 connectors. 11th World Conference on Timber Engineering – WCTE 2010, 20-24
5 June 2010, Riva del Guarda, Trentino, Italy.
- 6 ANSYS®, Academic Research, Release 12.0. (2009), ANSYS, Inc. Documentation for
7 Release 12.0.
- 8 Appleton, J. (2003). *Reabilitação de edifícios antigos patologias e tecnologias de*
9 *intervenção* ORION, 730 p. (*In Portuguese*)
- 10 Branco, J.M., Cruz, P.J.S., Piazza, M. (2009), Experimental analysis of laterally loaded
11 nailed timber-to-concrete connections. *Construction and Building Materials*. 23 (1):
12 400-410.
- 13 Branco, J.M., Tomasi, R. (2013), Analysis and strengthening of timber floors and roofs. In
14 Structural Rehabilitation of Old Buildings. Costa, A, Miranda Guedes, J, Varum H.
15 (eds.), Springer, ISBN: 978-3-642-39685-4, pp. 235 258.
- 16 Dahl, K.B. (2009), Mechanical properties of clear wood from Norway spruce. Ph.D
17 dissertation, Norwegian University of Science and Technology, Trondheim.
- 18 EN 338:2003, Structural timber - strength classes. European Committee for Standardization,
19 Brussels.

- 1 EN 1995-1-1:2004, Eurocode 5 – Design of timber structures, Part 1-1: General – Common
2 rules and rules for buildings, Brussels.
- 3 EN 26891:1991, Timber structures. Joints made with mechanical fasteners. General
4 principles for the determination of strength and deformation characteristics.
5 European Committee for Standardization.
- 6 ETA-06/0009 (2011), Multilayered timber elements for walls, ceilings, roofs and special
7 construction components. European Organisation for Technical Approvals.
- 8 Modena C., Valluzzi M.R., Garbin E., da Porto F. (2004), A strengthening technique for
9 timber floors using traditional materials. 4th Structural Analysis of Historical
10 Constructions, Proc. Intern. Symp., Padova, Italy, 10-13 November, Rotterdam:
11 Balkema, pages 911-921, 2004.
- 12 Piazza M., Tomasi R., Baldessari C., Acler E. (2008), Behaviour of refurbished timber floors
13 characterized by different in-plane stiffness. Structural Analysis of Historic
14 Construction: Preserving Safety and Significance, London, UK: Taylor & Francis,
15 2008, p. 843-850. VI International Conference on Structural Analysis of Historic
16 Construction, Bath, 2n-4th July 2008. - vol. 2, ISBN: 978-0-415-48107-6.
- 17 Tomasi R., Baldessari C., Piazza, M. (2009), The refurbishment of existing timber floors:
18 characterization of the in-plane behaviour. Prohitech Conference, 21-24 June,
19 Rome, 2009.

- 1 Tomasi, R., Crosatti, A., Piazza, M. (2010), Theoretical and experimental analysis of timber-
2 to-timber joints connected with inclined screws. *Construction and Building*
3 *Materials*. 24 (2010), 1560-1571.
- 4 Valluzzi, M., Garbin, E., Benetta, M. D., Modena, C. (2008), Experimental assessment and
5 modelling of in-plane behavior of timber floors. SAHC 2008 - Structural Analysis
6 of Historical Constructions, Bath, UK, 02-04 July.