Comparison of *in situ* and laboratory testing for the characterization of old timber beams before and after intervention

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Abstract In this paper an investigation campaign, carried out in occasion of the restoration of a timber floor in the Belasi Castle (Trentino, Italy), is reported. In order to validate a testing procedure for the calibration and control of an innovative wood-wood strengthening technique, results of tests performed *in situ* on the structural elements, in both the original and the repaired condition, have been compared with those obtained in laboratory on some dismantled beams. For the characterization of the material decay, both local mechanical and global vibrational testing have been carried out. For the mechanical characterization of the beams, before and after repair, direct static bending tests have been performed, with distributed loads, on site, and according to standard four-points loading schemes, in laboratory.

Keywords: wood-wood strengthening technique, strengthening calibration and control

Introduction

The analysis of ancient timber structures is undoubtedly very cumbersome for several inherent difficulties to be faced for both the material and the structural behavior characterization. In case of restoration, a throughout investigation is necessary, in order to comprehend the original, the current as well as the designed conditions of the structure. In particular, comprehensive analyses are required, if new intervention techniques are adopted.

In this paper, the experimental activity carried out during the repair of a timber floor in the Belasi Castle (Trentino, Italy) is reported. The consecutive operational stages of the program substantiate a general procedure for the analysis and the strengthening of old timber structures. In particular, the paper stresses the importance of controlling the efficiency of the intervention, as recommended in the Italian standard UNI 11138:2004 and in international documents (i.e. ICOMOS:2001). In the case of the reported research, the intervention control has been executed not only in view of the conservation of the studied artifact, but also with the aim of qualifying an innovative wood-wood strengthening technique.

The evaluation of the efficiency of an intervention can be carried out through direct physical experimentation or through numeric simulation. In the reported case study, an experimental phase on site has been followed by a further verification, in laboratory.

The strengthening technique

The technique proposed to increase the flexural stiffness and resistance of the wooden floor in the Belasi Castle consists in coupling the existing beams with thick timber planks, connected with crossed self tapping and full threaded screws (Fig.1). Screws are disposed with an inclination of 45°, in order to exploit their high resistance and stiffness against withdrawal and pushing in. The structural behavior of the resulting timber composite structure is governed by the strength and stiffness of the connector system adopted. Therefore, before to implement the method through the reported in situ application, a comprehensive research was carry out, at the DIMS laboratory of Materials and Structural Testing, University of Trento, with the scope of investigating the mechanical properties of continuous threaded screws connectors, and providing a reliable engineered model to predict strength and stiffness of the joints (Crosatti et al. 2009).

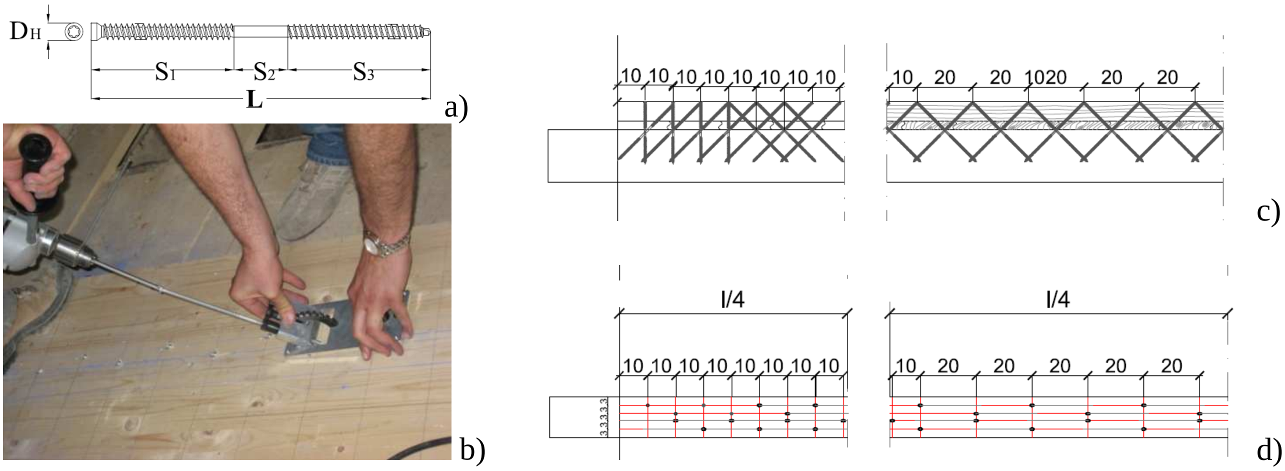

Figure 1: a) Full threaded screws; b) Insertion of the screws with an inclination of 45°; c) section and b) plan of the composite structure and geometry of the connections system

The advantages of the proposed method, compared with pioneering floor refurbishment systems, such as those, which couple the existing timber floor with a concrete slab (Turrini and Piazza, 1983), are the reversibility, the minimal sacrifice of material, the compatibility and stability of the repair materials, the reduction of the original permanent loads.

In situ testing

The chance to investigate the effectiveness of the proposed strengthening technique was given during the restoration of the Belasi castle (14th century), in the Non valley (Trento, Italy). The reported intervention has been executed on a timber floor in the north-east wing of the castle. The room has a trapezoidal shape; the twenty timber beams have variable reciprocal distances (99÷50 cm) and span length (6÷7.2 m).

Preventative evaluation of the state of the artifact. Despite the simplicity of the structure, a throughout investigation was carried out (Piazza et al. 2009). The geometric characteristics of the whole structure and of each element were surveyed in detail. Variation in the transverse section and existing deformations have been indicated in the inspection report, distinguishing between the deformations deriving from applied stresses or creep effects, and those caused by material features. Different wood species of the floor beams have been identified through in situ macroscopic analysis (UNI 11118:2004). The wood moisture content was estimated by means of the resistance method (EN 13183-2:2002). Visual inspection was performed according to the UNI standard 11119:2004. In order to visually grade the timbers, the strength affecting features on each wooden member were surveyed according to the UNI standards 11035:2003 part 1 and 11119:2004. The four longitudinal faces of the beams were visually analysed, thanks to the possibility of accessing the elements from both the intrados, by means of scaffolds, and from the extrados, after dismantling the decayed floorboards. Complementary to visual observations, resistance drilling tests were carried out, in order to identify and quantify decayed areas. Drillings profiles were also analyzed in order to roughly estimate the growth rate of the inspected timber.
Through the knowledge on wooden specie, geometry and morphology of the beam, defect position and extension, and with the results from non destructive instrumental inspection, each timber element, or a part of it, was graded according to strength (UNI 11035:2003 part 2).

Execution and efficiency control of the intervention. An incremental approach has been adopted for the execution of the intervention. Therefore, before to apply the strengthening technique to the whole floor, a single beam has been tested, before and after repair. For this purpose, after

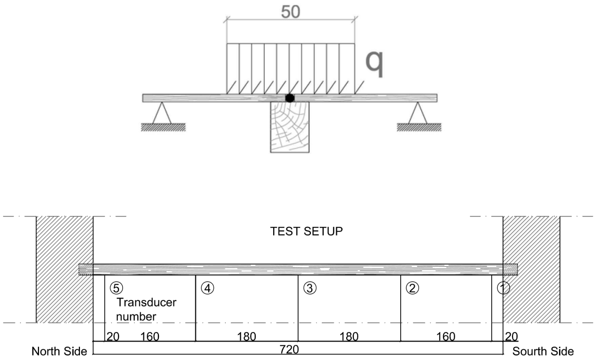

Figure 1*: On site bending test: loading and measurement system*

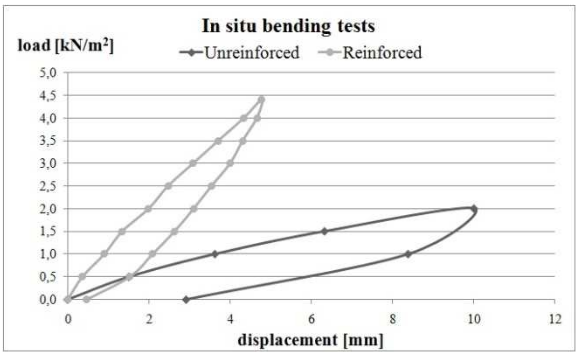

Figure 3: On site bending test: load-displacement curves (unreinforced and reinforced beam)

dismantling the decayed floorboards, a timber formwork was built on the beam, and then waterproofed with nylon sheets. The beam was instrumented at the intrados with five displacement sensors, and then monotonically loaded and unloaded pouring water, with load steps of 0.5 kN/m^2 and maximum load of 2 kN/m^2.

The same testing procedure was followed, after repair. The beam was coupled with glulam planks (strength class GL 24h according to EN 1194:1999), 70 mm in thickness. The new floorboard portion, large 500 mm, rested symmetrically and solely on the test beam. Self-tapping double thread screws were used, of two different lengths and strength class 10.9 ($f_{u,k}$ = 1000 MPa). The main feature is that each screw has two threads of different pitch but of equal length: one for penetrating and the other for tightening. The disposal of the inclined screws is designed to increase the stiffness and the strength capacity of the connection. Moreover, screws are staggered, in order to avoid the occurrence of splits along the fiber. The geometric scheme of the connection system is illustrated in Figure 1c-d. The design of the reinforcement was developed considering 3 kN for both dead and live load, and assuming for the static scheme a simple supported beam. Then the repaired portion of the floor has been tested. According to Figure 2, the boards were cut in two, above the beam, in order to avoid load transmission to not investigated lateral beams. In this case, the maximum test load was 4.5 kN/m^2, with load steps of 0.5 kN/m^2.

Laboratory testing

The test material. Nine of the twenty beams of the studied timber floor in the Belasi castle were considered severely decayed and dismantled. The removed material has been given to the Laboratory of the Department of Mechanical and Structural Engineering (DIMS) of the University of Trento, as test material. However, all the beams, except for a single one, have been damaged during demolition. Therefore, in order to carry out tests on full size members, repair works had to be done before tests. In this paper, the experimentation carried out on the only member which maintained the original size is described. Material has been accurately cleaned up with pressurized water and nails have been drawn out. The species of the tested beam, determined through microscopic analysis, is Scots Pine (*Pinus sylvestris* L.).

An accurate survey of the geometric data was done, taking measures at regular steps of 50 cm along the element length. Each cross section was represented by eight parameters, obtained by straightlining the corners. Besides, rectified photographic images of the element faces were taken.

Density was derived from the ratio between mass and volume of the element, according to the EN 408 standard. Volume was approximately determined, because of the irregular shape of the element (irregular and variable cross-sections, presence of splits, distortion and decayed areas).
Moisture content was estimated with the electrical resistance moisture meter.

Testing techniques for the material characterization. Testing techniques have been applied in laboratory, with the scope of characterizing the timber material according to its visible and internal macroscopic features. This part of the test is connected to a research activity, carried out at the DIMS,

aimed at the application of traditional and imaging NDT techniques, for the collection of information on structural features of the wood material, such as interfacial discontinuities, cracks and density variation. In particular, stress waves tomography as well as local mechanical testing, such as drill-resistance tests have been used, so far, for the analysis of the disassembled timber beams.
Drill-resistance tests were carried out along the radial direction of the material, on two adjacent faces, at steps of ≈50 cm along the element length, avoiding areas with knots, which can cause instrument needle to bend and consequent deviation in the drilling path.
Stress-waves time-of flight (TOF) tomography, applying the through-transmission technique, has been done, on the same transversal sections of drilling and, additionally, on three longitudinal sections at 1/4, 2/4 and 3/4 of the section base, respectively. Measurements were done using multi-channel sonic/ultrasonic equipment with 55 kHz transducers and an instrumented hammer. Inversion of TOF data was performed using software based on the integration of different reconstruction techniques (ART, SIRT, SDV and SVDT) (Camplani et al. 2009).

Drilling profiles have a resolution of 0.1 mm, which permitted to determine with accuracy the residual resistant cross section of the tested beam. In particular, depth of the decayed area on the extrados of the tested beam (decay max depth= 2 cm) and local extension of checks and splits were assessed. Two dimensional stress waves contour maps in cross-section planes and, especially, in longitudinal planes permitted to have information on macroscopic strength affecting material features, such as big knots or knots clusters.

Experimental validation of the strengthening technique. In order to validate the proposed strengthening technique, a stepwise approach has been adopted. A series of four point bending tests according to UNI EN 408:2004 has been carried out on three consecutive configurations of the beam: 1) unreinforced, 2) coupled with unconnected boards, 3) reinforced (Fig. 4).
The testing apparatus is illustrated in Figure 4. The specimen was loaded using an actuator with a 25 kN load cell, while the beam behaviour was monitored with four LVDT transducers connected to an acquisition system.
To control contingent asymmetrical deflection of the beam, the LVDT transducers were placed at the mid-span, on the opposite sides of the cross-section, using both yokes and direct measures.
Owing to the initial twist of the beam and considering that the presence of several flaws might have made local MOE inapt to represent the whole piece's behaviour, we determined (from every test) both local and global MOE's values. As a result, one can notice that local MOE's value is higher than global one (Solli, 2000). Accordingly, an additional bending test (in configuration 1) was carried out with the same span length (5.6 m) adopted for the composite beam. That test yielded a mean global MOE of 7.591 GPa, which has been used in further calculation (Table 1).
The strengthening intervention has been designed with the purpose of obtaining the same global effective bending stiffness of the *in situ* composite beam. The effectiveness of the reinforcement has been assessed by comparing the stiffness of the composite beam, measured in test configuration 2 and 3. An increase of more than four times the original bending stiffness was expected and has been confirmed by the test results. However, the experimental effective bending stiffness was almost 15% less than the expected one. This discrepancy could be prompted by the differences between the theoretical and experimental condition (e.g. twisting, warping and flaws of the tested beam).

Table 1: Experimental values of local and global MOE (UNI EN 408:2004)

	Span length 3.60 m			*Span length 5.60 m*
Midspan *x* coord. [m]	2.00 (Test 1)	3.00 (Test 2)	4.00 (Test 3)	3.00 (Test 4)
$E_{m,l}$ [GPa]	9.52	8.97	6.99	10.20
$E_{m,g}$ [GPa]	7.15	6.62	6.44	7,59

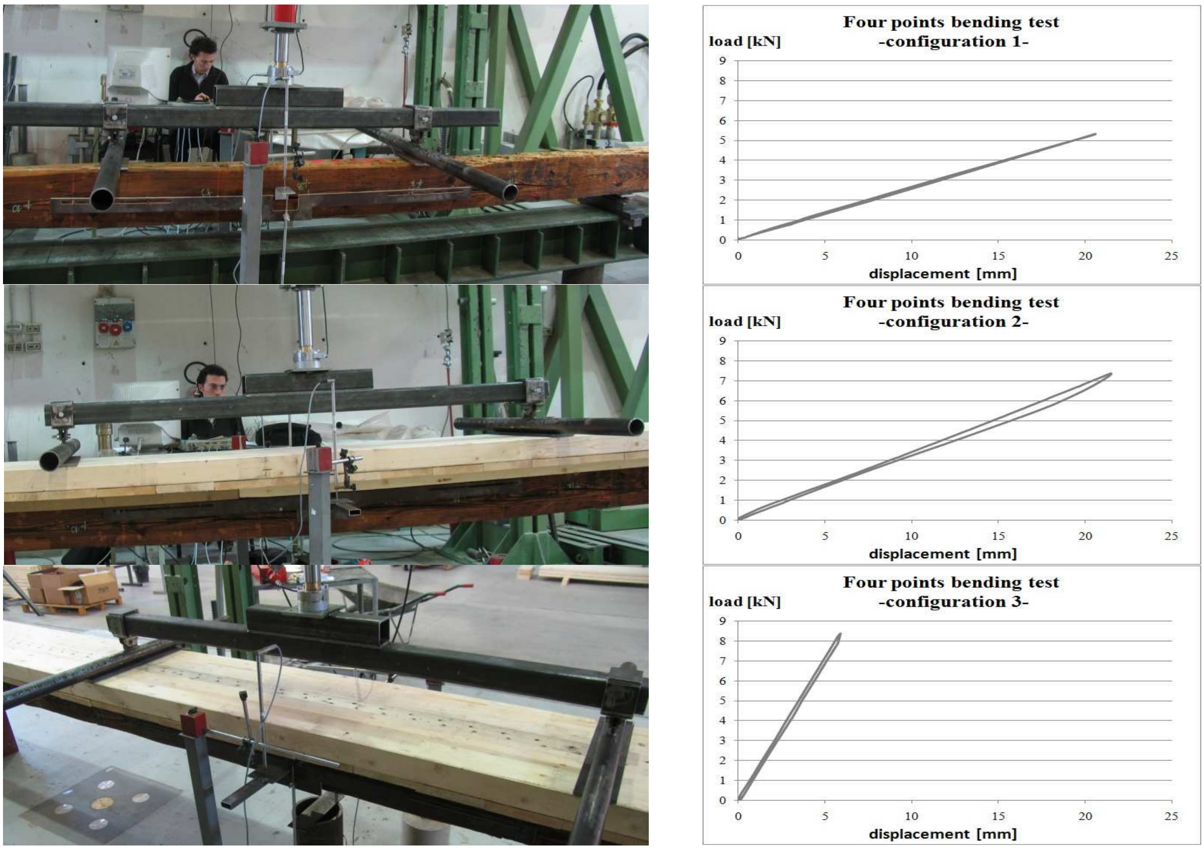

Figure 4: Four point bending tests. 1) unreinforced, 2) with unconnected boards, 3) reinforced beam

Comparison of in situ and laboratory testing

Differences between *in situ* and laboratory tests depend on several factors. First of all, in the former case the boundary conditions could not have been precisely determined, while they were accurately designed in laboratory. Moreover the two tested beams are not the same. Since the beam in service has been refurbished (it showed good mechanical conditions), for laboratory testing we have been obliged to choose among the discarded beams, which have different geometrical and mechanical properties. This led to some variation in the design detailing, with particular regard to the connection spacing (Table 2). Finally, while on site the beam was tested under distributed load, standard concentrated loads were applied on the dismantled beam.
Nevertheless, the two consequential testing campaigns showed a good agreement between theoretical and experimental results. In particular, an increase of more than four times of the effective bending stiffness was achieved in both conditions, after repair.

Final discussion and further developments

Some important aspects concerning the validation procedure of the new strengthening technique have been highlighted by comparison of *in situ* and laboratory testing results. In detail, a preliminary throughout diagnostic campaign allows reducing the uncertainty pertaining material properties and conditions. Indeed, the variability of timber elements in terms of geometry and mechanical behaviour makes a generalized intervention design unsuitable to be applied to traditional floors. On the other hand, an accurate control of the material features and structural performance lets us develop a tailor-made design.
In order to reduce the unknown variables in the assessment of the strengthening technique (such as those related to distortions and flaws in old members), new timber full-scale elements will be also tested in future research.

Table 2 : Geometrical data of the composite structure

	In situ test [m]	*Laboratory test [m]*
Span between supports	7.20	5.60
Beam (base x height)	0.15 x 0.20	0.16 x 0.20
Glulam plank (base x height)	0.50 x 0.08	0.50 x 0.08
Wooden boards arranged crossed to the beam	0.03	0.03
Max./min. distance between screw connections	0.20 / 0.10	0.10/ 0.09

Acknowledgement

The research was founded by the Italian ReLUIS Consortium, within the research program carried out for the Italian Agency for Emergency Management. The second Author was supported by the P.A.T., with a post-doc fellowship on DIGItal technologies in TIMBEr Restoration. Dr. Tiziana Urso is responsible of laboratory wooden species characterization. The Authors wish also to thank the company Rothoblaas s.r.l., the Soprintendenza Beni architettonici P.A.T., the SWS-Engineering S.p.A. and arch. Fabio Bartolini. Moreover the Authors are very grateful to the former under-graduated students Marcella Rizzi and Alessandro Crosatti for the work done during the research.

References

[1] UNI 11138 (2004). *Cultural heritage - Wooden artefacts - Building load bearing structures - Criteria for the preliminary evaluation, the design and the execution of works*. UNI Milano

[2] ICOMOS (2001). *Recommendations for the analysis, conservation and structural restoration of architectural heritage*. [Online]. Available: http://www.international.icomos.org/charters/structures_e.pdf

[3] Crosatti A., Piazza M., Tomasi R., Angeli A. (2009). “Refurbishment of traditional timber floor with inclined screw connectors”. In: *Proc. prohitech09*, 1st Int. Conf. Rome, 21-24. 12.2009

[4] Turrini G., Piazza M. (1983). “Il comportamento statico della struttura mista legno calcestruzzo”, in *Recuperare*: 6

[5] Piazza M., Riggio M., Tomasi R. Angeli A. (2009). “Operational stages and criteria in the rehabilitation of timber floors in the Belasi castle (Trentino, Italy)”. In: *REMO2009 Conf. Repair, Cons. and Strengthening of trad. erected buildings and historic buildings*. Poland 2-4-12 2009.

[6] UNI 11118 (2004). *Cultural heritage - Wooden artefacts - Criteria for the identification of the wood species*. UNI Milano

[7] EN 13183-2 (2002). *Moisture content of a piece of sawn timber - Part 2: Estimation by electrical resistance method*. European Committee for Standardization. Brussels

[8] UNI 11119 (2004). *Cultural Heritage - Wooden artifacts – Load-bearing structures – On site inspections for the diagnosis of timber members*. UNI Milano

[9] UNI 11035-1 (2003). *Structural timber. Visual strength grading: terminology and measurement of features*. UNI Milano

[10] UNI 11035-2 (2003). *Structural timber. Visual strength grading rules and characteristic values for Italian structural timber population.* UNI Milano

[11] EN 1194 (1999). *Timber structures. Glued laminated timber. Strength classes and determination of characteristic values.* European Committee for Standardization. Brussels

[12] UNI EN 408 (2004). *Timber structures. Structural timber and glued laminated timber. Determination of some physical and mechanical properties.* UNI Milano

[13] Camplani M., Cannas B., Carcangiu S., Concu G., Fanni A., Montisci A and Mulas M.L. (2008). “Acoustic tomography for non destructive testing of stone masonry”. In: *Lecture notes in Computer Science*. 5073:596-605. Springer Berlin/Heidelberg

[14] Solli K.H. (2000). "Modulus of elasticity – local or global values". In: *Proc. of World Conference on Timber Engineering*, Whistler Resort, British Columbia, Canada, July 31 - August 3, 2000