RILEM TC “Reinforcement of Timber Elements in Existing Structures”

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Abstract. The paper reports on the activities of the RILEM technical committee “Reinforcement of Timber Elements in Existing Structures”. The main objective of the committee is to coordinate the efforts to improve the reinforcement practice of timber structural elements. Recent developments related to structural reinforcements can be grouped into three categories: (i) addition of new structural systems to support the existing structure; (ii) configuration of a composite system; and (iii) incorporation of elements to increase strength and stiffness. The paper specifically deals with research carried out at the Bern University of Applied Sciences Switzerland (BFH), the University of Minho Portugal (UniMinho), and the University of Trento Italy (UNITN). Research at BFH was devoted to improve the structural performance of rounded dovetail joints by means of different reinforcement methods: i) self-tapping screws, ii) adhesive layer, and iii) a combination of self-tapping screws and adhesive layer. Research at UNITN targeted the use of “dry” connections for timber-to-timber composites, specifically reversible reinforcement techniques aimed at increasing the load-bearing capacity and the bending stiffness of existing timber floors. At UniMinho, double span continuous glulam slabs were strengthened with fibre-reinforced-polymers. All three examples demonstrate the improved structural performance of timber elements after reinforcing them.

Introduction

Timber has been used as structural material for centuries and numerous examples demonstrate its durability if properly designed and built. There is, however, a growing need to not only maintain but also upgrade existing buildings for economic, environmental, historical and social concerns. Worldwide, a large proportion of the existing building stock is more than 50 years old (over 80% of European buildings); many of these buildings need to be adapted for higher present and future requirements. About 50% of all construction in Europe is already related to existing buildings [1, 2]. The need for structural reinforcement of timber buildings results from various requirements such as change of use, deterioration, exceptional damaging incidents, new regulatory requirements, or interventions to increase resistance. The European Commission mandates the development of rules for the assessment of existing structures and their reinforcement (M/466 EN) [3].

Recent developments related to structural reinforcement [4-9] can be grouped into three categories: (i) addition of new structural systems to support the existing structure, (ii) configuration of a composite system (timber-concrete, timber-steel, timber-FRP, and timber-timber), and (iii) incorporation of reinforcing elements to increase strength and stiffness. In the latter category, the options range from mechanical fasteners like glued-in rods and self-tapping screws, adhesive systems, steel straps and plates, ever more widely fibre-reinforced polymers (also applied with adhesives), and most recently nanotechnology (e.g. carbon nanotubes with polymeric resins). Some of these methods, however, are often not adapted for their use in-situ depending on whether the structure is part of the regular building stock or belongs to cultural heritage.

The RILEM (The International Union of Laboratories and Experts in Construction Materials, Systems and Structures) Technical Committee (TC) “Reinforcement of Timber Elements in Existing Structures” (RTE) coordinated research efforts in this area.

RILEM Technical Committee RTE

The RILEM TC RTE was established in 2012 with the objectives to: (i) improve the reinforcement practice timber structural elements; (ii) disseminate up-to-date results to the industry, policy makers and society; and (iii) optimise collaboration of involved stakeholders in research and industry. The TC focuses on structural applications of timber in existing buildings of all ages and uses; other materials, non-structural timber applications, and product development are excluded. The scientific focus of this TC is the improvement of existing techniques for reliable reinforcement of structural timber elements; the development of new methods is not anticipated. The TC membership has on-going research programs and will facilitate research coordination, eliminate duplication, and permit faster dissemination of knowledge.

Technical environment. Previous research on structural timber was coordinated by the COST Action E55 "Performance of Timber Structures" and RILEM TC AST-215 "In-situ assessment of structural timber". Valuable information in form of a State-of-the-Art report and a guideline on the assessment of timber structures was provided [10, 11]. The reinforcement of timber is an active research domain: COST Action FP1004 "Enhance mechanical properties of timber" deals with the development of innovative reinforcing techniques targeting large timber structures and one of the topics of COST Action FP1101 "Assessment, Reinforcement and Monitoring of Timber Structures" is the on-site application of reinforcement methods in existing structures; typically smaller and mainstream buildings which constitute the largest proportion of the existing building stock.

The RILEM TC RTE builds on the findings from the previous consortia and targets existing shortcomings in regard to reinforcements. The TC benefits from multidisciplinary views and innovative solutions by the involved stakeholders, enable synergies between them, and provides an effective way of discussing and disseminating results from on-going projects. The RILEM TC liaises with the two before-mentioned COST Actions; as a world-wide organization it enriches the European efforts and fosters the world-wide exchange of knowledge through joint activities. These interactions will come in the form of co-organising conferences, and joint meetings and workshops. Several TC members are involved in the two COST Actions and will facilitate collaboration. Reinforcement techniques are also used in other materials such as concrete or masonry; some of the techniques are equally applicable to several materials, therefore collaboration between the pertinent RILEM TCs from all material domains is valuable and members of the corresponding TCs are invited to participate in the activities of TC RTE.

Working program. The scientific focus of this TC is the improvement of existing techniques for the reinforcement of structural timber. Activities will focus on consolidating current knowledge and answering the following questions: What is the current state of the art regarding methods and techniques? What methods from other materials and systems can be adapted to timber structures? Where is coordinated research required to develop new techniques and methods?

The scientific activities range from experimental to numerical and analytical approaches to study technologies for in-situ strengthening and will contain following tasks: (i) analysing approaches of different research groups and evaluating methods in terms of applicability, expenditure of time/cost, validity of results and constraints; (ii) facilitating the decision-making process for choosing an appropriate reinforcement method; and (iii) establishing common practices and harmonized recommendations and disseminating thereof. It is expected that the TC will:

- create a basis for exchange of ideas and research data, and a database of case studies;
- write joint articles for peer reviewed journals;
- write a state-of-the art report;
- propose harmonised recommendations;
- organize special sessions at international events, e.g. WCTE and SHATIS;
- attempt to develop collaborative research proposals.

In the following, different projects exemplify the research of RILEM TC RTE members.

Reinforced Rounded Dovetail Joints

Rounded Dovetail Joints (RDJs) are a versatile concept for connecting structural timber members, with the most common application being joist to beam connections. A number of experimental and analytical studies [12-16] provided valuable insight revealing that RDJ failure under shear loading is typically brittle, initiates at the bottom of the dovetail of the joist member, and occurs at load levels much below the member strength. Furthermore, the relative vertical deformation between members may reach considerably high values (approx. 3mm) at loads as low as 30% of the capacity. As a consequence, reinforcements are a possibility to improve the structural performance of RDJs. Tannert and Lam [14] evaluated three reinforcement methods for RDJs: i) joist reinforcement with self-tapping screws at an angle of 90^0, ii) reinforcement of joist and main beam with self-tapping screws at an angle of 55^0, and iii) reinforcement of joist and main beam with angled self-tapping screws crossing each other. All three methods significantly increased capacity, and stiffness was significantly higher when main beam and joist were reinforced.

Specimen description. In the research presented herein, three different types of reinforcements for RDJs under vertical shear loading were compared to two test series of non-reinforced RDJs: S0 control test series with loose-fitting joint; S1 test series with tight-fitting joint; S2 reinforcement with self-tapping screws at an angle of 45°; S3 reinforcement with an adhesive layer in the joint; and S4 a combination of self-tapping screws and adhesive layer. The joints were produced using an Arunda® steel jig and a hand-router. The purpose of the two series without reinforcements was to evaluate the effect of oversizing the tenon to create a tight-fitting joint. The main beams and joists were 480 and 600 mm long, respectively; the cross sectional dimensions were 80 x 120 mm.

Materials and methods. The timber species used was kiln-dried spruce (*Picea abies*) cut from high quality members. The material was conditioned to approx. 15% moisture content (MC) prior to manufacturing of the joints, and then stored in constant climate until testing. The density and MC of all members were determined: the mean MC was 15% with a standard deviation of 2%,. The mean density was 395 kg/m³ with a standard deviation of 21kg/m³. SFS® "WT" screws with d=6.5 mm and l=220 mm were, the glue was a stiff and brittle two-component epoxy – SikaDur330®.

A total of 42 joints (10 specimens of the control test series, and 8 specimens each for the studied reinforcement methods and the tight-fitting joints) were tested at BFH. From a plan-view, all experiments had a T-shape with a "main beam" as the top of the T, and a joist as the vertical of the T (see Fig. 1). Vertical shear-loading mode was chosen, identified by the load F. The main beams were supported on two 80 mm wide steel plates and not fixed, thus allowing for some rotation around their longitudinal axis. The free end of the joist was supported on another 80 mm wide steel plate on a spring support with a stiffness of 1.5 kN/mm, thus simulating a longer beam. The load was applied on a 100 mm wide steel plate with its centre at a distance of 320 mm from the joint.

Following quantities were recorded during each test: i) the load applied by the actuator; ii) the force at the support of the free joist end; and iii) the relative vertical joint displacement. The force transmitted by the joint was calculated as the difference between the applied load and the load recorded at the free end of the joist. The load was increased with a constant rate of loading so that ultimate failure occurred after approx. six minutes, in accordance with EN-26891.

Results and discussion. Two key results were extracted from the load-displacement response of each test specimen: the joint force at joint failure which indicates the ultimate limit-state of the joint (F_{max}); and the deformation at joint failure (d_{max}), which gives a measure of joint stiffness. Herein, failure was defined as the joist member of the joint fracturing in a brittle manner as shown in Fig. 2. Using analysis of variance, it was determined all three reinforcement methods increase capacity compared to the non-reinforced RDJs. Regarding d_{max}, oversizing the tenons (S1) and the reinforcement with self-tapping screws (S2) significantly decrease the relative vertical joint deformation. Reinforcement methods S3 and S4 further decrease the joint deformation, while between these two tests series, no difference was found.

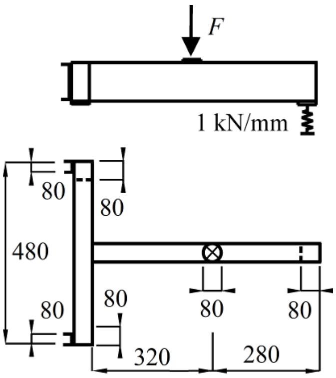

Fig. 1: Test setup

Fig. 2: Failed test specimen

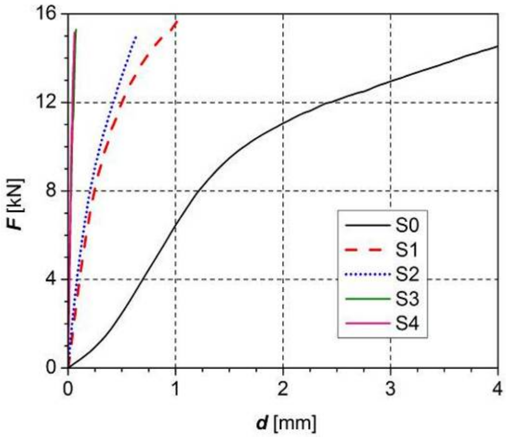

Fig. 3: Average load-displacement

The average load-displacement curves for the test series are shown in Fig. 3. These curves very clearly illustrate the findings in terms of relative vertical joint deformation: the test specimens of series S0 (lose fitting joints without reinforcement) exhibit very large displacements – similar to those encountered in previous tests on RDJs. Test specimens from series S1 and S2 exhibit much smaller deformation. This is caused in case of S1 by oversizing the tenon to achieve a tight-fitting joint, and in case of S2 by reinforcing the joint with self-tapping screws. A further significant decrease in relative vertical joint deformation was observed for test series S3 and S4. Here, the adhesive created a completely tight joint that exhibited almost no deformation before failure. The failure mode of the RDJs was not significantly changed by applying the reinforcement methods; typically, failure occurred by splitting of the joist member at the bottom of the dovetail. However, the increased stiffness of the reinforced RDJs caused significant compressions perpendicular to the grain below the metal plate where the load was applied.

Double span continuous glulam slabs strengthened with GFRP

An extensive experimental program was carried out at UniMinho, to assess the bond behaviour between glulam and different fibre-reinforced-polymer (FRP) systems and the effectiveness of near-surface mounted (NSM) and externally bonded reinforcing (EBR) glass-FRP (GFRP) strengthening on the moment redistribution capacity of double continuous span glulam slabs.

Specimen description. Six full-scale two span glulam slab strips organized in three different series were tested. The first series (REF) was composed by two non-reinforced slabs; the second and third series were comprised of glulam slab strips strengthened with NSM GFRP rods (V) and EBR GFRP sheet (M), respectively. In each series, one specimen was designed to increase the ultimate load capacity to 20% and the other to 40%, in comparison with the reference slabs.

Results and discussion. The main achievement obtained by the strengthening techniques was the increase of ductility. The NSM strengthening was more efficient in terms of increasing the ductility (Fig. 4): the originally linear elastic behaviour of the non-reinforced slabs became non-linear, with a considerable (nearly flat) post-elastic branch. On the other hand, the EBR technique was not able to modify the linear elastic behaviour of the glulam slabs strips (Fig. 5).

All strengthening techniques increased the maximum load while an insignificant change in the stiffness was observed (Figs. 4 and 5). The NSM technique with GFRP rods, however, did not reach the percentage of strengthening assumed in its design.

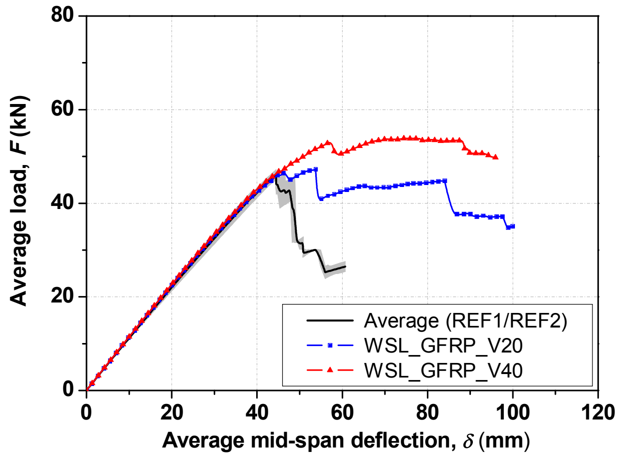

Fig. 4: Load-deformation curves NSM technique

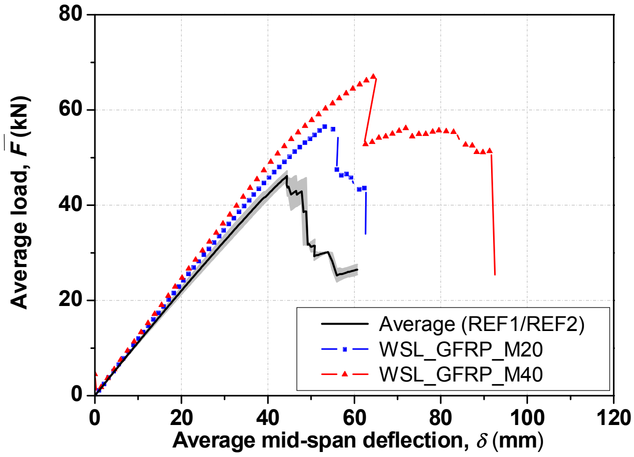

Fig. 5: Load-deformation curves EBR technique

The slab strips strengthened with the NSM technique showed an extensive cracking in the wood between the GFRP rods. Tension cracks appeared in three regions (hogging, sagging left and right), despite being more evident in the hogging. Local embedment in the compression side was always observed in the hogging region. In any case, failure of the GFRP rods was observed. Using the EBR technique, the failure occurred always in the longitudinal axis of the GFRP with local embedment in the compression region only when the percentage of strengthening was higher than 20%.

The research on strengthened double span continuous glulam slabs with GFRP was designed assuming an increase of the maximum load capacity (20% and 40% for NSM and EBR techniques, respectively). Although not designed for any moment redistribution, the NSM strengthening technique was also able to re-distribute the bending moment by approx. 25%.

Reinforcement of timber beams by screw fasteners

Results of recent research at the UNITN laboratory of Materials and Structural Testing are reported hereafter. The research focused on improving the behaviour of existing timber beams to: i) increase their in-plane stiffness; and ii) reduce their mid-span deflection. In both cases, the use of screw fasteners was investigated. Timber-to-timber joints connected with inclined screws, placed parallel to each other or X-crossed, were investigated [17]. The increase of in-plane stiffness of timber floor beams by coupling the existing beam and a new timber plank with inclined screws, was investigated both in laboratory, testing different geometries of the connectors [18], and on site, on a timber floor in a historical structure [19]. The possibility of cambering a timber beam by adding another beam on top and inserting screws inclined at 45° to the beam axis was also studied [19].

Specimen description. Herein, three different test series are reported:

T0) Reinforcement of an old timber beam coupled to a glulam plank GL24h with self-tapping double thread screws X-crossed with an angle $\alpha = 45°$: here the behaviour of the unreinforced and reinforced beam was compared.

T1) Comparison of the behaviour of glulam beams (GL24h) coupled to a glulam plank with different screws and configurations: a) double thread screws X-crossed at 45°; b) double thread screws parallel at 45°; c) fully thread screws X-crossed at 45°; d) single thread screws parallel at 90°. In both T0 and T1, a layer of 180×30 mm^2 floor-boards was placed between beams and planks.

T2) Analysis of the camber effect obtained coupling a timber beam to a new beam (both 100 x 100 x 4000 mm in size) with two rows of double thread screws at 45°, 100 mm spaced. Two different screw insertion modalities were compared: (Int-to-Ext) from the middle to the ends, and (Ext-to-Int) from the ends to the middle.

Materials and methods. Both T0 and T1 consisted of four-point bending tests of the unreinforced and reinforced beams up to failure. Previously, elastic bending tests were performed in order to determine the MOE of the considered elements. After determining the MOE of every single element, the composite beams without mechanical connections were tested. This way it was possible to evaluate to what extent the beams and planks worked together as parallel elements or whether they were affected by phenomena such as friction. Eventually, once the connectors were applied, the resulting composite beams were tested elastically, and the stiffness of reinforced floor was determined. Subsequently all specimens were tested up to failure. T2 tests were performed on three beams, two were cambered following the insertion procedure (Int-to-Ext) and one (Ext-to-Int). The three assembled specimens were monitored for 48 hours, to detect any camber loss.

Results and discussion. An important information gathered from T0 and T1 was the efficiency of the connection μ used in the reinforcement, ranging from $\mu = 0$ ($EJ_{ef} = EJ_0$) to $\mu = 1$ ($EJ_{ef} = EJ_\infty$), where EJ_{ef} is the bending stiffness of the reinforced beam, EJ_0 is the bending stiffness of the unreinforced beam, and EJ_∞ is the theoretic bending stiffness of the composite beam with an ideal (completely stiff) connection. The performed tests demonstrated that the reinforced floors behaved very similarly to the ideal composite beam, with μ being 95−96 %.

Results obtained from series T1 (Fig. 6) demonstrated that reinforcements with inclined screws (either X-crossed or parallel) had comparable effects in terms of stiffness increase, although different values of failure load were reached. On the other hand, the beam reinforced with screws orthogonal to the shear plane (type d), showed a noticeable decrease in stiffness that led to a failure load lower than 22-35% of those reached for reinforcement types a), b) and c). It was observed that frictional forces caused by the pressure generated by the screws affected the overall bending behavior of the reinforced beams (with the exception of the X-crossed screws, where the friction forces of a pair of crossed screws balance each other) [18].

Regarding the possibility of cambering timber beams with method T2, it was shown that the screwing procedure, from either the middle or the ends, significantly affected the results (Table 1). As expected a more effective cambering was reached, when starting the assembly from the centre and alternatively proceeding towards the ends of the beam, since the interface slip is maximal at the ends of the composite beam and minimal in the central part. In [20], an analytical formula is expressed to evaluate the beam camber according to the proposed simple method.

Table 1: Experimental upward chamber (series T2)

Sample No	Procedure	Max deflection [mm]
1	Int-to-Ext	13.4
2	Int-to- Ext	6.9
3	Ext -to-Int	14.9

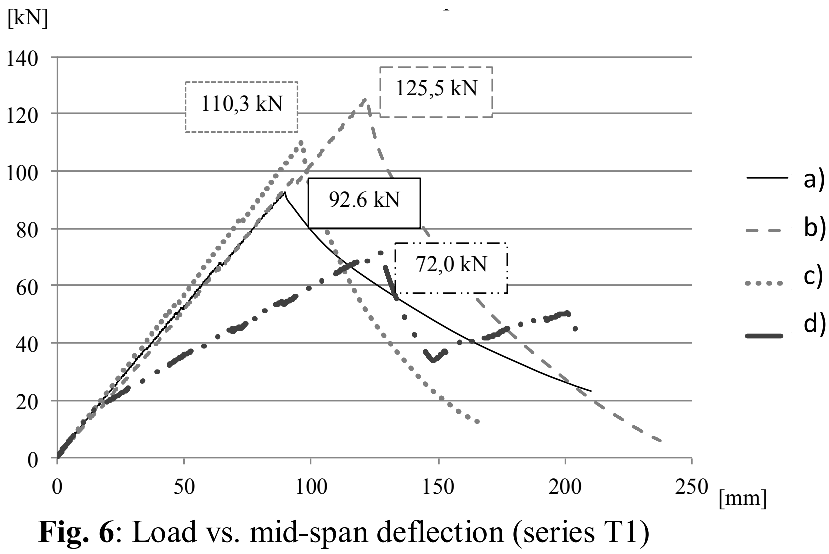

Fig. 6: Load vs. mid-span deflection (series T1)

Conclusions

The research on RDJs allows drawing following conclusions: i) the structural performance can be significantly improved by simple and economic means of reinforcements (self-tapping screws); and ii) applying an adhesive layer further increases the joint stiffness, and ii) a combination of both methods (adhesive layer screws) did not provide further improvements compared to the adhesive layer by itself. Based on the results presented in this work, RDJs should be reinforced with an adhesive layer recognizing that further research is required to evaluate their performance under different loading condition, specifically static long–term and fatigue loading, and the effect of elevated temperatures or MC or a combination of any of the before.

The research on timber-timber reinforcing systems with screw fasteners allows drawing the following general conclusions: i) the use of inclined screws to connect timber-timber composite structures significantly improves the behaviour of floor beams, by increasing the stiffness and reducing the deflection; ii) if the aim of the reinforcement is to camber a sagged beam, a specific sequence must be followed for the insertion of the screws (namely from the interior to the exterior). In case of refurbishment of old beams, the effectiveness of the proposed method is influenced by the presence and extent of decay, the entity and nature of geometrical irregularities and the residual load bearing capability of the member. Therefore, more research is recommended, in order to assess the actual condition of existing structures.

The experimental research on double span continuous glulam slabs strengthened with GFRP allows drawing the following general conclusions: i) the reference slabs behaved linearly up to the failure, with marginal levels of ductility and stress redistribution; ii) the slabs strengthened with the NSM technique did not reach the predefined load increment, the magnitude of the groove geometry possibly being be the reason. However, high levels of ductility and stress redistribution were attained. The plastic behaviour of the wood under compression parallel to the grain and non-linear behaviour at the GFRP/wood interface observed over the intermediate support are appointed as responsible for this high level of ductility and redistribution; iii) the slabs strengthened with the EBR technique reached the predefined load increment. In this series the slabs almost behaved linearly up to the failure, but revealed low levels of ductility and stress redistribution.

Improving the reinforcement of timber structural elements is a research domain with large-scale activity, which requires the exchange of information and identification of new research ideas. The before listed projects show the potential scientific, technological, and economic benefits that the research coordinated be the RILEM TC RTE can create. Increased knowledge of retrofitting techniques will help architects and engineers to make timber a viable option for more applications and new opportunities in design. When timber structures are reliably reinforced, structural failures and unnecessary decommissioning can be avoided, and resources can be used more sustainably.

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