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REINFORCEMENT OF TIMBER STRUCTURES

– THE ROUTE TO STANDARDISATION

Annette HARTE[1], Robert JOCKWER[2], Mislav STEPINAC[3], Thierry DESCAMPS[4], Vlatka RAJCIC[5], Philipp DIETSCH[6]

ABSTRACT

The reinforcement of new and existing timber structures has been the subject of considerable research and development in recent years. New materials and methods for reinforcement have been developed and used in practise. However, there is currently a lack of harmonised European standards governing this field. In this paper, the current 3-step pyramid applied in international standardisation for the construction sector is described. The pyramid is based on design, product and test standards. Two widely used reinforcement materials, namely self-tapping screws and glued-in rods, are discussed with reference to this framework. Existing standards are described, and the additional standards that need to be developed and implemented to complete the pyramid are discussed. In addition, the development of design rules for the reinforcement of carpentry joints and research needs in the area are reviewed.

Keywords: Timber structures, Reinforcement, Standard, Self-tapping screws; Glued-in rods, Carpentry joints

1. INTRODUCTION

Wood features many excellent characteristics as building material. However, the anisotropic properties of this natural material have to be taken into account during design and construction. It is undisputed that good design of timber structures should aim to minimise stresses for which timber has small capacities and brittle failure mechanisms (e.g. tensile stresses perpendicular to the grain and shear), thereby avoiding or at least minimizing the necessity for reinforcement. Despite this, there is still a multitude of reasons necessitating the structural reinforcement of timber buildings, not only in existing buildings but also for new structures.

In a recent report [1] prepared by members of COST Action FP1101, current and emerging methods that are available to repair or enhance the structural performance of timber structures are summarised. Criteria for selection and examples are given for the implementation of the various reinforcement

[1] Dr., College of Engineering and Informatics, National University of Ireland, Galway, Annette.harte@nuigalway.ie
[2] Dr. sc., Institute of Structural Engineering, ETH Zurich, jockwer@ibk.baug.ethz.ch
[3] PhD student, Faculty of Civil Engineering, University of Zagreb, Croatia, mstepinac@grad.hr
[4] Dr.-Ing. U.R.B.A.I.N.E, University of Mons, Thierry.DESCAMPS@umons.ac.be
[5] Full professor, Faculty of Civil Engineering, University of Zagreb, Croatia, vrajcic@grad.hr
[6] Dr.-Ing., Chair of Timber Structures and Building Construction, Technische Universität München, dietsch@tum.de

methods. For all construction works it has to be verified that essential requirements like mechanical resistance, stability and safety in use are met. The required performance is commonly verified by complying with corresponding harmonized technical rules for the structural design as well as products used in construction works. In cases where harmonized technical rules or technical approvals are not available, an approval in the individual case or comparable has to be sought.

Many reinforcement methods still lack harmonized technical rules. According to the European position on future standardization [2], harmonized technical rules shall be prepared for "common design cases" and shall contain "only commonly accepted results of research and validated through sufficient practical experience". The target audience for such rules is "competent civil, structural and geotechnical engineers, typically qualified professionals able to work independently in relevant fields". When preparing items for standardization it is important to take into account the approach within the internationally accepted system for standardization. Comparable to the approach taken by scientists when tackling a problem - (1) methods, (2) materials (3) results - the system for standardization is based on a 3-step-pyramid, see Fig. 1. This pyramid is based on (1) test standards (containing rules on how to test products). Relating to these, product standards (2) are developed (giving strength and stiffness parameters, boundary conditions and rules for production and quality control). The design standards (3) represent the tip of this pyramid (providing design equations and formulating specific requirements in e.g. spacing, edge distance, minimum anchorage length, etc.). When developing design rules it is a precondition to also develop (1) test procedures as well as (2) a product standard on the product or system used. Without the latter, rules in a design standard cannot be used since the basic parameters are missing, in other words, the pyramid will not be complete if one element is missing.

In this paper, two widely used reinforcement materials, namely self-tapping screws and glued-in rods, are discussed with reference to the standards that currently exist and those that are required to complete the pyramid. Recent developments at CEN standardisation committees are presented. In addition, the reinforcement of carpentry joints, which are found in many older European buildings, is reviewed. The design of reinforcement for these joints is a difficult task due to the complexity of the structure, and limited knowledge about the material properties. Some guidelines on how existing Eurocode 5 design procedures can be applied in specific cases are presented. Areas of further research required in order to develop additional design procedures are identified.

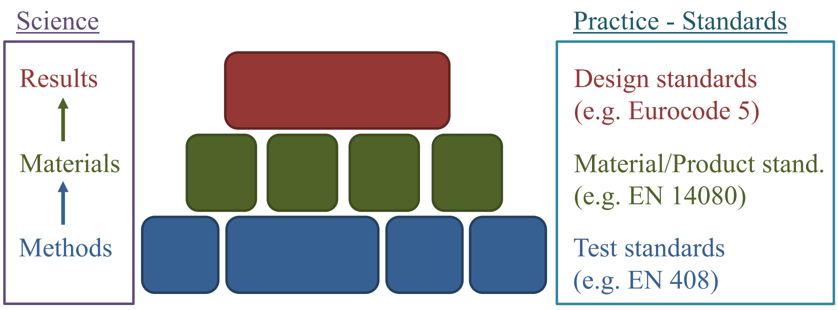

Fig. 1 Sketch of the 3-step-pyramid applied in international standardization for the construction sector

2. REINFORCEMENT WITH SELF TAPPING SCREWS

The most important situations where self-tapping screws can be used for reinforcing purposes are e.g.:

- Tension stresses perpendicular to the grain
- Compression stresses perpendicular to grain
- Shear stresses
- Connections with dowel-type fasteners
- Carpentry joints

All of these different situations require different specific properties of the reinforcement regarding embedment or axial strength and stiffness as well as slenderness.

2.1. Test standards

Currently the tests standards for self-tapping screws [3]-[8] are the same as for other dowel type fasteners as bolts, dowels, nails or staples. Due to the very recent development of self-tapping screws with regard to greater length and diameter and the use of high-strength steel for the screw, these test standards do not fully account for their specific properties. In [9] general requirements to assess self-tapping screws with respect to their application in timber structures are described.

The most important mechanical properties of self-tapping screws when being used as reinforcement are their stiffness and load-carrying capacities in the axial and, to a lesser extent, in the lateral direction. The following basic material and mechanical properties can be defined:

- Tensile capacity f_{tens}: Determined according to EN 1383 [4] as an adaption of the head pull through tests in which the wood part is replaced by steel. The tensile capacity of the screw is determined as the weakest point of the screw e.g. head pull-off or shank tensile capacity.
- Yield moment M_y: Determined according to the bending test in EN 409 [6]. The yield moment is used to specify the bending capacity of dowel type fasteners. Alternatively the yield moment can be calculated from the tensile strength of the screw according to EN 1995-1-1 [10] as it is done for nails or bolts. However, these equations do not account for the specific material and geometrical properties of the screws and are subject to discussion in literature [11], [12]. Sufficient ductility shall be achieved in the tests.
- Withdrawal parameter f_{ax}: Determined according to EN 1382 [4]. It is used to calculate the withdrawal or punch in resistance of the self-tapping screw.
- Head pull-through parameter f_{head}: Determined according to EN 1383 [4]. It is of relevance only when loads have to be transferred at the very surface of the timber element.
- Characteristic torsional moment R_{tor}: Determined in accordance with EN 15737 [7]. The use of self-tapping screws as reinforcement in beams of large height requires sufficient torsional resistance for an easy and safe screw-in process. This can be even of greater importance for the case of discontinuous screwing processes where high friction forces occur when restarting the screwing process.
- Embedment strength f_h: Determined according to EN 383 [5]. It is only of minor importance for situations of tensile and compression reinforcement. However, for the reinforcement of connections or for regions of high shear stresses or even shear cracks the embedment strength and stiffness is of importance. Recent studies show that the embedment strength is to a certain extent dependent on the diameter of the screw and the surface and thread shape. Especially for self-tapping screws and rods of larger diameter this can be of relevance [13], [14].

With respect to the further development of test procedures for self-tapping screws used as reinforcement, the following main objectives can be identified:

- Separate and direct determination of yield moment and tensile capacity of self-tapping screws for the different purposes of connection and reinforcement, respectively.
- Differentiating the structural behaviour for reinforcement with continuous load introduction in contrast to localized high stresses [15].
- Combined axial and lateral loading.
- Requirements regarding ductility (robustness), repeated loading etc.
- Reliable testing and declaration of stiffness properties for selected loading situations (e.g. continuous load introduction vs. localized high stresses).

2.2. Product standards

The product standard is the link between the test standards and the design standard. It defines the valid range of relevant geometrical parameters and material properties of the product for all approved applications of the product in construction.

In the current version of the product standard for dowel type fasteners, EN 14592 [16], the general manufacturing procedures, materials, geometries and relevant mechanical strength and stiffness properties are specified. The following geometrical parameters for screws are given:

- Outer thread diameter: 2.4 mm $\leq$ d $\leq$ 24 mm
- Inner thread diameter : 0.6 d $\leq d_i \leq$ 0.9 d
- Threaded length: l_g > 6d

In addition to these properties (which are mainly based on the use of screws for connection purposes) e.g. the screw head diameter and shape or thread with varying slope should be specified as well.
The large diversity of self-tapping screws for various possible applications, exceeding the above-given geometrical boundaries, lead to the development of a multitude of different European Technical Approvals (ETAs) for screws from different manufacturers. These ETAs are commonly based on the Common Understanding of Assessment Procedure for Self-tapping Screws for Use in Timber Constructions [9].

This development mirrors the need for a unified product standard for the definition of the relevant properties of self-tapping screws. A differentiation of self-tapping screws for the use in connections or as reinforcement could facilitate the standardization of equations for the calculation of material property values [17]-[18] and the application of design procedures.

In order to account for the specific properties of self-tapping screws in reinforcing applications the following parameters should be incorporated into a product standard:

- Extension of the permissible diameters and inclusion of threaded rods without screw head and screw tip: the high strength and stiffness that are required to reach an adequate reinforcing effect make it necessary to also use screwed-in threaded rods of larger diameter.
- Differentiating geometrical requirements and mechanical properties with respect to the use of screws as reinforcement and in connections. It could be beneficial to group screws with similar properties or with respect to the intended application. This could be realized by introducing classes of properties and/or application.

2.3. Design standards

Self-tapping screws can be used for various reinforcement purposes. These can be general situations in which also other types of reinforcement are possible [19] or they can be specific and only be practicable by means of screws [20]. In [21], the most common applications for the use of self-tapping screws or screwed-in threaded rods used as reinforcement are described including design equations and background information.

For the general situations, equations to determine the resulting forces to be transferred by the reinforcement are sufficient. The selection of the optimal reinforcing technique/reinforcing element is the task of the engineer. However, certain properties or performance characteristics that are required could be addressed to ease the choice of reinforcing element amongst the available types of internal or external reinforcement. Several of these design situations are already part of the German National Annex of Eurocode 5 [22]. It is foreseen to include them in the next revision of Eurocode 5 [23].

So far the design of self-tapping screws is based on the assumptions made for other dowel type fasteners. It has to be evaluated if specific design equations are necessary to fully utilize the properties of self-tapping screws as reinforcement. Amongst other, it is necessary to specify more clearly the axial and lateral strength and stiffness properties of self-tapping screws in order to best use the design equations in the relevant situations. A separation of the resistances in the axial and lateral loading situations is necessary.

To summarize, the following subjects should be addressed in more detail in a design standard:

- Differentiation between reinforcement and connections, e.g. the difference between localized load introduction in connections and continuous load introduction in some reinforcement applications.

- Spacing and end distance requirements for reinforcement.
- Behaviour of reinforcement with small compared to large diameter or length.
- Additional failure mechanisms potentially induced by the reinforcement, e.g. the restriction of free shrinkage or swelling [24].

3. REINFORCEMENT WITH GLUED-IN RODS

Glued-in rods (GiR) are an effective way to connect timber elements from both load bearing capacity/stiffness and aesthetic points of view. They are also widely accepted as a method for reinforcement of new and existing timber structures. The most common applications of glued-in rods to reinforce timber elements are [25]:

- all applications mentioned in Section 2.
- Flexural reinforcement of beams.
- Connections in beam end repairs.

The subject of glued-in rods in timber elements has seen extensive research and development over the last decades [25], [26]. Despite the enormous experience and knowledge gathered, there is still no universal approach, enabling the standardized design of GiR as connections or reinforcement. Potential reasons are contradicting results, the multitude of influencing parameters and disagreement between experts amongst others [27]. A potentially successful approach, that is currently also discussed in the relevant standardization committees CEN/TC 250/SC5 and CEN/TC 124/WG4, will be sketched in the following.

3.1. Test standards

Unified European test standards for GiRs do not exist. At present, there are several test methods and procedures applied in research and development [25], [26]. Most research and developments have been focused on the axial pull-out strength of one single GiR. The associated test setups are differentiated in pull – pull, pull – compression, pull – beam, pull – pile foundation and pull - bending. These test procedures have been applied and described by numerous researchers but it is obvious that the lack of one agreed and defined test procedure represents huge problem for the development of GiR. Tests can be carried out in accordance with a standardized method [3]. These tests in pull – compression are widely accepted because of their simplicity, low cost and comparability with other dowel-type fasteners. However, this setup is not representative of the loading arrangement in many practical applications [26].

Rods glued into structural timber elements form a very complex system comprising three completely different materials (steel/FRP rod, adhesive, timber/engineered wood product). The load-bearing capacity and overall behaviour is influenced by a multitude of parameters and mechanical properties, see Section 3.3.

For each of the materials/products involved in the system of GiR (rod, adhesive, wood), European test standards exist, e.g. [28] for rods, [29] for adhesives for load-bearing timber structures, [30], [31] for timber and timber products. These are suited to determine properties and capacities of the single materials involved. However, these methods are not suitable to determine properties and capacities of the system of rods glued into a structural timber element. One example is the bonding mechanism in which the load transfer may be a combination of adhesion and mechanical interlock.

A potentially successful approach is to seek to develop test standards for a system comprising the rod and compatible adhesive, which is certified for use with specific timber types. This approach has already been successfully applied for the development of Technical Approvals (TA) for particular systems of GiR, e.g. [32]-[35]. These TAs are based on general requirements to assess glued-in rods with respect to their application in timber structures, see e.g. [36]. Test standards developed on the basis of above mentioned documents should take into account the on-site use of adhesives, commonly featuring thicker gluelines, see e.g. [37], and methods for ambient and accelerated aging testing, e.g. [29], [38].

3.2. Product standards

European product standards for systems of GiR used as connection or reinforcement in timber elements currently do not exist. The practical application of GiR is currently only enabled through Technical Approvals for specific products and systems developed by industry. Examples include [32]-[35]. The development of Technical Approvals is commonly based on a so-called Common Understanding of Assessment Procedure (CUAP). These CUAPs, here [36], can be a good source when developing test and product standards. Product standards shall define:

- application (limits), e.g. permissible Service Classes (SC), loading conditions
- applicable adhesives (that are compatible with both the wood and the rod material)
- strength and stiffness parameters, e.g. pull-out strength and axial stiffness parameters
- geometric boundary conditions, e.g.
    - min/max anchorage length
    - min/max rod and hole diameter
    - angle between rod and grain respectively load on rod and grain
    - min/max number of rods
- production and execution rules
- quality control and inspection (third-party control).

It is clear that a product standard for GiR cannot be developed to account for the large number of possible combinations of rods, adhesives and timber species / products but only for certain systems comprising the rod and compatible adhesive, which is certified for use with specific timber species and products within certain limits, see above.

Precise workmanship and quality control is indispensable for this comparably complex system of steel/FRP rod, adhesive and wood product. This includes proper checking of moisture content and strength class of wood, the application of a suitable adhesive, proper drilling and subsequent cleaning of the hole and proper preparation and positioning of the rod in the wood. The use of qualified personnel is the prerequisite for good workmanship. This could be enforced by requiring a qualification certification (“gluing certification”) by manufacturers / craftsmen carrying out this type of application. In Germany this requirement has been successfully enforced for decades, see e.g. [39]. The certification is issued by Materials Testing Institutes in the name of the Building Authorities to individual representatives of companies after successful completion of a course.

A protocol for quality control on site was developed as part of the EU CRAFT Project LICONS [40] and later adopted by COST Action E34 [41]. Bonding on site is usually carried out using multi-component adhesives. Proper mixing and curing of the adhesive is critical to achieving the required joint strength. Work on developing draft standards for on-site acceptance testing of mixing and application of adhesives have been carried out by CEN TC 193/SC1/WG11[42]-[44], but needs to be completed and brought forward for implementation. The following tests methods are included: on-site sampling and measurement of the cure schedule for adhesives, on-site sampling and subsequent laboratory measurement of the shear strength of adhesive joints, and on-site sampling and proof loading of the strength of adhesive joints. Based on these tests, the actual properties obtained on site can be compared to the values used in the design. Some potential test methods are described in [45]. The requirement for undertaking any or all of the above tests will be established by the designer, taking into account specific conditions on site.

Upon request from the standardization committee responsible for Eurocode 5, CEN/TC 250/SC 5 [46], the standardization committee responsible to develop test and product standards for timber structures, CEN/TC 124, will discuss at its next plenary meeting the initiation of a Work Item (WI) for test and product standards on the system of glued-in rods.

3.3. Design standards

Despite many national and international projects and advances and many practical applications of glued-in rods in timber structures, there is still no universally accepted standard for their design as connection or reinforcement. A design equation which was part of prEN 1995-2 (2003) [46] was neglected in the final versions of EN 1995. Potential reasons are:

- The rather complex system of GiR comprising three different materials featuring potentially significant variations
  - steel / FRP rods (e.g. surface, stiffness)
  - PUR, EPX, PRF adhesives (e.g. stiffness, brittleness)
  - softwood, hardwood, engineered wood products (EWP) (e.g. density, Modulus of Elasticity (MOE), Timber Moisture Content (MC), permissible Service Class (SC))
- The rather complex mechanics of glued-in rods, especially when no geometric boundary conditions are set, e.g.
  - diameter of rod and hole, anchorage length, slenderness ratio
  - setting parallel or perpendicular to the grain, loading direction
  - distances / spacing and arrangement (one / multiple rods)
- Uncertainty about the long-term behaviour of GiR in timber elements.

Provided that test and product standards are developed for certain systems of GiR in timber elements, the provisions to specify in a design standard could be reduced to:

- Design equations to determine the strength and stiffness of one GiR, based on the application limits and boundary conditions as well as the strength and stiffness parameters defined in the product standard. The design equations should ensure ductile failure, i.e. be based on the failure of the steel rod.
- Distance and spacing requirements preventing splitting and ensuring ductile failure, i.e. they should be based on an equivalent timber area derived from the steel strength of the rod applied.

GiR have been highlighted as an important item in the course of the CEN/TC 250/SC 5 work programme for the next five years [48]. In case, the standardization committee responsible to develop test and product standards for timber structures, CEN/TC 124, agrees to initiate work on test and product standards on the system of glued-in rods, the standardization committee responsible for Eurocode 5, CEN/TC 250/SC 5, will correspondingly start discussing and developing corresponding design rules, both for GiR as connections as well as for GiR as reinforcement [46].

4. REINFORCEMENT OF CARPENTRY JOINTS

4.1. Typologies of carpentry joints

Common traditional carpentry joints found in old timber frames can be categorized in four main types, according to their arrangement and geometry (Fig. 2):

- *Mortise and tenon joints*: The tenon is inserted into the mortise cut into the corresponding member. These joints usually form an "L" or "T" type configuration.
- *Notched joints*: A notch is a "V" shaped groove generally perpendicular to the length of the beam.
- *Lap joints*: Lap joints are joints in which an end or section of one element is overlapped by an end or section of the other
- *Scarf joints (and splice joints)*: This is a method of joining two members end to end.

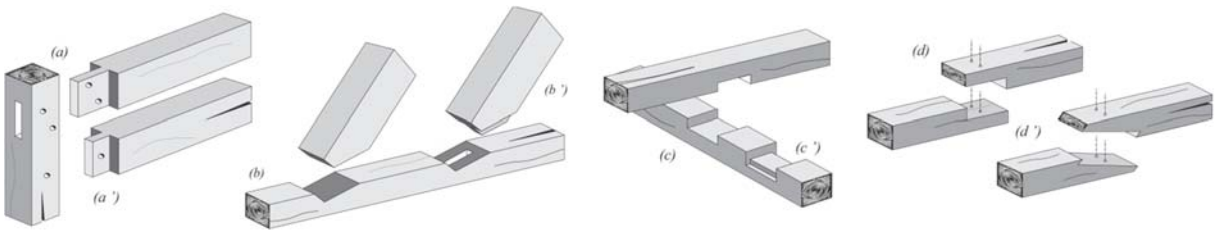

Fig. 2 Example of carpentry joints: (a) Through pinned mortise and tenon (a') blind pinned mortise and tenon, (b) Notched joint between main rafters and tie-beam. (b') A skewed tenon may be used to help in keeping all timber pieces co-planar. (c) Half-lap joint. (c') Cogged half-lap joint. (d) Halved-scarf joint (or half-lap splice joint). (d') Scarf joint with under-squinted ends.

4.2. Scientific knowledge and design standards

At the moment, Eurocode 5 does not give any guidelines for the design of carpentry joints and neither for their reinforcement. A survey led by Siem revealed [49], that carpentry joints are covered in the National Annexes (NAs) to Eurocode 5 of the Netherlands, Italy, Switzerland, Germany and Norway. It should be noted that design and reinforcement of these joints are mainly based on experience. There is still a noticeable lack of scientific results on the topic, pointing out the lack of research in this field:

- The check of carpentry joints essentially involves a check of the contact pressure between the assembled elements. In almost all joints, loads are transferred at an angle to the grain, a complex stress distribution may occur. The strength of timber loaded under an angle to the grain was first described by Hankinson in 1921 [49]. Scientific literature and code-type documents for the design of timber structures also suggest different equations. Some of them include the shear strength, some differentiate between the strength in tension and in compression at an angle to the grain.
- A widespread joint in timber frames is the notched joint. This typology of joint is covered by many national standards in Europe. However, differences remain about the general static scheme of the joints (how the load is balanced through contact pressures on surfaces) and how the geometry is defined.
- For all other typologies of carpentry joints, very little information is available.
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Table 1 sums up the standardization process and today's scientific background about carpentry joints in Europe.

Table 1 Standardization process and scientific background about carpentry joints in Europe

	Scientific background		**Standardization (Eurocode 5)**	
Strength at angles to the grain	*Large*		*(Yes)* *NAs only*	
	Design	**Reinforcement**	**Design**	**Reinforcement**
Mortise and tenon joints	*Low*	*Missing*	*(Yes)* *NAs only*	*No*
Notched joints	*Good*	*Low*	*(Yes)* *NAs only*	*No*
Lap joints	*Low*	*Missing*	*No*	*No*
Scarf joints	*Low*	*Missing*	*No*	*No*

4.3. How can existing standards be used in the design of reinforcement

- Pinned tenon joints feature a very low tensile capacity as only the pin acts. If the element has to be replaced, a traditional reinforcement technique consists in fashioning the joint with a dovetail tenon to increase the capacity in tension. If the element remains in service, a binding strip may be used as reinforcement in tension. The strip is screwed onto the edge of the supporting beam to avoid any crack. For the design of the fastening of the strip, Eurocode 5 expressions for double shear in timber-to-steel connections can be utilized. One may verify the tensile stress in steel and the compression perpendicular to the grain under the strip as follows:

$$\frac{N}{b.l_s} \leq f_{c,90,d} \quad and \quad \frac{N}{2.b_s.t_s} \leq f_u \quad and \quad F_{V,Rd} \geq N$$

where f_u is the tensile strength of steel and $F_{V,Rd}$ is the load-carrying capacity of the fastener in shear. To avoid any tensile forces in the element, a steel wire may be used as presented in Fig. 3 (centre). If broken pins are observed, replacing the wooden pins by steel ones is not suitable because the change in stiffness will cause problems in the tenon.

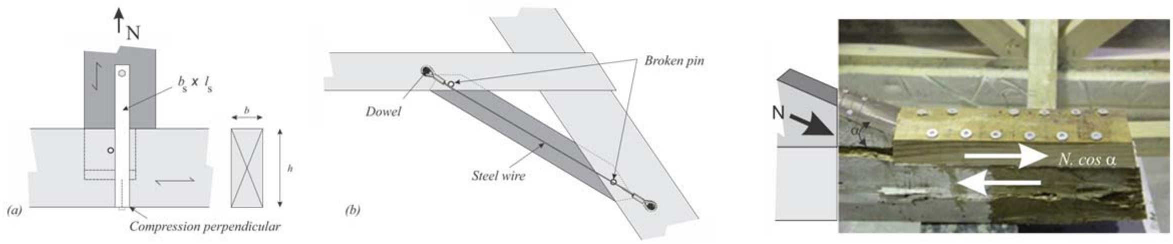

Fig. 3 Reinforcement of a tenon joint (left and centre) and notched joint (right) [51]

- The strengthening of existing notched joints mainly aims to avoid shear failure in the front portion of the notch (when used in heel joints for example). Most of the time, a beam end repair is required because of decay and a wooden prosthesis must be used to replace the degraded material. The prosthesis is mechanically jointed to sound wood (or resin). One may use the following verification:

$$N.cos\,\alpha \;\leq\; n_{ef}.F_{V,Rd}$$

  where n_{ef} is the effective number of fasteners and $F_{V,Rd}$ is their load-carrying capacity in shear. Using inclined fasteners with a tensile capacity, as e.g. screws, increases the load-carrying capacity of the prosthesis.

Half lap joints commonly failed because of their low shear strength. They can be reinforced with fully threaded self-tapping screws (screws are better than bolts in case of shrinkage). Inclined screws may achieve a better load-carrying capacity of the reinforced joint than screws screwed perpendicular to the grain direction due to their higher stiffness and load-carrying capacity in tension compared to shear. Design equations developed for notched beams can be used.

5. CONCLUSIONS

The requirements and procedures for the development of standards for the reinforcement of timber structures using self-tapping screws and glued-in rods within the framework of the 3-step pyramid approach to standardization have been presented. Existing test, product and design standards have been discussed and additional requirements either through updating of existing standards or the development of new standards have been identified. Many of these are actively under consideration by the relevant CEN standardization committees.

Design rules for the reinforcement of traditional carpentry joints are available for a limited number of joint typologies and failure scenarios. The use of EC5 design rules for reinforcement of notched joints is outlined. For other types of joint, further research is required before design standards for reinforcement of carpentry connections can be developed.

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