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REINFORCEMENT OF TIMBER STRUCTURES – STANDARDIZATION TOWARDS A NEW SECTION FOR EC 5

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In memory of Alfons Brunauer (1963 - 2018)

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Abstract *The reinforcement of timber structures has seen considerable research and development in recent years. New materials and methods for reinforcement have been developed and are now used in practice. Design standards in their current editions, however, lack specific guidance to design reinforcement for timber members and joints. To close this gap in the new generation of Eurocode 5, CEN/TC 250/SC 5, the standardization committee responsible for drafting the European Timber Design standard, has decided to establish a Working Group 7 "Reinforcement" on this item. This chapter presents the approach to this task, the work items, the work plan, the structure as well as design approaches and related background information of the proposed Eurocode 5 section.*

1 INTRODUCTION

The reinforcement of timber structures has seen considerable research and development in recent years, as compiled in a RILEM State of the Art report (due 2020) and a COST Action State of the Art report [1]. Recent developments such as self-tapping screws and screwed-in threaded rods offer potential in their use as reinforcement. For their use in construction works, it has to be verified that essential requirements like mechanical resistance, stability and safety are met. The required performance is commonly verified by complying with corresponding harmonized technical rules for the structural design as well as for 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 (depending on national building regulations) has to be sought. Many reinforcement methods still lack harmonized technical rules, and most current design standards do not comprise approaches to design reinforcement for timber members. This is also the case for the current (2004) edition of the European timber design standard, Eurocode 5 [2]. The use of reinforcements is standardized only in a few European countries by means of non-contradictory information (NCI), given in the National Annexes to Eurocode 5, most notable the German [3] and Austrian [4].

Closing the gap between recent developments and practical needs on the one side and missing standardization on the other, reinforcement for stresses perpendicular to the grain was classified high priority when defining the list of work items for the upcoming revision of Eurocode 5 [5]. In 2011, the European standardization committee responsible for Eurocode 5, CEN/TC 250/SC 5, decided to form a Working Group (WG) 7 “Reinforcement”. In addition, reinforcement of timber members was prioritized for Phase 1 (of 4 phases) of the standardization work to be mandated by the European Commission. The contracts for this work were signed in 2014, enabling the formation of Project Teams (PTs) that are mandated to draft specific Eurocode sections.

2 APPROACH TO STANDARDIZATION WORK

Standardization is the culmination of successful research and development that has seen positive application and acceptance in practice, see Fig. 1. According to the European position on future standardization [6], 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”.

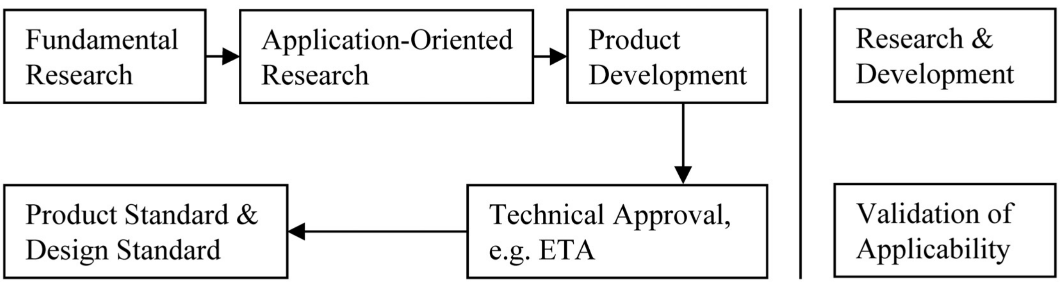

Figure 1: Development of products or methods and their legalization

3 ORGANIZATION OF STANDARDIZATION WORK

Different committees and groups of experts are contributing to European standardization in the field of the design of structures, see Fig. 2 for the example of timber structures. In the following, a short description of the main structure and organization within these committees and groups is given. For an in-depth description, the interested reader is referred to [7].

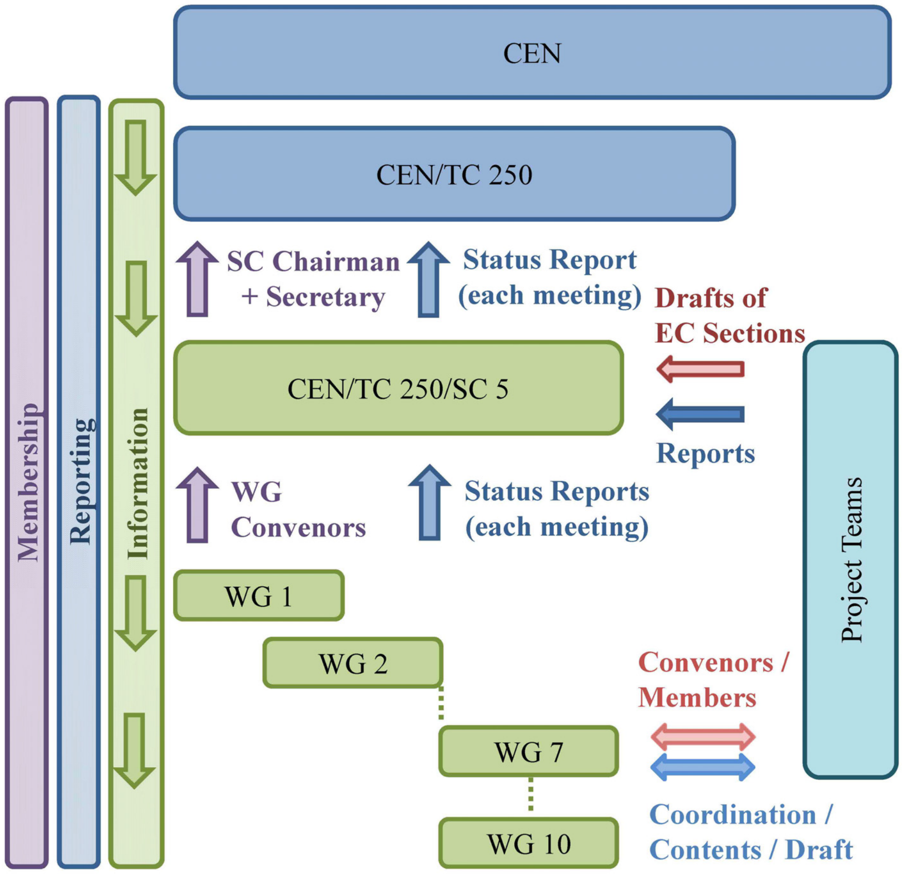

Figure 2: Organization, responsibilities and reporting within CEN

CEN/TC 250 is the head committee, responsible for the development and definition of the design rules of common structural building and civil engineering structures. This committee is substructured into 11 sub committees (SCs), each SC being responsible for the development and revision of one Eurocode. CEN/TC 250/SC 5 is responsible for Eurocode 5 (EN 1995). The members of these SCs are delegates sent by National Standardization Bodies (NSBs) that are members of CEN (Comité Européen de Normalisation / European Committee for Standardization).

For the technical work, each SC is supported by WGs that deal with specific items. Within CEN/TC 250/SC 5, WG 7 is responsible for reinforcement of timber structures, see [7] for a full overview. The WGs are responsible to develop the work programme, i.e. the items to be covered within their responsibility. In this connection, the WGs are meant to serve as platform for technical discussions resulting in technical proposals (methods, design approaches, design equations and details) for the section(s) under their responsibility. To achieve this objective, the National Standardization Bodies (NSB) send experts to the WGs. CEN/TC 250/SC 5/WG 7 “Reinforcement” currently has 20 members (experts and observers), about six experts contribute actively to the work.

The drafting of the standard text based on the technical proposals developed and agreed within the WGs is the responsibility of Project Teams (PTs), consisting of five members and one leader. The PT work is supported by the European Commission, hence they are established in a tender process based on individual applications. Within a given time frame (in this case 42 Months), the PTs have to deliver a draft of a new or revised Eurocode or a specific section of the same. In other words, the PTs have to bring the technical proposals into standard text including harmonized notations, terminology and references, adhering to the principles of “Ease-of-Use” [6]. In addition, the PTs have to develop “background documents” describing the technical reasoning and scientific background of all new or changed technical contents under their scope. From the members in PT SC5.T1 “Cross-laminated timber and reinforcement”, three members (A. Brunauer, T. Wiegand and the author) were actively involved in the drafting of the section on reinforcement while four members (G. Schickhofer, R. Tomasi, T. Wiegand and the author) actively contributed to the drafting of the section on CLT.

The liaison between the SCs, WGs and PTs can be summarized as follows: the SC is the responsible control institution while the WGs and PTs are the executive institutions developing the technical contents (WGs) and the drafts of the standard (PTs).

4 WORK ITEMS AND WORK PLAN

4.1 General

Adhering to the principles described in section 2, CEN/TC 250/SC 5/WG 7 “Reinforcement” decided to prioritize the following applications and reinforcement methods for preparation for the revised Eurocode 5. These items were also classified high priority during a pan-European survey carried out amongst a multitude of stakeholders in 2010 [5].

4.2 Applications

- Reinforcement of double tapered, curved and pitched cambered beams
- Reinforcement of notched beams
- Reinforcement of holes in beams
- Reinforcement of connections with a force component perp. to the grain
- Reinforcement of dowel-type connections ($n = n_{ef}$)
- Reinforcement of members with concentrated compression stresses perpendicular to the grain

Compared to the state-of-the art in research, see this RILEM State of the Art report or [1], this list is less comprehensive. For example, reinforcement to increase bending or shear capacity or reinforcement of carpentry connections is not included. Reason is the requirement discussed in Section 2 that only rules for “common design cases” based on “commonly accepted results of research” that are “validated through sufficient practical experience” shall be included in standards.

4.3 Materials

- Self-tapping screws or screwed-in threaded rods
- Glued-in rods
- Glued-on timber, plywood, LVL

Compared to the state-of-the art in research, see this RILEM State of the Art report or [1], this list again is less comprehensive. For example, FRP or Nanotechnology reinforcements are not included. The choice of materials is explained by the precondition that (1) test procedures as well as (2) a product standard or Technical Approvals for the product / material are available. Without these documents, rules in a design standard cannot be used since the basic input parameters are missing. This situation can best be described by a 3-step pyramid, see Fig. 3.

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, 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. For further information on this topic, the interested reader is referred to [8] where two widely used reinforcement materials (STS and GiR) are discussed with reference to existing standards and those required to complete the pyramid.

For applications or materials for which the abovementioned requirements cannot be met but for which sufficient accepted results are available, CEN offers the possibility of Technical Specifications (TS). A TS is a normative document, the development of which can be envisaged in anticipation of future harmonization and standardization, or for providing specifications for evolving technologies. A TS is established by a CEN TC, SC or WG and approved through the same system of weighted votes as European standards (≥ 55 % of the votes cast and population of the countries of the Members having voted positively ≥ 65 %) by the CEN national members. The TS shall be announced at national level and it may be adopted as a national standard. A TS may however not conflict with a European Standard, i.e. if a conflicting EN is published, the TS is withdrawn [9].

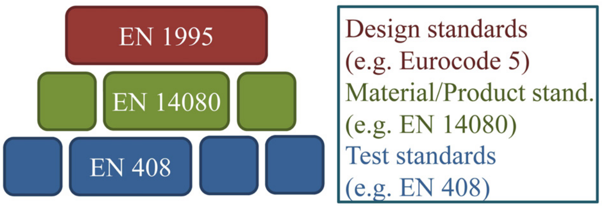

Figure 3: Sketch of the 3-step-pyramid applied in standardization for the construction sector [8]

5 WORK PLAN

While most WGs are permanent technical bodies within CEN, the time for the PTs to achieve their work plan is limited. Six months after the official start, the PTs have to deliver the first drafts. The respective CEN/TC 250/SCs have two months for review and comments. The SCs can draw upon the NSBs for additional review and comments to the drafts. The PTs are requested to answer all comments received during the work on the second draft, implementing all comments and proposals that are deemed useful and technically sound. The second drafts have to be delivered one year after the first, repeating the above-mentioned procedure. The third drafts have to be delivered six months after the second. These will be directly forwarded to the NSBs for a three-month enquiry. Following that, the PTs have two months to prepare the final documents, taking into account the comments received from the NSBs. The delivery of the final documents and the background documents, marking the end of the work of the PTs, is 42 months after the official beginning of the PT. Project Team 1 has delivered the Final Draft “Reinforcement” in May 2018, the contract of the PT has ended. Further refinements on the draft “Reinforcement” before consolidation of EN 1995-1-1 (expected March 2021) are the responsibility of WG 7.

6 PROPOSED STANDARD STRUCTURE

EN 1995-1-1 [2] in its current version does not contain provisions on reinforcement. Hence, a decision on the structure of this new section had to be taken. The obvious approach is to write a separate but continuous section on the design of reinforcement for timber members. This solution, however might not fully suit the designers needs in terms of applicability and navigation, hence might not fully obey to the principles on "Ease-of-Use". The proposal, which was accepted by CEN/TC 250/SC 5, was to integrate the provisions on reinforcement into the existing main part, i.e. following the sequence of a typical design task: general considerations – design of members in the unreinforced state – design of reinforcement for these members, see Fig. 4.

Section	**Title**
8	Ultimate limit states
8.1	Design of cross-sections subjected to stress in one principal direction
…	
8.1.5	Compression perpendicular to the grain
8.1.5.1	General
8.1.5.2	***Reinforcement of members with compression stresses perpendicular to the grain***
…	
8.4	**Design of members with special requirements based on geometrical form**
8.4.1	***General***
8.4.2	***Effects of moisture content changes in reinforced members***
8.4.3	Design of cross-sections in members with varying cross-section or curved shape
8.4.3.1	General
8.4.3.2	Single tapered beams
8.4.3.3	Double tapered, curved and pitched cambered beams
8.4.3.4	***Reinforcement of double tapered, curved and pitched cambered beams***
8.4.4	Notched members
8.4.4.1	General
8.4.4.2	Beams with a notch at the support
8.4.4.3	***Reinforcement of notches***
8.4.5	Holes in beams
8.4.5.1	General
8.4.5.2	Holes in beams with rectangular cross-section
8.4.5.3	***Reinforcement of holes in beams***
…	
10	Joints and Connections
10.1	General
10.1.4	Connection forces at an angle to the grain
10.1.4.1	Design of connections with a tensile force component perpendicular to the grain
10.1.4.2	***Reinforcement of connections with a tensile force component perpendicular***
...	***to the grain***
10.5	Bolted connections
10.5.1	Laterally loaded bolts
10.5.1.1	***General and bolted timber-to-timber connections***

Figure 4: Proposed structure for sections on reinforcement
(new sections in **bold**, sections on reinforcement in ***bold italic***)

7 CONTENTS OF THE DRAFT "REINFORCEMENT"

7.1 General

In the following, the core contents of the sections on reinforcement are given in form of italic writing, followed by relevant background information on these clauses. For a comprehensive overview of the current state of the art in the design of reinforcement including design equations and extensive background information, the interested reader is referred to [10] and [11]. The Figures shown do not represent the Figures for the standard text as they also include graphical representations produced to exemplify background information. Since the strength verifications required for the reinforcement are rather independent of the member or detail to be reinforced, these are presented in consolidated form in the first Section 7.1 "General". An exception is the reinforcement of members with compression stresses perpendicular to the grain, hence (and in difference to the proposed standard structure) the proposed standard text and necessary amendments to existing sections will be presented in consolidated form at the end of this Section.

Standard text (Section 8.4.1):

- *In the following clauses, the tensile capacity perpendicular to the grain of the timber is not taken into account in the determination of the load on the reinforcement.*
- *Pitched cambered beams should be reinforced for tensile stresses perpendicular to the grain. Where the design tensile stresses perpendicular to the grain exceed 60 % of the design tensile strength perpendicular to the grain of curved and double tapered beams, these should be reinforced.*
  NOTE: Reinforcement of notches and holes in beams leads to more robust members, especially in the case of large member sizes and/or large expected changes in timber moisture content.
- *Notched members, holes in beams, double tapered, curved and pitched cambered beams, assigned to Service Class 3 should be reinforced.*

Background for the clauses given above:

Within the approaches given, the tensile capacity perpendicular to the grain of the timber is neglected, i.e. a cracked cross-section is assumed in direction of tensile stresses perpendicular to the grain. This is in difference to the method presented in [12] in which only the force components, exceeding the tensile strength perpendicular to the grain of the timber, are applied for the design of the reinforcement. Before cracking of the cross-section perpendicular to the grain, a proportional share of tensile stresses perpendicular to the grain is transferred by the timber. The share depends on the stiffness of the reinforcement embedded in or around the timber compared to the stiffness of the timber member but also on the distance of the cross-section under consideration to the next reinforcing element.

Even if the verification of systematic, load-dependent tensile stresses perpendicular to the grain can be met, it is state of the art to reinforce double tapered, curved and pitched cambered beams against tensile stresses perpendicular to the grain. Reason is the superposition of the load-dependent stresses with moisture induced stresses perpendicular to the grain due to e.g. changing climatic conditions or a drying of the beam after the opening of the building, see e.g. [13]. In the lack of a method to reliably predict the magnitude of tensile stresses perpendicular to the grain, it was custom to apply reinforcement if the maximum load-dependent tensile stresses perpendicular to the grain exceeded 75 % of the permissible tensile strength perpendicular to the grain. With the transition from the system of permissible stresses to the semi-probabilistic system, this approach was transferred into the requirement that in unreinforced beams, the maximum load-dependent design tensile stresses perpendicular to the grain should not exceed 60 % of the design tensile strength perpendicular to the grain.

Since end-grain is exposed bare at a notch and in holes, the superposition of moisture induced stresses and load-dependent tensile stresses perpendicular to the grain around notches and holes can be significant [14]. Therefore, many authors recommend that notches and holes in beams should always be reinforced.

Members in SC 3 should always be reinforced. The reason are the strong moisture changes in SC 3, leading to moisture induced stresses in the timber member of magnitudes that leave no or only marginal capacity for systematic, load-dependent tensile stresses perpendicular to the grain. For members in SC 3 such as curved and pitched cambered beams it is recommended to apply external plane reinforcement glued onto the entire surface area under tensile stresses perpendicular to the grain. It should be attempted to enable a classification of the member in SC 2 by e.g. constructive protection measures.

- *The following internal, dowel-type reinforcement may be applied:*
  - *fully threaded screws in accordance with EN 14592 or European Technical Assessment;*
  - *screwed-in threaded rods with wood screw thread in accordance with European Technical Assessment;*
  - *glued-in threaded or ribbed steel rods.*
- *The following plane reinforcement may be applied:*
  - *glued-on plywood or solid wood panels in accordance with EN 13986;*
  - *glued-on structural laminated veneer lumber in accordance with EN 14374;*
  - *glued-on laminations made from either structural solid timber in accordance with EN 14081-1 or plywood in accordance with EN 13986 or structural laminated veneer lumber in accordance with EN 14374.*
  - *pressed-in punched metal plate fasteners.*
- *The reinforcement shall be applicable for the timber product and the Service Class of the reinforced timber element.*

The list of applicable internal or external reinforcements is – amongst other factors - based on the necessity of a continuous interconnection between the timber and the reinforcement as well as sufficient stiffness of this connection (to prevent cracking). Due to the latter argument, perforated metal plates or wood-based panels, both nailed onto the timber member, are not adequate reinforcements, see e.g. [14] and [15].

- *The distance between the peak tensile stresses perpendicular to the grain and the dowel-type reinforcement should be minimized but should not be below the following minimum values.*
  For glued-in threaded rods, the spacing between glued-in threaded rods, a_2, should not be less than $3 \cdot d$. The edge distance in grain direction, $a_{3,c}$, as well as the edge distance perpendicular to the grain, $a_{4,c}$, should not be less than $2{,}5 \cdot d$.
  For fully-threaded screws and screwed-in threaded rods, the spacing rules should be taken from (Table 8.6 in [2]) *or from the European Technical Assessment.*
- *For inclined dowel-type reinforcement, the spacing may be determined based on the centre of gravity of the dowel-type reinforcement in the section of the timber member, see Fig. 6 and Fig. 7.*

- *The reduction in the cross-sectional area due to internal reinforcement should be considered in the design of the timber member.*
- *In block glued members* (see e.g. [16])*, each component within the block should be reinforced, either by internal dowel-type reinforcement or by plane reinforcement glued to both side faces of each component. The reduction in the cross-sectional area due to glued in plane reinforcement should be considered in the design of the block glued member.*

The reinforcing effect of dowel-type or plane reinforcement is strongly dependent on the distance between the reinforcement and the location of peak stresses (in e.g. tension perpendicular to the grain or shear). Edge and end distances of glued-in steel rods are partly reduced compared to the minimum edge and end distances given in Chapter 8 of EN 1995-1-1:2004 [2], since such reinforcements are loaded by axial forces and their continuous interconnection with the wood prevents splitting [15]. Inclined dowel-type reinforcement allows to cater to the requirement to reduce as much as possible the distance between the reinforcement and the location of peak stresses, hence the possibility of applying inclined dowel-type reinforcement with distance requirements based on the position of the center of gravity of the dowel-type reinforcement in the timber member under consideration, given in [2] was introduced. The reinforcing effect of the applicable reinforcement elements over the width of a timber member is limited, hence each component of a block-glued timber member should be reinforced separately.

- *The design tensile force in a reinforcement should satisfy Formula (1):*

$$\frac{F_{t,90,Ed}}{F_{t,90,Rd}} \leq 1{,}0 \tag{1}$$

where

$F_{t,90,Ed}$ *is the design tensile force in the reinforcement, according to the formulae giv en in the following sections 7.3 – 7.7;*

$F_{t,90,Rd}$ *is the design tensile resistance of dowel-type or plane reinforcement according to formulae (2) – (4).*

- *The design resistance of dowel-type reinforcement or plane reinforcement should be taken as the minimum value found from formulae (2)-(4):*
  - *For fully threaded screws or fully threaded rods with wood screw thread* (see also 8.7 in [2]):

$$F_{t,90,Rd} = n_r \cdot \min\begin{cases} f_{ax,d} \cdot d \cdot l_{ad} \\ f_{tens,d} \end{cases} \tag{2}$$

  - *For glued-in steel rods:*

$$F_{t,90,Rd} = n_r \cdot \min\begin{cases} f_{b1,d} \cdot \pi \cdot d \cdot \ell_{ad} \\ f_{yb,d} \cdot A \\ 0{,}9 \cdot f_{ub,d} \cdot A_S \end{cases} \tag{3}$$

  - *For glued-on plane reinforcement:*

$$F_{t,90,Rd} = n_r \cdot \min\begin{cases} f_{b2,d} \cdot \ell_{ad} \cdot b_r \\ \dfrac{f_{t,d}}{k_k} \cdot b_r \cdot t_r \end{cases} \tag{4}$$

with:

$$l_{ad} = \min\begin{cases} l_{ad,t} \\ l_{ad,c} \end{cases} \tag{5}$$

(determined in accordance with the geometry of the detail to be reinforced, see e.g. Fig. 5 – Fig. 9)

where

n_r *is the number of reinforcing elements (typically 2, resp. 4 with the exception of curved and pitched cambered beams, where n = 1);*

$f_{ax,d}$ *is the design withdrawal strength of the fully threaded screw/rod;*

$f_{tens,d}$ *is the design tensile capacity of the fully threaded screw/rod;*

$f_{ub,d}$ *is the design ultimate strength of the steel rod;*

$f_{yb,d}$ *is the design yield strength of the steel rod;*

$f_{b1,d}$; $f_{b2,d}$ *is the design strength of the glue line;*

$f_{t,d}$ *is the design tensile strength of the plane reinforcement;*

d *is the outer thread diameter of the fully threaded screw or steel rod (≤ 20 mm);*

A *is the gross cross-section of the steel rod (see [17]);*

A_S *is the tensile stress area of the steel rod (see [17]);*

ℓ_{ad} *is the relevant effective anchorage length, glued-in length, relevant depth of plane reinforcement;*

$\ell_{ad,t/c}$ *is the relevant effective anchorage length above (below) the axis prone to splitting;*

b_r *is the width of the plane reinforcement;*

t_r *is the thickness of the plane reinforcement;*

k_k *is a factor to account for non-uniform distribution of stresses in the plane reinforcement. Without further verification,* $k_k = 2{,}0$ *may be assumed (for reinforcement of connections with a tensile force component perpendicular to the grain,* $k_k = 1{,}5$ *may be assumed; for reinforcement of curved or pitched cambered beams,* $k_k = 1{,}0$ *may be assumed);*

- *Reinforcement with punched metal plate fasteners should be designed in analogy to Formula (4) and should be placed according to the rules for plane reinforcement given in the following sections.*

The assembly of all equations to determine the resistance of the reinforcement in one place was undertaken with the aim to:

- realize a homogeneous set of equations, independent of the member / tail to be reinforced,
- enable a better overview of equations to determine resistances including all corresponding factors (ease-of-use),
- reduce the length of the document by 25 % compared to the preceding NAs.

The verifications follow the verification procedure introduced in EN 1993-1-8:2005 [17] (steel rods), Chapter 8 of EN 1995-1-:2004 [2] (fully threaded screws and rods with wood screw thread) and Chapter 6 of EC 5 [2] (plane reinforcement). The applicable anchorage length is the shorter of the two lengths above respectively below the location of crack onset (which is assumed identical with the location of peak stresses). The factor k_k is applied to take into account the characteristics of the non-uniform distribution of stresses and the concentration of stresses at the panel edge facing the peak stresses in the timber member [18]. The effective number of fasteners, n_{ef}, does not apply. The reason is that the load transfer mechanism is different compared to connections with axially loaded screws or rods ("passive" vs. “active” application). In the majority of cases, only 1-2 screws or rods are used for reinforcement of notched members and holes in beams. In curved and pitched cambered beams, each reinforcing element transfers the released stresses in a specific area, hence the load-transfer mechanism is different to a group of screws sharing one load in a connection.

7.2 Effects of moisture content changes

Standard text (Section 8.4.2):

- *The effects of moisture content changes in the timber (e.g. shrinkage cracks) shall be taken into account.*

Background for the clause given above:

Changes in wood moisture content lead to changes of virtually all physical and mechanical properties (e.g. strength and stiffness properties) of wood. An additional effect of changes of the wood moisture content is the shrinkage or swelling of the material and the associated internal stresses. If these stresses locally exceed the very low tensile strength perpendicular to the grain of wood, the result will be a stress relief in form of cracks, which can reduce the load-carrying capacity of structural timber elements in e.g. shear or tension perpendicular to the grain. Multiple evaluations of damages in timber structures, e.g. [19], [19], [21] show, that a prevalent type of damage is pronounced cracking in timber elements. Almost half of the damages in large-span glued-laminated timber structures can be attributed to low or high moisture content or severe changes of the same.

- *The effects of moisture content changes in the timber should be minimized. Potential measures to reduce the effects of moisture content changes include:*
    - *Before being used in construction, timber should be dried as near as practicable to the moisture content appropriate to its climatic condition in the building in use, unless the structure is able to dry without significant effects on the load-carrying capacity of its members;*
    - *During transport, storage and assembly, timber should be protected to minimize detrimental changes of moisture content in the timber;*
    - *In dry environments, controlled drying of the timber to service conditions should be planned.*
- *In the case of structures or members sensitive to moisture changes, temporary moisture control is recommended, until the expected equilibrium moisture content is reached.*

Effects of moisture content changes include e.g. changes in strength and stiffness properties (covered by k_{mod}). Another effect of moisture content changes are shrinkage cracks. These can be attributed to two different phenomena.

1. Large moisture gradient over the timber cross-section due to strong and fast wetting or drying (the latter prevailing in closed and heated buildings) of the timber member, e.g. throughout the process production – transport – storage – assembly – interior works – opening – operation (heating). Careful planning and moisture control during this process is recommended, especially if a dry environment is to be expected in the finished building. Specifications on moisture control could be given in an execution standard.
2. Prevention of free shrinkage or swelling deformation of the cross section by restraining forces, e.g. from connections covering larger heights or dowel-type reinforcements. In these cases, equilibrium of tensile and compressive moisture induced stresses is impeded, resulting in stresses of higher magnitude and eventually in deep shrinkage cracks.

Due to the fact that there is currently a lack of a method to reliably predict the magnitude of tensile stresses perpendicular to the grain from moisture changes, it was decided to introduce the term *effects of moisture content changes*.

- *The effects of reinforcement (or connections) that restrain moisture induced deformations of the timber member, should be minimized.*
- *Potential measures to reduce restraining effects from reinforcement include:*
  - *larger spacing between reinforcement;*
  - *reduction of height of the reinforced areas in the timber member;*
  - *reducing the angle between dowel-type reinforcement and grain direction of the timber member.*
- *Where reinforcement is necessary in applications with permanently dry or frequently changing climate, external plane reinforcement glued onto the entire surface area under tensile stresses perpendicular to the grain should be preferred as it decelerates the process of moisture changes or drying of the timber member.*

The restraining effect of dowel-type reinforcement was experimentally and analytically investigated in [22] and [23], demonstrating the positive effect of measures such as increased distance, reduced height or inclined positioning of dowel-type reinforcement. Attention should be paid to the additional stresses induced by the inclined reinforcement in the deformed timber beam (positive compression stresses perpendicular to the grain in the case of decreasing inclination, i.e. angle between load and grain, in the deformed shape vs. detrimental tensile stresses perpendicular to the grain in the case of increasing inclination in the deformed shape), see [24].

In the original draft, the proposed clauses on the effects of moisture content changes are separated into general clauses applicable to all timber elements (proposed as a new section *2.3.3 Effects of moisture content changes* within Section *2.3 Basic Variables*) and clauses applicable to reinforced timber elements (proposed for Section *6.4.2 Effects of moisture content changes in reinforced beams*). For reasons of representation, this differentiation was omitted in this contribution.

7.3 Reinforcement of double tapered, curved and pitched cambered beams

Standard text (Section 8.4.3.4):

- *For beams in which reinforcement to carry the full tensile stresses perpendicular to the grain is applied, the design tensile force in the reinforcement, $F_{t,90,Ed}$, should be calculated as follows:*

$$F_{t,90,Ed} = k_{ka} \cdot \sigma_{t,90,d} \cdot b \cdot a_1 \tag{6}$$

where

$\sigma_{t,90,d}$ *is the design tensile stress perp. to the grain (acc. to Eq. 6.54 in [2]);*

b *is the beam width;*

a_1 *is the spacing of the reinforcement in longitudinal direction of the beam at the height of its axis, see Fig. 5;*

k_{ka} *is a factor to account for the distribution of tensile stresses perpendicular to the grain along the beam axis*

k_{ka} *= 1,0 for curved beams and for the inner quarters of the length of the volume exposed to tensile stresses perp. to the grain, measured from the apex, in double tapered and pitched cambered beams;*

k_{ka} = 0,67 for the outer quarters of the area exposed to tensile stresses perp. to the grain, measured from the apex, in double tapered and pitched cambered beams;

Background for the clause given above:

The approach given is based on an integration of the sum of tensile stresses perpendicular to the grain in the plane of zero longitudinal stresses. Since in most design standards, e.g. [2], only formulae to determine the maximum tensile stresses perpendicular to the grain in the apex are given, the distribution of tensile stresses perpendicular to the grain along the beam axis has to be accounted for in simplified format. Depending on the form and loading of the beam, the tensile stresses perpendicular to the grain decrease with increasing distance from the apex (an exception being curved beams with mechanically jointed apex, i.e. secondary apexes, see subsequently). For simplification, the full tensile stresses perpendicular to the grain are used to design the reinforcement in curved beams and the inner quarters of the area exposed to tensile stresses perpendicular to the grain in double tapered and pitched cambered beams. In the outer quarters of double tapered and pitched cambered beams, the tensile stresses perpendicular to the grain are assumed to reach 2/3 of the maximum tensile stresses perpendicular to the grain, see Fig. 5.

- *For curved or pitched cambered beams with mechanically jointed apex, the reinforcement should be designed for:*
    - *the tensile stresses perpendicular to the grain at the inflection points (secondary apex at the end of the mechanically jointed apex) and*
    - *the tensile stresses perpendicular to the grain from curvature in the apex.*

The reinforcement at the inflection points should cover a length of at least $2{\cdot}h_{ap}$ in direction of the apex and $1{\cdot}h_{ap}$ in direction of the beam end. The reinforcement from the curvature in the apex should be arranged in the remaining curved parts. Between both areas, the spacing between the reinforcement may be linearly graded. If the tensile stresses perpendicular to the grain from curvature in the apex are higher than the tensile stresses perpendicular to the grain at the inflection points, the associated reinforcement should be arranged over the whole curved length.

Curved beams with mechanically jointed apex are neither regulated in EN 1995-1-1 [2] nor in NCI such as in [3], [4]. Nevertheless, these beams represent the most widely utilized form in practice. The most common type is curved beams with raised dry joint and mechanically jointed apex to realize the form of a pitched cambered beam. The top edge of the beam features a shorter curved length compared to the curved length of the bottom edge, leading to so-called secondary apexes at the transition points between the curved upper edge and the straight upper edge of the beam. The approach to design curved beams with mechanically jointed apex and the reinforcement of the same is to examine and verify two different cross-sections:

1. The apex, formed by the curved part of the beam and to be designed in analogy to curved beams;
2. The secondary apex, located at the transition point between curved upper flange and straight upper flange at the end of the mechanically jointed apex. This cross-section is to be designed in analogy to pitched cambered beams. The distance of the secondary apexes is limited to a minimum of twice the beam height in the apex to prevent the superposition of peak stresses from the secondary apex.

The length of area to be covered by the reinforcement determined for the two cross-sections is dependent on the length of area of decreasing stresses. The design approach is in the style of the information and results presented in [25], [26]. The distance requirements implicitly given by the factor k_{ka} do not apply for curved beams with mechanically jointed apex.

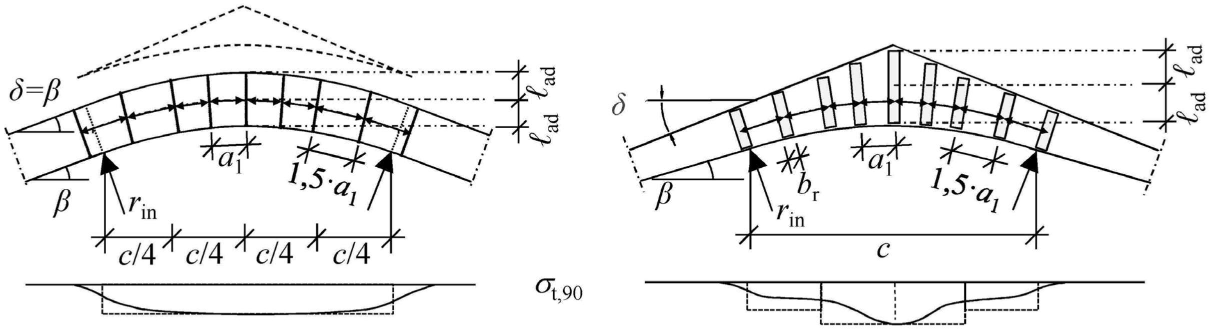

Figure 5: Curved and pitched cambered beams: stress distribution, reinforcement and geometries. Curved beam with indication of mechanically jointed apex.

- *The spacing of the reinforcement parallel to the grain, a_1, may be adapted according to the distribution of tensile stresses perpendicular to the grain along the length of the volume under tensile stresses perpendicular to the grain.*
- *Internal, dowel-type reinforcement should cover the full height of the beam excluding the outer laminations in bending tension. One reinforcing element should be placed in the cross-section below the apex respectively secondary apex (inflection point). The spacing, a_1, at the top side of the beam should not be less than 250 mm but not greater than $0{,}75 \cdot h_{ap}$.*
- *Plane reinforcement, e.g. panels or laminations, should be glued to both sides of the member and should cover the full height of the beam; at maximum it should exclude the outer laminations, see Fig. 5.*

The requirement to place reinforcement as close as possible to peak stresses also applies here. The spacing between the reinforcement is limited to ensure that the reinforcing effect is assured over the whole beam length exposed to tensile stresses perpendicular to the grain, see Fig. 5. The timber cross-section should not be reduced by reinforcement in the vicinity of maximum tensile bending stresses. The length requirements of the reinforcement are meant to exclude failure in tension perpendicular to the grain in the beam below or above the reinforcement.

7.4 Reinforcement of notches

Standard text (Section 8.4.4.3):

- *The following rules apply for reinforced notches in members with rectangular cross-section from kiln-dried solid timber, glulam and laminated veneer lumber. For members with a rectangular notch on the same side as the support with $a/h \leq 0{,}4$, see Fig. 6, the reinforcement may be designed for a design tensile force $F_{t,90,Ed}$:*

$$F_{t,90,Ed} = 1{,}3 \cdot V_d \cdot [3 \cdot (1-\alpha)^2 - 2 \cdot (1-\alpha)^3] \tag{7}$$

where
$\alpha = h_{ef}/h$; see Fig. 6.

Background for the clause given above:

The tensile force perpendicular to the grain, $F_{t,90,Ed}$, can be approximated by integration of the shear stresses below the notch, between the loaded edge and the corner of the notch, see Fig. 6. A more detailed analysis of the magnitude of the tensile stresses perpendicular to the grain around the notch has shown that these stresses are even higher [27]. For relationships $a \leq h_{ef}/3$ and $h_{ef}/h \geq 0{,}5$, the tensile force perpendicular to the grain, $F_{t,90,Ed}$, can be sufficiently estimated by applying an increase factor of 1,3. The reinforcement of notches can be transferred to connections resulting in comparable behavior (e.g. dovetail connections or modern primary beam – secondary beam connectors).

- *The reinforcement should cover the full height of the notched edge $\ell_{ad,c} = (h - h_{ef})$. The minimum length $\ell_{ad,t} = \min\{\ell_{ad,c}; 1{,}5 \cdot a\}$, see Fig. 6.*
- *Where the tensile force, $F_{t,90,Ed}$, according to Formula (7) is carried by internal dowel-type reinforcement, only one row of internal reinforcing elements at a distance $a_{3,c}$ from the edge of the notch should be considered, see Fig. 6. The dowel-type reinforcement may be inclined to reduce the distance between the peak tensile stresses perpendicular to the grain and the dowel-type reinforcement, see Fig. 6.*
- *Where the tensile force, $F_{t,90,Ed}$, according to Formula (7), is carried by internal dowel-type reinforcement, oriented perpendicular to the grain, the load-carrying capacity is limited to twice the load-carrying capacity of the unreinforced notched beam. In addition, the shear stresses (Formula (6.13) in [2]) should be satisfied in the notched part.*
- *Plane reinforcement, e.g. panels or laminations, should be glued to both sides of the member, with the following limits:*

$$0{,}25 \leq \frac{b_r}{h - h_{ef}} \leq 0{,}5 \tag{8}$$

where

b_r is the width of the reinforcement panel or lamination in direction of the beam axis at the side of the notch;

h, h_{ef} see Fig. 6.

The depth of the reinforcement should be sufficient such as to ensure adequate load transfer into the reinforcement and from the reinforcement into the support. The required length for the latter requirement is based on a load-distribution angle of 45°. Failure in tension perpendicular to the grain below the reinforcement should be prevented.

Only one row of dowel-type reinforcement at a distance $a_{3,c}$ should be considered as reinforcement. The distance between the dowel-type reinforcement and the notch, $a_{3,c}$, should be as small as possible. Reason is the limited distribution length of the tensile stresses perpendicular to the grain outside the corner of the notch. This can be achieved by inserting the screws at an inclined angle, as the distance requirements are based on the position of the centre of gravity of the dowel-type reinforcement in the timber member under consideration, $a_{3,CG}$, see Fig. 6. Rounding of the corners of the notch leads to a reduction in peak stresses.

The limitation of load-carrying capacity of notched members reinforced with dowel-type reinforcement arranged perpendicular to the grain is based on [28], where it was experimentally and analytically verified that the load-carrying capacity of reinforced notched members is not infinite but limited by the magnitude of the shear component on fracture of notched members.

The applicable width of reinforcement panels is limited due to the limited distribution length of the tensile stresses perpendicular to the grain outside the corner of the notch. In addition, this limitation is also implicitly directed at assuring panels of adequate thickness to prevent failure due to the stress singularities at the notch. To facilitate screw-press-gluing and to realize robust plane reinforcement, a minimum panel width is recommended. Irrespective of this recommendation, the abovementioned upper limits of panel width should to be applied in the stress verifications.

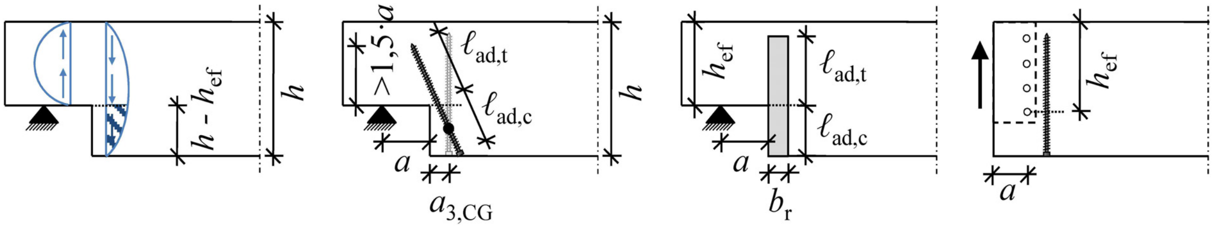

Figure 6: Notched beams: distribution of shear stresses (left), dowel-type reinforcement (middle left), plane reinforcement (middle right) and reinforced connector/group of fasteners (right)

7.5 Reinforcement of holes in beams

Standard text (Section 8.4.5.3):

- *The following rules apply for members with rectangular cross-section from kiln-dried solid timber, glulam and laminated veneer lumber with reinforced holes which comply with the geometrical boundary conditions given in Table 1.*

Table 1: Minimum and maximum dimensions of reinforced holes in beams with rectangular cross-section

$\ell_v \geq h$	$\ell_z \geq h$, *not less than 300 mm*[c]	$\ell_A \geq h/2$	$h_{rl(ru)} \geq 0,25 \cdot h$	$a \leq h$ $a/h_d \leq 2,5$	$h_d \leq 0,3 \cdot h^a$ $h_d \leq 0,4 \cdot h^b$
[a] *for internal dowel-type reinforcement* [b] *for plane reinforcement, e.g. panels or laminations* [c] l_z *is the clear spacing between two holes*					

Background for the clause given above:

The requirement to apply reinforced holes only in members from timber products that have been technically dried is based on the necessity to reduce moisture induced deformations (shrinkage including potential cracking) of reinforced timber members. The limitation of the permissible relative dimensions of the holes in dependency of the type of reinforcement, are described in [29] and [30]. Reason for the restriction in hole height is e.g. the concentrated stresses in grain direction close to the hole edges above and below the hole due to the necessary transfer of bending stresses around the hole. According to experimental and numerical investigations [32], these stresses can be several times higher than the bending stresses at the beam edge.

- *The reinforcement of holes in beams may be designed for a tensile force perpendicular to the grain, $F_{t,90,Ed}$, composed of $F_{t,V,d}$ from the transfer of shear stresses and $F_{t,M,d}$ from the transfer of bending stresses. In the case of rectangular holes, the tensile force, $F_{t,90,Ed}$, should be assumed to act on planes defined by the top and bottom faces of the hole, on the corners prone to tensile stresses perpendicular to the grain (see Fig. 7). In the case of circular holes, the tensile force, $F_{t,90,Ed}$, should be assumed to act under 45° from the center* *of the hole with regard to the beam axis (see Fig. 7). All areas prone to splitting from tensile stresses perpendicular to the grain should be analyzed.*

$$F_{t,90,Ed} = F_{t,V,Ed} + F_{t,M,Ed} = \frac{V_d \cdot h_d}{4 \cdot h} \cdot \left[3 - \frac{h_d^2}{h^2}\right] + 0{,}008 \cdot \frac{M_d}{h_r} \tag{9}$$

where
h_r = *min* $\{h_{rl}; h_{ru}\}$;
h_d *is the hole depth;*
h, h_d, h_{rl}, h_{ru} *see Fig 7.*

The tensile force perpendicular to the grain, $F_{t,V,Ed}$, can be approximated by integration of the shear stress between the axis of the member and the expected location of the crack at the corner of the hole prone to cracking. The location of crack onset for round holes has been determined by numerical investigations [29] and has also been observed in tests. The tensile force perpendicular to the grain, $F_{t,M,Ed}$, has been derived from tests [31] but is still under investigation [29].
Note to the reader:
The standard clauses for unreinforced holes in EN 1995-1-1, including the formulae to determine the tensile forces perpendicular to the grain at the location of stress peaks, $F_{t,90}$, are currently under development in CEN/TC 250/SC 5. It is expected that the formulae will be adapted to recent research results. This includes an adjustment of the tensile force perpendicular to the grain from the transfer of bending stresses, $F_{t,M,Ed}$ [30] as well as formulae for eccentrically arranged holes and groups of holes [32]. Due to the fact that this process was ongoing during the drafting of this contribution, it was decided to include the current state of the art in design formulae (see formula (9)). The applicability of the clauses given below is independent of the formulae to determine the tensile forces perpendicular to the grain, $F_{t,90,Ed}$.

- *Where the tensile force, $F_{t,90,Ed}$, is carried by internal dowel-type reinforcement, the relevant effective anchorage length ℓ_{ad}, should be taken as follows:*
  $\ell_{ad} = h_{rl}$ *or* h_{ru} *for rectangular holes;*
  $\ell_{ad} = h_{rl} + 0{,}15 \cdot h_d$ *or* $h_{ru} + 0{,}15 \cdot h_d$ *for circular holes;*
- *Where the tensile force, $F_{t,90,Ed}$, is carried by internal dowel-type reinforcement, only one row of internal dowel-type reinforcing elements at a distance $a_{3,c}$ from the edge of the hole should be considered, see Fig. 7. The distance between the location of maximum tensile stresses perpendicular to the grain and the dowel-type reinforcement should be minimized.*
- *The application of internal dowel-type reinforcement, positioned perpendicular to the grain, should be limited to locations in the timber member that are subjected to low shear stresses.*
- *In members with holes and internal dowel-type reinforcement, the increased shear stresses in the area of the edges of the holes should be accounted for. The maximum shear stress, τ_{max}, should be calculated as follows:*

$$\tau_{\max} = \kappa_{\max} \cdot \frac{1{,}5 \cdot V_d}{b_{ef} \cdot (h - h_d)} \tag{10}$$

where

$$\kappa_{\max} = 1{,}84 \cdot \left[1 + \frac{a}{h}\right] \cdot \left(\frac{h_d}{h}\right)^{0{,}2} \tag{11}$$

b_{ef} *is the effective width, (*see 6.1.7. [2] *taking into account the impact of shrinkage cracks on shear capacity);*
a, h, h_d *see Fig. 7.*
In the case of circular holes h_d *may be replaced by* $0{,}7 \cdot h_d$.

- *Where the shear verification with* τ_{max} *from Formula (10) is not fulfilled, internal reinforcement positioned perpendicular to the grain should not be used.*
- *Where internal dowel-type reinforcement is arranged according to Fig. 7, the spacing requirements given in Section 7.1 apply.*

The reinforcing effect of dowel-type or plane reinforcement is strongly dependent on the distance between the reinforcement and the location of peak stresses (in tension perpendicular to the grain or shear). To reduce this distance, dowel-type reinforcement can be rotated to e.g. 60°. This arrangement has additional advantages such that it also enables the transfer of shear stresses as well as a reduced restraining effect in case of shrinkage (see Section 7.2).

The limitation of applicability of dowel-type reinforcement, arranged perpendicular to the grain, to areas exposed to low shear stresses is based on the fact that this arrangement leads to restraint of free shrinkage. This results in reduced shear capacity of the reinforced timber member which, in the vicinity of holes, is exposed to increased shear stresses. Shear can only to a small extent be transferred by dowel-type reinforcement arranged perpendicular to the grain.

In the case of rectangular holes it is necessary to take into account the increased shear stresses around the edges of the holes. A description as well as an associated design equation is given in [33]. In [15] it is recommended to apply the same verification for circular holes as well, although this yields results on the safe side. The same publication describes a method to verify the bending stresses above respectively below rectangular holes, including the additional longitudinal stresses from the frame action (lever of the shear force) around the hole (see also [31]).

- *Where the tensile force,* $F_{t,90,Ed}$*, is carried by plane reinforcement, the relevant effective anchorage length* ℓ_{ad}*, should be taken as follows:*
  $\ell_{ad} = h_1$ *for rectangular holes;*
  $\ell_{ad} = h_1 + 0{,}15 \cdot h_d$ *for circular holes;*
  where
  h_1 *depth of plane reinforcement above or below a hole, see Fig. 7.*
- *The plane reinforcement, e.g. panels or laminations should be glued to both sides of the member, see Fig. 7, with the following limits:*

$$0{,}25 \cdot a \ \leq \ b_r \ \leq \ 0{,}6 \cdot l_{t,90} \tag{12}$$

where

$$l_{t,90} = 0{,}5 \cdot (h_d + h) \tag{13}$$

and

$$h_1 \geq \max \begin{cases} 80\ mm \\ 0{,}25 \cdot a \end{cases} \tag{14}$$

b_r *is the width of the plane reinforcement;*
$\ell_{t,90}$ *is the length under tensile stresses perpendicular to the grain;*
a, h_d, h *see Fig. 7.*
Depending on the type of product and type of application (e.g. screw press gluing), dimensions b_r *(respectively* h_1*), that exceed the upper limits given in Formula (12) (respectively (14)), may be required. The width* b_r *applied in Formula (4) should not exceed the upper limit given in Formula (12).*

- *For members from laminated veneer lumber (LVL) with holes it is recommended to use plane reinforcement, e.g. LVL with cross-veneers.*

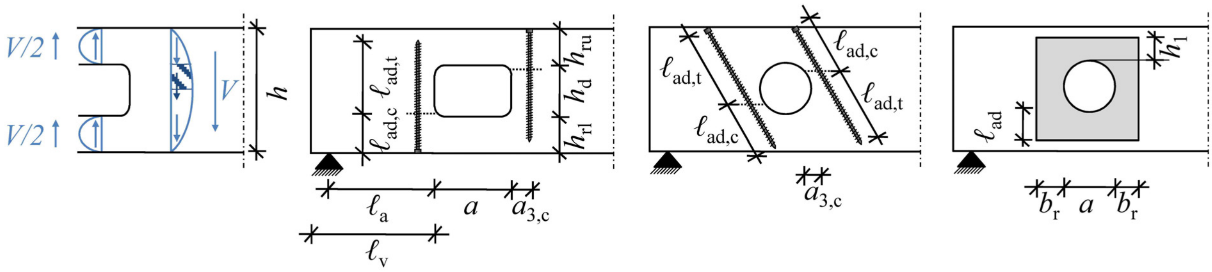

Figure 7: Holes in beams: distribution of shear stresses (left), dowel-type reinforcement (middle left), inclined reinforcement (middle right) and plane reinforcement (right).

The specifications concerning the edge distance and the permissible number of rows of dowel-type reinforcement, the applicable width and the recommended minimum width of the reinforcement are due to the same conditions as described in Section 7.4 (reinforcement of notches).

Tests have shown that dowel type reinforcement of holes in LVL beams do not necessarily increase the loadbearing capacity of the beams around the holes. It is therefore recommended to use LVL with cross veneers.

The requirement to produce rounded corners (radii $r/h_d > 0{,}1$), see Fig. 7, has been derived from the necessity of dispersion of shear stresses at the corners in order to not exceed the shear stresses determined with formula (11) in combination with practical considerations agreed by members of CEN/TC 250/SC 5/WG 7 “Reinforcement”.

7.6 Reinforcement of connections with a tensile force component perp. to the grain

Standard text (Section 10.1.4.2):

- *The reinforcement of connections with a tensile force component perpendicular to the grain (see Fig. 8) may be designed for a tensile force* $F_{t,90,Ed}$*:*

$$F_{t,90,Ed} = [1 - 3 \cdot \alpha^2 + 2 \cdot \alpha^3] \cdot F_{90,Ed} \tag{15}$$

where
$\alpha = h_{ef,Conn.}/h$ *see Fig. 8.*
$h_{ef,Conn.}$ *is the effective depth of the connection, see Fig. 8.*

- *Where the effective depth of the reinforcement,* $h_{ef,Reinf.}$*, see Fig. 8, is smaller than* $0{,}7 \cdot h$*, measured from the loaded beam edge, Formula (15) should be satisfied at the tip respectively edge of the reinforcement facing the unloaded beam edge.*

- *Where the tensile force, $F_{t,90,Ed}$ (according to Formula (15)) is carried by internal dowel-type reinforcement, only one row of internal dowel-type reinforcement at a distance $a_{3,c}$ from the edge of the connection should be considered, see Fig. 8.*
- *The plane reinforcement, e.g. panels or laminations should be glued to the member according to Fig. 8, with the following limits:*

$$0{,}25 \leq \frac{b_r}{\ell_{ad}} \leq 0{,}5 \qquad (16)$$

with

b_r *is the width of plane reinforcement*

ℓ_{ad} *is the relevant effective anchorage length, see Fig. 8*

Depending on the type of product and type of application (e.g. screw press gluing), a width b_r, exceeding the upper limit given in Formula (16), may be required. The width b_r applied in Formula (4) should not exceed the upper limit given in Formula (16).

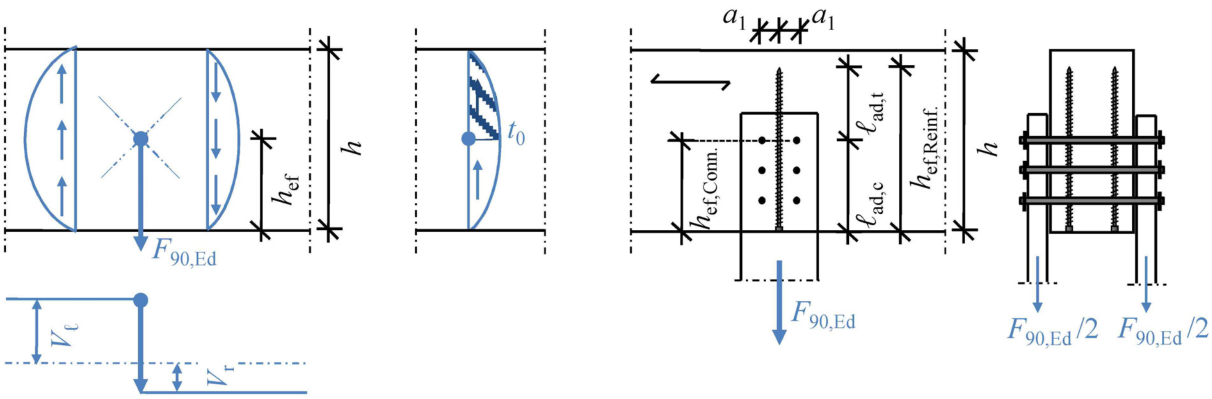

Figure 8: Reinforced cross-connection: distribution of shear stresses (left), reinforcement (right).

Background for the clauses given above:

The tensile force perpendicular to the grain, $F_{t,90,Ed}$, is the resultant of the tensile stresses perpendicular to the grain on the plane defined by the loaded edge distance to the center of the most distant fastener, $h_{ef,Conn.}$ (see e.g. [34]). According to beam theory, the connection force component perpendicular to the grain results in a step in the shear force distribution. The tensile force perpendicular to the grain, $F_{t,90,Ed}$, is determined by integration of the shear stress in the area between the row of fasteners considered and the unloaded edge. The term in brackets in Formula (15) is the result of this integration, a derivation can be found in e.g. [35].

The depth of the reinforcement should be sufficient such as to avoid moving the location of tensile failure perpendicular to the grain from the connection to the tip/edge of the reinforcement. In analogy to the experiences and rules for connections with a tensile force component perpendicular to the grain ([2], [3]), no additional verification is necessary for relationships $h_{ef,reinforcement}/h > 0{,}7$.

The distance between the dowel-type reinforcement and the connection is limited to take into account the limited distribution length of the tensile stresses perpendicular to the grain outside the connection. The same is valid for the applicable width of reinforcement panels. The recommended minimum width of the reinforcement is due to the same conditions as described in Section 7.4 (reinforcement of notches). With respect to the requirement to place reinforcement as close as possible to peak stresses, it is recommended to use the minimum possible spacing $a_{3,c}$ between dowel-type reinforcement and fastener and to place dowel-type reinforcement also between the fasteners of a connection.

7.7 Reinforcement of bolted / dowelled connections

Standard text (Section 10.5.1.1):

- *Where splitting of the timber is prevented through sufficient reinforcement perpendicular to the grain, the effective number of fasteners according to Formula* (8.34, *i.e. determination of* n_{ef} in [2]) *may be taken as* $n_{ef} = n$.
- *The characteristic tensile force in the reinforcement may be taken as* $F_{t,90,Ek} = 0{,}3 \cdot F_{v,Rk}$, *with* $F_{v,Rk}$ *determined for one bolt/dowel and one shear plane according to* (Formulae (8.6) – (8.7) and (8.9) – (8.13) in [2]).
- *The verification of block shear applies* (Annex A in [2]).

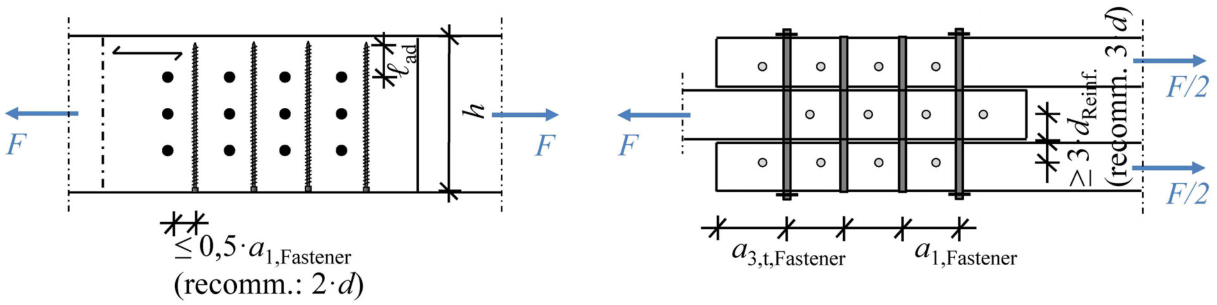

Figure 9: Reinforced bolted/dowelled connection, arrangement and distance requirements

Background for the clauses given above:

The load carrying capacity per dowel in connections with multiple dowels placed in a row parallel to the grain and loaded by a load component parallel to the grain is smaller as the load carrying capacity of a connection with one single dowel. This reduction in load carrying capacity in connections with multiple dowel-type fasteners is mainly the result of premature splitting of the timber in the direction of the rows of dowels. The effective number of dowels, according to (Formula (8.34) in [2]) is based on [36].

Splitting may be prevented by reinforcing the connection area, e.g. by self-tapping screws or wood-based panels. In [37] it is demonstrated that in connections with sufficient reinforcement between the dowels, the timber does not split and the effective number n_{ef} equals the actual number n of dowels in one row. With reference to [38], it is stated in [37] that timber splitting is prevented, if the axial load-carrying capacity $F_{ax,R}$ of each screw exceeds 30 % of the lateral load-carrying capacity, $F_{v,R}$, of one dowel and one shear plane. The axial load-carrying capacity of the dowel-type reinforcement is determined with the effective anchorage length between the outermost row of bolts/dowels and the tip of the dowel-type reinforcement. In practice, a distance between the dowel/bolt and the dowel-type reinforcement of twice the diameter of the reinforcement has proven sufficient to enable a safe insertion of the reinforcement. According to [38] splitting is also prevented if the dowel-type reinforcement is placed at larger distance, e.g. half the distance between two adjacent fasteners. The dowel-type reinforcement should be placed at minimum possible distance, $a_{4,c}$, to the respective shear plane to reduce the distance to the area of peak splitting stresses which is in the timber adjacent to the shear plane.

7.8 Reinforcement of members with compression stresses perpendicular to the grain

Standard text (Section 8.1.5.2):

- *This subclause applies for*
  - *members made from softwoods;*
  - *with reinforcements to carry compression stresses perpendicular to the grain;*
  - *either by fully threaded screws or screwed in threaded rods.*

The screws or rods shall be

- *applicable for the respective timber product and service class of the reinforced timber member;*
- *evenly distributed over the reinforced contact area;*
- *applied at an angle between screw or rod axis and grain direction of $45° \leq \alpha \leq 90°$;*
- *applied at an angle between screw or rod axis and contact surface of 90°;*
- *applied with its heads flush to the contact area.*

The contact area shall have

- *adequate stiffness (e.g. a steel plate of adequate thickness) and evenness to prevent penetration of the screw or rod heads into the contact member*
- *adequate rotational capacity where necessary, to provide an equal distribution of the compression force over all screws or rods;*

The contact width at the tip of the reinforcement shall be equal to the member width b, see Fig. 10.

For such reinforcements the characteristic resistance of the reinforced contact area should be taken as the minimum value from Formula (17):

$$F_{c,90,Rk} = \min \begin{cases} k_{c,90} \cdot b_c \cdot \ell_{ef,1} \cdot f_{c,90,k} + n \cdot \min\{F_{ax,\alpha,Rk}; F_{b,Rk}\} \\ b \cdot \ell_{ef,2} \cdot f_{c,90,k} \end{cases} \tag{17}$$

where

$k_{c,90}$ (*according to* 6.1.5.1 in [2])*;*

b_c *is the contact width, in mm see Fig. 10;*

$\ell_{ef,1}$ *is the effective contact length parallel to grain (according to 6.1.5 in [2]), in mm; For $\alpha < 90°$, $\ell_{ef} = \ell$, in mm;*

$n = n_0 \cdot n_{90}$ *is the number of fully-threaded screws or rods applied for reinforcement;*

n_0 *is the number of fully-threaded screws or rods arranged in a row parallel to the grain;*

n_{90} *is the number of fully-threaded screws or rods arranged in a row perpendicular to the grain;*

$F_{ax,\alpha,Rk}$ *is the characteristic withdrawal capacity at the given angle to the grain* (*according to* 8.7.2 in [2] *or Technical Assessment);*

$F_{b,Rk}$ *is the characteristic capacity of the screw in axial compression, in N, see below (or Technical Assessment);*

b *is the member width, in mm, see Fig. 10.*

$\ell_{ef,2}$ *is the effective distribution length parallel to grain in the plane defined by the screw or rod tips, see Fig. 10;*

with

$$\ell_{ef,2} = \ell_{ad} + (n_0 - 1) \cdot a_1 + \min\{\ell_{ad};\ a_{3,c}\} \textit{ for end supports} \tag{18}$$

$$\ell_{ef,2} = 2 \cdot \ell_{ad} + (n_0 - 1) \cdot a_1 \textit{ for intermediate supports} \tag{19}$$

where

ℓ_{ad} *is the point side penetration length of the threaded part of the screw or rod in the timber member, in mm, see Fig. 10;*

a_1, $a_{3,c}$ *are the spacing parallel to grain and end distance, in mm.*

- *Minimum spacings and end and edge distances should be taken from* (Table 8.6 in [2]) *or the European Technical Assessment.*

Background for the clauses given above:

Structural details in which the timber is loaded in compression perpendicular to the grain are very common, e.g. beam supports or sills/sole plates. The combination of high loads to be transferred over localized areas and low capacities in compression perpendicular to the grain can make it difficult to meet the associated verifications. Fully threaded, self-tapping screws or screwed-in threaded rods are a means to improve the stress dispersion into the timber. Partially threaded screws do not work in this application. The main developments in this field were presented in [39].

In contrast to the design approach applied for reinforcement to carry tensile stresses perpendicular to the grain, the load-carrying capacity of a reinforced support can be determined under the assumption of an additive coaction between the timber under compression stresses perpendicular to the grain and the screws/rods under compression. This assumption is valid if certain deformations of the loaded edge are accepted. This also explains why the effective number of fasteners, n_{ef}, does not apply in this application. In addition, verification of the compression resistance of a fully threaded screw (pushing-in or buckling) is necessary, see subsequently. Typically, buckling of the screw is limiting the ratio of effective length to diameter (ℓ/d). Finally it should be verified that the compression capacity perpendicular to the grain of the timber is not exceeded at the screw tips (transition between reinforced and unreinforced section), in a plane defined by an effective length, $\ell_{ef,2}$. The effective length is not to be interpreted as a support length, hence the factor $k_{c,90}$ is not applicable in this verification [39]. At the screw tips, the failure behaviour under compression stresses perpendicular to the grain is characterized by transverse deformations (elongation) over the member width. Over supports, this deformation is prevented by the bearing material. The angle of stress distribution applied to determine the effective length, $\ell_{ef,2}$ used for verification at the screw tips may be taken as 45°, measured from the screw heads. The definition of stress distribution has changed over the years (linear load distribution under 45°, measured from the edge of the steel plate [40]; exponential load distribution, measured from the edge of the steel plate [39]; linear load distribution under 45°, measured from the screw heads, e.g. [41]), hence different approaches can still be found in literature. For longer reinforcing elements, the assumed load distribution of 45°, measured from the screw heads, delivers results on the safe side. In case of support conditions with $45° \leq \alpha < 90°$, the load-distribution-angle will decrease with decreasing angle between load and grain. This is compensated by the use of $f_{c,90,k}$ (and not $f_{c,\alpha,k}$) for all angles between load and grain, delivering results on the safe side. The load distribution perpendicular to the grain, over the width of the member is smaller. If necessary, e.g. in block-glued members, the angle of load distribution perpendicular to the grain can be taken as 15° [42]. To guarantee a homogeneous transfer of shear into the reinforced support area, the contact width at the tip of the reinforcement, determined with the angle of load distribution perpendicular to the grain, should equal the member width, see Fig. 10.

The compression force must be evenly distributed to all screws and the compression stresses at the screw heads have to be absorbed by the bearing material. These two requirements can only be met by a hard bearing material. This can be realized in form of a hard intermediate layer from e.g. steel, designed in adequate thickness and thus capable to transfer the load uniformly. The screws shall be equally distributed over the bearing area and the screw heads shall be on one line with the surface of the timber member.

The distance requirements are the same as for screws in tension. It is not necessary to take into account an effective number of screws, n_{ef}.

- *The contact material (e.g. steel plate) should be designed for the load introduced by the screw head. The thickness of steel plates, t, may be assumed adequate, if Formula (20) is satisfied:*

$$t \geq \max\left(5{,}0;\quad 1{,}45 \cdot \sqrt{\frac{F_{c,\alpha,Ed}}{f_{y,d}}}\right) \tag{20}$$

where
t is the thickness of the steel plate, in mm;
$F_{c,\alpha,Ed}$ is the design compression force in one screw or rod, in N;
$f_{y,d}$ is the design yield strength of the steel plate, in N/mm².

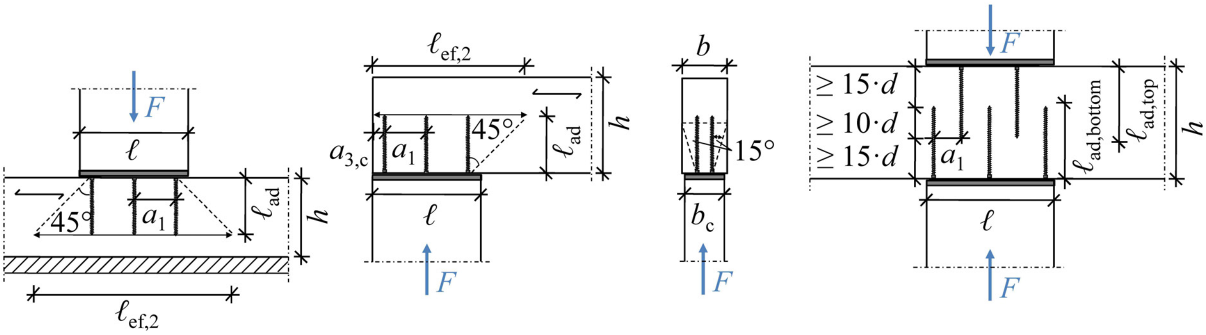

Figure 10: Reinforced support areas: member on continuous support (left) and discrete support (middle left), cross-section (middle right), transmission of perpendicular to grain forces (right)

- *Where rotation of the member results in indentation of the member due to the stiff contact material (e.g. steel plate), it is recommended to increase the rotational capacity (by e.g. an elastomeric bearing material), if the following limit is exceeded:*

$$\Delta w = \varphi \cdot \ell/2 \geq 1{,}0\ mm \tag{21}$$

where
Δw is the relative deformation of the member from rotation at the edge of the contact;
φ is the rotation of the member at the support at u_{fin} (see 2.2.3(3) in [2]);
ℓ is the contact length, see Fig. 10, in mm.

- *Screw or rods driven into the top and bottom of a member may overlap. The characteristic resistance may be determined according to the first part of Formula (17), if*
    - *the contact areas and the screws or rods are arranged axially symmetric on both opposite sides; and*
    - *the screws or rods overlap at least 10·d, where d is the screw or rod diameter; and*
    - *the distance between the screw or rod tips and the opposite contact area is at least 15·d, see Figure 10.*
- *Reinforcement with glued-in rods may be designed in analogy to the above given clauses.*
- *Section 7.2 (Effects of moisture content changes) applies.*
- *At supports where the support force is not fully transferred at the contact area (e.g. in case of reinforced support area) and at supports where the support force is transferred via connections fastened to the end grain, the reduction of total shear force (6.1.7 in [2]) should not be applied.*

Note to the reader: In the draft standard, the last bullet point is placed in section 6.1.7 in [2]. For reasons of representation, the introduction of this information in a separate section was omitted in this contribution.

The hard intermediate layer (e.g. steel plate) should (amongst others) be designed for the bending stresses from the forces induced by the screw heads. This verification can be converted into an equation which sets into relation the force in the dowel-type reinforcement in compression and the yield strength of the steel plate.

The requirement of adequate rotational capacity can be met by placing a softer interlayer (e.g. elastomeric bearing) between the steel plate and the member below. Not all types of support require high rotational capacity, e.g. mid-supports of a 2-span beam. The given threshold value is based on practical experience.

Reinforcement driven in from both edges of the beam to enable the transfer of compression perpendicular to grain stresses through the timber member has been introduced by [42] and was subsequently introduced into Technical Approvals [44]. The validity of the approach, the minimum overlap as well as the minimum distance between the screw tips and the opposite contact area has been numerically and experimentally verified in [45]. With respect to facilitated stress transfer between the screws applied from opposite edges it is recommended to use the minimum possible spacing and an alternating arrangement of the screws over the contact area.

For information on the verification of the fully threaded screws or screwed-in threaded rods in axial compression it is referred to the information given below. In [39] a calculation model to determine the stiffness of reinforced beam supports is proposed as well.

- *The characteristic compression resistance (pushing-in or buckling),* $F_{c,\alpha,Rk}$, *may be simplified as:*

$$F_{c,\alpha,Rk} = \min\{F_{ax,\alpha,Rk}; F_{b,Rk}\} \tag{22}$$

where

$F_{ax,\alpha,Rk}$ *is the characteristic withdrawal capacity according to* (Formula 8.39 *respectively* 8.40 in [2])*;*

$F_{b,Rk}$ $=1{,}18 \cdot k_c \cdot N_{pl,k}$ *is the characteristic load-carrying capacity of the screw in axial compression;*

with

values k_c *according to Table 2*

and

$$N_{pl,k} = \pi \cdot \frac{d_1^2}{4} \cdot f_{y,k}$$

d_1 *is the inner thread diameter;*

$f_{y,k}$ *is the characteristic yield strength of the screw.*

Table 2: Reduction factors k_c for buckling of screws ($\rho_k \geq 350$ kg/m^3)

	Angle α between screw axis and grain	
Characteristic value of yield strength of steel	$\alpha = 90°$	$\alpha = 0°$
$f_{y,k} = 1000$ *N/mm2*	$k_c = 0{,}6$	$k_c = 0{,}5$
$f_{y,k} = 800$ *N/mm2 (e.g. hot dip galvanized steel)*	$k_c = 0{,}65$	$k_c = 0{,}55$
$f_{y,k} = 500$ *N/mm2 (e.g. stainless steel)*	$k_c = 0{,}75$	$k_c = 0{,}65$
NOTE: for characteristic values of yield strength of steel in between the specified values, k_c can be determined by linear interpolation. For angles α between the specified values, k_c can be determined by linear interpolation.		

The characteristic compression resistance of a fully threaded screw is taken as the smaller of the pushing-in or buckling capacity. The pushing-in capacity is considered equal to the withdrawal capacity of the fully threaded screw. The full equations to determine the buckling capacity of fully threaded screws were determined in [39]. The simplification of equations proposed above has been developed in [46]. [39] also propose buckling capacities for the application of fully threaded screws with clamped heads in a steel plate. This application necessitates to countersink the steel plate in the form of the screw heads in such a way as the surface of the screw heads is flush with the lower steel plate surface. In practice this can be a challenge due the necessity of exact manufacturing in combination with the multitude of forms of screw heads available on the market.

8 CONCLUSIONS AND OUTLOOK

Despite the current lack of design approaches in Eurocode 5 and comparable standards on structural timber design, reinforcement for stresses perpendicular to the grain with fully-threaded, self-tapping screws, glued-in or screwed-in threaded rods or glued-on plywood and LVL can be considered state-of-the art in timber engineering practice. For numerous applications, design procedures are available which have already been clarified to an extent satisfying safety requirements and engineering needs. These are currently being prepared for introduction into the next generation of Eurocode 5. This contribution gives an overview of these developments. Future research and development should comprise the better quantification of the reinforcing effect of inclined dowel-type reinforcement, a clearer determination of stiffness properties of the reinforcement in the timber before cracking as well as a better understanding and quantification of the potentially harmful effect of reinforcement restricting the free shrinkage or swelling of the timber.

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