Self-tapping screws and threaded rods as reinforcement for structural timber elements – a state-of-the-art report

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Abstract

In timber engineering, self-tapping screws, optimized primarily for axial loading, represent the state-of-the-art in fastener and reinforcement technology. Their economic advantages and comparatively easy handling make them one of the first choices for application in both domains. This paper focuses on self-tapping screws and threaded rods applied as reinforcement, illustrating the state-of-the-art in application and design approaches in Europe, in conjunction with numerous references for background information. With regard to medium to large span timber structures which are predominately erected by using linear timber members, from e.g. glued laminated timber, the focus of this paper is on their reinforcement against stresses perpendicular to grain as well as shear. However, latest findings with respect to cross laminated timber are included as well.

Keywords: Self-tapping screws; Rods; Reinforcement; Glued laminated timber; Cross laminated timber; Stresses perpendicular to the grain; Shear stresses

1. Introduction

Wood is a highly anisotropic material, featuring low capacities in tension and compression perpendicular to the grain as well as shear. When designing structural elements from timber, it should be aimed at minimising e.g. tensile and compressive stresses perpendicular to the grain. If this cannotbe fully achieved, the timber element can be reinforced to compensate for these low strength properties. The list of applicable internal or external reinforcement 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). Fully threaded, self-tapping screws are a very economical alternative to the traditional reinforcement by glued-in steel rods or wood-based panels which are glued onto the timber member. After a brief introduction to wood screws in general, we focus on the state-of-the-art of fully-threaded self-tapping screws and threaded rods and associated design approaches common in Europe. In principle, the approaches presented in the following also apply to glued-in rods. For an in-depth overview on glued-in rods, the interested reader is kindly referred to [1]

Traditional wood screws feature a shank with a threaded and a smooth part, the outer diameter of the thread generally equaling the smooth shank diameter. Such screws are described in national standards, like DIN 7998 [2]. Typically, the length of the threaded part is only 60 % of the total length. For shank diameters $d > 6$ mm, pre-drilling is required (depending on e.g. density of the timber). Their axial load-carrying capacity is mostly limited by the pull-through capacity of the screw head. Thus the additional use of adequately designed washers is commonly meaningful. The combination of threaded and smooth shank and the use of mild- or low carbon steel allow using them for loading in shear and tension or a combination of both.

Constraints in the load-carrying capacity of primarily axially-loaded screws were overcome with the development of self-tapping screws. In contrast to traditional screws which have their threaded part turned down from the original rod diameter, the thread of self-tapping screws is produced by rolling or forging a wire rod around the shank, which consequently features a smaller diameter when compared to the outer cross sectional thread diameter (see also Fig. 1). Self-tapping screws mostly feature a continuous thread over the whole length. This leads to a more uniform load transfer between the screw and the wood material as well as a considerably enhanced axial load-carrying capacity, the type of loading for which they are optimized.

During manufacture, their thread is hardened, leading to an increased bending and torsion capacity, but also to a more brittle failure mechanism. In combination with the development of optimized drill tips and threads, self-tapping screws, featuring diameters up to 14 mm and lengths up to 1000 mm, are produced and applied today, see Fig. 1 and Fig. 2.

An extension of these geometric limits is possible by the application of threaded rods. These are a modification of self-tapping, fully threaded screws featuring screw threads over the full length. These can reach diameters of up to 20 mm and lengths of up to 3000 mm. Threaded rods with screw threads need pre-drilling with the core diameter and a coating and/or lubricant to reduce friction stresses when driving them in. In dependency of the length of the screw or threaded rod, their axial load-carrying capacity may be limited by the tensile capacity of the steel or, if loaded in compression, by buckling. Following EN 1995-1-1 [3] and investigations made in e.g. [4], a group of axially loaded screws may also fail in block shear.

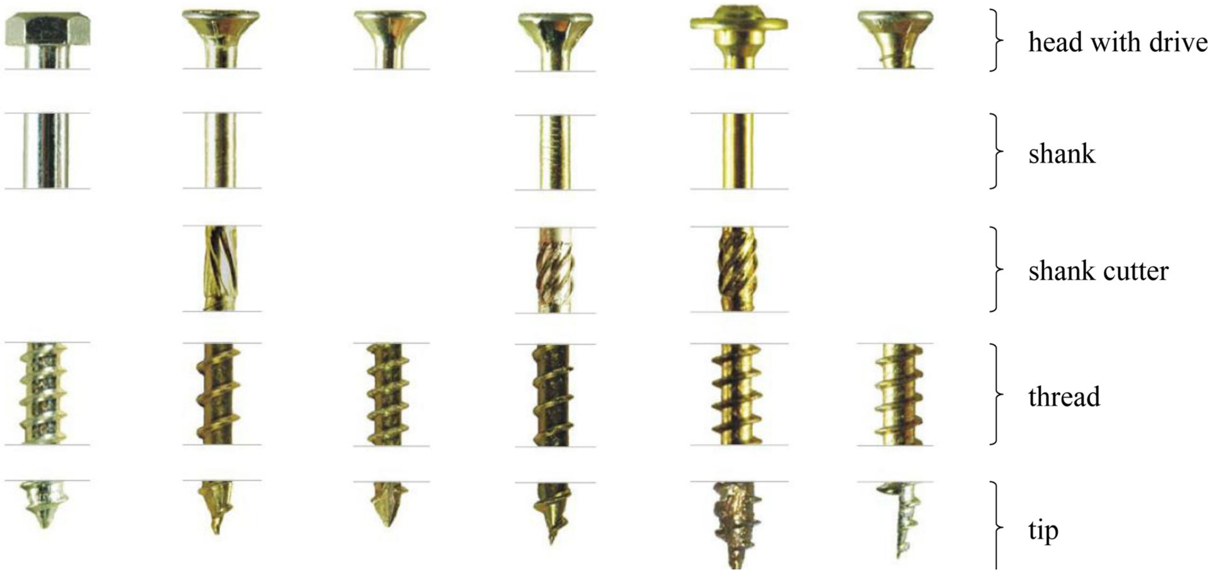


Fig. 1 Different forms of drill tips and threads (with and without shank cutter) as well as variations of screw heads; comparison with DIN-screw (third from right), from [5]

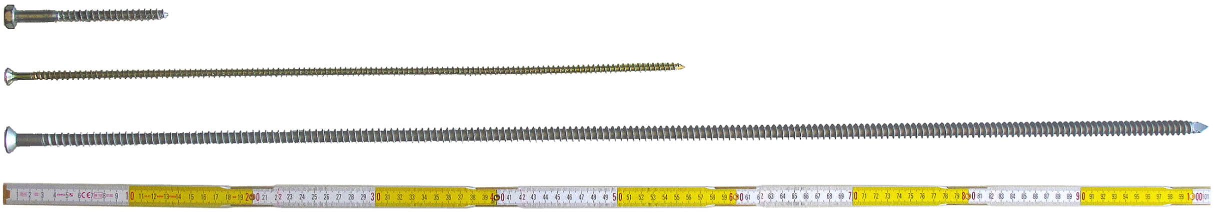
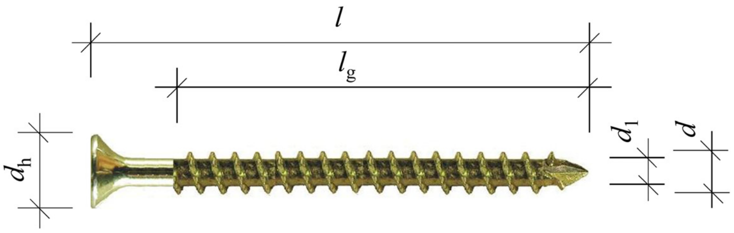


Fig. 2 Development of screw length (and implicitly load-carrying capacity) from traditional wood screws to self-tapping screws, from [6]

Requirements for self-tapping screws are for example given in EN 14592 [7]. Here, the nominal diameter equals the thread diameter d which has to be $2.4 \text{ mm} \leq d \leq 24 \text{ mm}$ (practical range: 8 mm, 10 mm and 12 mm for screws, 16 mm and 20 mm for threaded rods). The core diameter d_1 has to be $0.6 \cdot d \leq d_1 \leq 0.9 \cdot d$ ($0.6 \cdot d \leq d_1 \leq 0.75 \cdot d$ according to EN 1995-1-1 [3]). The minimum thread length is restricted to $l_g \geq 4 \cdot d$ (minimum embedment depth or effective penetration (anchoring) length, l_{ef}, according to EN 1995-1-1 [3] is: for axially loaded screws $6 \cdot d$ and for laterally loaded screws $4 \cdot d$,), see also Fig. 3.



d … nominal (thread) diameter
d_1 … core diameter
d_h … head diameter
l … length
l_g … thread length

Fig. 3 Geometry parameters for screws

The mechanical properties are defined by the characteristic values of (i) the yield moment, (ii) the withdrawal capacity of the threaded part, (iii) the tear-off capacity of the screw head, (iv) the pull-through capacity of the screw head, (v) the tensile strength of the screw, and (vi) the torsional strength of the screw,. The mechanical properties can be derived from tests or from equations given in e.g. EN 1995-1-1 [3]. The use of other screws as specified in EN 14592 [7] is allowed, provided their applicability is proven by a technical approval. These used to be issued by national building authorities; currently most national approvals are being converted into European Technical Approvals (ETAs). Between the products available on the market, there are a variety of head and thread forms and differences in shank-, tip- and thread-diameter as well as different ratios between thread to core diameter, see Fig. 1. However, a comprehensive comparative study on self-tapping screws of five different manufactures, tested at angles between screw axis and fibre direction of 90°, 45° and 0°, showed only minor differences in the withdrawal capacities. The range of ± 10 % is in-line with the technical approvals. More relevant are the differences in the practical application of the screws, see e.g. [5].

Meanwhile, many regulations in technical approvals have been adapted between different approvals, facilitating design and comparability. Nevertheless, there are a number of approvals in which special rules are given that must be followed. For example, there are different rules in the following areas:

- minimum spacings and distances, minimum member thickness requirements;
- axial withdrawal capacities (as a function of characteristic (5 %-quantile) density);

- permissible angles between screw axis and grain direction;
- wood species (mostly softwoods);
- tensile capacity;
- stability of the screws, i.e. buckling failure when loaded in compression;
- stiffness values (K_{ser}, $K_{ax,ser}$, K_{u}).

Because of these differences, specified screws shall not be substituted by other screws.

2. General rules on the application of self-tapping screws

The European basis for the design of self-tapping screws is the design concept given in Eurocode 5 (EN 1995-1-1 [3]) in combination with the provisions given in the European Technical Approvals (ETAs). For applications which are not covered by Eurocode 5, design approaches can be given in the National Annexes to Eurocode 5 (as non-contradictory, complementary information (NCCI)). Some ETAs, e.g. [8], [9] and [10], also feature annexes containing design provisions for certain applications.

One advantage of self-tapping screws is that they do not require pre-drilling, given the density of the timber is not too high (e.g. $\rho < 550$ kg/m^3, given for most softwoods). However, research results in [11] indicate, that for the application of self-tapping screws in timber with temperature below zero, pre-drilling may be required to prevent splitting of the timber which becomes more brittle at these temperatures. In more recent technical approvals, pre-drilling is allowed. Here, the borehole diameter shall not be greater than the core diameter of the screw. Pre-drilling can have a positive effect on the precision of the screw positioning. This is of special importance if the screws are positioned at an angle to the grain, which is challenging if carried out free-handed, especially if screws of small diameter (e.g. $d = 6$ mm) and high slenderness are used. For this, placement devices or CNC machinery can be used. Some ETAs allow to reduce the minimum spacing if pre-drilling is applied. Most self-tapping screws feature a special drill-tip which allows the use of reduced spacings and distances even without pre-drilling. For such screws, most technical approvals (e.g. [8], [9] and [10]) contain the spacing and distance requirements for axially loaded screws given in Tab. 1 (see also Fig. 4). In the case of screws positioned at an angle between grain and screw axis, the centroid of the threaded part of the screw in the respective timber member shall be used as reference for determining spacings and distances (see Fig. 4 and e.g. [8], [9], [10] and [12]). In the case of reinforcement against tensile stresses perpendicular to the grain, the distance between the reinforcement and the (mostly localized) area of stress peaks should be minimized, e.g. by using the minimum of $a_{3,c}$ (see e.g. [12]).

Tab. 1 Typical minimum spacings and minimum distance requirements given in technical approvals for axially loaded self-tapping screws

a_1	a_2	$a_{3,c}$	$a_{4,c}$
$5 \cdot d$ [a]	$5 \cdot d$ [a]	$5 \cdot d$	$4 \cdot d$ [b]
[a] may be reduced to $2.5 \cdot d$, if the condition $a_1 \cdot a_2 \geq 25 \cdot d^2$ is fulfilled. [b] in some cases, $3 \cdot d$ is allowed.			

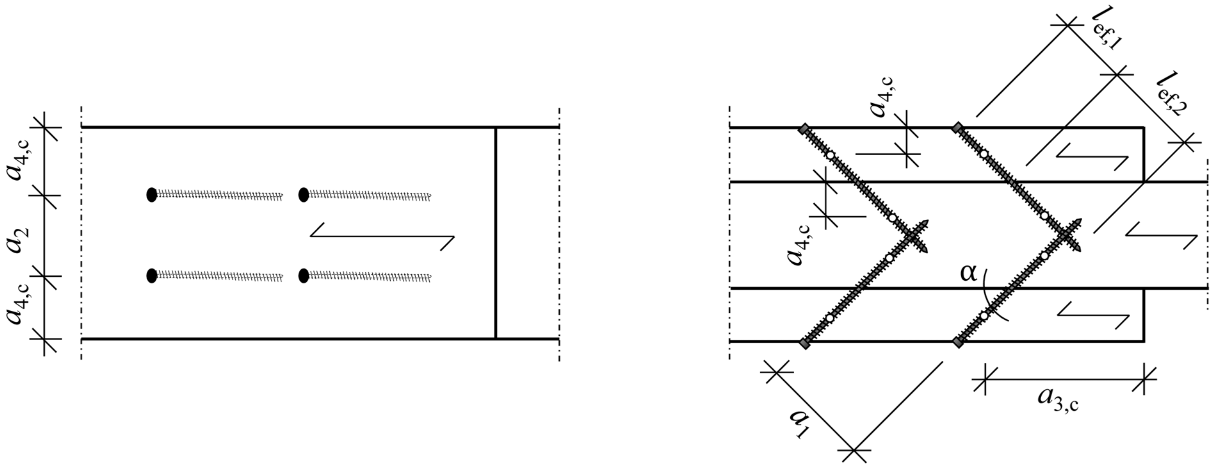


Fig. 4 Definition of spacings, end and edge distances for axially loaded screws

According to Eurocode 5 (EN 1995-1-1 [3]), a reduction in cross-section, caused by screws do not need to be considered in cases of $d \leq 6$ mm (without pre-drilling) and for screws placed in areas under compressive stresses. For nominal diameters $d > 6$ mm, a reduction of the cross-section shall be taken into account. This is typically realized by considering only the cross-sectional area of the screws, cut at an angle α at the timber cross section featuring the highest number of penetrating screws (e.g. [12]). However, tension parallel to grain tests on butt-joints with inclined fully threaded self-tapping screws showed, that the net cross section is better approximated by the timber area between the projected screws, see Fig. 5, right. Thus, the sole consideration of the screw holes as loss in net cross section was shown to be not sufficient [13]. Recent research results [14] indicate that a reduction of the cross-section should also be considered in members under compression, even if the holes are filled with a material of higher stiffness than the wood. This is explained by stress peaks developing in the vicinity of the fasteners. The exception is glued-in rods since the glue-line shall lead to a reduction in stress peaks.

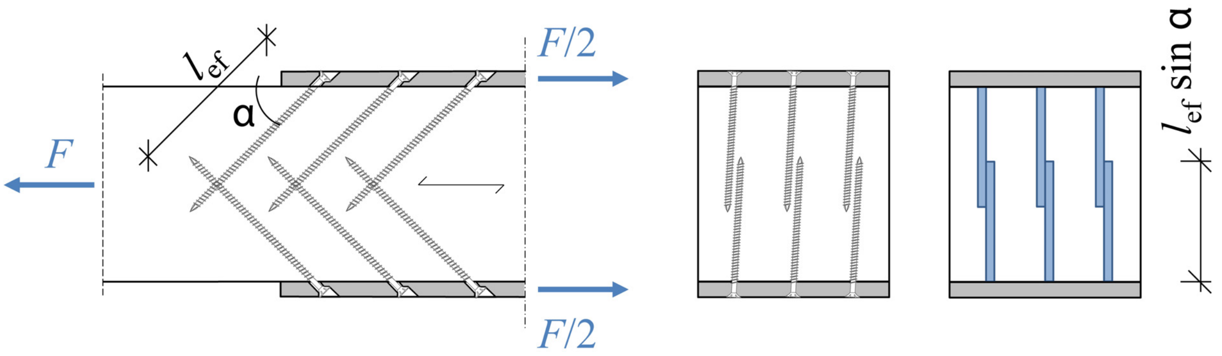


Fig. 5 Butt-joint with self-tapping screws and proposal for definition of net cross section, from [13]

The characteristic axial load-carrying capacity of the screw, $F_{ax,Rk}$, is determined as the minimum of the characteristic tensile capacity, $F_{t,Rk}$, (or characteristic buckling capacity, $F_{ki,Rk}$) and the characteristic withdrawal capacity, $F_{ax,\alpha,Rk}$, of the screws, see Eq. (1). The characteristic withdrawal capacity, $F_{ax,\alpha,Rk}$, is calculated as the product of the characteristic withdrawal parameter, $f_{ax,k}$, (given in the technical approval; conforming with the characteristic withrawal strength multiplied by $\pi = 3.14$), the nominal diameter, d, and the effective anchorage length, ℓ_{ef}. In the case that screws are positioned at an angle α between grain and screw axis, most approvals contain an equation with which the withdrawal capacity can be determined according to the values for α = 90°. Some technical approvals allow to use the values determined for α = 90° in case of angles α ≥ 45°.

$$F_{ax,Rk} = \min\begin{Bmatrix} F_{t,Rk} \text{ or } F_{ki,Rk} \\ f_{ax,k} \cdot d \cdot l_{ef} \end{Bmatrix} \tag{1}$$

The slip moduli, K_{ser} (slip moduli in shear) and $K_{\mathrm{ax,ser}}$ (axial slip moduli), are needed e.g. in the case of mechanically jointed (e.g. doubled) beams which are designed with the γ-method or shear analogy (see chapter 6). Experiments to determine the axial slip modulus, $K_{\mathrm{ax,ser}}$, show large variations in results (e.g. [15] and [16] contain values approximately twice as high as in [17]). This variety of results is also observed in different technical approvals, which report different values of the slip modulus. Eq. (2), which is based on tests on screws from different manufacturers featuring maximum penetration lengths of 120 mm [17]), is generally reported in many technical approvals. Other technical approvals report different equations delivering higher results.

$$K_{ax,ser} = 780 \cdot d^{0.2} \cdot l_{ef}^{\;0.4} \tag{2}$$

Test results reported in [15] and [18] show that the slip moduli are also significantly dependent on the angle α between screw axis and grain direction. In contrast to the withdrawal capacity the slip moduli increase with decreasing angle α. In [18], tests on screwed-in rods featuring penetration lengths of 200 mm and 400 mm are reported that indicate a disproportionate (above-average) increase of the axial stiffness when doubling the penetration length.

3. Self-tapping screws as reinforcement to carry tensile stresses perpendicular to the grain

Screws under axial loading are very stiff, favoring their use as reinforcing elements. In the following subsections, typical applications of self-tapping screws as reinforcement to carry tensile stresses perpendicular to the grain in timber structures are presented. Within the approaches presented, the tensile capacity perpendicular to the grain of the timber is neglected, i.e. a cracked tension zone is assumed. This is different from to the approach taken by [19] in which only the force components, exceeding the tensile strength perpendicular to the grain of the timber, are considered for the design of the reinforcement.

3.1 Reinforcement of connections with a tensile force component perpendicular to the grain

The approach to design the reinforcement of connections with a tensile force component perpendicular to the grain explained in the following is standardized [20], previous sources include [21] and [22]. The approach is explained in [23] as well as [24], previous works include [25].

The design tensile force perpendicular to the grain, $F_{t,90,d}$, 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_e, (see e.g. [26]). 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, $F_{t,90,d}$, see Eq. (3), is determined from this change in shear stress by integration of the shear stress in the area between the row of fasteners considered and the unloaded edge, as indicated by the shaded area in Fig. 6 right. A derivation of this approach can be found in e.g. [27].

$$F_{t,90,d} = \left[1 - 3\cdot\alpha^2 + 2\cdot\alpha^3\right]\cdot F_{v,Ed} \qquad (3)$$

with: $\alpha = h_e / h$

$F_{v,Ed}$ design value of the shear force component perpendicular to the grain

The design approach for reinforcement of connections with a tensile force component perpendicular to the grain can also be translated to the reinforcement of girder hangers or the mortise part of a dovetail connection.

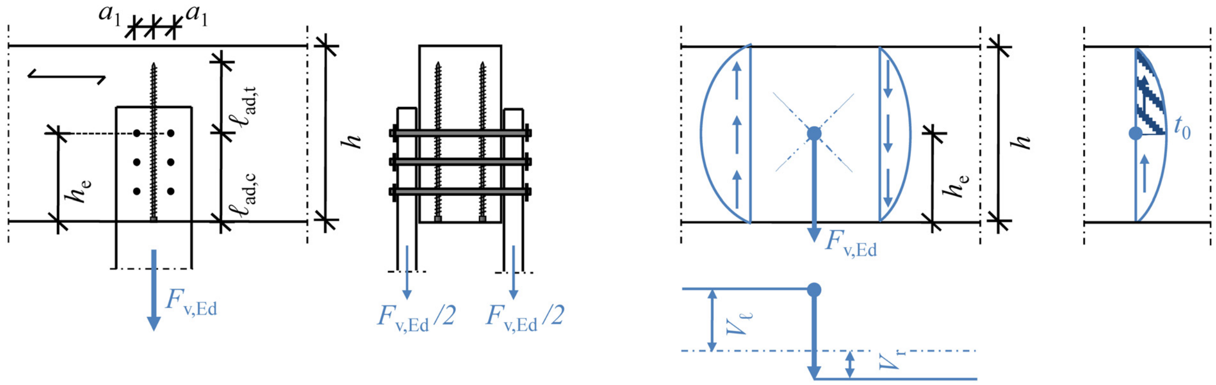


Fig. 6 Reinforced cross-connection: reinforcement (left) and distribution of shear stresses and shear flow (right, see also [27])

The highest tensile stresses perpendicular to the grain occur in direct vicinity of the fasteners. Therefore, the distance between the screw and the fasteners, a_1, should be minimal. It is ideal to place the reinforcement (also) in between the fasteners, as shown in Fig. 6 left. With respect to further geometric considerations for the reinforcement, the specifications given in 3.2 apply. The load-carrying capacity of the screw is determined in dependence of the length of the screw between the row of fasteners considered and the unloaded edge, $\ell_{ad,t}$. The thread of the reinforcement should at least cover 75 % of the beam height, see e.g. [28]. In all other cases, the tensile stresses perpendicular to the grain at the screw tip have to be verified as well.

3.2 Reinforcement of notched members

The approach to design the reinforcement of notches in members with rectangular cross-section explained in the following is standardized [20], previous sources include [21] and [22]. The approach is explained in [23], [24] as well as [12]. Preceding works include e.g. [25]. The tensile force perpendicular to the grain, $F_{t,90,d}$, can be approximated by integration of the shear stress in the area between the inner and outer corner of the notch (see shaded area in Fig. 7 right). A derivation of this approach can be found in [27].

A more detailed analysis of the magnitude of the tensile stresses perpendicular to the grain around the notch, using plate theory, has shown that these stresses are increased due to the eccentricity between the support and the inner edge of the notch ([29], [30]). For relationships $x \leq h_{\mathrm{ef}} / 3$ (see Fig. 7), the tensile force perpendicular to the grain, $F_{\mathrm{t,90,d}}$, can be sufficiently estimated by applying an increase factor of 1.3.

The design tensile force, $F_{\mathrm{t,90,d}}$, to be carried by the reinforcement, can be determined according to Eq. (4).

$$F_{t,90,d} = 1.3 \cdot V_d \cdot [3 \cdot (1-\alpha)^2 - 2 \cdot (1-\alpha)^3], \text{ for } x \leq h_{ef}/3 \tag{4}$$

with: $\alpha = h_{ef}/h$

V_d design value of the shear force

The design approach for notched members can also be used for the reinforcement of the tenon part of a dovetail connection, as e.g. applied by [31].

Due to the limited distribution length of the tensile stresses perpendicular to the grain outside the corner of the notch, the distance between the screw and the notch, $a_{3,\mathrm{c}}$, should be minimized, see Fig. 7 left. Only one row of screws at a distance $a_{3,\mathrm{c}}$ should be considered, hence it should be aimed at placing all necessary screws in the first row, utilizing – if necessary – the minimum possible distance a_2 between the screws (see Fig. 4).

The load-carrying capacity of the screw is determined in dependence of the smaller of both anchorage lengths, with $\ell_{\mathrm{ef}} = \ell_{\mathrm{ad}}$.

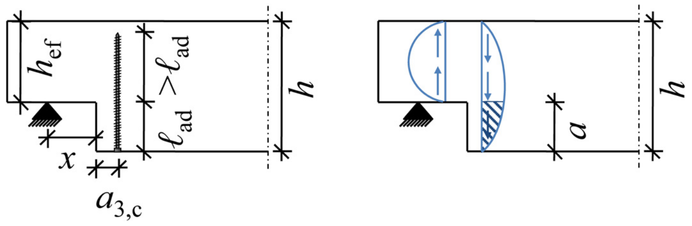


Fig. 7 Notched beam: reinforcement (left) and distribution of shear stresses (right)

Since end-grain is exposed and commonly not sealed at a notch, the superposition of moisture induced stresses and load-dependent tensile stresses perpendicular to the grain around holes can be significant [32]. Therefore, some authors recommend that notched members should always be reinforced, see e.g. [12], [33].

Experiments on notched members reinforced with screws have shown the potential of a crack developing from the corner of the notch. The crack development ends just after it has crossed the screw. The reason for this can be seen in the very small deformation capacity of timber before exceeding the tensile strength perpendicular to grain. Although it could be considered a visual deficiency, such a crack is not a sign of reduced load-carrying capacity of the notched beam.

Recent research [34] indicates that Eq. (4) might not be conservative for all cases since it does not account for shear failure of the reinforced notch. The authors state that a combination of reinforcement to cover both shear and tensile stresses perpendicular to the grain, has a positive effect on the structural behavior of reinforced notched beams.

Recent developments also include self-tapping screws with changing angle of the thread along the screw. Such screws can be used to induce compressive stresses perpendicular to the grain, thereby reducing the effect of load-dependent or moisture induced tensile stresses perpendicular to the grain [35]. The maximum acceptable displacement between the thread and the wood material is limited, implying that this approach could be most adequate for details with localized areas of high tensile stresses perpendicular to the grain. So far, the influence of relaxation on the long-term occurrence of the imposed compressive stresses perpendicular to the grain could not be clarified.

3.3 Reinforcement of members with holes

The approach to design the reinforcement of members with holes explained in the following is standardized [20], previous sources include [21] and [22]. The approach is explained in [23] as well as [24], research on this approach is presented in [36]. Modifications to the approach are explained in [37] and [38]. Modifications constitute the limitation of the permissible relative dimensions of the hole in dependency of the type of reinforcement (e.g. $h_d \leq 0.3 \cdot h$ in case of reinforcement with screws). Information on the behavior of holes in timber beams in general can be found in e.g. [39], [40], [41], [42] and [43].

The tensile force perpendicular to the grain, $F_{t,90,V,d}$, see Eq. (5), can be approximated by integration of the shear stress between the axis of the member and the corner of the hole under tensile stresses perpendicular to the grain as indicated by the shaded area in Fig. 8 right. A derivation of this approach can be found in [27]. Experimental results given in [40] also show a tensile failure perpendicular to the grain at holes in areas without shear. From the experimental results, a tensile force component due to bending moment, $F_{t,90,M,d}$, was determined which has to be added to the force component due to shear. In the case of circular holes, the parameter h_r may be increased by $0.15 \cdot h_d$ to account for the fact that potential fracture will occur at a position described by an angle of 45° from the center line of the hole. The applicable effective anchorage length, $\ell_{ef,}$ is equal to the applicable distance h_r from the edge of hole to the upper/lower edge of the member, given the length of the screw after the potential failure plane exceeds h_r.

$$F_{t,90,d} = F_{t,90,V,d} + F_{t,90,M,d} = \frac{V_d \cdot h_d}{4 \cdot h} \cdot \left[3 - \frac{{h_d}^2}{h^2}\right] + 0.008 \cdot \frac{M_d}{h_r} \tag{5}$$

with:	V_d	design value of the shear force at the edge of the hole
	M_d	design value of the bending moment at the edge of the hole
	a	hole length
	h_d	hole depth
	h_{rl}	distance from lower edge of hole to bottom of member
	h_{ru}	distance from upper edge of hole to top of member
	h_r	$= \begin{cases} \min\{h_{ro}; h_{ru}\} \text{ for rectangular holes} \\ \min\{h_{ro} + 0{,}15 \cdot h_d; h_{ru} + 0{,}15 \cdot h_d\} \text{ for round holes} \end{cases}$
	l_A	support distance of a hole

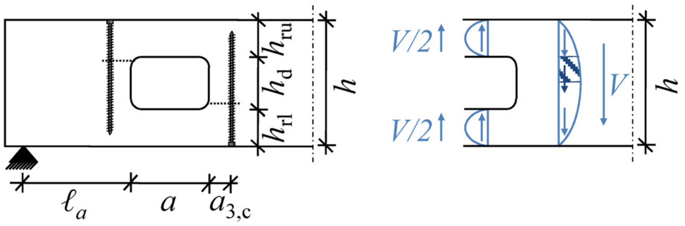


Fig. 8 Beam with hole: reinforcement (left) and distribution of shear stresses (right)

The superposition of moisture induced stresses and load-dependent tensile stresses perpendicular to the grain around holes can be significant [32], in particular if the end-grain in the holes is not sealed. Therefore, some authors recommend that members with holes should always be reinforced, see e.g. [33]. In most cases, the necessity to reinforce holes will be given by the geometrical boundary conditions for unreinforced holes ($h_d \leq 0.15 \cdot h$). With respect to geometric considerations for the reinforcement, e.g. distances, the specifications given in 3.2 apply.

It shall be emphasized that besides the reinforcement with screws also a verification of the shear strength of the timber in the vicinity of the hole is required. The distribution of the shear stresses in the vicinity of the hole deviates considerably (polynomial stress distribution instead of parabolic stress distribution), its maxima can reach significantly higher values compared to the values determined according to beam theory. A description as well as an associated design equation is given in [24], see Eq. (6). In [44] it is recommended to apply the same verification for round holes as well. In the same publication, a method is described to verify the bending stresses above or below rectangular holes, including the additional longitudinal stresses from the frame action (lever of the shear force) around the hole (see also [40]).

$$\tau_{\max} = \kappa_{\max} \cdot \frac{1{,}5 \cdot V_d}{b \cdot (h - h_d)} = 1{,}84 \cdot \left[1 + \frac{a}{h}\right] \cdot \left(\frac{h_d}{h}\right)^{0.2} \cdot \frac{1{,}5 \cdot V_d}{b \cdot (h - h_d)} \tag{6}$$

with: $\kappa_{\max}$ factor to take account for the increased shear stresses
in the area of the edge of the hole
description of terms see Eq. (5)
$\mathrm{h_d}$ may be replaced by $0.7 \cdot \mathrm{h_d}$ in case of round holes

3.4 Reinforcement of double tapered, curved and pitched cambered beams

Double tapered, curved and pitched cambered beams mostly feature beam depths which exceed the maximum length of self-tapping screws. An alternative reinforcement is given by threaded rods which are produced in lengths of up to 3000 mm and installed by aid of pre-drilling with the core diameter. Threaded rods featuring screw threads constitute a modification of self-tapping, fully threaded screws, i.e. the main specifications given above apply.

A standardized approach to design the reinforcement of curved and pitched cambered beams is given in [20], previous sources include [21] and [22]. The approach is explained in [23]. It is differentiated between reinforcement to carry the full tensile stresses perpendicular to the grain and reinforcement to only carry the tensile stresses perpendicular to the grain from climatic conditions, i.e. the moisture induced tensile stresses perpendicular to the grain.

The first approach is based on an integration of the sum of tensile stresses perpendicular to the grain in the plane of zero longitudinal stresses. The equations given in [3] (based on [45]) only provide the maximum tensile stresses perpendicular to the grain in the apex. Depending on the form and loading of the beam, the tensile stresses perpendicular to the grain decrease with increasing distance from the apex. They even spread to some extent into the straight parts of the beam, see Fig 9 and [46]. In [47] and [48], these results were verified and extended to beams with mechanically fixed apex, see Fig 9 below right. For simplification, reinforcement in the inner quarters of the area exposed to tensile stresses perpendicular to the grain is designed for the full tensile stresses perpendicular to the grain, see Eq. (7).

$$F_{t,90,d} = \frac{\sigma_{t,90,d} \cdot b \cdot a_1}{n} \tag{7}$$

with:
$F_{t,90,d}$ design tensile force perpendicular to grain in the reinforcement
$\sigma_{t,90,d}$ design tensile stress perpendicular to grain
b beam width, in [mm]
a_1 distance between fasteners in grain direction
n number of reinforcing fasteners within a_1

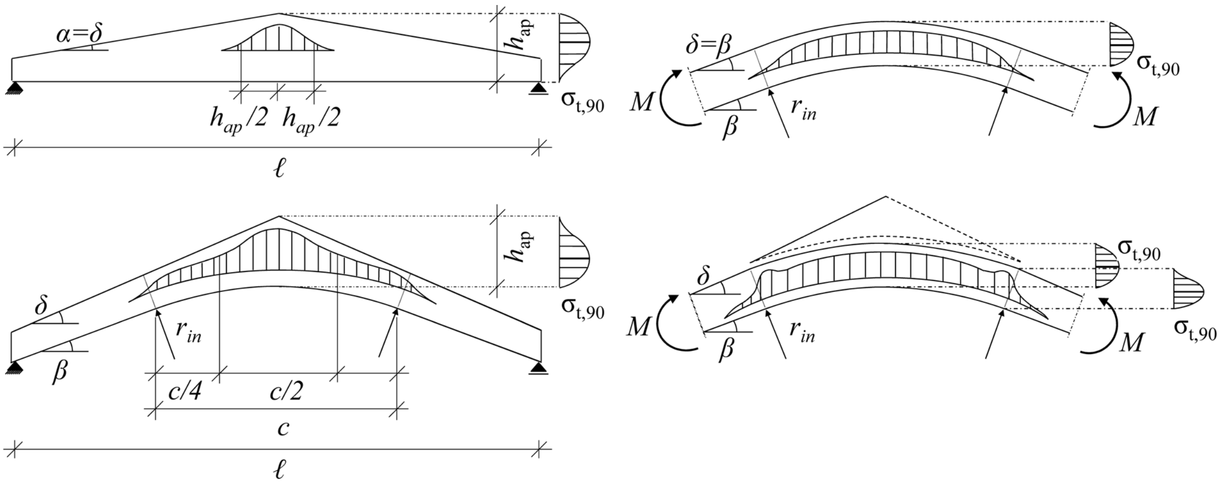


Fig. 9 Distribution of tensile stresses perpendicular to the grain over the beam depth and length in double tapered (above left), curved (above right), pitched cambered (below left) and cuved beam with mechanically fixed apex, i.e. secondary apexes (below right)

In the outer quarters, the tensile stresses perpendicular to the grain are assumed to reach 2/3 of the maximum tensile stresses perpendicular to the grain determined with Eq. (7), see Fig 9.. The spacing between the reinforcement is limited to $a_1 \leq 0.75 \cdot h_{ap}$ (h_{ap} as height of the apex) to ensure that the whole area exposed to tensile stresses perpendicular to the grain is covered by reinforcement.

Even if the requirements regarding systematic, load-dependent tensile stresses perpendicular to the grain can be met, see [3], it is state of the art to reinforce double tapered, curved and pitched cambered beams. 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. [49], [50]. In the lack of a method to reliably predict the magnitude of tensile stresses perpendicular to the grain, it is custom to apply reinforcement if the maximum load-dependent tensile stresses perpendicular to the grain exceeded 60 % of the design tensile strength of the timber member perpendicular to the grain. Some authors recommend that double tapered, curved and pitched cambered beams are always reinforced, independent from the magnitude of tensile stresses perpendicular to the grain, see e.g. [33]. Eq. (8) represents one approach to design reinforcements to carry moisture induced tensile stresses perpendicular to the grain ([20], [21] and [44]). It is based on the assumption that 1/4 of the tensile stresses perpendicular to the grain from external loads are carried by the reinforcement. It is also based on the assumption that the potential magnitude of moisture induced stresses increases with increasing member width, i.e. increases due to decelerated adaption of timber moisture content in the interior of the cross-section. For a member width $b = 160$ mm, Eq. (8) lends ¼ of the full reinforcement determined by Eq. (7), less reinforcement for smaller member widths and more reinforcement for larger member widths.

$$F_{t,90,d} = \frac{\sigma_{t,90,d} \cdot b^2 \cdot a_1}{640 \cdot n} \tag{8}$$

In the case of reinforcement to carry the tensile stresses perpendicular to the grain from climatic conditions, the spacing between the reinforcement should be kept constant. It is recommended that the spacing is limited to the member depth [44].

Recent research has begun to examine the question of the influence of reinforcement on the magnitude of moisture induced stresses since reinforcement restricts the free shrinkage or swelling of the timber beam. Experimental studies (short-term tests) and analytical considerations, presented in [51] and [52], indicate that a reduction of timber moisture content of 3 % to 4 % around threaded rods, positioned perpendicular to the grain, can lead to critical stresses with respect to moisture induced cracks. In addition, a substantial mutual influence of adjacent reinforcing elements could be identified. Experiments on drying glulam members reinforced by screwed-in threaded rods placed perpendicular to the grain are presented in [53]. The results indicate that moisture induced stresses in the timber can lead to forces in the reinforcement in the order of the steel capacity of the rods.

3.5 Reinforcement of connections with a tensile force component parallel to the grain

The load-carrying capacity of connections with multiple fasteners in one row parallel to the grain can be lower than the sum of the load-carrying capacities of the single fasteners (depending on the fastener distances parallel to the grain). This is due to the splitting forces (tensile stresses perpendicular to the grain) induced by the fasteners. The tendency to splitting increases with decreasing spacing of the fasteners parallel to the grain, a_1 (Fig. 10). In the codes, this is accounted for by an effective number of fasteners, n_{ef}, [3] (based on [54]). Placing self-tapping screws with continuous thread perpendicular to the fastener axis and to the grain direction may prevent splitting, i.e. $n_{ef} = n$ may be used, see Fig. 10. The closer the screw is placed to the dowel-type fastener, the better the effect. Since the splitting force is highest close to the joint between two connected members, the screws should be positioned with a minimum edge distance, $a_{4,c}$, see Fig. 10 right. In [44] it is recommended to design the self-tapping screws for an axial force of 30 % of the load transferred by each dowel-type fastener and shear plane.

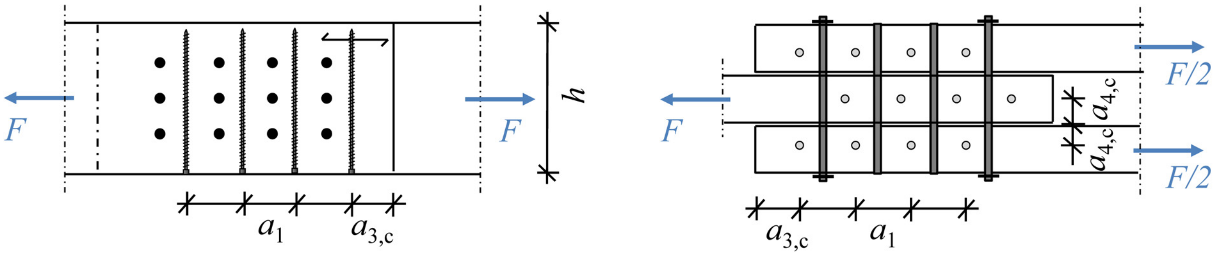


Fig. 10 Reinforcement of dowel-type connections

According to [55], [56] as well as [57], the load-carrying capacity of dowel-type connections, reinforced with self-tapping screws with continuous thread can be further increased, if the screw is in direct contact with the dowel-type fastener. This necessitates very exact positioning which is not always feasible. Pre-drilling can have a positive effect on the precision of screw positioning.

4. Self-tapping screws as reinforcement to carry compressive stresses perpendicular to the grain

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 are a means to improve the stress dispersion into the timber, see Fig. 11. Research on this type of reinforcement is presented in [56], background information as well as a design approach is presented in [58].

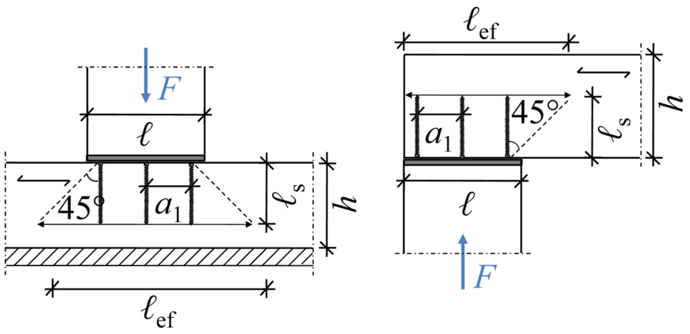


Fig. 11 Reinforcement of support areas

The load-carrying capacity of a reinforced support can be determined under the assumption of an interaction between the timber under compressive stresses perpendicular to the grain and the screws under compression, see Eq. (9). This assumption is valid if certain deformations of the loaded edge are accepted. In addition 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), i.e. at a distance equaling the point side penetration depth, ℓ_S, of the screw. For this, an angle of stress distribution of 45° may be applied. On the safe side, this angle should be measured from the screw heads, see Fig. 11. Here, the factor $k_{c,90}$ shall be taken as $k_{c,90} = 1.0$.

$$F_{90,Rd} = \min \begin{cases} F_{c,90,Rd} + n_S \cdot F_{ax,Rd} \\ b \cdot l_{ef} \cdot f_{c,90,d} \end{cases} \qquad (9)$$

with:

$F_{90,Rd}$	design force perpendicular to grain with reinforcement
$F_{c,90,Rd}$	design compression perp. to grain capacity without reinforcement, with $F_{c,90,Rd} = k_{c,90} \cdot b \cdot l \cdot f_{c,90,d}$ (see [2])
$F_{ax,Rd}$	design axial load-carrying capacity according to Eq. (1) (without $R_{t,Rk}$)
$f_{c,90,d}$	design compression perp. to grain strength
$k_{c,90}$	factor adjusting compression perp. to grain strength to real design situations (see [3])
n_S	total number of screws
b	beam width (support width $\geq b$)
l	length
l_{ef}	effective length
l_s	point side penetration length

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, see Tab. 1 and Fig. 4.

5. Self-tapping screws as reinforcement to carry shear stresses in glued-laminated timber and cross-laminated timber

5.1 Reinforcement of glued-laminated timber against shear stresses

The shear strength of timber is in the range of five times the magnitude of tension perpendicular to the grain strength. However, there can be applications in which the shear stresses exceed the shear capacity of a timber beam. Examples are double tapered or pitched cambered beams, where the changing depth leads to high shear stresses in the area of the supports, see Fig. 12. With respect to an economic use of reinforcing elements it is of interest, whether a proportionate distribution of shear stresses between the timber beam and the shear reinforcement can be achieved in the unfractured state. In [51] (see also [59] and [60]), an analytical approach is proposed to determine the load-carrying capacity of timber beams in the uncracked state, featuring shear reinforcement like screws or threaded rods. This approach is based on common theoretical concepts and constitutive equations for material properties and enables the incorporation of the semi-rigid composite action between the reinforcement and wood material, as well as the interaction of shear stresses and stresses perpendicular to the grain. The applicability and accuracy of the approach is verified by laboratory tests, also taking into account research carried out and presented in [18]. It appears that the redistribution of load from the timber to the shear reinforcement is comparatively low. Considering the uncracked state, comparative calculations indicate that, under realistic construction conditions, an increase in shear capacity of up to 20 % is feasible.

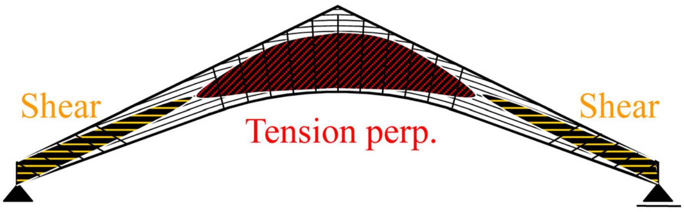
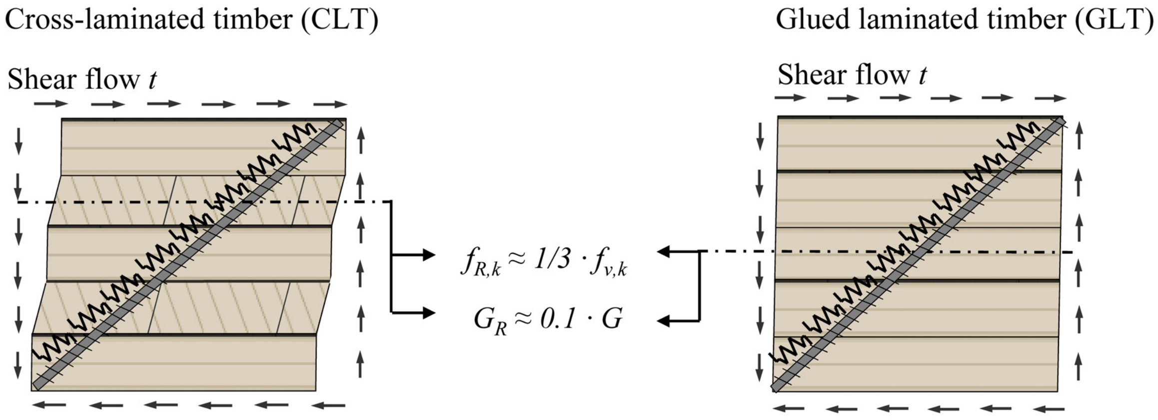


Fig. 12 Pitched cambered beam – potential reinforcement zones (from [59])

Since wood is characterized by very brittle failure mechanisms both in shear and tension perpendicular to the grain, it is beneficial to design the corresponding reinforcements so that they are able to also carry the corresponding stresses in the fractured state, see e.g. [61]. The shear analogy ([62], [63], [64]) represents an applicable approach to calculate the semi-rigid composite action between both sections in the fractured state. A numerical study on highly stressed shapes of glulam beams (see [51] and [59]), featuring the minimum required reinforcement to carry the stresses that are released in the case of cracking shows, that the maximum increase in bending stresses between the intact state and the fractured state is in the range of one third.

5.2 Reinforcement of cross-laminated timber against shear stresses

The load-carrying capacity of cross-laminated timber (CLT) elements can be limited by the rolling shear strength, which is in the range of only 1/3 of the shear strength of softwood parallel to the grain, see Fig. 13. Possible examples are CLT elements loaded out of plane under high concentrated loads or point supports. Fully threaded, self-tapping screws used as shear reinforcement can have a distinct positive influence on the shear capacity of CLT elements. The reason is that CLT elements feature significantly larger shear deformations than GLT elements. This can mainly be explained with the low rolling shear modulus of the transverse layers ($G_R \approx 0.1 \cdot G$), see Fig. 13. This results in a larger share of the screws in the proportionate distribution of shear stresses between the timber beam and the shear reinforcement.


Cross-laminated timber (CLT)

Glued laminated timber (GLT)

$f_{R,k}$: rolling shear strength (perpendicular to the grain)
G_R: rolling shear modulus (perpendicular to the grain)

$f_{v,k}$: shear parallel to grain strength
G: shear modulus parallel to grain

Fig. 13 Shear reinforcement of CLT and GLT – deformation and strength capacities, from [60]

In [65] and [66] a design concept is proposed which is validated by means of experiments, see also [67]. The concept is based on a strut-and-tie model and takes into account the positive influence of the interaction of compression perpendicular to the grain and rolling shear stresses, by a factor $k_{R,90}$, as well as the load-carrying capacity of the screws in direction of the potential fracture plane, see Eq. (10) and Fig. 14. In [67] it could also be shown that in the case of biaxial load transfer, additional effects are activated, leading to an increase in the rolling shear capacity compared to that of beam elements.

$$\overline{f}_{R,k} = k_{R,90} \cdot f_{R,k} + \frac{R_{ax,k} \big/ \sqrt{2}}{\sqrt{2} \cdot a_1 \cdot a_{2,ef}} \tag{10}$$

with: $k_{R,90} = \min \begin{cases} 1 + 0{,}35 \cdot \sigma_{c,90} \\ 1{,}20 \end{cases}$ and $\sigma_{c,90} = \dfrac{R_{ax,k} \big/ \sqrt{2}}{\sqrt{2} \cdot a_1 \cdot a_{2,ef}}$

$\overline{f}_{R,k}$	characteristic load-carrying capacity of the reinforced CLT under stress	[N/mm^2]
$f_{R,k}$	characteristic rolling shear capacity (according to technical approvals)	[N/mm^2]
$R_{ax,k}$	characteristic load-carrying capacity of a screw parallel to its axis	[N]
a_1	distance between screws parallel to the load-bearing direction	[mm]
$a_{2,ef}$	effective distance between screws perpendicular to the load-bearing direction	[mm]
l_{ef}	effective embedment length of the screws for calculation of $R_{ax,k}$	[mm]
$k_{R,90}$	parameter for the consideration of the stress interaction	[-]

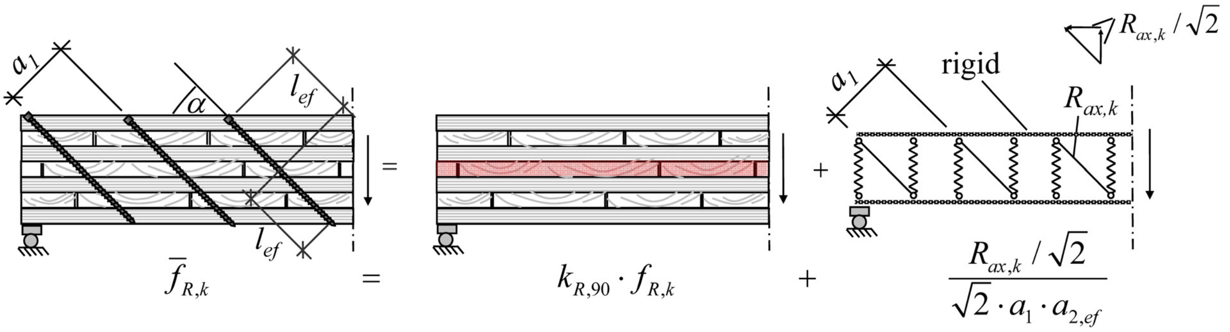


Fig. 14 Design concept for shear reinforcement in CLT on the basis of a strut and tie model, adapted from [65]

6. Self-tapping screws to realize mechanically jointed beams

Fully threaded, self-tapping screws can also be used to strengthen existing beams by mechanically joining an additional cross-section to the existing beam. Screws feature significantly higher axial slip moduli, $K_{ax,ser}$, compared to slip moduli in shear, K_{ser}, see Fig. 15. Therefore they should be positioned at an angle to the joint (e.g. 45°), to enable axial loading of the screw, see Fig. 16. Models for calculation of these slip moduli can be found in e.g. [17], see Eq. (2) and [68] and [69].

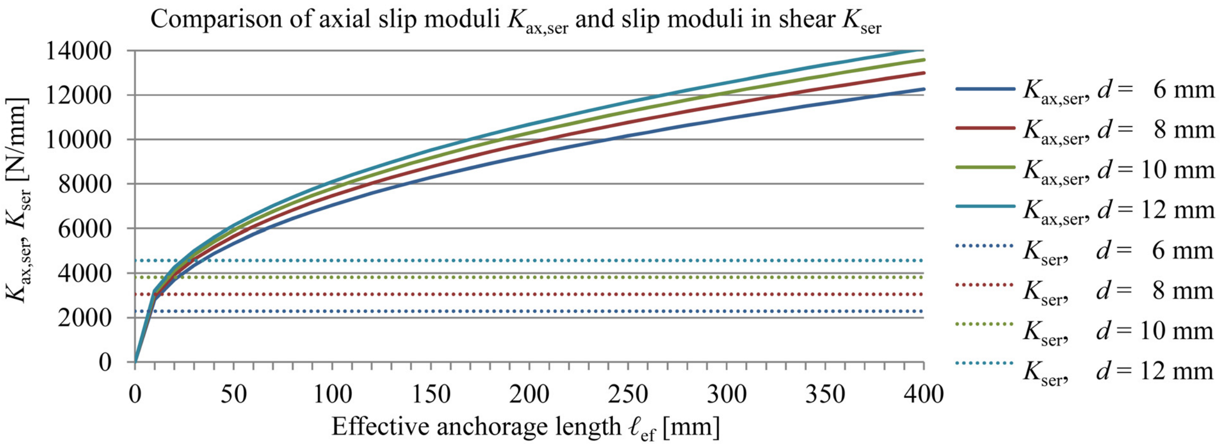


Fig. 15 Comparsion of axial slip moduli $K_{ax,ser}$ (see Eq. (2)) and slip moduli in shear K_{ser} (see [3]) for different screw diameters and lengths.

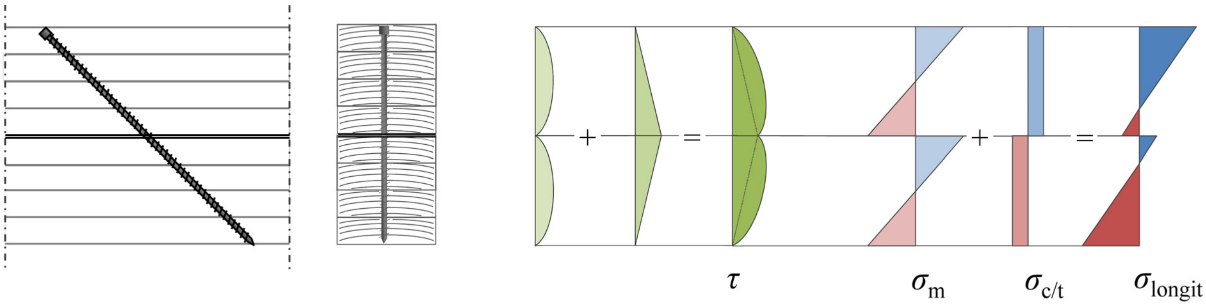


Fig. 16 Example of two cross-sections, mechanically jointed by screws incl. schematic illustration of composition of shear stresses and longitudinal stresses

A common, standardized method [3] to design such beams is the “gamma-method” [70]. The coefficient γ symbolizes the efficiency of the connection ($\gamma = 1 \rightarrow$ rigid connection, $\gamma = 0 \rightarrow$ no connection). It is used to determine an effective moment of inertia of the beam with which the stresses in the beam as well as the shear flow in the joint can be determined. For cases, in which the basic assumptions for the “gamma-method” are not met (e.g. continuous joint stiffness and cross-section, single-span or symmetric continuous beams), an alternative is given by the “shear analogy method” [62], [63] and [64].

The timber members to be connected by screws should be fixed in their position so that no gap occurs in the joint when the screws are driven in. If the screws are positioned so that they are loaded in axial tension, they could close a potential gap due to a rope-effect. Another option is to place the screws crosswise, i.e. one screw is mainly loaded in axial tension, and the other screw is mainly loaded in axial compression. The shear flow in the joint can be distributed to the screws using a triangle of forces. When determining the joint stiffness of a mechanically jointed beam, the slip moduli of the threaded parts of the screws in both beams have to be accounted for. For common types of mechanically jointed beams with self-tapping screws (e.g. [8]-[10]) set at an angle between screw axis and fibre direction of 45°, i.e. loaded primarily in axial direction, values in the range of $\gamma = 0.8$ can be obtained.

7. Conclusions and remarks

Fully-threaded, self-tapping screws represent the latest developments in screwing technology for timber engineering, providing a significant load-carrying capacity if loaded in axial direction. The screws enable stiff connections but limited plastic potential. Apart from their obvious application as fasteners in timber connections, fully-threaded, self-tapping screws feature a high potential for numerous reinforcement applications. An overview of possibilities and related design procedures is given, including relevant literature for background information.

For numerous applications, design procedures exist, which have already been clarified to an extent satisfying engineering needs, e.g. reinforcement taking the full tensile stresses perpendicular to the grain. Other applications are well developed but require some additional research, e.g. reinforcement approaches which consider proportional load sharing between the timber and the reinforcement, including the modelling of stiffness properties (K_{ser}, $K_{ax,ser}$, K_u), as well as reinforcement against compressive stresses perpendicular to the grain. However, there is a need for further efforts in research, e.g. considering the potentially harmful effect of reinforcement restricting the free shrinkage or swelling of the timber.

Although fully threaded, self-tapping screws have undoubtedly a great potential for use in timber structures, should their potential application as reinforcement always be considered with care. For centuries, excellent timber structures have been designed without the need for reinforcement.

Wood features a multitude of positive characteristics in view of its application as building material, i.e. a general reinforcement of timber elements – as known from concrete structures – is not necessary. Although recent developments have largely increased the range and forms of structures to be realized with timber products, good design of timber structures should still aim at minimizing stresses for which timber only features 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.

8. References

[1] Steiger, R., Serrano, E. et al., "Strengthening of timber structures with glued-in rods", Construction and Building Materials, *this issue*, 2015

[2] DIN 7998:1975-02, *Threads and Thread Ends for Wood Screws*, DIN, Berlin, 1975.

[3] EN 1995-1-1:2004-11, *Eurocode 5: Design of timber structures – Part 1-1: General – Common rules and rules for buildings*, CEN, Brussels, 2004.

[4] Mahlknecht, U., Brandner, R., Ringhofer, A., Schickhofer G., „Resistance and Failure Modes of Axially Loaded Groups of Screws", in: *Proceedings of the RILEM Timber Structures Conference „Materials and Joints in Timber Structures – Recent Advancement of Technology"*, Stuttgart, Germany, 2013.

[5] Pirnbacher, G., Schickhofer G., „Schrauben im Vergleich – eine empirische Betrachtung", in: *Proceedings of the 6. Grazer Holzbau-Fachtagung (6. GraHFT'07) „Verbindungstechnik im Ingenieurholzbau"*, F 1–22, Graz, Austria, 2007.

[6] Dietsch, P., Winter, S., "Eurocode 5 – Future Developments towards a More Comprehensive Code on Timber Structures", *Structural Engineering International*, Vol. 21, No. 2, 2012, pp. 223-231.

[7] EN 14592:2012-05, *Timber structures – Dowel type fasteners – Requirements*, CEN, Brussels, 2012.

[8] ETA-12/0062, *SFS intec AG: Self-tapping screws for use in timber constructions*, European Technical Approval, OIB, p. 17, 18.06.2012.

[9] ETA-11/0112, *SPAX International GmbH & Co. KG: Self-tapping screws for use in timber constructions*, European Technical Approval, ETA-Danmark, p. 84, 05.09.2012.

[10] ETA-11/0190, *Adolf Würth GmbH & Co. KG: Self-tapping screws for use in timber constructions*, European Technical Approval, DIBt, p. 99, 27.06.2013.

[11] Pirnbacher, G., Brandner, R., Schickhofer, G., „Base Parameters of Self-Tapping Screws", *CIB-W18 / 42-7-1, Proceedings of the international council for research and innovation in building and construction*, Working commission W18 – timber structures, Meeting 42, Duebendorf, Switzerland, 2009.

[12] Colling, F., *Holzbau – Grundlagen und Bemessung nach EC5*, 3. Auflage, Springer Vieweg, ISBN 978-3-8348-1789-1, 2012.

[13] Ringhofer, A., Brandner, R., Schickhofer, G., „Entwicklung einer optimierten Schraubengeometrie für hochbeanspruchte Stahl-Holz-Verbindungen“, *Bautechnik*, Vol. 91, No. 1, 2014, pp. 31-37

[14] Enders-Comberg, M., Blaß, H.J., “Influence of fasteners in the compression area of timber members”, *CIB-W18 / 46-7-8, Proceedings of the international council for research and innovation in building and construction*, Working commission W18 – timber structures, Meeting 46, Vancouver, Canada, 2013.

[15] Ringhofer, A., Grabner, M., Brandner, R., Schickhofer, G., *„SGSC 3.2.1_1 – Prüftechnische Ermittlung des Tragverhaltens der Einzelschraube in der BSP-Schmalfläche“*, Internal Research Report, holz.bau forschungs gmbh, Institute of Timber Engineering and Wood Technology, Graz University of Technology, 2013.

[16] Krenn, H., Schickhofer, G., „Joints with inclined screws and steel plates as outer members“, *CIB-W18 / 42-7-2, Proceedings of the international council for research and innovation in building and construction*, Working commission W18 – timber structures, Meeting 42, Duebendorf, Switzerland, 2009.

[17] Blaß, H. J., Bejtka, I., Uibel, T., „*Tragfähigkeit von Verbindungen mit selbstbohrenden Holzschrauben mit Vollgewinde*“, Forschungsbericht der Versuchsanstalt für Stahl, Holz und Steine, Abt. Ingenieurholzbau, Universität Karlsruhe (TH), 2006.

[18] Blaß, H.-J., Krüger, O., *Schubverstärkung von Holz mit Holzschrauben und Gewindestangen*, Karlsruher Berichte zum Ingenieurholzbau, Band 15, Universitätsverlag Karlsruhe, 2010.

[19] Brüninghoff, H., Schmidt, C., Wiegand, T., „Praxisnahe Empfehlungen zur Reduzierung von Querzugrissen bei geleimten Satteldachbindern aus Brettschichtholz“, *Bauen mit Holz*, Vol. 95, No. 11, 1993, pp. 928-937.

[20] DIN EN 1995-1-1/NA:2010-12, *National Annex – Nationally determined parameters – Eurocode 5: Design of timber structures – Part 1-1: General – Common rules and rules for buildings*, DIN, Berlin, 2010.

[21] DIN 1052:2008-12, *Entwurf, Berechnung und Bemessung von Holzbauwerken – Allgemeine Bemessungsregeln und Bemessungsregeln für den Hochbau*, DIN, Berlin, 2008.

[22] DIN 1052:2004-08, *Entwurf, Berechnung und Bemessung von Holzbauwerken – Allgemeine Bemessungsregeln und Bemessungsregeln für den Hochbau*, DIN, Berlin, 2004.

[23] Blaß, H.J., Steck, G., „Querzugverstärkungen von Holzbauteilen: Teil 1 – Teil 3“, *Bauen mit Holz*, Vol. 101, No. 3, pp. 42-46, No. 4, pp. 44-49, No. 5, pp. 46-50, 1999.

[24] Blaß, H.J., Bejtka, J., “Reinforcements perpendicular to the grain using self-tapping screws”, in: *Proceedings of the 8th World Conference on Timber Engineering*, Lahti, Finland, 2004.

[25] Möhler, K., Siebert, W., „Untersuchungen zur Erhöhung der Querzugfestigkeit in

gefährdeten Bereichen“, *Bauen mit Holz*, Vol. 86, No. 6, 1984, pp. 388-393.

[26] Ehlbeck, J., Görlacher, R., Werner, H., “Determination of Perpendicular-to-Grain Tensile Stresses in Joints with Dowel Type-Fasteners”, *CIB-W18 / 22-7-2, Proceedings of the international council for research and innovation in building and construction*, Working commission W18 – timber structures, Meeting 22, Berlin, West Germany, 1989.

[27] Kreuzinger, H., „Holzbau“, in: Zilch, K., Diederichs, C.J., Katzenbach, R. (eds.), *Handbuch für Bauingenieure*, Springer, Berlin, 2002.

[28] Mahlknecht, U., Brandner, R., *„focus_sts 3.1.2_1: Untersuchungen des mechanischen Verhaltens von Schrauben – Verbindungsmittelgruppen in VH, BSH und BSP“*, Internal Research Report, holz.bau forschungs gmbh, Institute of Timber Engineering and Wood Technology, Graz University of Technology, 2013.

[29] Henrici, D., *Beitrag zur Spannungsermittlung in ausgeklinkten Biegeträgern aus Holz*, Dissertation, Technische Universität München, 1984.

[30] Henrici, D., „Beitrag zur Bemessung ausgeklinkter Brettschichtholzträger“, *Bauen mit Holz*, Vol. 92, No. 11, 1990, pp. 806-811.

[31] Tannert, T., Lam, F.; “Self-tapping screws as reinforcement for rounded dovetail connections”, *Structural Control and Health Monitoring*, Vol. 16, No. 3, 2009, pp. 374-384.

[32] Gustafsson, P.J., “Notched beams and holes in glulam beams”, in: Blaß, H.J., Aune, P., Choo, B.S., et al. (eds). *Timber Engineering STEP 1 – Basis of design, material properties, structural components and joints*, Centrum Hout, Almere, 1995

[33] Neuhaus, H.; *Ingenieurholzbau – Grundlagen, Bemessung, Nachweise, Beispiele*, 3. Auflage, Vieweg&Teubner, ISBN 978-3-8348-1286-5, 2010.

[34] Jockwer, R., Frangi, A., Steiger, R., Serrano, E., “Enhanced design approach for reinforced notched beams”, *CIB-W18/ 46-6-1, Proceedings of the international council for research and innovation in building and construction*, Working commission W18 – timber structures, Meeting 46, Vancouver, Canada, 2013.

[35] Steilner, M., Blaß, H.J., „Vorspannen von Holz mit Vollgewindeschrauben“, *Proceedings 17. Internationales Holzbau-Forum*, Garmisch-Partenkirchen, 2011.

[36] Blaß, H.J., Bejtka, I., *Querzugverstärkungen in gefährdeten Bereichen mit selbstbohrenden Holzschrauben*, Forschungsbericht der Versuchsanstalt für Stahl, Holz und Steine, Abt. Ingenieurholzbau, Universität Karlsruhe (TH), 2003.

[37] Aicher, S., Höfflin, L., “Glulam Beams with Holes Reinforced by Steel Bars”, *CIB-W18 / 42-12-1, Proceedings of the international council for research and innovation in building and construction*, Working commission W18 – timber structures, Meeting 42, Duebendorf, Switzerland, 2009.

[38] Aicher, S., “Glulam Beams with Internally and Externally Reinforced Holes – Test, Detailing and Design”, CIB-W18 / *44-12-4, Proceedings of the international council for research and innovation in building and construction*, Working commission W18 – timber structures, Meeting 44, Alghero, Italy, 2011.

[39] Kolb, H., Frech, P., „Untersuchungen an durchbrochenen Bindern aus Brettschichtholz“,

Holz als Roh- und Werkstoff, Vol. 35, No. 4, pp. 125-134

[40] Kolb, H., Epple, A., *Verstärkungen von durchbrochenen Brettschichtholzbindern*, Schlussbericht zum Forschungsvorhaben I.4 – 34810, Forschungs- und Materialprüfungsanstalt Baden-Württemberg, Stuttgart, 1985.

[41] Aicher, S., Höfflin, L., "Glulam Beams with Round Holes – a Comparison of Different Design Approaches vs. Test Data", *CIB-W18 / 35-12-1, Proceedings of the international council for research and innovation in building and construction*, Working commission W18 – timber structures, Meeting 35, Kyoto, Japan, 2002.

[42] Aicher, S., Höfflin, L., "Design of rectangular holes in glulam beams", *Otto-Graf-Journal*, Vol. 14, 2003, pp. 211-229.

[43] Aicher, S., Höfflin, L., Reinhardt, H.-W., „Runde Durchbrüche in Biegeträgern aus Brettschichtholz, Teil 2: Tragfähigkeit und Bemessung", *Bautechnik*, Vol. 84, No. 12, 2007, pp. 867-880.

[44] Blaß, H.J., Ehlbeck, J., Kreuzinger, H., Steck, G., *Erläuterungen zu DIN 1052:2004-08*, Bruderverlag, Karlsruhe, 2004.

[45] Blumer, H., *Spannungsberechnungen an anisotropen Kreisbogenscheiben und Satteltträgern konstanter Dicke*, Lehrstuhl für Ingenieurholzbau und Baukonstruktionen, Universität Karlsruhe, 1972/1979.

[46] Ehlbeck, J, Kürth, J., „Influence of perpendicular-to-grain stressed volume on the load-carrying capacity of curved and tapered glulam beams", *CIB-W18 / 24-12-2, Proceedings of the international council for research and innovation in building and construction*, Working commission W18 – timber structures, Meeting 24, Oxford, United Kingdom, 1991.

[47] Moser, M., *Theoretische Betrachtung der Berechnungsgrundlagen für auf Querzug beanspruchte BSH-Bauteile*, Master Thesis, Institute of Timber Engineering and Wood Technology, Graz University of Technology, 2012.

[48] Dietsch, P., Winter, S.; *Untersuchung von nicht in DIN EN 1995-1-1 geregelten Formen von Satteldachträgern im Hinblick auf den Nachweis der Querzugspannungen,* Research Report, Lehrstuhl für Holzbau und Baukonstruktion, Technische Universität München, 2014.

[49] Gowda, S, Ranta-Maunus, A., *Curved and cambered glulam beams - Part 1: Short term load Tests*, Research Notes 1500, Technical Research Centre of Finland, Espoo, 1993.

[50] Dietsch, P., Gamper, A., Merk, M., Winter, S.; "Building Climate – long-term measurements to determine the effect on the moisture gradient in large-span timber structures", *CIB-W18 / 45-11-1, Proceedings of the international council for research and innovation in building and construction*, Working commission W18 – timber structures, Meeting 45, Växjö, Sweden, 2012.

[51] Dietsch, P., *Einsatz und Berechnung von Schubverstärkungen für Brettschichtholzbauteile,* Dissertation, Technische Universität München, 2012.

[52] Dietsch, P., Kreuzinger, H., Winter, S.; "Effects of changes in moisture content in reinforced glulam beams", in: *Proceedings of the 13th World Conference on Timber*

Engineering, Quebec, Canada, 2014.

[53] Wallner, B., *Versuchstechnische Evaluierung feuchteinduzierter Kräfte in Brettschichtholz verursacht durch das Einbringen von Schraubstangen*, Master Thesis, Institute of Timber Engineering and Wood Technology, Graz University of Technology, 2012.

[54] Jorissen, A.J.M., *Double shear timber connections with dowel type fasteners*, Dissertation, Delft University of Technology, Netherlands, 1998.

[55] Bejtka, I., Blaß, H.J., "Self-tapping screws as reinforcements in connections with dowel-type fasteners", *CIB-W18 / 38-7-4, Proceedings of the international council for research and innovation in building and construction*, Working commission W18 – timber structures, Meeting 38, Karlsruhe, Germany, 2005.

[56] Bejtka, I., *Verstärkung von Bauteilen aus Holz mit Vollgewindeschrauben*, Dissertation, Band 2 der Reihe Karlsruher Berichte zum Ingenieurholzbau, KIT Scientific Publishing, Karlsruhe, 2006.

[57] Kobel, P., *Modelling of strengthened connections for large span truss structures*, Master Thesis, Institute of Structural Engineering, ETH Zürich, Switzerland & Division of Structural Engineering at Lund University/LTH, Sweden2011.

[58] Bejtka, I., Blaß, H.J., "Self-tapping screws as reinforcements in beam supports", *CIB-W18/ 39-7-2, Proceedings of the international council for research and innovation in building and construction*, Working commission W18 – timber structures, Meeting 39, Florence, Italy, 2006.

[59] Dietsch, P., Kreuzinger, H., Winter, S., "Design of shear reinforcement for timber beams", *CIB-W18/ 46-7-9, Proceedings of the international council for research and innovation in building and construction*, Working commission W18 – timber structures, Meeting 46, Vancouver, Canada, 2013.

[60] Dietsch, P., Mestek, P., Winter, S., "Analytischer Ansatz zur Erfassung von Tragfähigkeitssteigerungen infolge von Schubverstärkungen in Bauteilen aus Brettschichtholz und Brettsperrholz", *Bautechnik*, Vol. 89, No. 6, 2012, pp. 402-414.

[61] Dietsch, P., "Robustness of large-span timber roof structures – Structural aspects", *Engineering Structures*, Vol. 33, No. 11, 2011, pp. 3106-3112.

[62] Kreuzinger, H., „Platten, Scheiben und Schalen – ein Berechnungsmodell für gängige Statikprogramme“, *Bauen mit Holz*, Vol. 101, No. 1, 1999, pp. 34-39.

[63] Kreuzinger, H., „Verbundkonstruktionen“, in: *Holzbaukalender 2002*, Bruderverlag, Karlsruhe, 2001, pp. 598-621.

[64] Kreuzinger, H., "Mechanically Jointed Beams: Possibilities of Analysis and some special Problems", *CIB-W18 / 34-12-7, Proceedings of the international council for research and innovation in building and construction*, Working commission W18 – timber structures, Meeting 34, Venice, Italy, 2001.

[65] Mestek, P., Kreuzinger, H., Winter, S., "Design Concept for CLT – Reinforced with Self-Tapping Screws", *CIB-W18/ 44-7-2, Proceedings of the international council for research and innovation in building and construction*, Working commission W18 – timber structures, Meeting 44, Alghero, Italy, 2011.

[66] Mestek, P., Winter, S., „Punktstützung von Brettsperrholzkonstruktionen – Schubverstärkungen mit Vollgewindeschrauben“, *Bauingenieur*, Vol. 86, No. 12, 2011, pp. 529-540.

[67] Mestek, P., *Punktgestützte Flächentragwerke aus Brettsperrholz (BSP) – Schubbemessung unter Berücksichtigung von Schubverstärkungen*, Dissertation, Technische Universität München, 2011.

[68] Kevarinmäki, A., “Joints with inclined screws”, *CIB-W18 / 35-7-4, Proceedings of the international council for research and innovation in building and construction*, Working commission W18 – timber structures, Meeting 35, Kyoto, Japan, 2002.

[69] Tomasi, R., Crosatti, A., Piazza, M. "Theoretical and experimental analysis of timber-to-timber joints connected with inclined screws", *Construction and Building Materials*, Vol. 24, 2010, pp. 1560-1571.

[70] Möhler, K., *Über das Tragverhalten von Biegeträgern und Druckstäben mit zusammengesetzten Querschnitten und nachgiebigen Verbindungsmitteln*, Habilitation, Universität Karlsruhe, 1956.