Reinforcements perpendicular to the grain using self-tapping screws

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Summary

This paper shows the efficiency of screws used as tensile and compressive reinforcements perpendicular to the grain. Fully threaded screws used as reinforcements in notched beam supports, connections with load components perpendicular to the member axis and beams with holes are designed using the same principles as for conventional reinforcements as e.g. glued-in rods. For reinforced beams with holes, an extended design model to take into account the shear stress peaks close to the hole is proposed. Further on, for reinforced beam supports a calculation model is proposed to design the self-tapping screws as compressive reinforcement.

Keywords: Self-tapping screw, reinforcement, beam with hole, notched beam, connection with load component perpendicular to the member axis, beam support, connection with multiple fasteners, tensile strength, compressive strength

1. Introduction

The tensile and the compressive strengths of timber perpendicular to the grain are much lower than the respective strength values parallel to the grain. The characteristic tensile strength perpendicular to the grain for solid timber is about 1/25 to 1/60 of the tensile strength parallel to the grain. The ratio of the characteristic compressive strength perpendicular to the grain to the compressive strength parallel to the grain for solid timber is about 1/8. Timber structures hence should be detailed in order to minimise tensile and compressive stresses perpendicular to the grain.

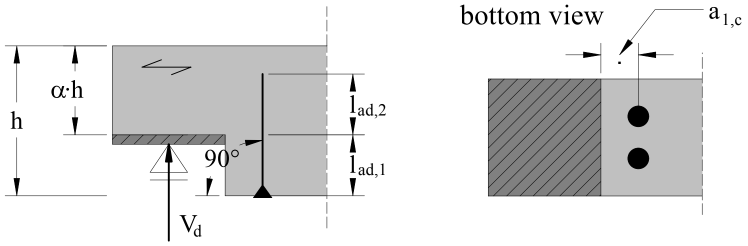
Examples for structural details where tensile stresses perpendicular to the grain occur are notched beam supports, connections with load components perpendicular to the member axis, beams with holes as well as connections with multiple fasteners in a row. An example for a structural detail with compressive stresses perpendicular to the grain is a beam support. Glued-in threaded rods and glued-on plywood plates are traditionally used as reinforcements. Screws with continuous threads present an alternative to the traditional reinforcement methods and show new and economic possibilities as reinforcements in connections and beam supports. With diameters up to 12 mm and lengths up to 600 mm, fully threaded screws may be used in many structural members as tensile and compressive reinforcements perpendicular to the grain.

2. Self-tapping screws as tensile reinforcements perpendicular to the grain

2.1 State of the art

The load-carrying capacities for notched beam supports, for connections with load components perpendicular to the member axis as well as for beams with holes reinforced with self-tapping screws may be calculated using the same models used for conventional reinforcements. The calculation model generally assumes that the load component perpendicular to the grain is entirely transmitted by tensile forces in the reinforcing screws. The tensile strength perpendicular to the grain of the timber is not taken into account. Consequently, the withdrawal capacity $R_{ax,d}$ and the tensile strength of the screw are the only parameters determining the load-carrying capacity for reinforced structural details where tensile stresses perpendicular to the grain occur.

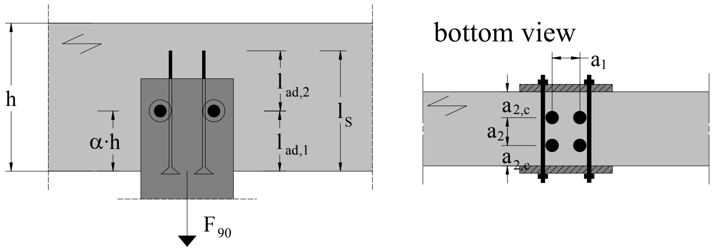
Based on the design procedure in [2], the load-carrying capacity for reinforced notched beam supports (*Fig. 1*) is calculated according to equation (1):



$$V_d \leq \frac{n \cdot R_{ax,d}}{1{,}3 \cdot \left[3 \cdot (1-\alpha)^2 - 2 \cdot (1-\alpha)^3\right]} \tag{1}$$

Fig. 1: Reinforced notched beam support

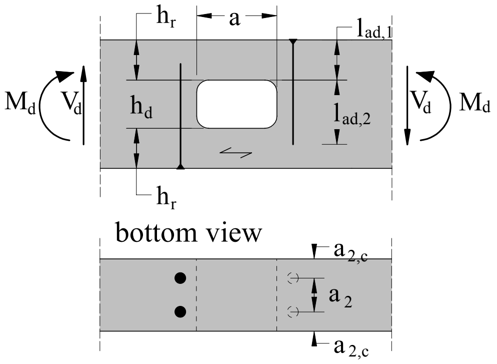
Similarly, the load-carrying capacity for reinforced connections with load components perpendicular to the member axis (*Fig. 2*) may be calculated according to equation (2):



$$F_{90,d} \leq \frac{n \cdot R_{ax,d}}{\left[1 - 3 \cdot \alpha^2 + 2 \cdot \alpha^3\right]} \tag{2}$$

Fig. 2: Reinforced connection

Finally, the load-carrying capacity for reinforced beams with round or rectangular holes (*Fig. 3*) can be calculated according to equation (3):



$$\frac{V_d \cdot h_d}{4 \cdot h} \cdot \left[3 - \frac{h_d^{\,2}}{h^2}\right] + 0{,}008 \cdot \frac{M_d}{h_r} \leq n \cdot R_{ax,d} \tag{3}$$

Fig. 3: Reinforced beam with a rectangular hole

The design value of the axial load-carrying capacity $R_{ax,d}$ is calculated according to equation (4):

$$R_{ax,d} = min\begin{Bmatrix} d \cdot l \cdot f_{1,d} \\ R_{t,u,d} \end{Bmatrix} \qquad \text{with} \qquad l = min\left\{l_{ad,1}\ ;\ l_{ad,2}\right\} \tag{4}$$

with

d	Nominal or outer diameter of the self-tapping screw
$f_{1,d}$	Design value of the withdrawal capacity parameter ([2])
n	Number of screws in a row perpendicular to the grain direction
$R_{t,u,d}$	Design value of the tensile capacity of the screw

For self-tapping screws loaded in axial direction the minimum spacing, end and edge distances in *Fig. 1* to *Fig. 3* are defined as:

$$a_1 \geq 5 \cdot d \qquad a_2 \geq 2{,}5 \cdot d \qquad a_1 \cdot a_2 \geq 25 \cdot d^2 \qquad a_{1,c} \geq 5 \cdot d \qquad a_{2,c} \geq 4 \cdot d$$

In [1] about 140 test results for reinforced and non-reinforced structural details, where tensile stresses perpendicular to the grain occur, are presented. For reinforced notched beams and for reinforced connections with load components perpendicular to the member axis the calculated load-carrying capacities were always lower than the test results and hence conservative. Only for some reinforced beams with holes the calculated load-carrying capacities significantly extended the test results. The failure of these beams with holes was controlled by large shear stresses close to the hole.

2.2 Extended equation for reinforced beams with holes

Due to the existence of the hole, the distribution of the shear stresses in the vicinity of the hole considerably deviates from the distribution according to beam theory. *Fig. 4* shows a schematic representation of the shear stresses where τ_1 and τ_4 are shear distributions according to beam theory and τ_2 and τ_3 result from the influence of the hole. In general $\tau_2 > \tau_3 > \tau_1 > \tau_4$. The maximum value of τ_2 is close to the corner of the hole and of τ_3 in the beam axis at a distance of about h_d from the hole.

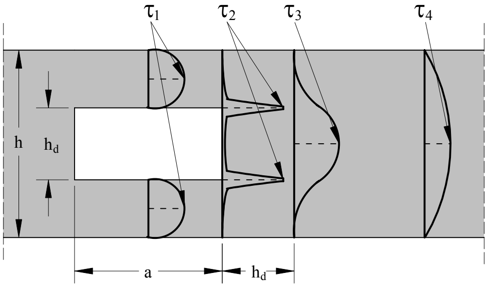


Fig. 4: Distribution of the shear stresses in a beam with hole

In order to estimate the maximum shear stresses around a hole about 2000 FE calculations with different geometries were performed and an empirical equation was derived [1]. For a constant shear force and for a hole geometry with $0{,}1 \le a/h \le 1{,}0$ and $0{,}1 \le h_d/h \le 0{,}4$ the maximum shear stress τ_{max} in the vicinity of a hole may be estimated using the following equation:

$$\tau_{max} = \kappa_{max} \cdot 1{,}5 \cdot \frac{V_d}{b \cdot (h - h_d)} \qquad \text{with} \qquad \kappa_{max} = 1{,}84 \cdot \left[1 + \frac{a}{h}\right] \cdot \left(\frac{h_d}{h}\right)^{0{,}2} \tag{5}$$

Particularly for larger rectangular holes the shear design according to equation (5) governs the load-carrying capacity and a reinforcement using glued-on plywood leads to higher capacities.

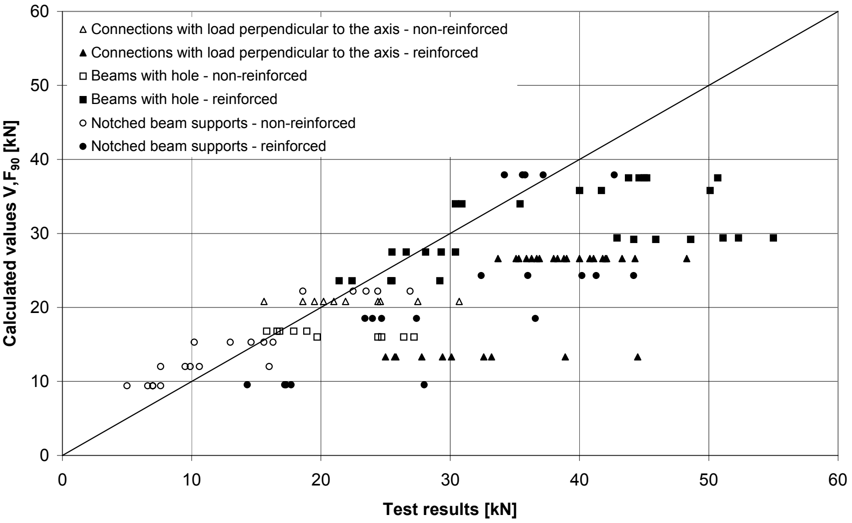


Fig. 5 shows the comparison between the test results and the calculated load-carrying capacities V and F_{90} for reinforced and non-reinforced structural details where tensile stresses perpendicular to the grain occur. The values for non-reinforced details were calculated according to [2]. The values for reinforced details were calculated taking into account equation (1) to (5).

Fig. 5: Comparison between tests results and calculated values

2.3 Reinforced connection areas

Tensile stresses perpendicular to the grain also occur in multiple fasteners connections with dowel-type fasteners where the timber is prone to splitting along the fastener row. The splitting tendency increases with decreasing fastener spacing parallel to the grain and decreases the effective number of fasteners. Splitting may be prevented by reinforcing the connection and consequently, the effective number of fasteners increases. Self-tapping screws with continuous threads represent a simple and economic reinforcement method. The screws are placed near the dowel-type fasteners, perpendicular to the dowel axis and to the grain direction (*Fig. 6*). They transfer the tensile forces perpendicular to the grain direction. At the University of Karlsruhe a research project with reinforced multiple fastener connections is presently carried out. First test results show that in connections with sufficient reinforcement the effective number equals the actual number of dowels.

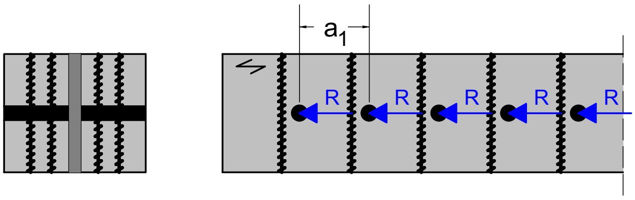


Fig. 6: Reinforced connection with dowel-type fasteners

3. Self-tapping screws as compressive reinforcements perpendicular to the grain

3.1 Tests with reinforced beam supports

Tests were made to compare the load-carrying-capacity of reinforced and non-reinforced beam supports. As reinforcement, self-tapping screws with continuous threads were placed at the beam supports (*Fig. 7*). The angle between the screw axis and the grain direction was 90°. To evenly apply the support load on the screws and on the timber, a steel plate was placed between the lower beam surface and the support.

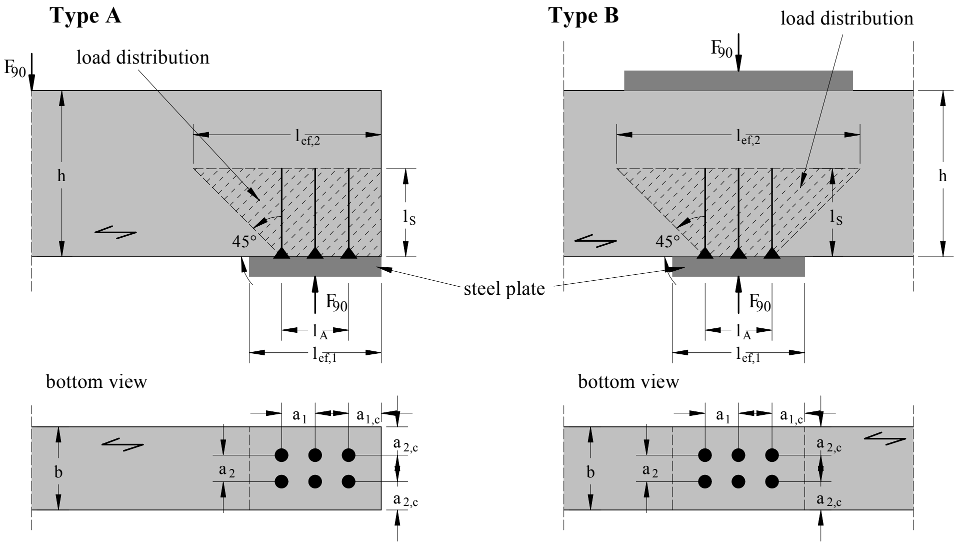


Fig. 7: Tested beam supports

In these tests, the type of screw (screw diameter d and length l_S), the number n of screws as well as the dimensions $b \times l_{ef,1}$ of the support area were varied. A part of the test results for different influencing parameters is shown in *Tab. 1*.

Comparing the test results, the load-carrying capacity of the reinforced beam supports was between 231 % and 429 % of the load-carrying capacity of the non-reinforced beam supports. Depending on the type of screw, three different failure modes (FM) were observed:

FM 1: The load-carrying capacity of the reinforced beam support was characterised by pushing the screws into the timber. Simultaneously, the compressive strength perpendicular to the grain at the lower beam surface was reached. For screws the pushing-in capacity is considered equal to the withdrawal capacity. This failure mode was observed at beam supports reinforced with short screws.

FM 2: The load-carrying capacity of the reinforced beam support was characterised by buckling of the screws. Simultaneously, the compressive strength perpendicular to the grain at the lower beam surface was reached. This failure mode was observed at beam supports reinforced with slender screws.

FM 3: The load-carrying capacity of the reinforced beam support was characterised by reaching the compressive strength perpendicular to the grain in a plane formed by the screw points. This failure mode was observed at beam supports reinforced with short screws.

Tab. 1: Test results

Specimen		Screws				Beam support				
Type A/B	Number n	Diameter d [mm]	Length l_S [mm]	Number n [-]	Effective length l_{ef} [mm]	Width b [mm]	Length l [mm]	Load $F_{c,90}$ [kN]	Load increase [%]	Failure Mode
A	10	-	-	0	-	120	90	57,1	-	-
A	10	6,5	160	6	220	120	90	132	131%	3
B	3	-	-	0	-	120	90	56,4	-	-
B	3	7,5	180	6	390	120	90	195	246%	1/3
B	3	8	260	6	550	120	90	228	304%	2
B	3	8	400	6	830	120	90	242	329%	2

3.2 Design equations for reinforced beam supports

Taking into account the different failure modes, the load-carrying capacity $R_{90,d}$ of a reinforced beam support may be calculated as follows:

$$R_{90,d} = min\left\{\begin{matrix} n \cdot R_d + k_{c,90} \cdot l_{ef,1} \cdot b \cdot f_{c,90,d} \\ b \cdot l_{ef,2} \cdot f_{c,90,d} \end{matrix}\right\} \qquad (6)$$

where

$$R_d = min\left\{R_{ax,d} \; ; R_{c,d}\right\} \qquad (7)$$

$$R_{ax,d} = d \cdot l_S \cdot f_{1,d}$$

$$R_{c,d} = \kappa_c \cdot \frac{N_{pl,k}}{\gamma_M} \qquad \text{with} \qquad \gamma_M = 1,1$$

$$\kappa_c = 1 \qquad \text{for} \qquad \overline{\lambda}_k \leq 0,2$$

$$\kappa_c = \frac{1}{k + \sqrt{k^2 - \overline{\lambda}_k^2}} \qquad \text{for} \qquad \overline{\lambda}_k > 0,2$$

with

$$k = 0,5 \cdot \left[1 + 0,49 \cdot \left(\overline{\lambda}_k - 0,2\right) + \overline{\lambda}_k^2\right]$$

$$\overline{\lambda}_k = \sqrt{\frac{N_{pl,k}}{N_{ki,k}}} \qquad \text{with} \qquad N_{pl,k} = \pi \cdot \frac{(0,7 \cdot d)^2}{4} \cdot f_{y,k}$$

and

d Screw diameter

n Number of screws

$l_S; b; l_{ef,1}; l_{ef,2}$ see in *Fig. 7*

$f_{1,d}$ Design value of the withdrawal capacity parameter

$f_{c,90,d}$ Design value of the compressive strength perpendicular to the grain

$f_{y,k}$ Characteristic yield strength (for conventional screws: $f_{y,k} = 400\ N/mm^2$)

$k_{c,90}$ Coefficient $k_{c,90} \in [1\ ;\ 1{,}75]$ for the load distribution, see [2].

$N_{ki,k}$ Characteristic buckling load for a screw taking into account the elastic foundation perpendicular to the screw axis, a triangular normal load distribution along the screw axis as well as the support condition of the screw head. For hinged head supports the characteristic buckling loads are summarised in *Tab. 2*. For clamped head supports see [3].

For axially loaded self-tapping screws the minimum spacing, end and edge distances in *Fig. 7* are defined as:

$$a_1 \geq 5 \cdot d \qquad a_2 \geq 2{,}5 \cdot d \qquad a_1 \cdot a_2 \geq 25 \cdot d^2 \qquad a_{1,c} \geq 5 \cdot d \qquad a_{2,c} \geq 4 \cdot d$$

Tab. 2: Characteristic buckling loads

$N_{ki,k}$ in [kN]		ρ_k = 310 kg/m^3					ρ_k = 380 kg/m^3					ρ_k = 410 kg/m^3					ρ_k = 450 kg/m^3				
		Screw diameter d in [mm]					Screw diameter d in [mm]					Screw diameter d in [mm]					Screw diameter d in [mm]				
		4	**6**	**8**	**10**	**12**	**4**	**6**	**8**	**10**	**12**	**4**	**6**	**8**	**10**	**12**	**4**	**6**	**8**	**10**	**12**
Screw length l_S in [mm]	**20**	5,34	5,55	5,58	5,59	5,59	6,47	6,78	6,83	6,84	6,85	6,94	7,31	7,37	7,38	7,39	7,57	8,02	8,09	8,10	8,11
	40	8,85	15,0	16,3	16,6	16,7	9,84	17,8	19,8	20,3	20,4	10,2	19,0	21,3	21,8	22,0	10,8	20,4	23,3	23,9	24,1
	60	8,77	18,4	26,8	29,4	30,1	9,76	20,6	31,5	35,6	36,8	10,2	21,5	33,4	38,2	39,6	10,7	22,6	35,8	41,6	43,3
	80	8,71	18,5	30,6	40,3	43,9	9,69	20,7	34,4	47,3	53,0	10,1	21,6	36,0	50,1	56,7	10,6	22,7	37,9	53,6	61,7
	100	8,67	18,6	31,0	44,9	55,2	9,64	20,8	34,8	50,9	64,9	10,0	21,6	36,3	53,2	68,7	10,5	22,7	38,3	56,2	73,5
	120		18,6	31,4	45,8	60,8		20,8	35,2	51,7	69,4		21,6	36,8	54,0	72,7		22,7	38,7	57,0	77,0
	140			31,7	46,6	62,6			35,4	52,5	70,8			36,9	54,8	74,1			38,8	57,9	78,4
	160			31,8	47,3	63,7			35,5	53,1	72,1			37,0	55,4	75,4			38,9	58,4	79,7
	180				47,6	64,8				53,4	73,2				55,7	76,5				58,7	80,8
	200				47,9	65,7				53,6	73,9				55,9	77,2				58,9	81,5
	220					66,2					74,5					77,7					81,9
	>240					66,7					74,9					78,1					82,3

Note: Interim values by linear interpolation

4. Conclusions

The efficiency of self-tapping screws used as tensile and compressive reinforcements perpendicular to the grain is shown. Self-tapping screws are characterised by simple assembling without pre-drilling the timber. Compared with conventional fasteners, self-tapping screws with diameters up to 12 mm and lengths up to 600 mm show a high tensile strength and a high withdrawal capacity. Generally, self-tapping screws can be used in timber-to-timber connections to transfer tensile and compressive forces or to compensate the low tensile and the low compressive strength values of timber perpendicular to the grain. Self-tapping screws both as fasteners and as reinforcements open new opportunities for numerous applications in timber structures.

5. References

[1] Blass H.J., Bejtka I., “Querzugverstärkungen in gefährdeten Bereichen mit selbstbohrenden Holzschrauben”, *Forschungsbericht* 2003. *Versuchsanstalt für Stahl, Holz und Steine, Universität Karlsruhe.*

[2] Blass H.J., Ehlbeck J., Kreuzinger H., Steck G., “Entwurf, Berechnung und Bemessung von Holzbauwerken“, *Schlussentwurf Bemessungsnorm Holzbau BEKS* - 2002 *in Tagungsband* 2002 - *Ingenieurholzbau - Karlsruher Tage.*

[3] Bejtka I., “Querzug- und Querdruckverstärkungen - Aktuelle Forschungsergebnisse“, *in Tagungsband* 2003 - *Ingenieurholzbau - Karlsruher Tage.*