JOINTS IN TIMBER STRUCTURES LOADED PERPENDICULAR TO GRAIN – COMPARISON OF DESIGN APPROACHES

QUERANSCHLÜSSE IM HOLZBAU – EIN VERGLEICH VON BEMESSUNGSANSÄTZEN

ASSEMBLAGES DES STRUCTURES EN BOIS CHARGEES PERPENDICULAIREMENT AU FIL – UNE COMPARAISON DES APPROCHES DE DIMENSIONNEMENT

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SUMMARY

The paper reports on the design of joints in timber beams loaded perpendicular to grain. Such joints are highly prone to splitting and in most cases the load-carrying capacity of the joint depends on the tension resistance perpendicular to grain rather than on the lateral load capacity of the dowel type fastener. The models developed for design of such joints with respect to failure in tension perpendicular to grain can be grouped in strength of materials approaches and linear fracture mechanics models. A design based on tension strength perpendicular to grain is implemented in the new version of DIN 1052:2004 being very close to the quasi-standardised design procedure in the frame of the still valid "old" German timber design code based on permissible stresses. Contrary, Eurocode 5 contains a fracture mechanics based model.

In the paper presented, a specific joint type with a single dowel-fixed steel plate in a glulam beam is considered and the design capacities according to the different code rules are evaluated. As parameters, the numbers and rows of fasteners are varied. Configurations with large effective joint heights, i.e. with a large distance of the loaded beam edge to the innermost dowel, are of special interest. Despite rather good agreement for smaller effective heights some model dependent discrepancies occur for larger effective height to beam height ratios.

ZUSAMMENFASSUNG

In dem vorliegenden Aufsatz wird über die Bemessung von Queranschlüssen an Holzträger berichtet. Solche Verbindungen sind sehr spaltempfindlich und in den überwiegenden Fällen wird die Tragfähigkeit des Anschlusses durch die Zugbeanspruchbarkeit rechtwinklig zur Faserrichtung und nicht durch die

Schertragfähigkeit der stiftförmigen Verbindungsmittel bestimmt. Die Bemessungsmodelle für derartige Anschlüsse betreffend Querzugbeanspruchbarkeit lassen sich in Festigkeitsnachweise und in linear bruchmechanische Modelle gliedern. Eine Bemessung basierend auf der Zugfestigkeit rechtwinklig zur Faserrichtung ist in der Neufassung der DIN 1052:2004 implementiert. Die Vorgehensweise entspricht weitgehend dem quasi-genormten Bemessungsprocedere im Rahmen der noch gültigen „alten“ deutschen Holzbaunorm, die auf zulässigen Spannungen beruht. Im Gegensatz dazu enthält der Eurocode 5 ein bruchmechanisch basiertes Bemessungsmodell.

In dem Beitrag wird ein spezieller Verbindungstyp mit einer in einen Brettschichtholzträger eingeschlitzten und mittels Stabdübeln angeschlossenen Stahlplatte betrachtet, und es werden die Bemessungswerte der Anschlusstragfähigkeiten nach den unterschiedlichen Normvorschriften ermittelt. Als Parameter werden die Anzahl und die Reihen der Verbindungsmittel variiert. Von besonderem Interesse sind Konfigurationen mit großen effektiven Anschlusshöhen, d. h. mit einem großen Abstand des am weitesten innenliegenden Stabdübels vom belasteten Trägerrand. Ungeachtet einer vergleichsweise guten Übereinstimmung bei kleineren effektiven Anschlusshöhen sind abhängig vom Bemessungsmodell teilweise merkliche Unterschiede bei größeren Verhältnissen von effektiver Anschlusshöhe zu Trägerhöhe festzustellen.

RESUME

Cet article rend compte du dimensionnement des assemblages des poutres en bois chargés perpendiculairement au fil du bois. De tels assemblages sont très susceptibles au fendage et la capacité portante est dans la plupart des cas déterminée par la résistance en traction perpendiculaire au fil, et non pas par la résistance au cisaillement des chevilles. Les méthodes de dimensionnement pour la sollicitation en cisaillement perpendiculaire au fil pour ces assemblages peuvent être classés en deux groupes: celui des procédures utilisant un critère de résistance des matériaux et celui des modèles basés sur la mécanique de la rupture. La démarche correspond largement à la procédure de dimensionnement "quasi normalisée" dans le cadre de l'"ancienne" norme allemande sur les constructions en bois, laquelle est basée sur les contraintes admissibles. L'Eurocode 5, par contre, contient un modèle basé sur la mécanique de la rupture.

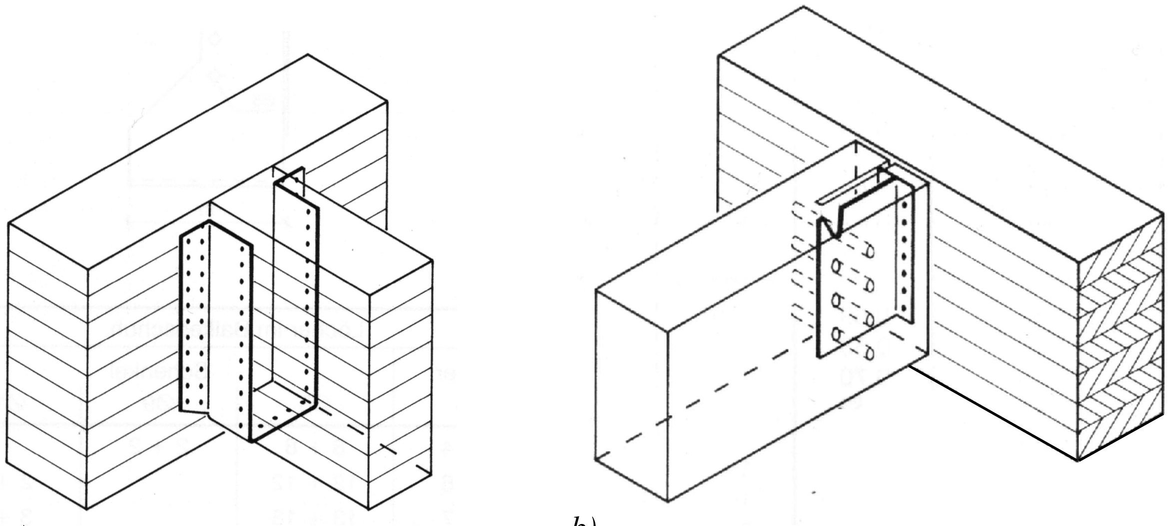
Dans cet article est présenté un type d'assemblage avec une plaque d'acier logée dans une rainure de la poutre en bois lamellé collé et fixée par des chevilles; les capacités de charge sont déterminées selon les différentes normes. Les paramètres variables sont le nombre et les rangées des éléments de fixation. Les configurations avec une grande hauteur utile, c.-à-d. un grand écart entre le bord sollicité de la poutre et la cheville la plus éloignée sont d'un intérêt particulier. Une bonne concordance est observée pour les petites hauteurs utiles. En revanche, pour un rapport élevé de la hauteur utile à la hauteur totale de la poutre, des divergences parfois importantes se manifestent en fonction du modèle de dimensionnement.

KEYWORDS: Perpendicular-to-grain-joints, comparison of timber design codes, effective joint height, failure mode transition, dowel type fasteners

1 INTRODUCTION

Joints transferring loads perpendicular to grain are employed in all cases where loads are hung at the bottom side of (glued laminated) timber beams and at connections of secondary beams to main beams. At so-called perpendicular-to-grain-joints (PGJ), tensile stresses perpendicular to grain direction occur in the main girder. Consequently, the load-carrying capacity of lateral joints depends not only on the resistance of the fasteners and the connection construction but also considerably on the transverse material resistance against splitting.

Types of PGJ are joist hangers, T-beam-connections, tenon type joints and modern front side connectors with two complementary attaching plates, e.g. fit connectors. Figure 1a shows a joist hanger. The T-beam-connections are hidden inside the wood (Fig. 1b). Their advantage are the good fire protection characteristics, as the steel is protected by the wood on all sides, and their good appearance. By use of doweled connections with a steel plate slit in the timber, loads can be hung on the bottom side of glulam beams (Fig. 4). This type of connection can also be used when fire protection is required.



a) b)

Figure 1: Examples of perpendicular-to-grain-joints (see also Figs. 2 and 4)
a) Joist hanger
b) T-beam-connection

The design of PGJ has been subject to intensive research in the past. Amongst others the main topic is related to the question whether a classical strength of materials approach or a fracture mechanics based design are more appropriate for prediction of the joint load capacity. Increasingly a fracture mechanics related failure mechanism is considered to apply, however, in several of today's design codes the strength of material approach is implemented.

The paper presents a comparison of three different joint design rules. In detail, the joint design according to the new German timber design code, based on ultimate states, the permissible stress design approach used in Germany so far (DIN 1052:1988) and the Eurocode 5 approach are regarded. The comparison of the design is performed exemplarily for a dowel type joint with a steel plate mounted in a central slit. Some consideration is given to configurations with high ratios of effective joint height, i.e. for large distances of the loaded beam edge to the innermost dowel and to several dowel rows.

2 JOINT DESIGN GIVEN IN DIN 1052:2004

The load-carrying capacity and hence the design depends pronouncedly on the ratio of effective joint height to beam height a/h (Fig. 2). Below a ratio of $a/h = 0{,}2$, perpendicular-to-grain-joints shall only be used for short time loads, e.g. wind loads. Further, the standard specifies that the verification of the transverse tensile stresses can be omitted for effective joint heights $a > 0{,}7\ h$. In this case the joint can be designed on the basis of the lateral load capacity of the fasteners and, not explicitly stated, with respect to the beam shear force capacity. For $0{,}2 \le a/h \le 0{,}7$, the design equation and the design resistance $R_{90,d}$ of the PGJ is

$$\frac{F_{90,d}}{R_{90,d}} \le 1$$
$$R_{90,d} = k_s \cdot k_r \cdot \left(6{,}5 + \frac{18 \cdot a^2}{h^2}\right) \cdot \left(t_{ef} \cdot h\right)^{0,8} \cdot f_{t,90,d} \quad (1)$$

where

$$k_s = \max\left\{1;\ 0{,}7 + \frac{1{,}4 \cdot a_r}{h}\right\} \quad (2)$$

and

$$k_r = \frac{n}{\sum_{i=1}^{n}\left(\frac{h_1}{h_i}\right)^2} \quad (3)$$

In above equations, the following definitions apply:

n	number of fasteners parallel to the applied load
$F_{90,d}$	design tension force acting on the joint (see Fig. 2)
t_{ef}	effective fastener depth depending on type of fastener and jointed material combination (e.g. wood-based boards jointed by nails or screws to main glulam beam)
$t_{ef} = \min\{b;\ t;\ 6d\}$	effective fastener depth for one sided dowel connection
$f_{t,90,d} = f_{t,90,k} \cdot k_{mod} / \gamma_M$	design value and characteristic value of tension strength perpendicular to grain
γ_M	partial safety factor for the material property ($\gamma_M = 1{,}3$)
k_{mod}	modification factor accounting for the climate service class and the duration of load

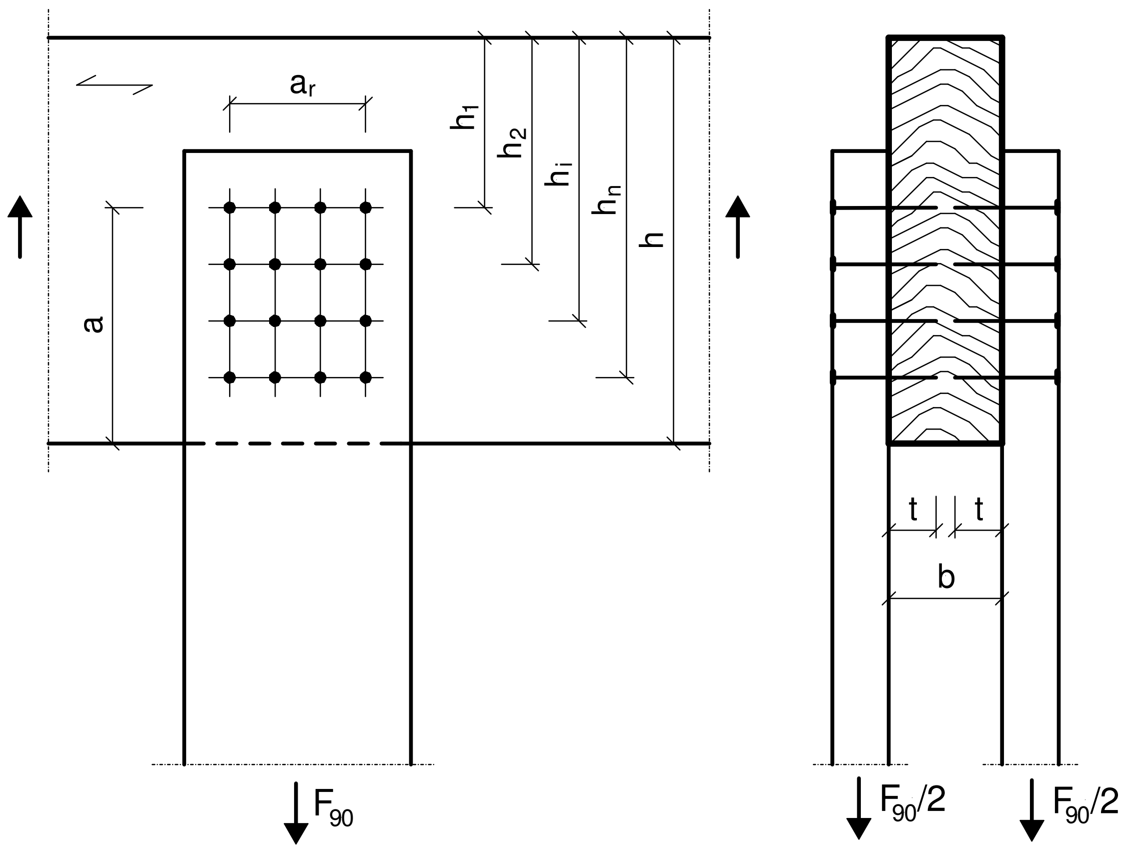


Figure 2: Example of a two-sided perpendicular-to-grain-joint and dimensions according to DIN 1052:2004

Adjacent joints (groups of fasteners) can be considered as independent joints, provided that the clear distance between the adjacent groups is larger than or equal 2 h. In case the clear distance is smaller than $2h$ but larger/equal to $0{,}5h$, the design load-carrying capacity has to be reduced by the coefficient

$$k_g = \frac{l_g}{4h} + 0{,}5 \tag{4}$$

where l_g is the clear distance between lateral joints. In the case of a clear distance $l_g < 0{,}5\ h$, the adjacent joints have to be considered as a single joint.

3 DESIGN WITHIN THE FRAME OF DIN 1052:1988

The design of perpendicular-to-grain-joints is not regulated explicitly in the still valid "old" German timber design code DIN 1052:1988 based on the permissible stress concept. However, a design concept based on this standard is given in [2] and presently state of the art of such joints in Germany. The cited approach based on work by Ehlbeck et. al. [11] actually formed the basis for the above presented limit state design in DIN 1052:2004. The influence of the ratio of joint height to beam height a/h is considered by the factor f_1 within the same a/h–boundaries as above ($0{,}2 \le a/h \le 0{,}7$):

$$f_1 = \frac{1}{1 - 3 \cdot \left(\frac{a}{h}\right)^2 + 2 \cdot \left(\frac{a}{h}\right)^3} \tag{5}$$

The influence of several fastener rows is taken into account by factor f_2 which fully corresponds to k_r given in Eq. (3). The interaction of adjacent joints with a clear distance of less than $2h$ is considered by the factor

$$f_3 = 1 + \frac{W_m}{W_m + a} \tag{6}$$

where W_m is the centroidal distance of adjacent joints. The type of fastener is taken into account by factor f_4 (e.g. 1,0 for dowel type fasteners). The effective joint width $ef\,W$ is

$$ef\,W = \sqrt{a_r + (Ch)^2}$$ for horizontal distance between adjacent fasteners less than $(0{,}8h - a)$

$$ef\,W = C \cdot h \cdot \left[1 + (m-1) \cdot \frac{a_r}{a_r - a}\right]$$ else (7)

where $$C = \frac{4}{3} \cdot \sqrt{\frac{a}{h} \cdot \left(1 - \frac{a}{h}\right)^3} \tag{8}$$

The effective joint area is calculated as

$$ef\,A = ef\,W \cdot t_{ef} \tag{9}$$

using the effective fastener depth t_{ef} as before. The permissible tension stress perpendicular to grain depends on the area stressed perpendicular to the grain direction

$$zul\ \sigma_{t,90} = 0{,}333 \cdot (ef\,A \cdot 10^2)^{-0{,}2}$$ for glulam

$$zul\ \sigma_{t,90} = 0{,}200 \cdot (ef\,A \cdot 10^2)^{-0{,}2}$$ for solid wood (10)

The allowable force of the perpendicular-to-grain-joint is finally evaluated as

$$zul\ F_{t,90} = zul\ \sigma_{t,90} \cdot ef\,A \cdot f_1 \cdot f_2 \cdot f_3 \cdot f_4 \tag{11}$$

4 DESIGN ACCORDING TO EUROCODE 5

The Eurocode 5 (EN 1995-1-1:2004 [4]) design of (dowel) joints loaded perpendicular to grain is based on the linear fracture mechanics approaches introduced by van der Put [7], van der Put and Leijten [8], Leijten and Jorissen [9], and Larsen and Gustafsson [10, 14]. The principle load capacity equation closest to the below given Eurocode 5 design is (Leijten and Jorissen [9])

$$V_u = 0{,}4b\sqrt{a\,GG_{c,I}}\sqrt{\frac{1}{1-(a/h)}} \tag{12}$$

It can be seen that the joint load capacity, unlike the DIN approaches depends on the square root of a and a/h, representing the fundamental size relationship of linear fracture mechanics. Further, the material resistance is no more defined by tension strength perpendicular to grain but by mode I fracture energy in tension perpendicular to grain $G_{c,I}$ and shear stiffness G of the timber. The apparent fracture parameter $\sqrt{GG_{c,I}}$ depends considerably on the type of the connection. Calibration to test results forwarded for the mean values a range of $9{,}3 \leq \sqrt{GG_{c,I}}$ [N/mm^{1,5}] ≤ 34 (Leijten and Jorissen [9]). Based on Eq. (12) and the mentioned apparent fracture parameter fitting the characteristic load-carrying capacity perpendicular to grain given in Eurocode 5 is for a joint with several fasteners in one row (except for nail plates)

$$F_{90,Rk} = 14b\sqrt{\frac{a}{1-\frac{a}{h}}} \tag{13}$$

The design has to verify the condition

$$\frac{F_{v,Ed}}{F_{90,Rd}} \leq 1 \tag{14}$$

where

$F_{v,Ed} = \max\begin{cases} F_{v,Ed,1} \\ F_{v,Ed,2} \end{cases}$ design values of shear forces on either side of the connection resulting from $F_{Ed} \cdot \sin\alpha$ (see Fig. 3)

$F_{90,Rd} = k_{mod} \cdot \frac{F_{90,Rk}}{\gamma_M}$ design load-carrying capacity perp. to grain

Contrary to the DIN approaches no explicit rules are given how to handle the design in case of several parallel rows of fasteners.

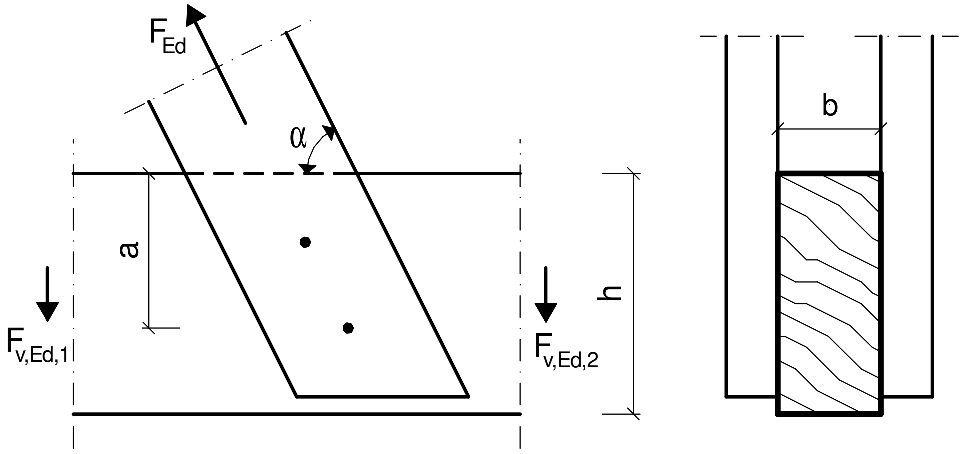


Figure 3: Connection with force at an angle to the grain and dimensions acc. to Eurocode 5

5 CASE STUDY

In the frame of the conducted parameter study, a dowel type joint with a steel plate mounted in a central slit of the timber beam is regarded exemplarily (Fig. 4). The distance of the fasteners closest to the bottom edge is kept constant: $h-h_n$ = 140 mm. The parameter variations comprised the joint height to beam height ratio a/h and the number n of dowel rows. A range beginning with n = 2 and a/h = 0,22 and increasing to n = 10 and a/h = 0,86 was investigated. Further, the number of fastener columns is varied; hereby one and three parallel columns are regarded. The required minimum distances of the dowels according to DIN 1052:2004, chapter 12.3, table 8 were fulfilled. The cross section of the glulam beam is 240 mm x 1000 mm. The glulam strength class is GL28h (characteristic density: 410 kg/m³). The dowel diameter and the thickness of the steel plate were 20 mm and 16 mm, respectively. A view of the joint layout for the case of n = 4 is given in Fig. 4.

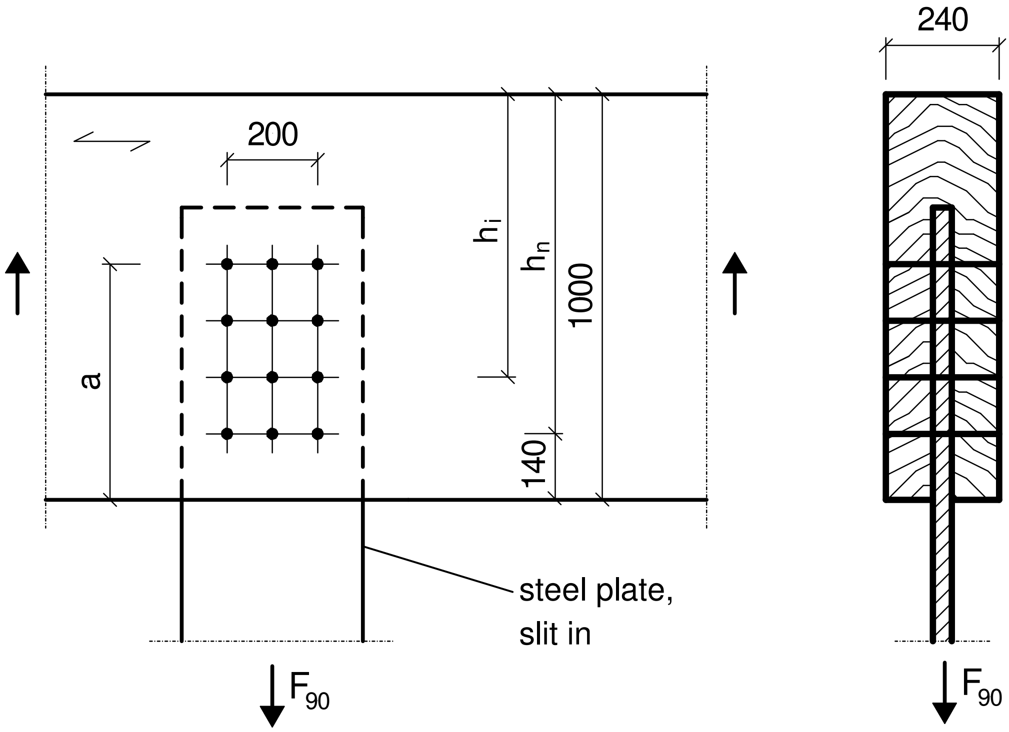


Figure 4: Double shear dowel joint, parameter configuration n = 4

First, the results for the joint comprising one column of fasteners are discussed. The results are presented graphically in Figure 5 showing the sustainable characteristic loads depending on the ratio of effective joint height to beam height. With respect to determination of the given values, the following details are noteworthy. In case of DIN 1052:2004 the sustainable characteristic load $R_{90,d}/\gamma_L = R_{90,k}/\gamma_G$ is given which equals in principle the permissible load of the "old" design concept. (Note: γ_L is the partial safety factor for actions, $\gamma_G = \gamma_L \cdot \gamma_M / k_{mod}$ is global safety factor.) In the discussed example, the partial safety factors were chosen as γ_L = 1,425 and γ_M = 1,3 for tension perpendicular to grain resistance and shear load capacity and γ_M = 1,2 for fastener load capacity; k_{mod} was taken as 0,8 standing for medium duration of load in service classes 1 and 2. The characteristic tension strength perpendicular to grain is $f_{t,90,k}$ = 0,5 N/mm².

For DIN 1052:1988 *zul* $F_{t,90}$ as specified in chapter 3 is depicted.

In case of the Eurocode 5 design, specified by Eqs. (13) and (14) the maximum characteristic tension perpendicular to grain resistance is reached in the case of a design load $F_{v,Ed} = F_{v,Ed,1} = F_{v,Ed,2} = F_{Ed} / 2$, reflecting the situation where the load (for instance a secondary beam connected to the main beam) is applied at midspan. This yields a maximum design tension perpendicular to grain resistance of 2 $F_{90,Rd} / \gamma_L$.

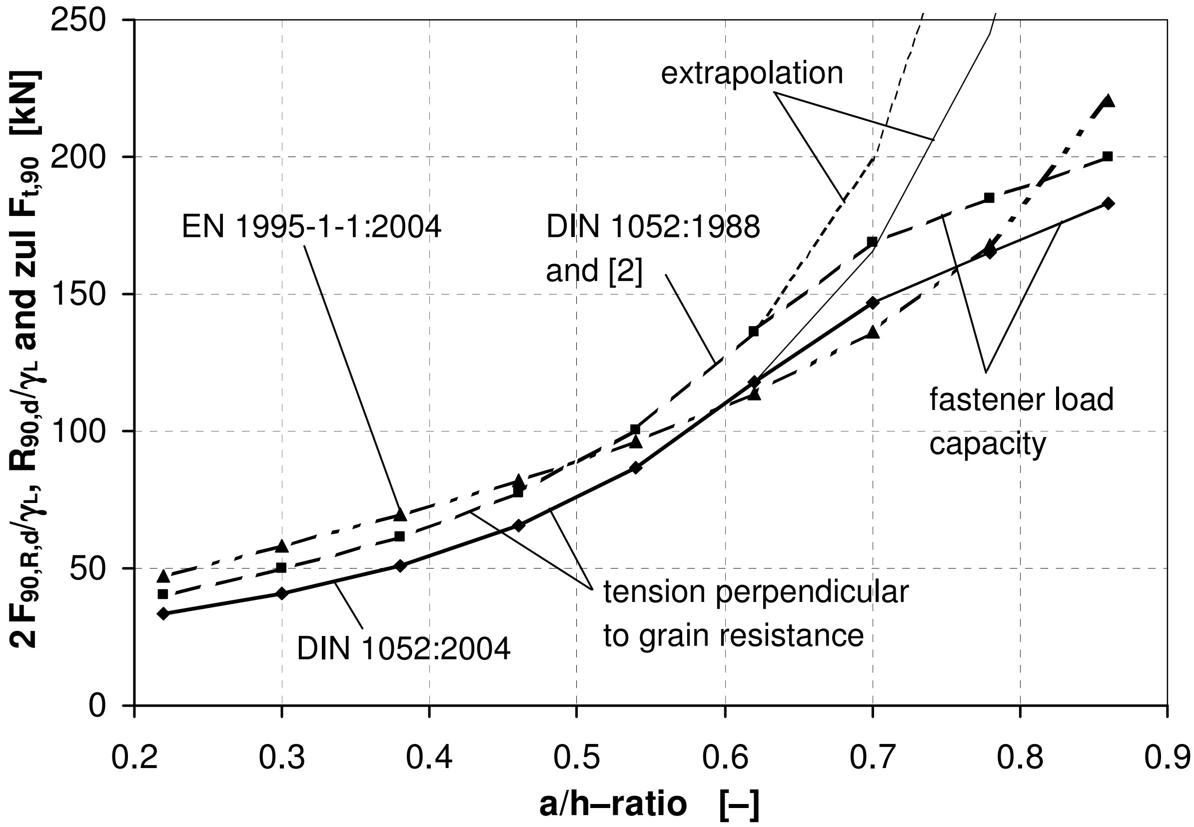


Figure 5: Sustainable characteristic and permissible loads perpendicular to grain according to different design approaches for a PGJ with one column of fasteners depending on the effective joint height ratio

It can be seen from Fig. 5 that all three approaches deliver comparable sustainable characteristic or permissible loads. Despite that, the quantitative differences are in parts not negligible. For instance for a a/h-ratio of 0,3 the results for DIN 1052:1988 and Eurocode 5 are 122% and 141% of the solution acc. to DIN 1052:2004, respectively.

All design approaches deliver a steady load capacity evolution with increasing effective joint height. This is trivial in case of the Eurocode 5 solution where one equation for a single failure mode applies. In case of the DIN solutions the change of failure mode from tension perpendicular to grain capacity to lateral fastener capacity is astonishingly smooth. This however, is dependant on the specific joint configuration, as shown below.

Following, the results for the joint comprising three columns of fasteners are discussed. The results are presented graphically in Figure 6. As Eurocode 5 does not contain explicit rules on how to handle multiple fastener columns, exclusively the DIN solutions are regarded. At first, the DIN 1052:2004 results are discussed.

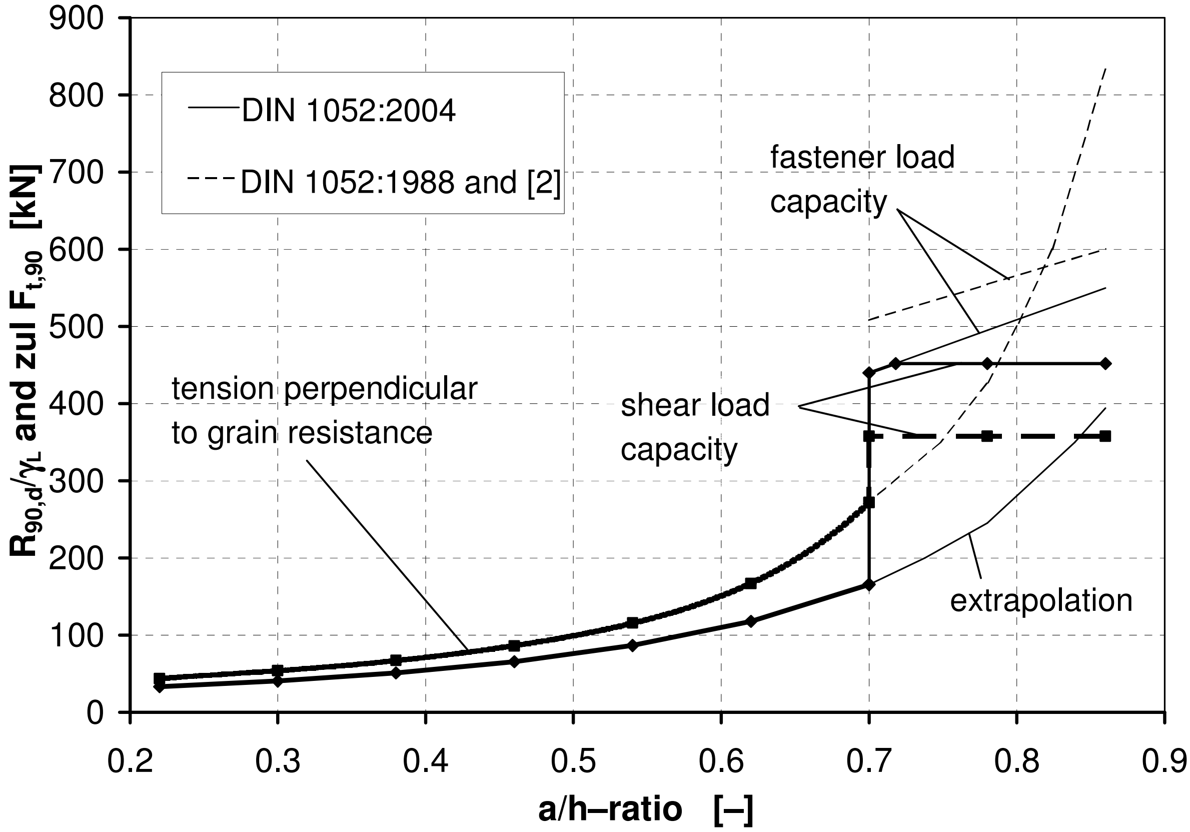


Figure 6: Sustainable characteristic and permissible loads perpendicular to grain according to different design approaches for a PGJ with three columns of fasteners depending on the effective joint height ratio

In the range of $0,2 \leq a/h \leq 0,7$ the load-carrying capacity, depending exclusively on the tension perpendicular to grain resistance, increases progressively in the form of a power type function. Beyond an *a/h*–ratio of 0,7, the tension perpendicular to grain resistance can be disregarded according to the DIN design concepts in [1] and [2]; then the load capacity is determined either by the lateral load-carrying capacity of the dowel type fasteners or by the bulk shear force capacity of the beam. Resulting from this, a point of discontinuity is located at $a/h = 0,7$. The sustainable characteristic load capacity curve for DIN 1052:2004 reveals a step increase by a factor of 2,7. This means that a small increase of the *a/h*–ratio by a minor shift of the fasteners towards a larger effective joint height can raise the design load-carrying capacity significantly. Above $a/h = 0,7$ the joint resistance is initially limited by the fastener resistance and then by the shear load capacity ($[2V_{Rd}/\gamma_G = 2 \cdot ((2/3) \cdot h \cdot b \cdot f_{v,k} \cdot k_{mod}/\gamma_G)]$ and $f_{v,k}$ = 3,5 N/mm²).

A load-carrying capacity characterised by a step function with an extreme discontinuity of a factor of 2,7 does not seem physically reasonable. Even in tests [5] with a very high *a*/*h*–ratio of 0,75 a transverse tension crack occurred at the upper fastener row. Thus, irrespective of the exact *a*/*h*–ratio it is necessary to account for the transverse tensile stress also in the very high *a*/*h*–range. By introducing a simple interaction formula for transverse tensile stress and shear stress, it is possible to smooth the step function considerably.

In the permissible stress design concept [2], the curve of $zul\ F_{t,90}$ depending on the *a*/*h*–ratio resembles the load capacity evolution acc. to DIN 1052:2004. However, quantitatively significant differences can be stated, both below and beyond $a/h = 0{,}7$. For small and medium effective joint height ratios up to about $a/h = 0{,}55$ the permissible values are about 30% higher as compared to DIN 1052:2004. In the *a*/*h*–range of 0,6 to 0,7 the differences increase up to a factor of circa 1,6.

The step of the DIN 1052:1988 approach at $a/h = 0{,}7$ is considerably smaller as in case of DIN 1052:2004 being due to two reasons: i) the capacity based on tension strength perpendicular to grain ($a/h < 0{,}7$) is higher and ii) $2 \cdot zul\ V = 358$ kN is noticably (20%) smaller than $2 \cdot V_{Rd} / \gamma_G = 452$ kN. Beyond $a/h = 0{,}7$ the load-carrying capacity is limited by the permissible shear force capacity. The continued power function and the horizontal line of the shear force resistance intersect shortly after the discontinuity. Thus, the unbalance of the tension perpendicular to grain and the shear capacities are restricted to a very small *a*/*h*–range and the design method according to [2] can be considered reasonable.

6 CONCLUSIONS

In some cases perpendicular-to-grain-joints with very high effective joint height ratios (*a*/*h*) can be demanded by the specific structural circumstances. In the design concept of DIN 1052:2004, a sharp transition in the failure mode is implemented going from the transverse tension failure to the load-carrying capacity of the fastener or to the bulk shear force capacity of the beam. This failure mode change at an *a*/*h*–ratio of 0,7 is associated with a discontinuous increase of the load-carrying capacity ranging up to a factor of about 3 depending on the joint configuration. Such a pronounced discontinuity in the load-carrying capacity is physically not reasonable. It is proposed to smooth the step function by an interaction equation for shear stress and tensile stress perpendicular to grain. A second and simple alternative is to abolish the rather arbitrary failure mode transition at *a*/*h* = 0,7 and to determine the sustainable characteristic load of the joint as the smallest value resulting either from tension perpendicular to grain capacity, lateral fastener capacity or shear capacity. The fracture mechanics based Eurocode 5 approach for the joint load capacity is more appealing from view of the applied mechanical concept. The absolute load capacities are rather similar to those of the DIN strength of materials approach in case of the regarded joint with one fastener column. However, for multiple columns a plausible rule has to be implemented.

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