DESIGN OF RECTANGULAR HOLES IN GLULAM BEAMS

BEMESSUNG RECHTECKIGER DURCHBRÜCHE IN BRETT-SCHICHTHOLZ

DIMENSIONNEMENT DE TROUS RECTANGULAIRES DANS DES POUTRES EN BOIS LAMELLE COLLE

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SUMMARY

The paper deals with rectangular holes in glulam members subjected to bending. Introductory, the decisive design relevance of the stresses perpendicular to fiber and beam direction is outlined. Then, exemplarily, the influence of essential geometric quantities, being – radius of curvature of the corners and aspect ratio of the rectangular holes – are revealed. Hereby the stochastic defect structure of the material glulam is considered, too.

Next, the design approaches according to the drafts of DIN 1052 and EC 5, differing fundamentally with respect to idealisation of the mechanical problem, are outlined. The design proposal of DIN 1052 incorporates a classical strength of materials criterion whereas the EC 5 design model is based on fracture mechanics.

A comparison of the two stated design approaches reveals partly extreme differences of the computational characteristic load capacities. The reason therefore results from the different mechanical models and the different recognition of obviously relevant influencing parameters. A newly granted research project shall contribute to the elaboration of a unanimously accepted, empirically validated design model for holes in glulam beams.

ZUSAMMENFASSUNG

Der Beitrag befaßt sich mit rechteckigen Durchbrüchen in biegebeanspruchten Brettschichtholzträgern. Einführend wird kurz die ausschlaggebende

Bemessungsrelevanz der Spannungen rechtwinklig zur Faser- und Trägerrichtung dargelegt. Es werden sodann exemplarisch die Einflüsse wesentlicher geometrischer Größen – Ausrundungsradius der Ecken und Seitenverhältnis der Rechteckdurchbrüche – aufgezeigt. Die stochastische Defektstruktur des Werkstoffes Brettschichtholz wird hierbei mitberücksichtigt.

Es folgt eine Darlegung der Bemessungsansätze in den Entwürfen zu DIN 1052 und EC 5, die sich hinsichtlich der Idealisierung des mechanischen Problems fundamental unterscheiden. Dem Bemessungsvorschlag in DIN 1052 liegt ein klassisches Höchstspannungskriterium zugrunde während das EC 5 Bemessungsmodell von einem bruchmechanischen Ansatz ausgeht.

Ein Vergleich der genannten Bemessungsvorschriften zeigt zum Teil extreme Unterschiede der rechnerischen charakteristischen Tragfähigkeiten auf, deren Ursache in den unterschiedlichen mechanischen Modellen und der unterschiedlichen Berücksichtigung offensichtlich relevanter Einflußgrößen liegt. Ein neu bewilligtes Forschungsvorhaben soll dazu beitragen ein allgemein akzeptiertes und empirisch abgesichertes Bemessungsmodell für Durchbrüche in Brettschichtholzträgern zu erarbeiten.

RESUME

On s'intéresse dans cet article à la présence de trous rectangulaires dans des poutres en lamellé collé sollicitées en flexion, en portant l'attention sur les contraintes perpendiculaires aux fibres, décisives pour le dimensionnement. Ainsi, par exemple, l'influence de grandeurs géométriques essentielles – rayon de courbure des angles et rapport de forme du trou – est mise en évidence.

La nature stochastique des défauts du lamellé collé est également considérée. En s'appuyant sur les règles de dimensionnement relatives aux projets de normes DIN 1052 et EC5, on obtient des différences fondamentales sur l'idéalisation du problème mécanique. La proposition émanant de la norme DIN 1052 utilise un critère de résistance des matériaux, alors que le modèle de dimensionnement de l'EC5 est basé sur la mécanique de la rupture.

La comparaison des deux approches fait apparaître des différences extrêmes sur la capacité portante simulée. La raison provient donc des différents modèles mécaniques utilisés et d'une prise en compte différente de paramètres dont l'influence est évidente. Un nouveau projet de recherche financé contribuera à l’élaboration d’un modèle de dimensionnement unanimement accepté, et validé expérimentalement.

KEYWORDS: Glulam, rectangular holes, design approaches, stresses perpendicular to grain, Weibull stress, hole aspect ratio, curvature of corner

1. INTRODUCTION

The design of glulam beams with holes is treated considerably different in timber design codes. Examples are the latest drafts of Eurocode 5 and of the German timber design code DIN 1052. In the first case a solution based on a linear fracture mechanics approach is stated whereas in the latter case a strength of materials design is given. Further, in both design models essential geometrical and section force influences are treated considerably different. Concerning round holes, the stated differences have been treated earlier in [1]. In this paper the issue of rectangular holes is discussed.

The paper first shortly reveals the design relevance of tension stresses perpendicular to grain. Following the influence of radius of curvature of the corners and of aspect ratio of the hole is discussed. Both mentioned design approaches are then compared for representative configuration of different beam, hole and section force combinations. The effect of different glulam strength classes is considered, too.

2. SOME BASIC CONSIDERATIONS ON THE PROBLEM

In the following only straight beams subjected to bending are regarded. This means that the hole periphery is in general subjected to a combined shear force and moment action. In rare occasions pure moment loading of the member section with the hole may occur.

The hole disturbs the stress flow due to shear force V and/or bending moment M; this influences all stress components. The distributions of the stresses σ_x, σ_y and τ_{xy} at selected paths parallel to beam depth in the area/vicinity of a square hole for a general, combined M + V load case are shown in Fig. 1. In the given example with M/V = 3, the radius of the not sharp edged corner was taken as $r = 0.05\ h_d$. This matter is discussed in more detail in chap. 3. The orthotropic stiffness ratios employed in the FE analysis were throughout assumed as $E_x/E_y = 30$, $E_x/G_{xy} = 16$ and $\nu_{xy} = 0.015$. The diagrams show that at the design relevant path II all stress components reveal a pronounced peak at the locations of the corners. At the upper corner of path II the peaks of *tension* stresses parallel and perpendicular to grain interact with a shear stress peak. Regarding the magnitude of the three stresses relative to their respective strength values, for instance via a Norris stress interaction criteria, we see that tension stress perpendicular to grain is by far most damage relevant. This is the reason that the design approaches in the drafts of DIN 1052 and EC 5 account explicitely (DIN 1052) or implicitly (EC 5) exclusively for a damage relevance of tension stress perpendicular to grain. Following the focus is also only on tension stress perpendicular to grain, however the sketched stress interaction should be kept in mind.

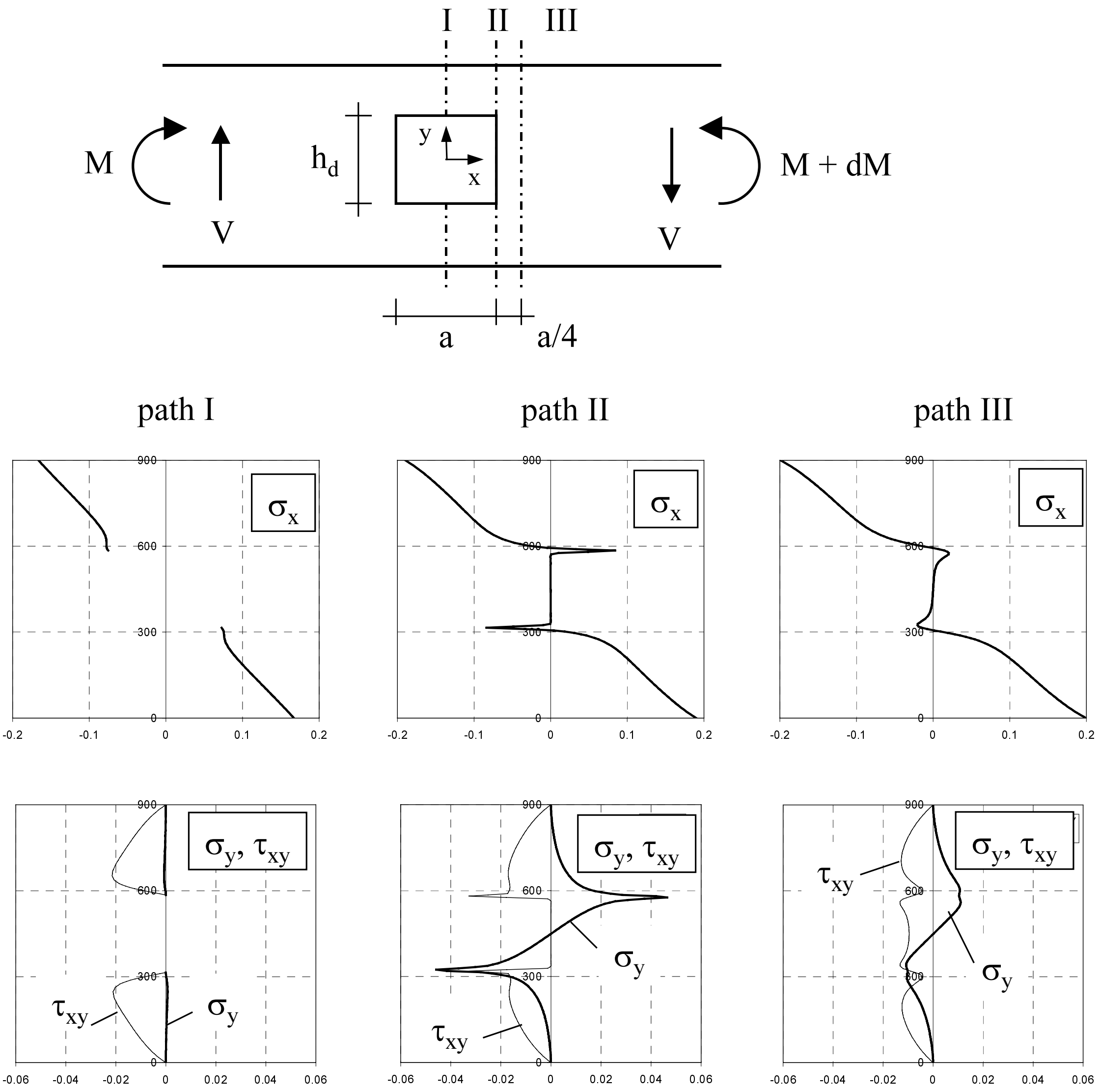

Fig. 1: *Distributions of stresses σ_x, σ_y and τ_{xy} along selected paths in the vicinity of a rectangular hole subject to a combined moment/shear force load case M/V = 3 h. Beam geometry, sizes: $h_d/h = h/3$, $h = 900$ mm, $b = 120$ mm, $r = 0.05\ h_d$*

For assessment of the influences of section forces M and V, considered differently in both code drafts, it is advantageous to regard the effect of the load case pure moment action and the fictive load case “pure” shear force action separately. A detailed description of the stress computation for the fictive “pure” V load case is stated in [2].

Due to pure moment action M the stress concentration is located at the vertical edge of the hole (Fig. 2a) whereas due to “pure” shear force action V the stresses concentrate in the corners of the hole (Fig. 2b). The shapes of the stress fields for the two load cases are similar to those obtained for round holes [2]. A combined M+V load case produces an unsymmetrical stress field around the hole which is a superposition of the two pure load cases.

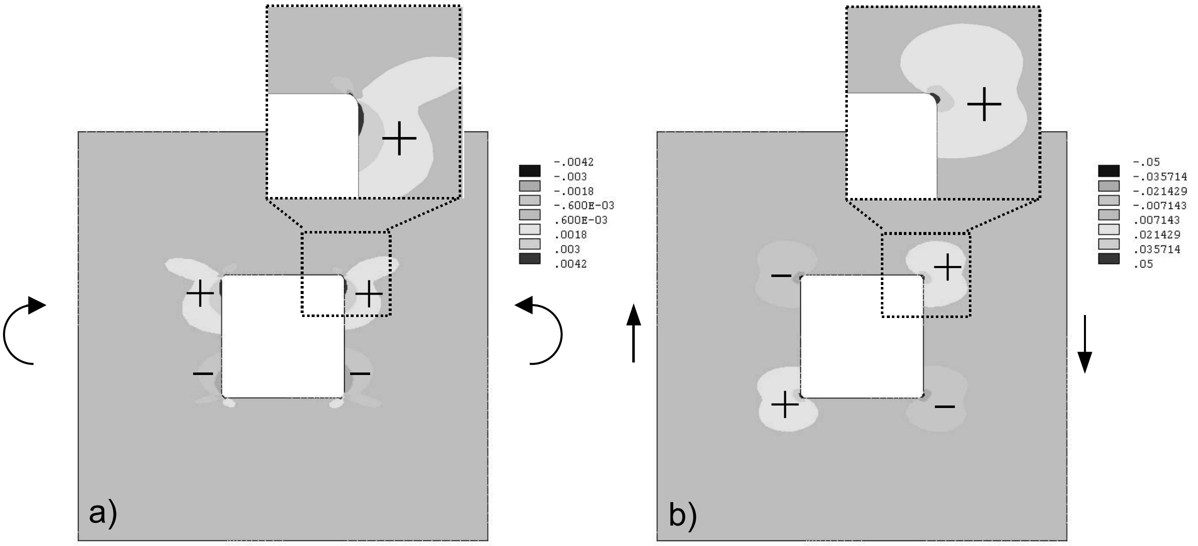

Fig. 2a, b: Stress distributions perpendicular to grain at the hole periphery for the two pure load cases
a) pure moment action b) “pure” shear force action

3. EFFECT OF CURVATURE OF THE CORNERS

A crucial matter for rectangular holes are the corners. In case of rectangular sharp notched corners, i.e. radius of curvature → 0, a stress singularity arises. In order to avoid this, the corner generally will not be made right-angled but produced with a curvature 1/r. It is trivial that the maximum stress depends strongly on the radius. However, for failure initiation due to tension stresses perpendicular to grain in a brittle material with stochastically distributed defects, the area/volume, here denoted by Ω, and the shape of the stress distribution $\sigma_y = \sigma_{90}$

of the high stressed region are more relevant. An adequate procedure to quantify the damage relevancy of an inhomogeneously stressed volume is the so-called Weibull stress

$$\sigma_{90,\mathrm{wei}} = \left(\frac{1}{\Omega} \int_{\Omega} \sigma_{90}{}^{m}(x,y,z)\, d\Omega \right)^{1/m} . \qquad (1)$$

The effect of two different radii on maximum and Weibull stresses is revealed exemplarily for a beam of depth h = 900 mm with a relative hole size of $h_d/h = 0.3$ ($h_d = 270$ mm) subjected to “pure” shear force action (Fig. 3). An increase of the radius from $r = 0.05\ h_d = 13.5$ mm to $r = 0.15\ h_d = 40.5$ mm forwards a strong reduction of the maximum stresses at the corner, giving a stress ratio of

$$\sigma_{90,\max,r=0.15h_d} / \sigma_{90,\max,r=0.05h_d} = 0.64$$

Apart from the immediate hole vicinity the stress distribution is not affected by differences of the radii as shown in Fig. 3. Considering now the whole stress field perpendicular to grain in the corner area and calculating the Weibull stress with a generally agreed size exponent m = 5 the difference becomes considerably smaller

$$\sigma_{90,\mathrm{wei},r=0.15h_d} / \sigma_{90,\mathrm{wei},r=0.05h_d} = 0.88 .$$

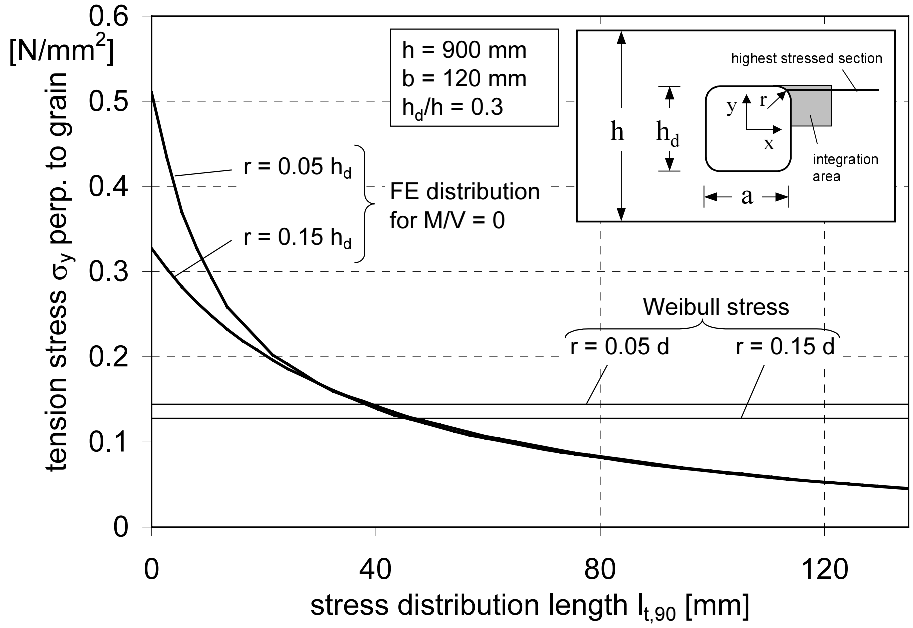

Fig. 3: Tension stress perpendicular to grain $\sigma_y = \sigma_{t,90}$ at highest stressed section for two different radii of the corners in case of “pure” shear force action of 10 kN

In the drafts of DIN 1052 and EC 5 the corner radius is equally prescribed as $r \geq 15$ mm, irrespective of hole and beam size. According to the authors' knowledge, this construction detailing is not bound to any considerations of the above type and should be analysed appropriately.

4. INFLUENCE OF THE ASPECT RATIO OF THE HOLE

The aspect ratio of the rectangular hole is considered considerably different in the drafts of DIN 1052 and EC 5. Whereas DIN 1052 does not consider any influence of the aspect ratio of the hole on load capacity, EC 5 specifies a significant load capacity reduction with increasing aspect ratio for same hole depth h_d. Apart thereof, both design codes state equally the following absolute/relative limits for the dimensions of rectangular holes, being

$a \leq h$ and $h_d \leq 0.4\,h$

where a and h_d are the hole dimensions parallel and normal to beam axis. Thus the maximum "allowable" aspect ratios reach from

$a/h_d \leq 10$ for $h_d/h = 0.1$ to

$a/h_d \leq 2.5$ for $h_d/h = 0.4$.

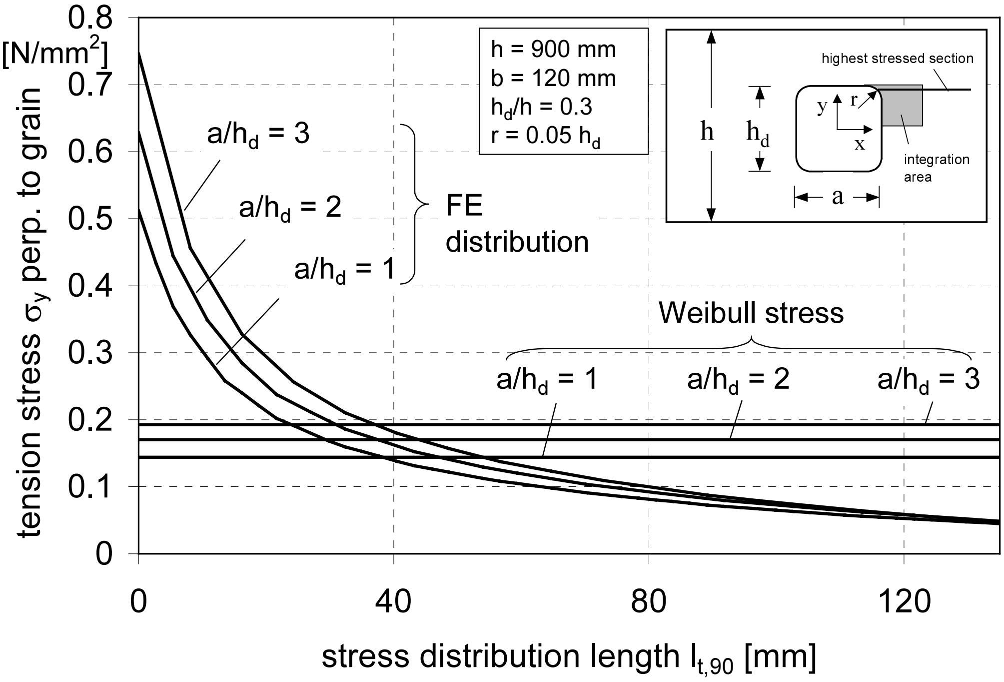

Fig. 4: Tension stress perpendicular to grain $\sigma_y = \sigma_{t,90}$ at highest stressed section acc. to "pure" shear force action of 10 kN for three different aspect ratios

Table 1: Maximum and Weibull stresses for different aspect ratios; also given are the stress values normalised to the square hole reference case

stress	unit	aspect ratio a/h_d		
		1	2	3
$\sigma_{y,max}$	N/mm^2	0.512	0.628	0.746
σ_{wei}	N/mm^2	0.144	0.170	0.193
$\sigma_{y,max,n}$ [1)]	-	1.00	1.23	1.46
$\sigma_{wei,n}$ [1)]	-	1.00	1.18	1.34

[1)] normalised to the aspect ratio $a/h_d = 1$

The appropriateness of a consideration of the aspect ratio in the design equations was checked in the frame of this paper exemplarily for the beam configuration, studied before with respect to the influence of the corner radius. Now, in all cases $r = 0.05\ h_d = 13.5$ mm is considered. Additionally to the square hole aspect ratio of $a/h_d = 1$ regarded in Fig. 3, Fig. 4 specifies the σ_y stress distributions for the aspect ratios $a/h_d = 2$ and 3. Table 1 contains the maximum and Weibull stresses for the different aspect ratios; also given are the stress values normalised to the square hole reference case. It can be seen that the maximum stresses increase for the aspect ratios $a/h_d = 2$ and 3 pronouncedly by 23% and 46%, respectively. The Weibull stresses increase slightly less but comparable by 18% and 34%. It is evident, that the aspect ratio should be accounted for in the design equations.

5. DESIGN OF RECTANGULAR HOLES ACCORDING TO DRAFT DIN 1052

Following the design for rectangular holes as specified in the revised draft of the new semi-probabilistic German timber design code [3] is given. The design model represents a classical strength of materials approach. Hereby the design tension force perpendicular to grain at the hole periphery, $F_{t,90,d}$, is compared to the design value of the resistance $R_{t,90,d}$ ($R_{t,90,d}$ not specified explicitly)

$$\frac{F_{t,90,d}}{R_{t,90,d}} = \frac{F_{t,90,d}}{0.5\ l_{t,90}\ b\ f_{t,90,d}} \leq 1 \tag{2a}$$

where

$$l_{t,90} = 0.5\ (h_d + h) \tag{3}$$

is the distribution length of the assumed triangular stress distribution perpendicular to grain (see also Fig. 5), b is beam width and $f_{t,90,d}$ is the design tension strength perpendicular to grain. Rewritten as the ratio of a design stress $\sigma_{t,90,d}$ vs. design strength $f_{t,90,d}$, Eq. (2a) reads

$$\frac{\sigma_{t,90,d}}{f_{t,90,d}} \leq 1 \qquad \text{where} \qquad \sigma_{t,90,d} = \frac{F_{t,90,d}}{0.5\, l_{t,90}\, b}. \qquad \text{(2b), (4)}$$

The design value of the tension force $F_{t,90,d}$ is composed of two additive parts bound to the separate actions of shear force and bending moment

$$F_{t,90,d} = F_{t,V,d} + F_{t,M,d} \qquad (5)$$

where

$$F_{t,V,d} = V_d\, \eta_V \quad \text{and} \quad \eta_V = \frac{1}{4}\frac{h_d}{h}\left[3 - \frac{h_d^2}{h^2}\right] \qquad (6)$$

$$F_{t,M,d} = M_d\, \eta_M \quad \text{and} \quad \eta_M = \frac{0.008}{h_r} \qquad (7)$$

and V_d, M_d absolute values of design shear force and bending moment at the hole edge[1]

and

$h_r = \min\{h_{rl}; h_{ru}\}^2$ where $h_{rl(ru)} \geq 0.25\, h$ (see also footnote 2). (8)

Further, as already mentioned in chap. 3, the restrictions $h_d \leq 0.4\, h$, $a \leq h$ and $r \geq 15$ mm apply.

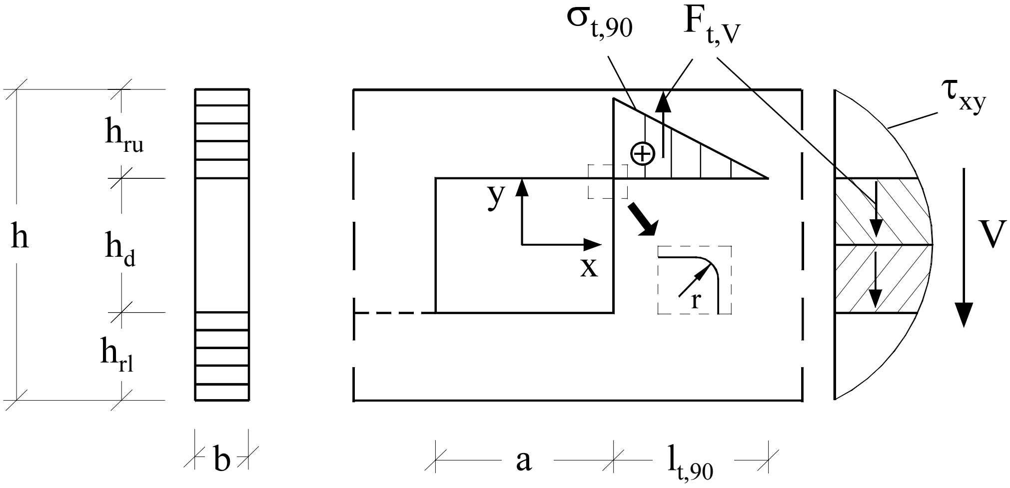

Fig. 5: Geometry notations[2] of a rectangular hole in a glulam beam acc. to draft DIN 1052 and schematic illustration of the simplified shear and tension perpendicular to grain stresses concerning the derivation of tension force $F_{t,V}$ bound to shear force V

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[1] whichever delivers unfavorable results

[2] DIN notations h_{ro} and h_{ru} were changed to EC 5 notations h_{ru} and h_{rl}

Some comments on the background and limits of the specified equations seem appropriate (in the following, for sake of simplicity, the subscript d is omitted, i.e. nominal resp. characteristic values are regarded):

- Tension force $F_{t,V}$ bound to the shear force V, specified in Eq. (6), represents one half of the resultant of the shear stresses τ_{xy} which can not be transferred in the hole area (see Fig. 5)

  $$F_{t,V} = b \int_0^{h_d/2} \tau_{xy}\, dy = V\, \eta_V\,, \quad \tau_{xy} = \frac{3}{2}\frac{V}{b\,h}\left(1 - 4\frac{y^2}{h^2}\right) \tag{9a,b}$$

  By integration of the stresses perpendicular to grain, as resulting from FE analysis, it can be shown that Eqs. (6) and (9) deliver the correct stress resultant when the integration is performed over the whole stress distribution length (including also compression stress areas until the stresses perpendicular to grain become zero).

- Tension force $F_{t,M}$ bound to the bending moment, specified in Eq. (7), is not based on analytical or numerical stress analysis but stems from a calibration to experimental data in different literature sources [4]. The performed calibration procedure can be questioned. A preliminary finite element study for determination of $F_{t,M}$ delivered a considerably different result similarly as in the analogous case of round holes, analysed in [2].

- The assumed triangular stress distribution represents a rather crude but somehow acceptable engineering approximation of the actually exponential stress distribution. However the distribution length $l_{t,90}$ as specified by Eq. (3) is considerably too long. This is illustrated exemplarily in Fig. 6. The graph shows the distribution of tension stress perpendicular to grain according to finite element analysis and for the given DIN 1052 design approach for a “pure” shear force load case (M/V = 0). Two different radii of curvature are regarded. In detail, the comparison of the stress distributions is performed for the ultimate (= characteristic) shear force state V_k defined by the DIN approach through Eqs. (2a), (5), (6) and (7), giving

  $$V_{k(DIN)} = f_{t,90,k}\; 0.5\; l_{t,90}\; b \,/ \left(\eta_V + \eta_M \frac{M}{V}\right). \tag{10}$$

With tension strength $f_{t,90,k}$ = 0.5 N/mm^2 (constant for all glulam strength classes according to draft DIN 1052). Eq. (10) delivers $V_{k(DIN)}$ = 80.5 kN as input for the FE analysis. It can be seen from the graphs that the nonlinear stress distribution according to continuum analysis shows a distinctly higher stress gradient and a much higher stress level closer to the hole periphery and hence shorter stress distribution lengths $l_{t,90}$. The maximum stresses according to continuum analysis might at first view be considered too high; however for this judgement, not followed up here, the actually stressed volume has to be taken into account.

- The assumed triangular stress distribution according to DIN 1052 is independent from the moment/shear force ratio, what is not corresponding with numerical solutions.

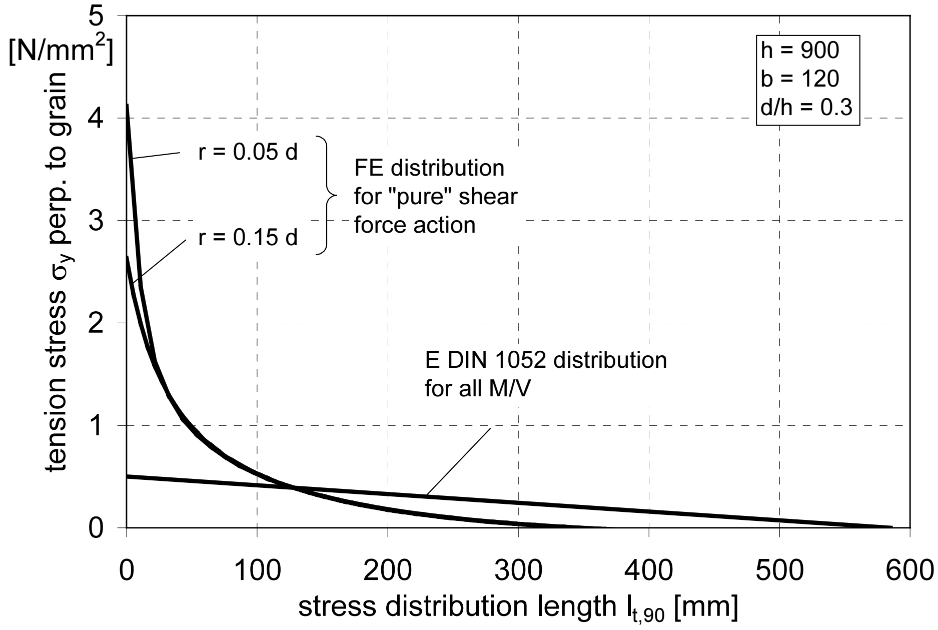

Fig. 6: Tension stress σ_y perpendicular to grain vs. stress distribution length $l_{t,90}$ at highest stressed section for a "pure" shear load action at failure state V_k according to E DIN 1052 (V_k = 80.5 kN) and according to continuum analysis bound to load $V_{k(DIN)}$

- Tension stress/force perpendicular to grain, $F_{t,90}/\sigma_{t,90}$, according to E DIN 1052 are equal for square and rectangular holes. However, as shown in chap. 3, the aspect ratio of the hole has an influence on stresses which increase considerably with aspect ratios $a/h_d > 1$.

6. DESIGN OF RECTANGULAR HOLES ACCORDING TO DRAFT OF EUROCODE 5

The linear fracture mechanics based strength verification for a glulam beam with a rectangular hole subjected to design shear force V_d and design moment M_d at the center of the hole is conducted as for a notched beam subjected to a shear force $V_d/2$ [5] (see Fig. 7). The effect of the additional moment on the load capacity is not considered. The design equation formally reads as an approach based on the comparison of design shear stress τ_d vs. design shear strength $f_{v,d}$ which is reduced by a factor k_V depending on absolute beam depth and relative hole size

$$\frac{\tau_d}{k_V\, f_{v,d}} \le 1 \qquad \text{and} \qquad \tau_d = \frac{1.5\, V_d}{b\, h_{ef}}. \tag{11a, b}$$

Factor k_V is defined by

$$k_V = \min \begin{cases} 1 \\ \dfrac{k_n}{\sqrt{h^*}\left(\sqrt{\alpha\,(1-\alpha)} + 0.8\,\dfrac{x}{h^*}\sqrt{\dfrac{1}{\alpha} - \alpha^2}\right)} \end{cases} \tag{12}$$

where

$h^* = h/2$

x = distance from line of shear force action to the corner = $a/2$

$\alpha = h_{ef}/h^*$

$$k_n = \begin{cases} 5 & \text{for solid timber} \\ 6.5 & \text{for glulam} \end{cases}$$

The relevant constructive restrictions were mentioned in chap. 3.

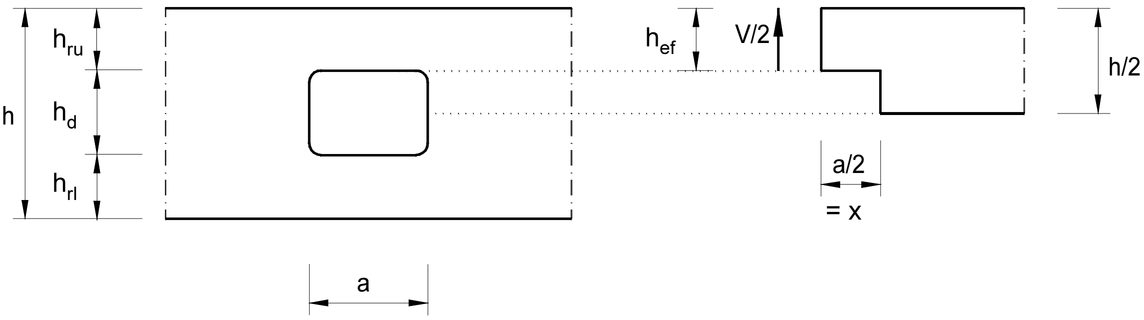

Fig. 7: Dimensions of rectangular holes in beams and respective approximations for the notched beam design according to EC 5; leftside: actual geometry; rightside: notched beam approximation

The following comments on the background and limits of the specific equations seem appropriate:

- The fracture mechanics bound design equation for an end-notched beam is based on total energy release rate [6]. As fracture mechanism, exclusively Mode I crack opening was assumed. So the implicitly incorporated basic material resistance is the characteristic fracture energy $G_{f,k}$ in tension perpendicular to grain. The formally shear strength based resistance side in Eq. (11a) is simply the result of an equation multiplication by $f_{v,k}/f_{v,k}$.
- The basic analytical end-notched beam solution was calibrated to experimental results for the **end-notched beam case** with a factor of 2/3.
- Characteristic fracture energy $G_{f,k}$ was eliminated from the resistance side by the approximation that

  $$k_n = \frac{1}{3}\sqrt{\frac{G_{f,k}E_{90,05}}{f_{v,k}^2}} \tag{13}$$

  results approximately in 5 and 6.5 for solid wood and glulam, respectively, throughout all strength classes.
- The design according to EC 5 takes into account the shape of the rectangular hole. Coinciding with the results in chap. 3, rectangular holes with aspect ratios $a/h_d > 1$ result in reduced k_v values.

7. COMPARISON OF LOAD CAPACITIES ACCORDING TO DRAFTS OF E DIN 1052 AND EC 5

For a quantitative comparison of both design approaches these are evaluated for characteristic shear force with and without consideration of a bending moment influence. The comparison comprises the following beam, hole sizes and geometries:

- beam depth h: $h_1 = 450$ mm, $h_2 = 2\ h_1 = 900$ mm and

  $h_3 = 3.33\ h_1 = 1500$ mm
- beam width b: b = constant = 120 mm
- hole to depth ratio: ranging from 0.1 to 0.4

Another important aspect when comparing the two drafts consists in the considered glulam strength class. In principle, strength class should have no impact, i.e. both design approaches should agree/disagree similarly for all strength classes. Unfortunately this is not the case, as shear strength $f_{v,k}$ and tension strength perpendicular to grain $f_{t,90,k}$, relevant in this context, are not specified equally for same glulam strength classes in DIN 1052 and EN 1194. (Note: The latter standard is the European glulam strength class standard to be used in EC 5.) The differences are shown in Tab. 2. It can be seen that the characteristic strength values $f_{t,90,k}$ and $f_{v,k}$ according to DIN 1052 remain constant for all glulam strength classes whereas the respective values according to EN 1194 depend strongly on the glulam strength class. So, the comparison of the design models for holes in glulam is superimposed by obvious uncertainties on the true strength properties $f_{t,90,k}$ and $f_{v,k}$. Therefore the hole design comparison is conducted for two glulam strength classes, one with rather dissimilar strength values/ratios (= the low glulam strength class GL 24c) and one with rather similar strength values in both codes (= the high glulam strength class GL 32h).

Table 2: Characteristic strength values [N/mm^2] for glulam of combined (c) and homogeneous (h) build-up acc. to European Standard EN 1194 and the German draft design code DIN 1052

standard	charact. strength value	glulam strength class							
		GL 24c	GL 24h	GL 28c	GL 28h	GL 32c	GL 32h	GL 36c	GL 36h
DIN 1052	$f_{t,90,k}$	0.5							
	$f_{v,k}$	3.5							
EN 1194	$f_{t,90,k}$	0.35	0.40	0.40	0.45	0.45	0.50	0.50	0.60
	$f_{v,k}$	2.20	2.70	2.70	3.20	3.20	3.80	3.80	4.30

First, the computational shear force capacities without consideration of a bending moment influence (M/V = 0) are regarded. Figures 8a, b show the shear force capacity V_k depending on the hole to depth ratio h_d/h for the 3 different beam depths as resulting from the EC 5 and DIN 1052 approach. Figure 8a illustrates the case for strength class GL 24c and Fig. 8b refers to GL 32h. A comparison of the results of the different design approaches reveals in general considerable discrepancies, discussed below in more detail.

Regarding strength class GL 24c (Fig. 8a), the two design approaches reveal similar characteristic shear force capacities for small beams (here: h = 450 mm). However, with increasing beam depth the shear force capacities differ extremely. This is an immediate consequence of the different recognition of the depth effect in the linear fracture mechanics approach (EC 5) and in the strength

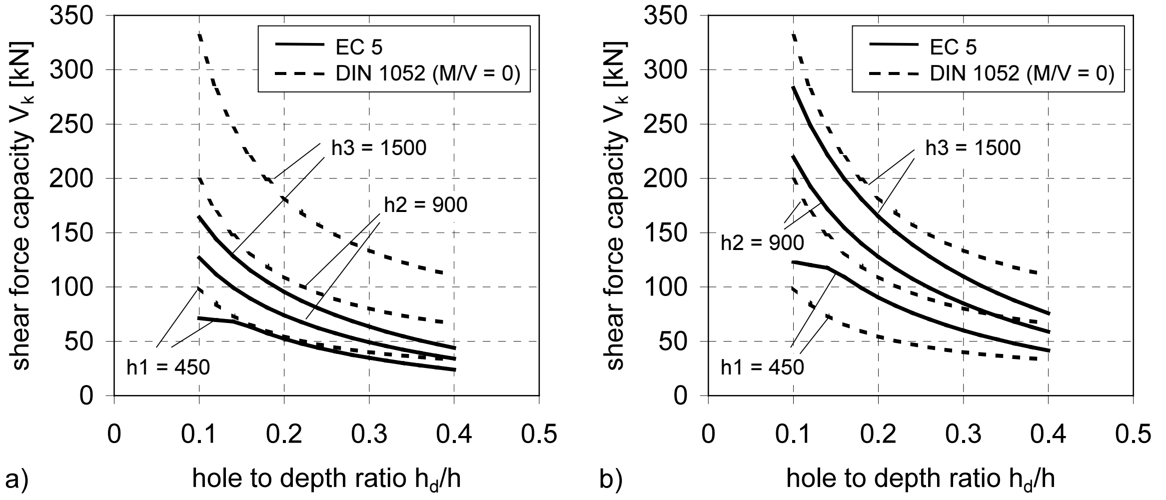

Fig. 8a, b: Characteristic shear force capacity of glulam beams with a square hole without consideration of a bending moment influence according to drafts of EC 5 and DIN 1052 depending on the hole to depth ratio and on the beam depth

a) for glulam strength class GL 24c
b) for glulam strength class GL 32h

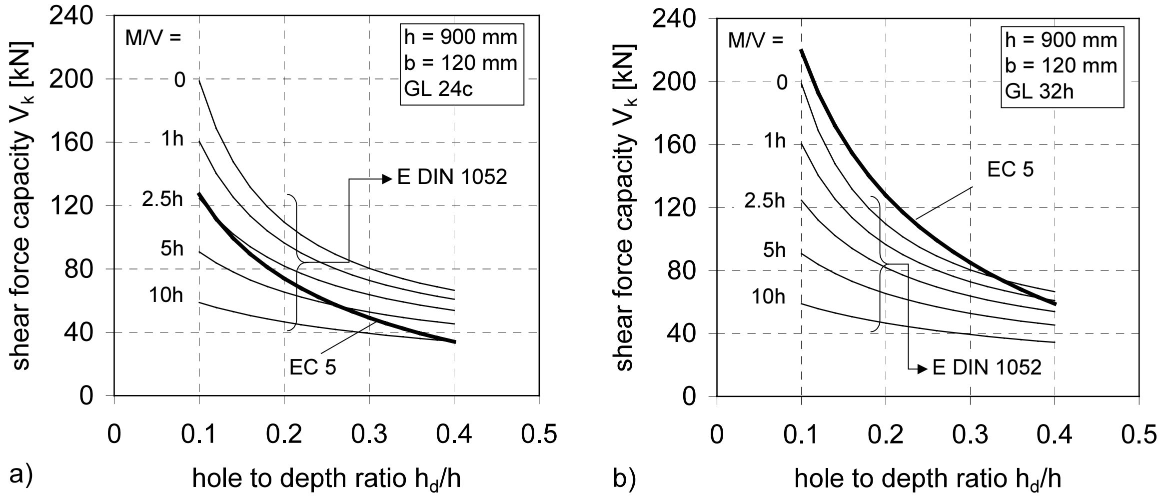

Fig. 9a, b: Characteristic shear force capacity of a glulam beam with a square hole depending on the hole to depth ratio for different moment shear force ratios M/V according to drafts of EC 5 and DIN 1052
a) for glulam strength class GL 24c
b) for glulam strength class GL 32h

of materials approach (DIN 1052), respectively. In the first case, load capacities increase proportional to $\sqrt{h}$ and in the second case proportional to h.

Regarding strength class GL 32h (Fig. 8b) the characteristic shear force capacities according to EC 5 increase by the ratio of characteristic shear strengths 3.8/2.2 = 1.7 vs. the results specified for GL 24c whereas the values according to DIN 1052 do not change. Consequently, now the predicted load capacities differ strongly for small beams whereas for medium sized beam depths throughout a rather good agreement can be stated. This is also true for large beams when regarding medium sized holes ($h_d/h \approx 0.15 - 0.25$).

Figures 9a, b show the shear force capacity for both design approaches, now considering the influence of a bending moment, too. In detail the results are given for a medium sized beam (h2 = 900 mm) for the glulam strength classes GL 24c and GL 32h. The parametric dependency of the DIN solution on the section force ratio M/V is specified for the realistic range of M/V = 0 to 10 h. Ratios M/V of up to about 2.5 h relate to holes very close to the supports, the larger ratios increasingly mirror constructions with holes closer to mid-span. It can be taken from the graph that the additional incorporation of the bending moment influence results in a tremendous reduction of the load capacity of the beam according to DIN 1052 as compared to the EC 5 approach.

Finally, the differences of both design codes concerning aspect ratio of the hole are quantified. As stated, DIN 1052 does not account explicitly for the aspect ratio of the hole. (Note: Implicitly the effect is considered in some way, as the design section forces in DIN 1052 are to be evaluated for the vertical edges of the hole what includes aspect ratio on the action side.) Contrary, EC 5 incorporates an expressed influence of the aspect ratio on the resistance side. The effect is depicted in Fig. 10 as the ratio of shear force capacity of a rectangular hole with aspect ratio $a/h_d > 1$ vs. a square hole with $a/h_d = 1$. The ratio is given for different hole to depth ratios h_d/h. Further the specified constructive limits $a \leq h$ and $h_d/h \leq 0.4$ are accounted for.

The graph reveals a marked capacity reduction with increasing aspect ratios. So for example, for a realistic hole geometry with a hole to depth ratio of $h_d/h = 0.3$ and an aspect ratio of $a/h_d = 3$, the shear force capacity drops by 40% vs. the square hole. This strength reduction may be compared with the results of the continuum calculation on the influence of aspect ratio in chap. 4. There, the

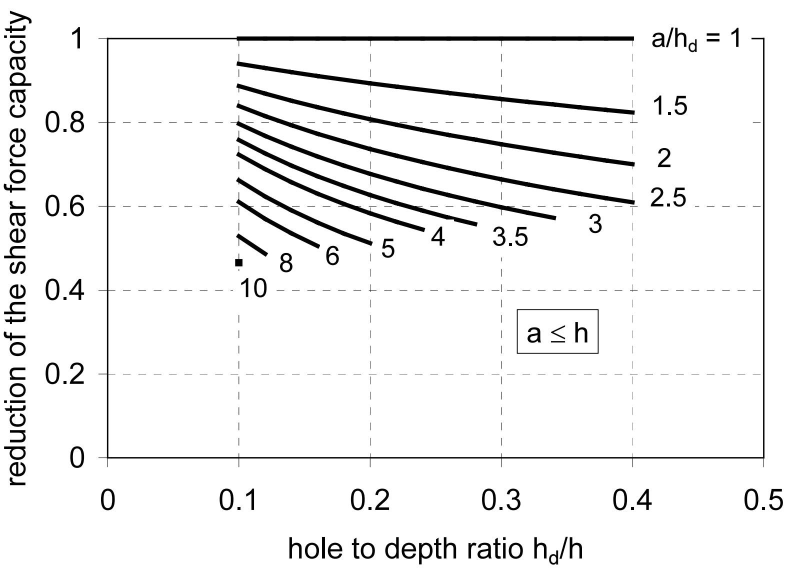

Fig. 10: Influence of the aspect ratio a/h_d on shear force capacity acc. to draft EC 5

studied example delivered for the same hole geometry shows increases of maximum and Weibull stresses of 1.46 and 1.34, respectively. Assuming a usual strength of materials criterion, the load capacity reduction vs. the square hole case would be 32% and 25%, respectively. This confirms very roughly the order of magnitude indicated by the EC 5 approach, which probably delivers a too conservative estimate of the influence of the aspect ratio.

8. CONCLUSIONS

A comparison of the design approaches in DIN 1052 and EC 5 for rectangular holes in glulam beams revealed strong discrepancies in many aspects. The design approaches which are based on fundamentally different mechanical models differ not only in the predicted load capacities, being very unsatisfactory from a safety point of view, but also in a different recognition of essential parameters. Important influences which should be accounted for, are:

- size effect (generally acknowledged in tension perpendicular to grain problems)
- moment to shear force ratio
- hole to depth ratio
- aspect ratio of the hole
- model invariance vs. different glulam strength classes

The two design approaches account for the above mentioned parameters as following:

- A size effect is considered in EC 5 but not in DIN 1052. The EC 5 model incorporates a depth influence according to linear fracture mechanics with the factor $\sqrt{h}$.
- The moment to shear force ratio is considered in DIN 1052 but not in EC 5. However, the magnitude of the M influence according to DIN 1052 does not agree with results from FE analysis.
- Both design approaches describe the influence of the hole to depth ratio similar for the "pure" shear force case.
- The aspect ratio of the hole is taken into account in EC 5 but not in DIN 1052. It was confirmed in this paper that a correct model should consider this influence.
- The agreement/disagreement of both design models depends strongly on the specifically regarded glulam strength class as the design relevant strength values are specified different in the respective codes/supplementary standards.

In view of the multiplicity of important design parameters and of the strength variability of the material glulam, it is obvious that an improved, commonly agreed model needs a substantial experimental data base for design equation calibration. The discussed aspects are followed up in a ongoing research project at Otto-Graf-Institute.

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