A CONTRIBUTION TO THE ANALYSIS OF GLULAM BEAMS WITH ROUND HOLES

EIN BEITRAG ZUR BERECHNUNG VON BRETTSCHICHTHOLZ - TRÄGERN MIT RUNDEN DURCHBRÜCHEN

CONTRIBUTION A L´ANALYSE DE POUTRES LAMELLEES - COLLEES PERCEES DE TROUS CIRCULAIRES

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ABSTRACT

The paper deals with the analysis of glulam beams with round holes; here exclusively a pure moment action is considered. First results of the on-going investigations, finally aiming at an extension of Eurocode 5, are compared to proposals given for the mentioned load case in the draft of the new German timber design code E DIN 1052. Some findings of the finite element study presently complemented by experimental investigations can be summarized as following:

A pure moment action at the location of a hole clearly introduces tension stresses perpendicular to the grain at the hole periphery, thus being contrary to some background literature of the draft. The non-singular peak stress, the distribution length and the resulting tension force due to the local stress disturbance differ considerably from the code proposal. A consistent design approach obviously necessitates the inclusion of size effects, both, on the variable stress and on the strength side.

ZUSAMMENFASSUNG

Der Aufsatz beschäftigt sich mit der Berechnung des Einflusses von runden Durchbrüchen in Brettschichtholzträgern; es wird zunächst ausschließlich eine reine Momentenbeanspruchung betrachtet. Erste Ergebnisse der andauernden Untersuchungen, die letztlich auf eine Erweiterung von Eurocode 5 abzielen, werden mit den im Neuentwurf zu DIN 1052 für diesen Lastanteil enthaltenen Vorschlägen verglichen. Einige Ergebnisse der Finite Element Berechnungen die z.Z. durch experimentelle Untersuchungen ergänzt werden, lassen sich wie folgt zusammenfassen:

Eine reine Momentenbeanspruchung im Durchbruchsbereich verursacht sehr wohl Spannungen rechtwinklig zur Faserrichtung in der Lochumgebung; dies steht teilweise im Widerspruch zur Literatur. Die nicht-singuläre Höchstspannung, die Abklinglänge und die resultierende Zugkraft infolge der lokalen Spannungsstörung unterscheiden sich erheblich von den Norm-Vorschlägen. Ein konsistenter Bemessungsansatz erfordert offensichtlich die Berücksichtigung von Größeneffekten, sowohl auf der Seite der veränderlichen Spannungen wie auf der Festigkeitsseite.

RÉSUMÉ

L'article traite de l'analyse de poutres lamellées-collées percées de trous circulaires soumises à de la flexion pure. Cette étude toujours en cours vise à compléter l'Eurocode 5. Ses premiers résultats sont comparés aux préconisations de charges du projet de norme des nouvelles règles allemandes de calcul des structures en bois E DIN 1052. Une approche par Eléments Finis complétée par des expérimentations a permis de conclure au principal résultat suivant :

Une flexion pure dans une zone où il existe un percement engendre des contraintes de traction perpendiculaire au fil du bois contrairement à ce qu'indiquent les références bibliographiques du projet de norme. La concentration de contrainte non-singulière, sa distribution sur la longueur et la traction perpendiculaire induite, engendrées par la perturbation locale des contraintes, diffèrent de la proposition normative de façon importante. Un dimensionnement convenable requiert la prise en compte de l'effet d'échelle à la fois sur la distribution variable des contraintes locales et sur la résistance en traction perpendiculaire.

KEYWORDS: glulam, round holes, pure moment action, tension stress perpendicular to grain, distribution length of stress disturbance

1. INTRODUCTION

The draft for the new German timber design code, E DIN 1052, contains a considerably extended set of design rules for holes in glulam and LVL beams as compared to the present code version, issued in 1988. In the course of reviewing the draft code a research project was set up in order to provide a consistent basis for validation and amendment of the draft rules. This work shall also serve as a contribution to an extension of Eurocode 5 which today does not provide design rules for holes.

The paper focuses on one specific aspect of the on-going investigations, being the stress field disturbance in the vicinity of a hole in a beam subjected exclusively to a constant bending moment. In more detail, the tension stresses and the resultant force perpendicular to beam and wood fiber (grain) direction, initiated by the hole, are regarded. The issue of the pure moment action, discussed rather controversially in background papers, needs some clarification in order to obtain a better understanding of the usual loading situations with rather deliberate shear force-moment ratios. Further, this paper deals exclusively with round holes.

The analysis and design of glulam beams with round and rectangular holes has been subject to a considerable number of experimental and theoretical studies for many years. On the theoretical side two basically different strategies, based either on continuum mechanics combined with a strength of materials approach or on fracture mechanics can be differentiated. For contributions to the first mentioned approach (here solely unreinforced holes) see i.a. Krabbe and Schowe, 1977; Johanesson, 1977, 1983; Pentalla, 1980; Kolb and Epple, 1985. Fracture mechanics studies on the subject are given i.a. by Logemann, 1991; Pizio, 1991; Petersson, 1995; Aicher et al., 1995; Gustafsson et al., 2000.

Both methodically different approaches have their assets. From a theoretical point of view, taking into account the extreme brittleness of the material wood in tension perpendicular to grain, fracture mechanics seems to be the more appropriate approach. For code purposes and special respect to round holes, a refined strength of materials approach can be considered feasible, too, when size effects are included appropriately.

2. DESIGN ACCORDING TO DRAFT STANDARD E DIN 1052

2.1 General requirements

Figure 1 specifies all relevant dimensions for the placement of round holes; rectangular holes are treated similar except for the hole dimensions. Holes acc. to E DIN 1052 have a diameter > 50 mm; unreinforced holes shall only be used in service class 1 and 2. They shall not be placed in unreinforced areas of beams with regular design stresses perpendicular to grain. The maximum size of the hole and the shift of the hole center relative to the beam axis shall conform to the conditions

$$d/h \leq 0{,}4 \quad \text{and} \quad h_{ro\,(ru)} \geq 0{,}25\ h. \tag{1a,b}$$

Further prescriptions for distances l_A, l_v and especially on l_z are not important in ***this*** context.

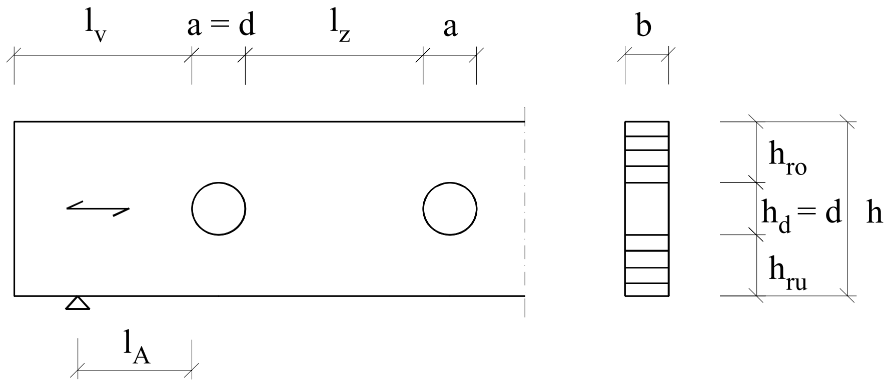


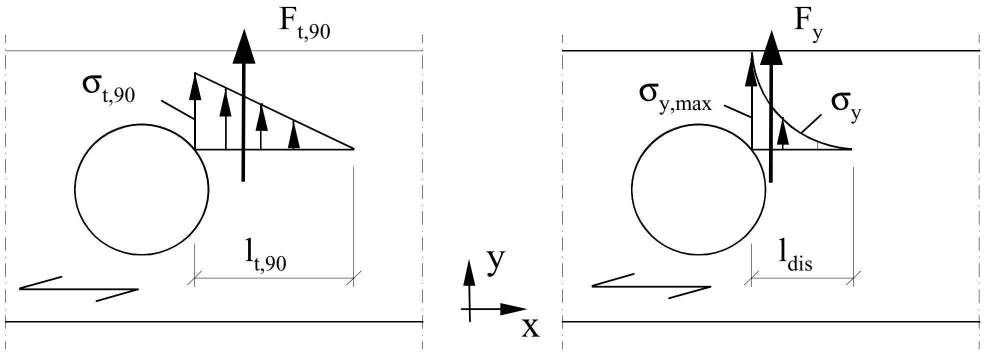
Fig. 1 Dimensions for holes in glulam and LVL beams acc. to E DIN 1052

2.2 Design rules

The following condition shall be fulfilled:

$$\sigma_{t,90,d} = \frac{F_{t,90,d}}{0{,}5 \cdot l_{t,90} \cdot b} \leq f_{t,90,d} \qquad (2)$$

where



a) b)

Fig. 2 Schematic illustrations concerning the design relevant tension stress distribution perpendicular to grain
a) notation acc. to E DIN 1052
b) general notation

$\sigma_{t,90,d}$	design tension stress perpendicular to grain at the hole periphery (note: $\sigma_{t,90,d}$ is not specified explicitly in the draft)
$F_{t,90,d}$	design tension force perpendicular to the grain = stress resultant ($\int_{l_{dis}} \sigma_y \, dx \approx \sigma_{t,90} \, l_{t,90} \, b \,/\, 2$) of an approximated triangular stress distribution (see Fig. 2)
$l_{t,90}$	$= 0{,}353\ d + 0{,}5\ h$ distribution length l_{dis} of the assumed triangular stress distribution (3)
$f_{t,90,d}$	design tension strength perpendicular to grain

The design tension force $F_{t,90,d}$ is composed of two parts, one resulting from the design shear force V_d and the other from the design moment M_d, both at the edge of the hole[1] , i.e.

$$F_{t,90,d} = F_{t,V,d} + F_{t,M,d} \quad . \qquad (4)$$

[1] This wording has to be specified more precise for a deliberate V + M action thus, that both hole edges closer and further from support have to regarded to evaluate the unfavourable edge

As lined out introductory, this paper deals exclusively with the second term, the tension force resp. the stress resulting from the action of a constant moment, i.e. V = 0 and soforth $F_{t,V,d} = 0$. According to E DIN 1052 the moment contribution is

$$F_{t,M,d} = M_d \frac{0{,}008}{h_r} \tag{5}$$

where

$$h_r = \min\left[h_{ro(ru)}\right] + 0{,}15\ d \tag{6a}$$

resp. in case of a symmetrically placed hole ($h_{ro} = h_{ru}$)

$$h_r = 0{,}5\ h - 0{,}35\ d. \tag{6b}$$

Note, that "min" in eq. (6a) is not specified in E DIN 1052 but delivers the conservative solution. In the following the subscript d (d = design) is omitted and nominal load, stress and (characteristic) strength values are regarded.

The moment contribution acc. to eq. (5), as well as the shear force contribution $F_{t,V}$, here not given explicitly, is based on work by Kolb and Epple (1985), who investigated a large variety of questions concerning unreinforced and reinforced holes in glulam beams[2]. Whereas the latter mentioned shear force term $F_{t,V}$ stems from an analytical equilibrium consideration, this is different for $F_{t,M}$. The given reference states that a FE analysis did not forward tension stresses perpendicular to grain for a pure moment action. However, in order to account for experimentally observed load capacity losses in case of pure moment loading, expression (5) was derived by some calibration to experimental results.

In the following chapters the issue of tension stresses perpendicular to grain due to pure moment action is revisited, as it is obvious and well proven by analytical solutions in isotropic stripes and beams with holes (i.a. Sawin, 1956; Girkmann, 1978) that the stress flow around a hole must generate a stress component normal to the direction of the far field stress state. A further look is given to the distribution length l_{dis} of this stress component as the length $l_{dis} = l_{t,90}$ acc. to eq. (3) seems too long for the rather local stress disturbance effect.

[2] there may well be similar/equal earlier expressions for $F_{t,V}$ proposed by other authors outside Germany, followed up in on-going literature review

3. ANALYZED CONFIGURATIONS AND FEM MODEL

The moment effect on tension stresses perpendicular to beam and grain direction was analyzed by plane FEM analysis for the hole and moment configuration shown in Fig. (3) whereby the following hole (diameter) to beam depth ratios d/h and absolute beam depths h were investigated:

d/h = 0,1; 0,2; 0,3; 0,4; 0,45 and 0,5
h = 500; 1000 and 1500 mm.

The applied moment was equal for all regarded configurations (50 kNm at the hole center).

The analysis was performed for plane stress conditions with an orthotropic constitutive law, employing the following elasticity coefficients (x = beam axis and fiber direction, y = perp. to fiber, Poisson ratio: first index denotes strain)

$E_x = 12000$ N/mm2, $E_y = 480$ N/mm2, $G_{xy} = 600$ N/mm2, $\nu_{xy} = 0{,}03$.

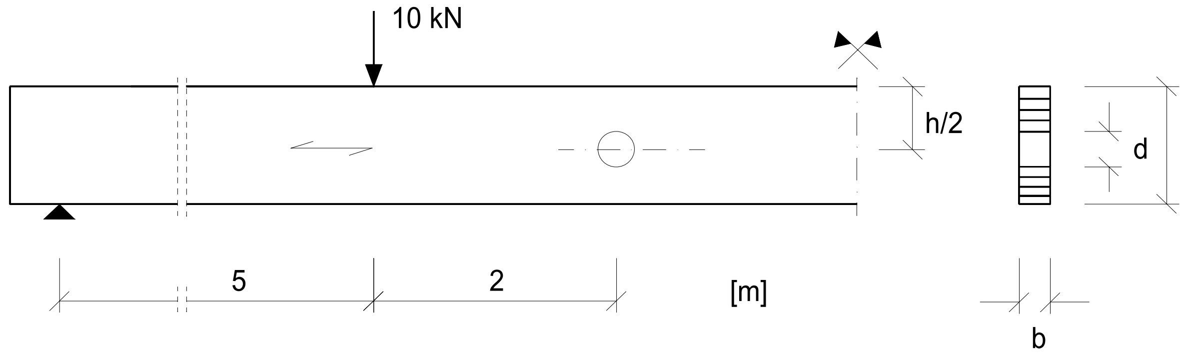


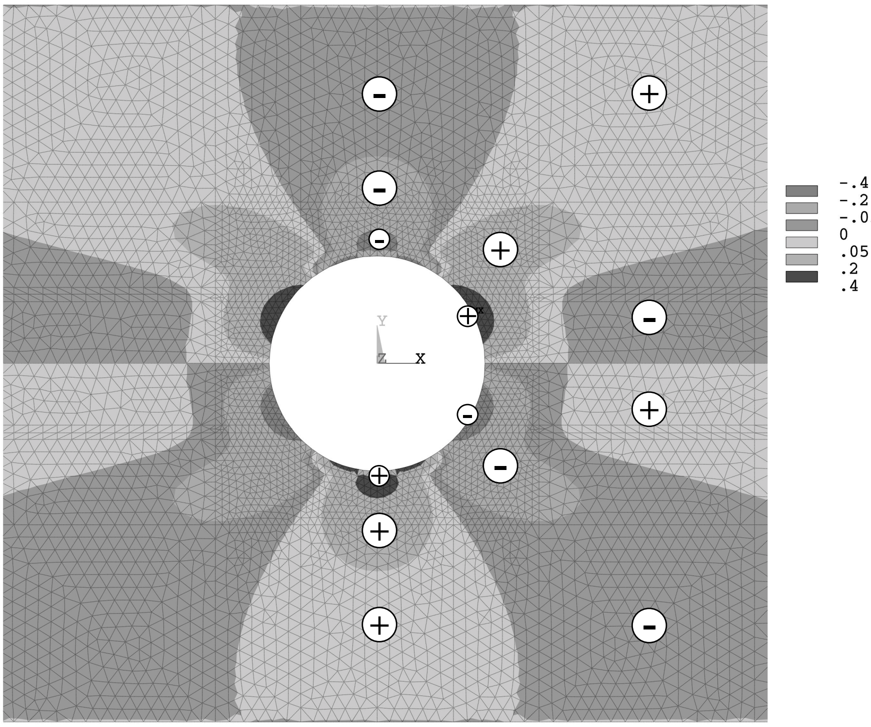
Fig. 3 Investigated constant moment configuration for a glulam beam with a round hole; for dimensions d and h, see text

Figure 4a shows the hole vicinity of one of the finer FE meshes, employing isoparametric 6node triangular elements, used to determine the mesh sensitivity of the solutions. The results presented in the given parameter study are based on a somewhat coarser mesh based on isoparametric 8node rectangular elements, whereby the mesh divisions were scaled equally throughout all investigated configurations. The regarded problem is rather insensitive to mesh variations; the results of rather fine discretization deviate by maximally 1 to 2% from the employed coarser idealisations, the latter being however still considerably finer than those used by Kolb and Epple (1985).

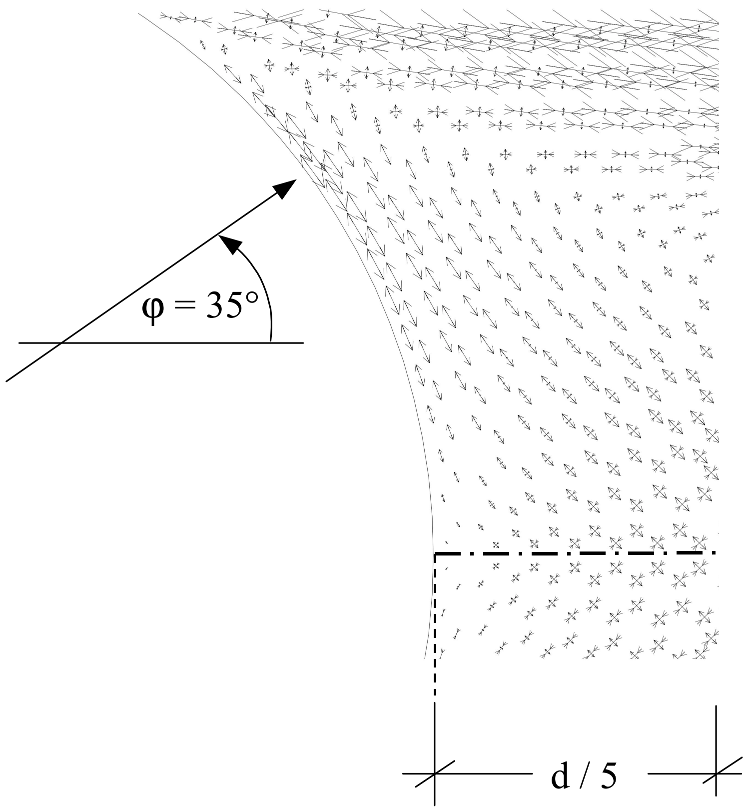
4. RESULTS

General views of the distribution of stress σ_y perpendicular to grain and of the principle stresses in the hole vicinity are given in Figs. 4a and b, respectively. Of course, the stress distribution shape is symmetric to orthogonal axes (parallel and perpendicular to beam axis) through the hole center. Contrary to the stress distribution resulting from shear forces, the design relevant tension stress fields occur symmetrically at opposite hole sides at the bending compression part of the beam. Functionally seen, the tension stresses act as "hold back" stresses for the inclined bending compression stresses, what is visualized by a principle stress vector plot of the tension stress field, shown in Fig. 4b.

Figure 5 depicts the variation of stress σ_y and the absolute maximum principal stress σ_I along the hole periphery (r = const. = d/2) for an angle range of $-90° \leq \varphi \leq 90°$. The stress maxima for σ_y do not occur at $\pm$ 45°, as might be supposed from some literature, but somewhat closer to the neutral axis; within the range of $25° \leq \varphi \leq 35°$ the stress is rather evenly distributed (decrease of 1-2% of the maximum value). The peak value of the maximum principal stress σ_1 is about 30% higher as compared to σ_y and located at $\varphi = \pm 38°$, rather evenly distributed within the range of $\pm 35° \leq \varphi \leq \pm 40°$. For further considerations on both, the stress distribution with increasing distance from the hole periphery and on the resultant tension force, throughout $\varphi = 35°$ was chosen.



a)



b)

Fig. 4a,b Stress distribution in the vicinity of a round hole in a glulam beam due to constant moment action

a) stress contour plot of component σ_y perpendicular to beam and grain axis

b) vector plot of principle stress in a close-up of the hole vicinity between $5° \leq \varphi \leq 50°$

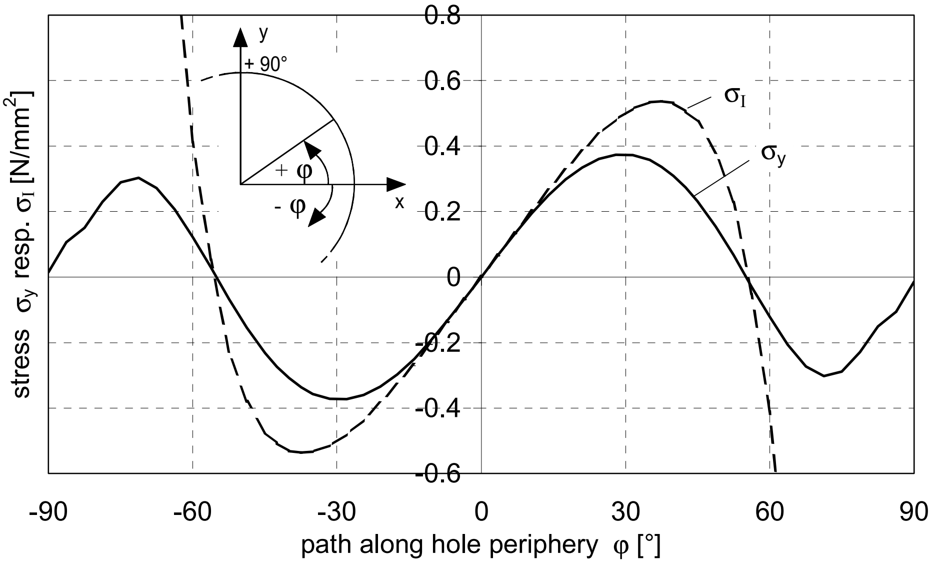


Fig. 5 Variation of stresses σ_y and σ_I = max $/\sigma_1$, $\sigma_2/$ along the hole periphery (r = const. = d/2) within -90° ≤ φ ≤ +90°

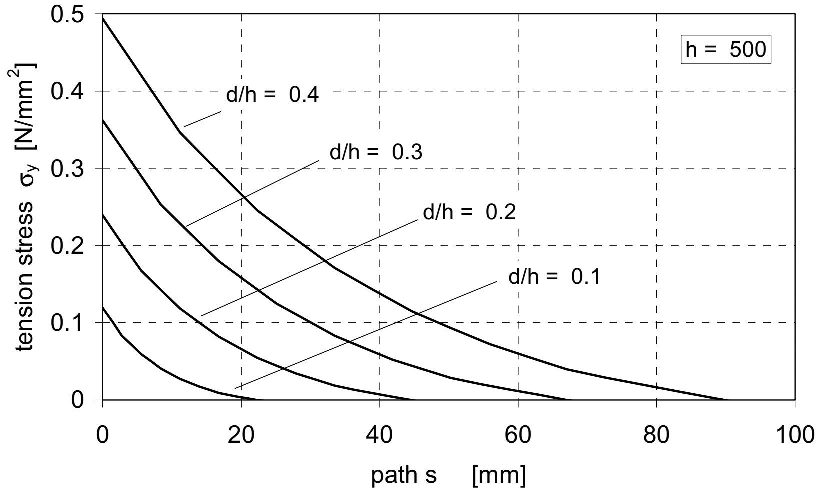
Figures 6a and b show the distribution of stress σ_y along path s parallel to beam axis at a constant beam depth of y = const. = (d/2) sin 35° for several different configurations. Figure 6a gives for a beam of constant depth the stress distributions depending parametrically on the hole to depth ratios d/h = 0,1; 0,2; 0,3 and 0,4. Figure 6b specifies for a beam with constant ratio d/h = 0,3 the effect of beam depth.

Briefly, the graphs give the following information:

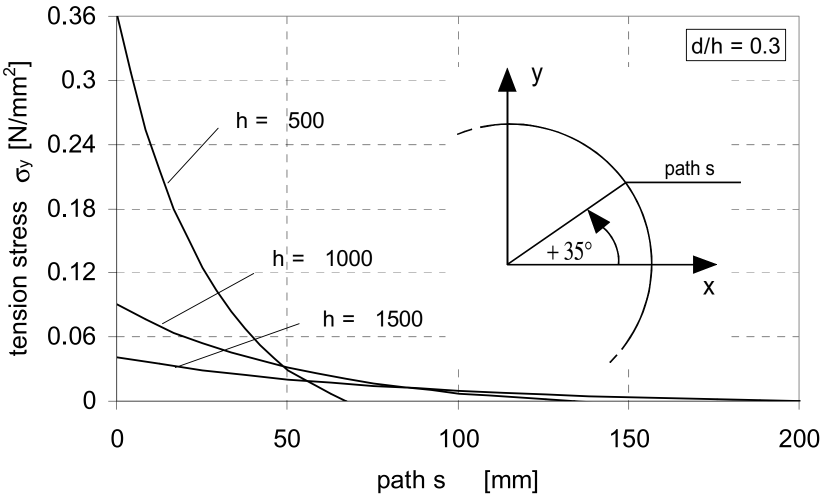
- stress σ_y declines not linearly as suggested by eq. (2) but roughly exponentially.
- the maximum stress is considerably higher as predicted by eqs. (2) to (6), see below.
- the distribution length l_{dis} is by far shorter as specified by eq. (3) and seems to depend exclusively on the absolute size d of the hole for a d/h ratio of maximally about 0,4.

Figure 7 shows the maximum stress $\sigma_{y,max}$ (filled dots, triangles and rhombs) depending on d/h and h. In the range of d/h ≤ 0,4 stress $\sigma_{y,max}$ can be approximated very well by the simple linear expression

$$\sigma_{y,max} = \frac{M}{b\,h^2}\,\frac{d}{h}\,0{,}6\,. \tag{7}$$



a)



b)

Fig. 6a,b *Distribution of stress σ_y along path s showing roughly the highest tension perp. to grain stresses for different hole configurations*
a) h = const. = 500; d/h = 0,1; 0,2; 0,3 and 0,4
b) d/h = const. = 0,3; h = 500; 1000 and 1500 mm

The solution acc. to eq. (7) is given in Fig. 7 by the solid lines, too. Beyond d/h = 0,4 the maximum stress is increasingly nonlinear in d/h.

Figure 8 visualizes the very pronounced difference between the □y,max stresses derived here and those predicted by E DIN 1052; eqs. (2) to (6) deliver (approximately):

$$\sigma_{y,max} = \frac{0{,}016 \cdot M}{b\,((0{,}5\ h)^2 - (0{,}35\ d)^2)} \ . \tag{8}$$

So, acc. to *mere* linear elastic maximum stress, yet not being subject to any geometric resp. stress singularity, the draft standard solution is highly unconservative. However, on the other hand, the resultant tension force, strongly influenced by the shape and declination length of the stress distribution is fairly lower as predicted by eq. (5). With respect to a realistic material relevant design the quoted dilemma poses immediately the question on the damage relevant volume or area, especially as tension strength perpendicular to grain incorporates a generally accepted extreme size effect, described roughly by a Weibull size exponent of m = 5. A solution following the indicated way will be forwarded.

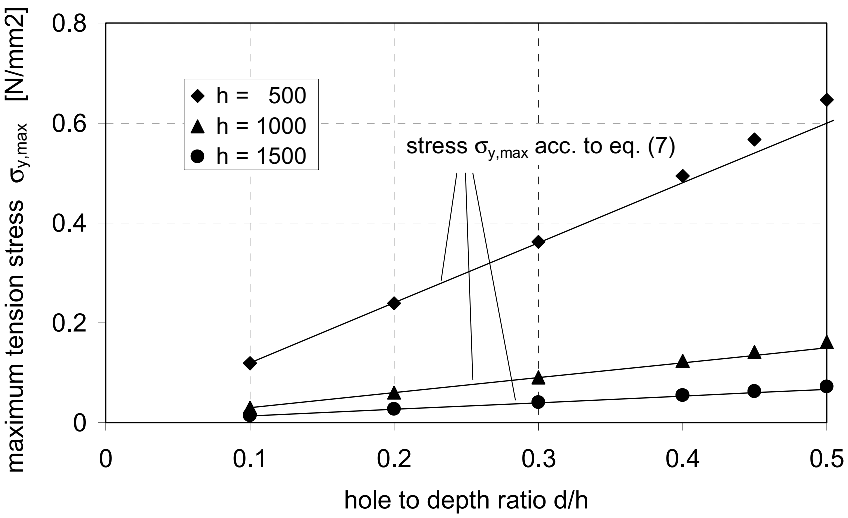


Fig. 7 Stress $\sigma_{y,max}$ perpendicular to grain depending on hole to depth ratio and beam depth; also given is the derived linear approximation (d/h ≤ 0,4) acc. to eq. (7)

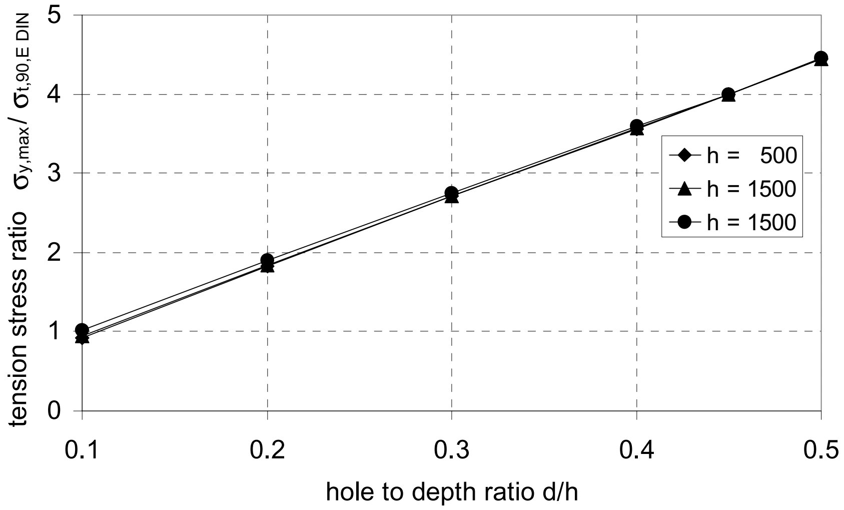


Fig. 8 Ratio of maximum tension stress perpendicular to grain at the hole periphery acc. to FE results vs. E DIN 1052 solution

6. CONCLUSIONS

For glulam beams with round holes subjected to a pure moment action, the following preliminary conclusions can be stated:

- the literature known statement that pure moment action does not forward tension stresses perpendicular to grain at the periphery of a hole is incorrect.
- the (maximum) tension stress at the hole circumference, as predicted implicitly by draft standard E DIN 1052, is by far too low.
- the distribution length of the stress concentrations at the hole, as assumed by E DIN 1052, is by far too long and further not dependant on absolute beam depth (for hole to depth ratios ≤ 0,4).
- the resultant tension force acc. to stringent FE analysis is considerably ***lower*** as compared to the calibrated value given in E DIN 1052.
- the discrepancies between the obtained computational results and the draft standard proposals are followed up in more depth , backed by experimental investigations, in on-going work.

7. ACKNOWLEDGEMENTS

The authors owe many thanks to Deutsche Forschungsgesellschaft for the substantial financial support of this work via grants to the Sonderforschungsbereich 381 „Characterization of damage evolution in fiber composite materials by nondestructive testing“ and hereby especially to sub-project A8: „Damage and nondestructive testing of the natural composite material wood“. Further, we gratefully acknowledge the contribution of Philippe Galimard, from Laboratoire de Rheoleogie du Bois de Bordeaux, providing the professional French abstract of our paper.

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