Tension perpendicular to the grain in joints

STEP lecture C2
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Objectives

To describe the special problem of tension stresses perpendicular to the grain in joints when the force in the joint acts at an angle to the grain and to present different design methods.

Prerequisites

B2 Tension and compression
B4 Shear and torsion
B5 Notched beams and holes in glulam beams
C1 Mechanical timber joints - General

Summary

Illustrated examples are given of joints which tend to fail due to perpendicular-to-grain tensile stresses. The failure modes are explained. EC5 provides a simple application rule for designing against these failures, but some more sophisticated design procedures based on fracture mechanics as well as on purely empirical equations are presented. Practical applications following such procedures are demonstrated by design examples.

Introduction

The load-carrying capacities of timber joints with mechanical fasteners loaded at an angle to the grain direction are normally determined by taking into account the bending resistance of the fasteners and the embedding strength of the timber. However, local stresses perpendicular to the grain may under certain conditions lead to failure at a lower load level.

Some typical examples (Figure 1) where tension perpendicular to the grain in joints occurs are:

(a) joist hangers (steel-to-wood joints)
(b) punched metal plate fastener joints
(c) joints with dowels or ring and shear-plate connectors (glulam beams)
(d) glued-in bolts

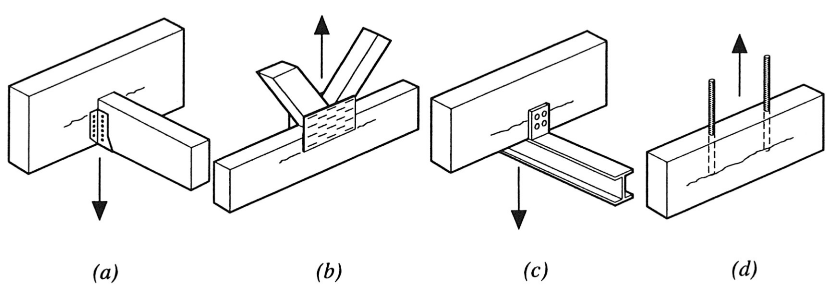

Figure 1 Examples of tension perpendicular to the grain in joints with probable crack propagation path.

Tension perpendicular-to-grain stresses combined with shear and bending stresses can be estimated by means of the finite element methods. However, such calculated stresses do not directly compare with the characteristic tensile strength determined from standard test specimens. Since the stresses in joints loaded perpendicular to grain are similar to the stresses in notched beams, similar calculation methods, for example based on fracture mechanics as adopted in EC5 for notched beams, could be used.

Other methods for taking into account these stresses use empirical solutions. The perpendicular to grain design is replaced by a shear design procedure with certain fictitious strength reductions or by assigning the load component acting perpendicular to the grain to an assumed effective area and comparing the resulting stresses with certain design stresses perpendicular to grain.

Reducing the risk of a tension perpendicular to the grain failure

First, the factors influencing the load carrying capacity of joints loaded perpendicular to the grain are described. From these factors structural rules for reducing the risk of a tension perpendicular to the grain failure are derived. Figure 2 shows a mechanical timber joint loaded perpendicular to the grain. The force F_{90} is acting perpendicular to the grain and is transferred to the beam by dowel-type fasteners. The fasteners are spread over a certain area.

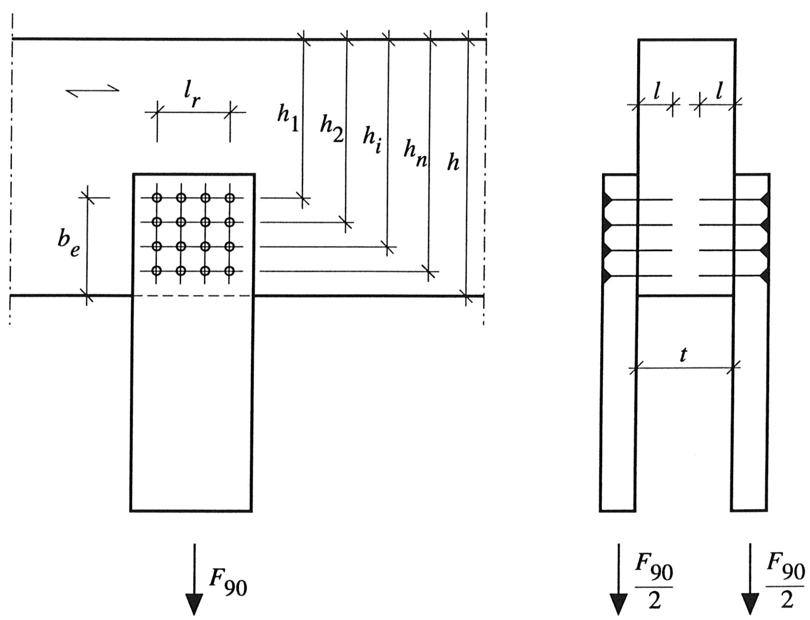

Figure 2 Joint with F acting perpendicular to the grain (notation).

The load-carrying capacity of this connection is influenced by the following parameters:

- The ratio between the distance b_e of the furthest row of fasteners from the loaded beam edge and the beam depth *h*. Therefore, fasteners should be placed as near as possible to the unloaded beam edge to avoid tension perpendicular to the grain failures.

- Several fasteners in a row spaced along the grain direction distribute the acting force over a larger stressed area in such a way that the stresses perpendicular to the grain are considerably reduced. This advantageous influence increases with the number of rows and with large spacings.

- Increasing the depth h or the width t of the beam leads to increasing load-carrying capacities. Attention must be paid to the fact that only a part of the width is stressed with tension perpendicular to the grain.

- Spreading the fasteners over many rows reduces the tension perpendicular to the grain stresses.

- The tension perpendicular to the grain strength of the timber depends on the actual stressed volume and consequently influences the load-carrying capacity of joints in beams with different sizes.

Design of tension perpendicular to the grain in joints

Design according to EC5

Unless a more detailed calculation is made, for the arrangement shown in Figure 3 it should be shown that the following condition is satisfied:

$$V_d \leq \frac{2\, f_{v,d}\, b_e\, t}{3} \qquad (1)$$

provided that $b_e > 0{,}5h$. The symbols are defined as follows:

V_d is the design shear force ($\max(V_{1,d}, V_{2,d})$) produced in the member of thickness t by the fasteners ($V_1 + V_2 = F \sin\alpha$),

b_e is the distance from the loaded edge to the furthest fastener or connector and

α is the angle between force F and grain direction.

This design procedure substitutes the design perpendicular to the grain with a fictitious shear design over the residual cross section. Some important factors influencing the load-carrying capacities are, however, not taken into consideration. In the case of $b_e < 0{,}5h$ a more detailed calculation is required in any case.

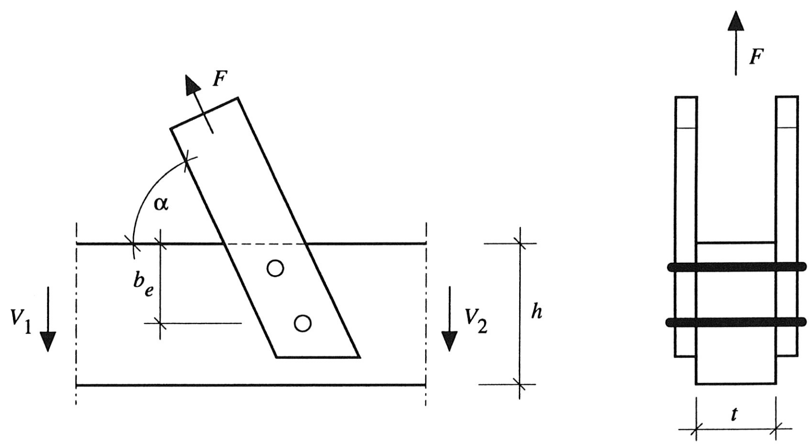

Figure 3 Joint force acting at an angle to the grain.

Design based on fracture mechanics

The design of notched beams according to EC5 is based on the theory of fracture mechanics. Although tension stresses perpendicular to the grain in joints are similar to those in notched beams the design methods according to fracture mechanics have not been adopted in EC5. Nevertheless there is a proposal (Van der Put, 1990) based on fracture mechanics and supported by test results.

$$V_d \le \frac{2\, f_{v,d}\, b_e\, t}{3} \sqrt{\frac{130}{h}} \qquad for \qquad \frac{M_d}{V_d\, h} > 2{,}1 \tag{2}$$

$$V_d \le \frac{2\, f_{v,d}\, b_e\, t}{3} \sqrt{\frac{130}{h} \cdot \frac{2{,}1}{M_d \,/\, (V_d\, h)}} \qquad for \qquad \frac{M_d}{V_d\, h} < 2{,}1 \tag{3}$$

and

$$V_d \le \frac{2\, f_{v,d}\, h\, t}{3} \qquad for \qquad b_e > 0{,}7h \tag{4}$$

where symbols are defined as follows:

t is the thickness of the member,
b_e is the distance from the loaded edge to the furthest fastener,
h is the beam depth (in *mm*),
M_d is the maximum design bending moment nearest to the joint and
V_d is the design shear force introduced in the member by the fasteners.

This design proposal modifies the EC5 design rules by taking into account the influence of the beam depth h. By this means, the restriction $b_e > 0{,}5\, h$ is omitted. Note that this design proposal based on fracture mechanics leads for deep beams ($h >> 130$ *mm*) and with $0{,}7\, h > b_e > 0{,}5\, h$ to substantially lower design values than EC5. On the other hand there is a discontinuous point at $b_e = 0{,}7\, h$. For infinitesimally small changes of b_e there is a "design jump".

Design based on experimental and theoretical investigations

Based on test results and their conclusions (Ehlbeck et al., 1989), design for tension perpendicular to the grain in joints can be carried out by checking that the following condition is satisfied:

$$\sigma_{t,90,d} = \eta\, k_r\, \frac{F_{90,d}}{A_{ef}} \le 15\, A_{ef}^{-0{,}2}\, f_{t,90,d} \tag{5}$$

This equation was derived for a characteristic perpendicular-to-grain strength related to a volume of 0,02 m^3. Since EC5 now relates to a reference volume of 0,01 m^3 Equation (5) should be modified by a factor $(0{,}01\ m^3/0{,}02\ m^3)^{0{,}2} = 0{,}87$. Thus, Equation (5) should read:

$$\sigma_{t,90,d} = \eta\, k_r\, \frac{F_{90,d}}{A_{ef}} \le 13\, A_{ef}^{-0{,}2}\, f_{t,90,d} \tag{6}$$

The factor η makes allowance for the fact that only part of the load $F_{90,d}$ causes tensile stresses, some of it also causing compressive stresses perpendicular to the grain.

$$\eta = 1 - 3\left(\frac{b_e}{h}\right)^2 + 2\left(\frac{b_e}{h}\right)^3 \tag{7}$$

The factor k_r allows for the fact that the load $F_{90,d}$ is distributed over several rows of fasteners so that only a reduced portion of tensile stresses is acting in the line of the furthest row of fasteners:

$$k_r = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{h_1}{h_i}\right)^2 \tag{8}$$

The effective area A_{ef} represents a fictitious area, because the perpendicular-to-grain stresses are unevenly distributed along the length, l_r, of the row of fasteners and, in addition, also stresses the timber for a certain distance beyond both ends of the row. It can be roughly assumed that

$$l_{r,ef} = \sqrt{l_r^2 + (ch)^2} \tag{9}$$

with

$$c = \frac{4}{3}\sqrt{\frac{b_e}{h}\,(1 - \frac{b_e}{h})^3} \tag{10}$$

The effective thickness, t_{ef}, can approximately be assumed as the sum of the depths of penetration, l, of the fasteners (Figure 2).

$$t_{ef} = \Sigma l \leq t \tag{11}$$

For nails and screws l should not be assumed to be greater than 12 d

If two groups of fasteners are positioned near to each other with a centroidal distance of l_1 the effective area increases by the factor

$$\left(1 + \frac{l_1}{l_1 + b_e}\right) \tag{12}$$

In cases where the joint is near to the beam end, it should be realized that the load or the stresses cannot distribute unchecked. If the distance of the joint from the beam end is less than the beam depth itself, only half the effective length should be taken into account.

Examples

Design of a joint with force acting perpendicular to the grain.
Joint with dowels acting perpendicular to the grain of a glulam beam with a cross section of t x h, 100 x 600 *mm* (Figure 4)
Service class 1: k_{mod} = 0,8

Strength class GL 28 according to prEN 1194 "Timber structures - Glued laminated timber - Strength classes and determination of characteristic values."

$f_{v,g,k}$ = 3,0 N/mm^2 $\quad$ $f_{t,90,g,k}$ = 0,45 N/mm^2

Design values:

$f_{v,g,d}$ = 1,85 N/mm^2 $\quad$ $f_{t,90,g,d}$ = 0,28 N/mm^2

Design load-carrying capacity per shear plane per dowel: R_d = 8,15 *kN*
Design load-carrying capacity of the joint: $R_{d,joint} = 2 \cdot 12 \cdot 8{,}15 = 196$ *kN*

Design of tension perpendicular to grain in joints according to EC5:

$$V_d \leq \frac{2\,f_{v,d}\,b_e\,t}{3} = \frac{2 \cdot 1{,}85 \cdot 300 \cdot 100}{3}\,10^{-3} = 37{,}0\ kN$$

$$F_{90,d} = 2\,V_d \leq 2 \cdot 37 = 74\ kN$$

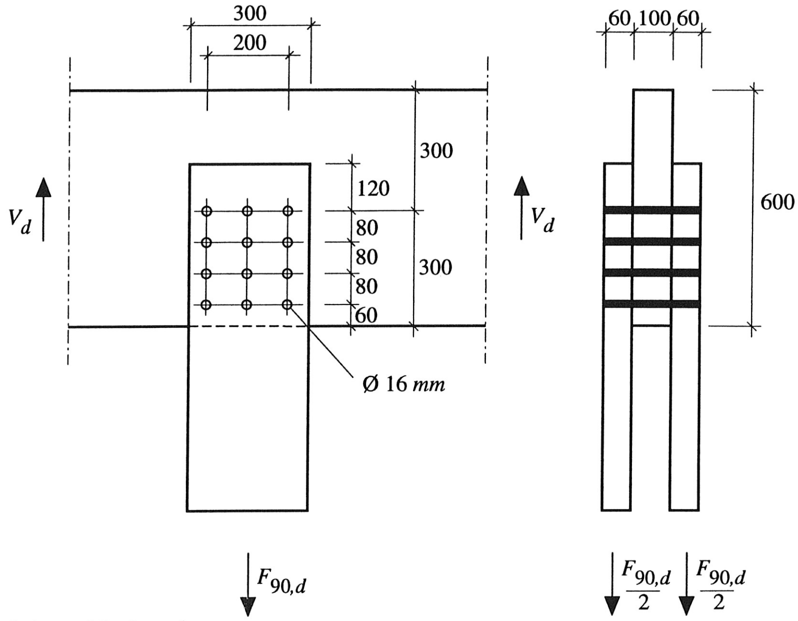

Figure 4 Joint with dowels.

Design based on fracture mechanics:
Assumption:

$$\frac{M_d}{V_d\, h} > 2{,}1$$

$$V_d \leq \frac{2\, f_{v,d}\, b_e\, t}{3} \sqrt{\frac{130}{h}} = \frac{2 \cdot 1{,}85 \cdot 300 \cdot 100}{3} \sqrt{\frac{130}{600}} \cdot 10^{-3} = 17{,}2\ kN$$

$$F_{90,d} = 2\ V_d \leq 2 \cdot 17{,}2 = 34{,}4\ kN$$

Design based on experimental investigations:

$$\eta = 1 - 3\left(\frac{b_e}{h}\right)^2 + 2\left(\frac{b_e}{h}\right)^3 = 1 - 3\left(\frac{300}{600}\right)^2 + 2\left(\frac{300}{600}\right)^3 = 0{,}5$$

$$k_r = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{h_1}{h_i}\right)^2 = \frac{1}{4}\left(\left(\frac{300}{300}\right)^2 + \left(\frac{300}{380}\right)^2 + \left(\frac{300}{460}\right)^2 + \left(\frac{300}{540}\right)^2\right) = 0{,}59$$

$$c = \frac{4}{3}\sqrt{\frac{b_e}{h}\left(1 - \frac{b_e}{h}\right)^3} = \frac{4}{3}\sqrt{\frac{300}{600}\left(1 - \frac{300}{600}\right)^3} = 0{,}33$$

$$l_{r,ef} = \sqrt{l_r^2 + (ch)^2} = \sqrt{200^2 + (0{,}33 \cdot 600)^2} = 283\ mm$$

$$t_{ef} = \Sigma l \leq t = 100\ mm$$

$$A_{ef} = l_{r,ef}\ t_{ef} = 28300\ mm^2$$

$$F_{90,d} \leq \frac{13\ A_{ef}^{-0,2}\ f_{t,90,d}}{\eta\ k_r}\ A_{ef} = \frac{13(28300)^{-0,2} \cdot 0,28}{0,5 \cdot 0,59}\ 28300 \cdot 10^{-3} = \underline{44,9\ kN}$$

Discussion of the design results

In Ehlbeck, Görlacher and Werner (1989) some test results with dowelled joints in glulam beams under heavy loads perpendicular to the grain are presented. One of these test specimens corresponds to the design example shown in Figure 4. The short term load-carrying capacity of this joint was 110 *kN*. Assuming the same k_{mod} value and safety factor as used in the design example the comparable test value is 110 · 0,8 / 1,3 = 67,7 *kN*. Assuming a 5-percentile of 0,6 to 0,8 times the single test value the design values is about 41 to 54 *kN*.

The EC5 design method in many cases seems to be on the unsafe side, whereas the two other design methods lead to more realistic values. In a future version of EC5 one of the more precise methods is likeley to be included.

Concluding summary

- Joints may fail under certain conditions due to perpendicular to the grain stresses.

- In order to reduce this risk of failure the fasteners should be placed as near as possible to the unloaded edge.

- Spreading the fasteners over a certain area reduces the tension perpendicular to the grain stresses and increase the safety.

- The EC5 design of joints with loads acting perpendicular to grain is very simple but does not take into consideration some important factors influencing the load-carrying capacities. Test results indicate that the design according to EC5 may lead to unsafe design situations.

- Some more sophisticated design rules do exist and should be used in cases where 0,7 $h > b_e > 0,5\ h$.

References

Ehlbeck, J., Görlacher, R., Werner, H. (1989). Determination of perpendicular-to-grain tensile stresses in joints with dowel-type-fasteners. Proc. of the CIB W 18 Meeting, Berlin, Germany, Paper 22-7-2.

Van der Put, T. A. C. M. (1990). Tension perpendicular to the grain at notches and joints. Proc. of the CIB W 18 Meeting, Lisbon, Portugal, Paper 23-10-1.