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Chapter 5

Holes and notches

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5 Holes and notches
The introduction of a hole or a notch in a member constitutes a sudden change in the cross section, which significantly influences the stress state and may in a timber member reduce the strength considerably. The flow of normal stress parallel to grain and of shear stress is disturbed. Instead, the local stress state will be characterized by concentrated, perpendicular-to-grain tensile stress and shear stress in the vicinity of the hole or the notch. This stress situation may lead to crack initiation for relatively low external loads and crack propagation in the fibre direction, which typically occurs in a very brittle manner. As for other applications with similar types of loading, experimental tests have shown a significant beam size dependency of the strength for both notched beams and beams with a hole.

Design considerations for unreinforced beams with a notch at the beam end or a hole or are treated in Section 5.1 and Section 5.3 respectively. Field notching on the tension side should not be allowed, unless the beam is properly reinforced. Due to the large strength reduction commonly related to beams with a notch or a hole, some type of reinforcement is generally advisable. Reinforcement of end-notched beams is treated in Section 5.2 and reinforcement of beams with a hole is treated in Section 5.4.

5.1 End-notched beams
Notches at beam ends should be handled with great care in design, as even a small notch constitutes a starting point for a potential crack and may hence reduce the load carrying capacity considerably. For a beam with fibre direction coinciding with the beam length direction, an end notch at the tension side introduces concentrated tensile stresses perpendicular to grain and shear stresses, which according to linear elasticity tend to infinity at the tip of a right angled notch. The failure type is typically very brittle, with crack initiation at the tip of the notch and propagation in the fibre direction. An end notch on the compression side gives a less severe reduction of the load carrying capacity compared to an end notch on the tension side.

If notches cannot be avoided they should preferably, at least if placed on the tension side, be tapered or given a corner radius of at least 25 mm. Larger notches than 0.5h or 500 mm should not be allowed without reinforcement. Special care should be taken with structures where there is a risk of major variations in the moisture content. All surfaces in a notch shall be surface treated.

The load carrying capacity of an unreinforced beam with an end notch can be checked using the following method found in Eurocode 5, with notation according to Figure 5-1. The method is based on a fracture mechanics analysis of right angled notches presented by Gustafsson (1988). Although the design criterion formally reads as a comparison between a nominal shear stress and a reduced shear strength, the action of both perpendicular to grain tensile stress and shear stress is implicitly considered. The decisive material properties in the fracture mechanics approach are the fracture energy in tension perpendicular to grain, the stiffness in beam length direction and the shear stiffness. These parameters enter the design equation through the factor $k_n$, via assumptions of their relations with the shear strength $f_n$. The modification term related to the notch inclination $i$ is an addition to the original fracture mechanics equation, based on experimental tests of beams with tapered notches presented by Ribeiroholt et al. (1992). For a beam with a rectangular cross section and with fibre direction coinciding with the beam length direction, the following criterion should be fulfilled.
\[
\tau = \frac{3}{2} \frac{V}{bh_{ef}} \leq k_v f_v
\]  

(5-1)

where for beams with the notch at the compression side \( k_v = 1.0 \), while for beams with the notch at the tension side

\[
k_v = \min \left\{ 1, k_a \left( 1 + \frac{1}{\sqrt{h}} \frac{h_{\text{ef}}i^{1.5}}{h} \right) \right\} \frac{\sqrt{h} \left( \sqrt{\alpha (1-\alpha)} + 0.8 \frac{x}{h} \left( \frac{1}{\alpha} - \alpha^2 \right) \right)}{\sqrt{h} \left( \sqrt{\alpha (1-\alpha)} + 0.8 \frac{x}{h} \left( \frac{1}{\alpha} - \alpha^2 \right) \right)}
\]  

(5-2)

and where

- \( V \) is the shear force
- \( b \) is the beam width
- \( h, h_{\text{ef}} \) is the total beam depth and effective beam depth respectively, in mm
- \( x \) is distance from support load line of action to notch tip, in mm
- \( i \) is notch inclination, see Figure 5-1
- \( \alpha = h_{\text{ef}}/h \) is the effective to total beam depth ratio
- \( k_a = 6.5 \) for glulam (4.5 for LVL and 5.0 for solid timber)

**Figure 5-1. Notation for design of end-notched beams according to Eurocode 5.**

### 5.2 Reinforcement of end-notched beams

Beams with an end notch can be externally or internally reinforced in order to increase the beam capacity. Internal reinforcement may consist of glued-in threaded rods, glued-in concrete reinforcement bars or fully threaded screws. External reinforcement may consist of glued-on panels such as LVL or plywood, glued-on lamellas or pressed-in punched metal plate fasteners. Design approaches for external and internal reinforcement of beams with a rectangular cross section and a rectangular notch \((i = 0, \text{see Figure} \ 5-1)\) are presented below, based on the German National Annex to Eurocode 5 (DIN EN 1995-1-1/NA). The basic idea is that the reinforcement should be designed to resist the entire force resultant of the damage relevant perpendicular to grain tensile stress along the potential crack plane starting from the corner of the notch. The perpendicular to grain tensile strength of the beam itself is neglected. The perpendicular to grain tensile force resultant \( F_{t,90} \) is determined from integration of the beam theory shear stresses below the depth of the notch, as indicated in Figure 5-2. A modification factor of 1.3 is applied to account for the discrepancy
between the beam theory assumptions and the true behaviour, yielding the following expression for the tensile force resultant

\[ F_{t,90} = 1.3V \left( 3(1-\alpha)^2 - 2(1-\alpha)^3 \right) \]  

(5-3)

where \( V \) is the shear force and \( \alpha = \frac{h_{eff}}{h} \). Use of the modification factor 1.3 yields sufficiently accurate values for \( x \leq \frac{h_{eff}}{3} \). For larger values of \( x \), the expression given in (5-3) may yield un-conservative values of \( F_{t,90} \). The entire shear force \( V \) may then be assigned to \( F_{t,90} \).

![Figure 5-2. Schematic illustration of stress distribution at notch corner and illustration of tensile force resultant \( F_{t,90} \).](image)

![Figure 5-3. Notation for internal (1) and external (2) reinforcement of end-notched beams (DIN EN 1995-1-1\(\text{NA} \)).](image)

### 5.2.1 Internal reinforcement of end-notched beams

For glued-in rods it should be checked that the stress \( \tau_{cf} \) in the glue “line” (cylinder), assumed to be evenly distributed, satisfies the following expression

\[ \tau_{cf} = \frac{F_{t,90}}{n \cdot d_r \cdot \pi \cdot l_{ad}} \leq f_{k,1} \]  

(5-4)

where

- \( F_{t,90} \) is the force resultant of the perpendicular to grain tensile stress, see (5-3)
- \( n \) is the number of rods, only one row in beam length direction may be considered active
- \( d_r \) is the outer thread diameter of the internal reinforcement, \( d_r \leq 20 \text{ mm} \)
- \( l_{ad} \) is the effective anchorage length, see Figure 5-3
- \( f_{k,1} \) is the shear strength of the glue line, see Table 5-1 for characteristic values \( f_{k,1,k} \)
Table 5-1. Characteristic shear strength of glue line for glued-in rods when used for reinforcement. These values may be used if the applicability of the glue system has been proven (DIN EN 1995-1-1/NA).

<table>
<thead>
<tr>
<th>Effective glued-in length $l_{ad}$ of steel rod [mm]</th>
<th>( \leq 250 )</th>
<th>( 250 &lt; l_{ad} \leq 500 )</th>
<th>( 500 &lt; l_{ad} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Characteristic shear strength $f_{k,2}$ of glue line [MPa]</td>
<td>4,0</td>
<td>5,25 – 0,005$l_{ad}$</td>
<td>3,5 – 0,0015$l_{ad}$</td>
</tr>
</tbody>
</table>

The tensile axial capacity of the steel rods should also be checked.

Only one row of steel rods in the beam length direction should be considered as reinforcement. The minimum length of each steel rod is $2l_{ad}$ and the outer thread diameter is limited to $d_r \leq 20$ mm. Edge distances and spacing of the reinforcement elements should be such that $3d_r \leq a_2$ and $2,5d_r \leq a_{3,c} \leq 4d_r$ and $2,5d_r \leq a_{4,c}$ with notation according to Figure 5-3. Since the perpendicular to grain tensile stress is highly concentrated to the vicinity of the notch corner, the edge distance $a_{3,c}$ should be kept as small as possible without violating the minimum required edge distance. For members exposed to tension parallel to grain, the reduction in net cross section area due to the internal reinforcement should be considered. Fully threaded screws may also be used as internal reinforcement and should then be designed for the tensile force $F_{t,90}$ with respect to withdrawal and tensile axial capacity.

In addition to verification of the internal reinforcement capacity, the shear stress of the reduced cross section should also be verified according to (5-1) with $k_r = 1,0$. Attention should also be paid to the shear stress concentrations at the notch corner when using internal reinforcement.

### 5.2.2 External reinforcement of end-notched beams

For glued-on panels it should be checked that the stress $\tau_{cf}$ in the glue line, assumed to be evenly distributed, satisfies the following expression

$$\tau_{cf} = \frac{F_{t,90}}{2 \cdot (h - h_{cf}) \cdot l_r} \leq f_{k,2}$$  \hspace{1cm} (5-5)

where
- $F_{t,90}$ is the force resultant of the perpendicular to grain tensile stress, see (5-3)
- $h, h_{cf}$ are the total beam depth and effective beam depth respectively, see Figure 5-3
- $l_r$ is the width of the reinforcement panels, see Figure 5-3
- $f_{k,2}$ is the shear strength of the glue line. DIN EN 1995:1-1-1/NA states characteristic value $f_{k,2,\text{lc}} = 0,75$ MPa for glue systems which have been proven to be applicable.

The tensile stress $\sigma_i$ in the panels should satisfy the following expression

$$\sigma_i = \frac{F_{t,90}}{2 \cdot t_r \cdot l_r} \leq \frac{f_t}{k_k}$$  \hspace{1cm} (5-6)

where
- $F_{t,90}$ is the force resultant of the perpendicular to grain tensile stress, see (5-3)
- $t_r$ is the thickness of one reinforcement panel, see Figure 5-3
- $l_r$ is the width of the reinforcement panels, see Figure 5-3
- $f_t$ is the tensile strength of the reinforcement panel in the direction of $F_{t,90}$
- $k_k$ is a factor accounting for the non-uniform stress distribution. DIN EN 1995:1-1-1/NA states that $k_k = 2,0$ may be applied without further verification.
Reinforcement panels should be glued onto both sides of the member according to Figure 5-3 with panel width limited by $0.25 \leq l_r/(h-h_o) \leq 0.5$ and panel thickness $t_r \geq 10$ mm. Sufficient pressure during gluing should be ensured, e.g. by the use of threaded nails or screws with appropriate anchorage length and spacing. Punched-in metal plate fasteners may also be used as external reinforcement, and should be designed in analogy with the above given recommendations.

In addition to verification of the external reinforcement capacity, the shear stress of the reduced cross section should also be verified according to (5-1) with $k_r = 1.0$. The capacity with respect to shear stress concentrations at the notch corner may be assumed to be sufficient when using external reinforcement designed in accordance with the above given recommendations.

### 5.3 Beams with a hole

Holes in members should preferably be avoided. A hole constitutes a sudden change in the cross section which impedes the flow of forces in the member and generally reduces the beam strength considerably. For a beam loaded in bending with fibre direction coinciding with the beam length direction, the flow of parallel to grain normal stress and shear stress is disturbed and instead there appear concentrated perpendicular to grain tensile stress and shear stress in the vicinity of the hole. Such concentrated stresses also appear for members axially loaded in compression or tension. The magnitude and the distribution of the unfavourable stress fields depend on many parameters such as type of loading, hole shape, hole size and hole position relative to the beam depth direction. Schematic illustrations of the perpendicular to grain tensile stress distribution are shown in Figure 5-4 for a beam with a circular hole in different types of loading situations. The associated failure type, with crack initiation at the hole periphery and crack propagation in the beam direction, is typically very brittle.

![Figure 5-4](image)

**Figure 5-4.** Schematic illustrations of perpendicular to grain tensile stress distribution; hole placed in shear force dominated region (left), pure bending (middle) and axially loaded member (right).

If holes cannot be avoided there are some basic recommendations concerning hole shape and placing. Holes should preferably be placed at the neutral axis of the beam, especially holes placed in a position of dominating bending moment action. Circular holes are to be preferred over rectangular or quadratic ones. The sides of the hole should be surface treated to reduce variation in the moisture content and thus the risk of splitting. Hot pipes and ducts passing through holes shall be insulated. Holes should not be used in outdoor structures or elsewhere in places where there is a risk of large variations in the moisture content. Special care is necessary for members where the geometrical form itself causes perpendicular to grain tensile stress, for example in the apex region of double tapered beams. In curved structural members, including frame haunches and pitched cambered beams, holes should not be permitted at all. For beams with holes - as for end-notched beams and other applications where strength is limited predominantly by perpendicular to grain tensile stress - experimental tests show a significant beam size influence on the strength. Hence special attention should be paid when making holes in large members. Since the perpendicular to grain tensile stress is
not limited to the absolute vicinity of the hole, the case of multiple holes in a beam should be treated with great care.

Design of unreinforced beams with a hole is a challenging task. Despite recent research efforts, there is at the moment no fully accepted and reliable design method which is based on a completely sound and rational mechanical background. The German National Annex to Eurocode 5 (DIN EN 1995-1-1/NA) does, however, state design equations for unreinforced beams with a hole. The method is based on linear elastic stress analysis and equilibrium considerations and originates from the work presented by Kolb and Epple (1985), although simplifications and empirical modifications have been added over time. Due to the uncertainties related to strength and design of such beams with a hole, it is recommended to reinforce the beam if holes cannot be avoided. Unreinforced beams with a hole may only be used in service class 1 and 2, while properly reinforced beams with a hole may be used also in service class 3. Reinforcement of beams with a hole is dealt with in Section 5.4.

Regulations concerning hole size and placement are stated in Table 5-2 with notation according to Figure 5-5. Holes with a diameter or diagonal length \(d\leq 50\text{ mm}\) and \(h_d\leq 0,15h\) may be treated as a reduced cross section, if placed close to the neutral axis.

Table 5-2. Regulations concerning hole size and location for beams with circular and rectangular holes, according to DIN EN 1995-1-1/NA with the exception of minimum hole corner radius, where DIN EN 1995-1-1/NA states \(r\geq 15\text{ mm}\).

<table>
<thead>
<tr>
<th>(l_i\geq h) or at least 300 mm</th>
<th>(l_i\geq 1,5h)</th>
<th>(l_i\geq 0,5h)</th>
<th>(h_{nw}\geq 0,35h)</th>
<th>(h_{nw}\geq 0,35h)</th>
<th>(a\leq 0,4h)</th>
<th>(h_d\leq 0,15h)</th>
<th>(r\geq 25\text{ mm})</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image.png" alt="Diagram" /></td>
<td><img src="image.png" alt="Diagram" /></td>
<td><img src="image.png" alt="Diagram" /></td>
<td><img src="image.png" alt="Diagram" /></td>
<td><img src="image.png" alt="Diagram" /></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 5-5. Notation for design of a beam with a rectangular or circular hole.

The design criterion, (5-7), reads as a comparison of perpendicular to grain tensile stress with the corresponding strength, modified by an empirically based beam depth factor. Perpendicular to grain tensile stresses appear on both sides of the hole, at different locations depending on the type of loading and hole shape. Potential crack planes are for circular and rectangular holes, respectively, assumed at locations according to Figure 5-6. The tensile stress along these planes is further assumed to have a triangular distribution. The magnitude of the perpendicular to grain tensile stress is determined by its force resultant \(F_{v,90}\) which in turn is determined based on contributions from the shear force and bending moment. The contribution \(F_{v,90,v}\) from the shear force \(V\) is assumed to be equivalent to the integral of the beam theory shear stresses from beam mid-axis to the potential crack plane for a beam with a centrically placed hole, as illustrated schematically in Figure 5-6. The contribution \(F_{v,90,M}\) from the bending moment \(M\) is empirically based.
With a slight modification of notation compared to DIN EN 1995-1-1/NA, the design criterion is formulated as a comparison of perpendicular to grain tensile stress $\sigma_{t,90}$ and the corresponding strength $f_{t,90}$ according to

$$\sigma_{t,90} \leq k_{t,90}f_{t,90}$$

(5-7)

where

$$F_{t,90} = F_{t,90,V} + F_{t,90,M} = \frac{Vh_d}{4h} \left( 3 - \frac{h_d^2}{h^2} \right) + 0,008 \frac{M}{h_t}$$

(5-8)

and where for circular holes $h_d$ may be replaced by $0,7h_d$ in (5-8) and

$$h_r = \min \left\{ \begin{array}{l} h_{ru} \\ h_{ro} \end{array} \right\}$$

for rectangular holes

(5-9)

$$h_r = \min \left\{ \begin{array}{l} h_{ru} + 0,15h_d \\ h_{ro} + 0,15h_d \end{array} \right\}$$

for circular holes

(5-10)

The length $l_{t,90}$ of the assumed triangular perpendicular to grain tensile stress distribution is given by

$$l_{t,90} = 0,5(h_d + h)$$

(5-11)

$$l_{t,90} = 0,35h_d + 0,5h$$

(5-12)

and the strength reduction related to beam depth is given by

$$k_{t,90} = \min \left\{ \frac{1}{(450/h)^{0.5}} \right\}$$

with $h$ in mm

(5-13)
In addition to the perpendicular to grain tensile stresses, in general being most relevant in design, also shear stress concentrations appear in the vicinity of a hole, especially for rectangular holes. The German National Annex to Eurocode 5 does not give explicit recommendations regarding this design issue. For rectangular holes, however, the maximum value of the shear stress at a hole corner may according to Blaß & Bejtka (2003) be approximated with

\[
\tau_{\text{corner}} \approx \kappa_{\text{corner}} \cdot \frac{3V}{2bh} \quad \text{where} \quad \kappa_{\text{corner}} = 1.84 \cdot \frac{1 + a/h}{1 - h_d/h} \left( \frac{h_d}{h} \right)^{0.2}
\]  

(5-14)

where \( \kappa_{\text{corner}} \) expresses the increase of the maximum shear stress from the one in the conventional beam theory (for a beam without a hole). The exact shear stress is closely related to the hole corner radius and a smaller corner radius yields higher maximum shear stress. The approximation according to (5-14) may yield un-conservative values for certain geometry and load configurations.

The capacity with respect to normal stress parallel to the grain, \( \sigma_{0N} \) due to bending moment \( M \) (and possibly also normal force \( N \)), should further be verified for the reduced cross section. For rectangular holes, the additional bending stress in the upper and lower parts of the net cross section with respect to their shear forces \( V_u \) and \( V_d \) and the lever arm \( a/2 \) should be taken into account, see Figure 5-7.

![Figure 5-7. Normal stress parallel to the grain for a beam with a hole.](image)

### 5.4 Reinforcement of beams with a hole

Beams with a hole should in general be reinforced, since introduction of a hole commonly decreases the beam capacity significantly and also since the design recommendations for unreinforced beams with a hole are related to uncertainties. Design recommendations for reinforcement of beams with a hole are given below, based on the approach in the German National Annex to Eurocode 5 (DIN EN 1995-1-1/NA). The design philosophy is equal to that for reinforcement of end-notched beams given in Section 5.2 above; the reinforcement is designed to resist the force resultant of the perpendicular to grain tensile stress at a potential crack plane, while the perpendicular to grain strength of the beam itself is neglected. The perpendicular to grain tensile force \( F_{\text{gr}} \) may be approximated according to (5-8) and the potential crack planes are assumed to be located according to Figure 5-6. Regulations concerning hole size and placing for a reinforced beam with a hole are given in Table 5-3, with notation according to Figure 5-5.
Table 5-3. Regulations concerning hole size and location for a beam with a reinforced circular or rectangular hole, according to DIN EN 1995-1-1/NA with the exception of minimum hole corner radius, where DIN EN 1995-1-1/NA states \( r \geq 15 \) mm.

<table>
<thead>
<tr>
<th>( l_r \geq h )</th>
<th>( l_r \geq 1,0h ) or at least 300 mm</th>
<th>( l_r \geq 0,5h )</th>
<th>( h_{n,u} \geq 0,25h )</th>
<th>( a \leq 1,0h )</th>
<th>( h_{d} \leq 0,30h )</th>
<th>( h_{d} \leq 0,40h ) ( h_{d} \leq 0,30h )</th>
<th>( r \geq 25 ) mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) = for internal reinforcement, b) = for external reinforcement</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5.4.1 Internal reinforcement of beams with a hole

Internal reinforcement may consist of glued-in threaded rods, glued-in concrete reinforcement bars or fully threaded screws. The beam should be reinforced with respect to the potential crack planes relevant for the specific loading condition according to Figure 5-6. It should for the internal reinforcement on both sides of the hole be verified that the stress \( \tau_{ef} \) in the glue line, assumed to be evenly distributed, satisfies the following expression

\[
\tau_{ef} = \frac{F_{r,90}}{n \cdot d_r \cdot \pi \cdot l_{ad}} \leq f_{k,1} \tag{5-15}
\]

where

- \( F_{r,90} \) is the force resultant of the perpendicular to grain tensile stress, see (5-8)
- \( n \) is the number of rods, only one row in beam length direction may be considered active
- \( d_r \) is the outer thread diameter, \( d_r \leq 20 \) mm
- \( f_{k,1} \) is the shear strength of the glue line, see Table 5-1 for characteristic values \( f_{k,1,a} \)
- \( l_{ad} = h_{n\,u} \) or \( h_{n\,o} \) for rectangular holes, see Figure 5-8
- \( l_{ad} = h_{n\,u} + 0,15h_{d} \) or \( h_{n\,o} + 0,15h_{d} \) for circular holes, see Figure 5-8

The tensile axial capacity of the rods should also be checked.

Only one row of steel rods in the beam length direction should be considered as reinforcement. The minimum length of each steel rod is \( 2l_{ad} \) and the outer thread diameter is limited to \( d_r \leq 20 \) mm. Edge distances and spacing of the internal reinforcement elements should be such that \( 3d_r \leq a_2 \) and \( 2,5d_r \leq a_{3,2} \leq 4d_r \) and also \( 2,5d_r \leq a_{3,4} \) with notation according to Figure 5-8. Since the perpendicular to grain tensile stress is highly concentrated to the vicinity of the hole, the edge distance \( a_{3,2} \) should be kept as small as possible without violating the minimum required edge distance. Fully threaded screws may also be used as internal reinforcement and should then be designed for the tensile force \( F_{r,90} \) with respect to withdrawal capacity and tensile axial capacity.

In addition, the shear stress concentrations at the hole corners should also be considered for beams with internal reinforcement and rectangular holes, see Section 5.3. The capacity with respect to normal stress along grain should be also verified for the reduced cross section at hole center, see Section 5.3.
5.4.2 External reinforcement of beams with a hole

External reinforcement may consist of LVL or plywood. It should be verified that the stress $\tau_{ef}$ in the glue line, assumed to be evenly distributed, satisfies the following expression:

$$\tau_{ef} = \frac{F_{t,90}}{2 \cdot a_r \cdot h_{ad}} \leq f_{k,2}$$

(5-16)

where
- $F_{t,90}$ is the force resultant of the perpendicular to grain tensile stress, see (5-8)
- $a_r$ is effective length of reinforcement panels, see Figure 5-9
- $h_{ad} = h_1$ for rectangular holes, with $h_1$ according to Figure 5-9
- $h_{ad} = h_1 + 0.15h_d$ for circular holes, with $h_1$ and $h_d$ according to Figure 5-9
- $f_{k,2}$ is the shear strength of the glue line. DIN EN 1995:1-1-1/NA states characteristic value $f_{k,2} = 0.75$ MPa for glue systems which have been proven to be applicable.

The tensile stress $\sigma_t$ in the panels, glued onto the member, should satisfy the following expression:

$$\sigma_t = \frac{F_{t,90}}{2 \cdot t_r \cdot a_r} \leq \frac{f_t}{k_k}$$

(5-17)

where
- $F_{t,90}$ is the force resultant of the perpendicular to grain tensile stress, see (5-8)
- $t_r$ is the thickness of one reinforcement panel, see Figure 5-9
- $a_r$ is effective length of reinforcement panels, see Figure 5-9
- $f_t$ is the tensile strength of the reinforcement panel in the direction of $F_{t,90}$
- $k_k$ is a factor accounting for the non-uniform stress distribution. DIN EN 1995:1-1-1/NA states that $k_k = 2.0$ may be applied without further verification.

The reinforcement panels should be glued onto the member according to Figure 5-9 with panel size limited by $0.25a \leq a_r \leq 0.3(h_d + h)$ and $h_1 \geq 0.25a$. The thickness $t_r$ of the panels should be at least 10 mm. Sufficient pressure during gluing should be ensured, i.e. by the use of threaded nails or screws with appropriate anchorage length and spacing.
The capacity with respect to normal stress along grain should also be verified for the reduced cross section at hole center, see Section 5.3. The capacity with respect to shear stress concentrations at hole corner may however be assumed to be sufficient when using external reinforcement designed in accordance with the above given recommendations.

Figure 5-9. Notation for external reinforcement of a beam with a hole.

5.5 References


