Mar-20

LVL by Stora Enso

Holes and notches in beams

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1. Design of notched beams

The effect of stress concentrations at notches shall be taken into account in the strength verification of members according to EN1995-1-1, chapter 6.5.2 .

The effect of stress concentrations may be disregarded in the following cases:

- Tension or compression parallel to the grain;
- Bending with tensile stresses at the notch, if the taper is not steeper than 1:i = 1:10, that is i ≥ 10, see Figure 1)
- Bending with compressive stresses at the notch, see Figure 1 B)

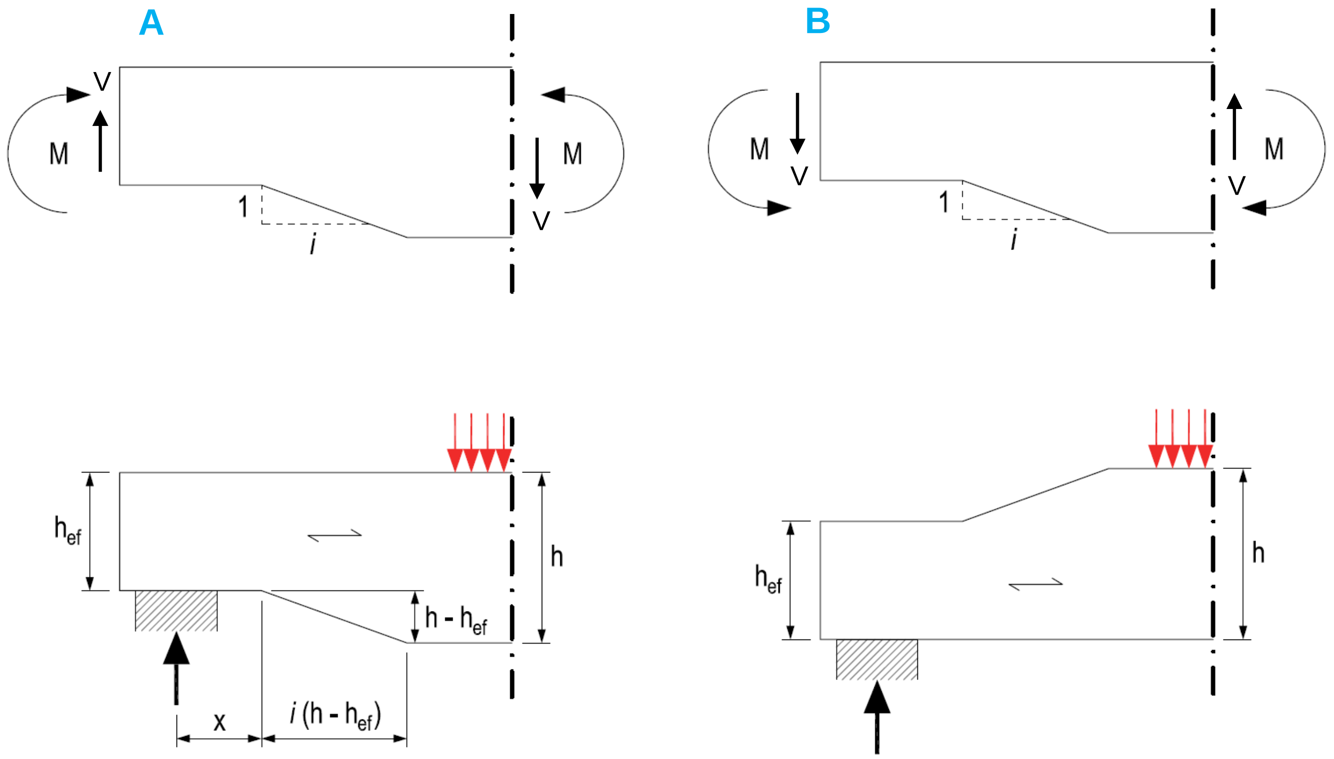

Figure 1: Bending at a notch A) with tensile stresses at the notch B) with compressive stresses at the notch (EN1995-1-1, Figure 6.10 and 6.11).

When the taper at the notch at tensile side is steeper than 1:10, it can be located only at the support. For beams with rectangular cross sections and where the grain runs essentially parallel to the length of the member, the shear stresses at the notched support should be calculated using the effective (reduced) depth h_{ef}, see Figure 1). It should be verified that

$$\boldsymbol{\tau_d = \frac{1,5 \cdot V_d}{b \cdot h_{ef}} \leq k_V \cdot f_{v,0,edge,d}} \qquad \text{Eq 1}$$

Where $\boldsymbol{k_V}$ is a reduction factor defined as follows:

- For beams notched at the opposite side to the support, see Figure 1 B), $\boldsymbol{k_V} = 1$
- For beams notched on the same side as the support, see Figure 1 A)

$$k_V = min\left(1\,;\,\frac{k_n \cdot \left(1 + \frac{1{,}1 \cdot i^{1{,}5}}{\sqrt{h}}\right)}{\sqrt{h} \cdot \left(\sqrt{\alpha \cdot (1-\alpha)}\right) + 0{,}8 \cdot \frac{x}{h} \cdot \sqrt{\frac{1}{\alpha} - \alpha^2}}\right) \qquad \text{Eq 2}$$

where

i is the notch inclination, (for rectangular notches $i = 0$);
h is the beam depth in [mm];
x is the distance from the line of action of the support reaction to the corner of the notch [mm];

$$\alpha = \frac{h_{ef}}{h}$$ Eq 3

$k_n = 4{,}5$ for LVL in general

At supports, the contribution to the total shear force of a concentrated load F acting on top side of the beam and within a distance h or h_{ef} from the edge of the support may be disregarded. For beams with notches, at the supports, this reduction in the shear force applies only when the notch is on the opposite side to the support. For uniformly distributed loads, the determining shear force maybe taken at a distance of the member h from the support.

At the support, the design shear stress is calculated by:

$$\boldsymbol{f_{v,0,edge,d} = \frac{k_{mod} \cdot f_{v,0,edge,k}}{\gamma_M}}$$ Eq 4

The shear strength for LVL by Stora Enso products are:

$f_{v,0,\mathrm{edge},d} = 4{,}1\ N/mm^2$	LVL-S
$f_{v,0,\mathrm{edge},d} = 4{,}5\ N/mm^2$	LVL-X

Maximum design shear force capacity V_d is given by:

$$\boldsymbol{V_d \leq \frac{k_V \cdot f_{v,0,\mathrm{edge},d} \cdot b \cdot h_{ef}}{1{,}5}}$$ Eq 5

In Table 1 and Table 2 examples of the maximum shear force capacities of notched LVL-S and LVL-X beams are given.

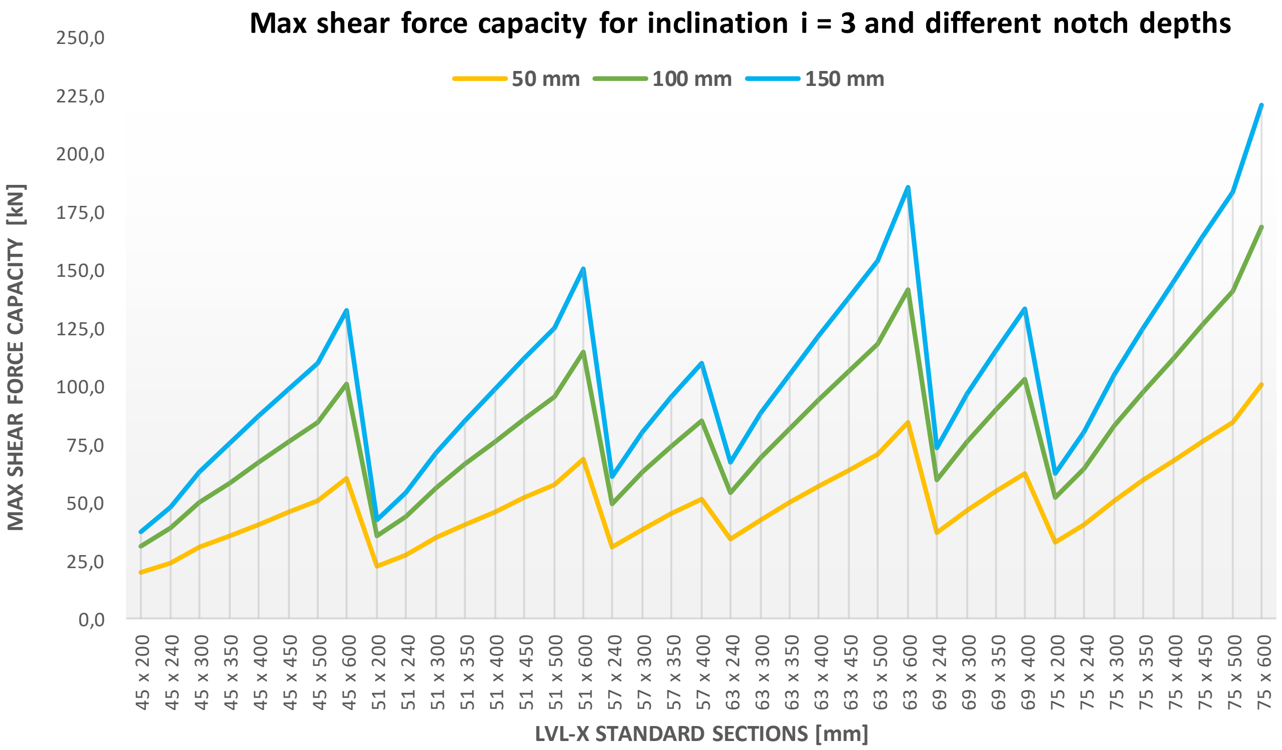

*Table 1: Max shear force capacity V_k [kN] of **LVL-S** beams with different notch depths and inclination, distance x from the support line to the edge of the notch $x = 100mm$.*

Notch depth ($h-h_{ef}$)		50 mm				100 mm				150 mm			
Beam size (b x h) [mm]	V_k without notch [kN]	V_k with notch											
		i = 0 [kN]	k_v	i = 3 [kN]	k_v	i = 0 [kN]	k_v	i = 3 [kN]	k_v	i = 0 [kN]	k_v	i = 3 [kN]	k_v
45 x 200	24,6	12,8	0,69	18,0	0,98	7,3	0,59	10,2	0,83	4,0	0,65	5,6	0,91
45 x 240	29,5	16,0	0,69	22,0	0,94	9,7	0,56	13,2	0,77	6,2	0,56	8,5	0,77
45 x 300	36,9	20,8	0,68	27,7	0,90	13,1	0,53	17,4	0,71	9,2	0,50	12,3	0,66
45 x 350	43,1	24,8	0,67	32,4	0,88	16,0	0,52	20,8	0,68	11,6	0,47	15,2	0,62
45 x 400	49,2	28,8	0,67	37,0	0,86	18,8	0,51	24,2	0,65	14,0	0,45	18,0	0,58
45 x 450	55,4	32,7	0,66	41,5	0,84	21,6	0,50	27,4	0,64	16,3	0,44	20,7	0,56
45 x 500	61,5	36,7	0,66	46,0	0,83	24,4	0,50	30,7	0,62	18,6	0,43	23,4	0,54
45 x 600	73,8	44,5	0,66	54,9	0,81	30,0	0,49	37,0	0,60	23,2	0,42	28,6	0,52
51 x 200	27,9	14,5	0,69	20,4	0,98	8,3	0,59	11,6	0,83	4,5	0,65	6,4	0,91
51 x 240	33,5	18,2	0,69	24,9	0,94	10,9	0,56	15,0	0,77	7,0	0,56	9,6	0,77
51 x 300	41,8	23,6	0,68	31,4	0,90	14,9	0,53	19,8	0,71	10,4	0,50	13,9	0,66
51 x 350	48,8	28,1	0,67	36,7	0,88	18,1	0,52	23,6	0,68	13,2	0,47	17,2	0,62
51 x 400	55,8	32,6	0,67	41,9	0,86	21,3	0,51	27,4	0,65	15,8	0,45	20,4	0,58
51 x 450	62,7	37,1	0,66	47,1	0,84	24,5	0,50	31,1	0,64	18,5	0,44	23,5	0,56
51 x 500	69,7	41,5	0,66	52,2	0,83	27,7	0,50	34,7	0,62	21,1	0,43	26,5	0,54
51 x 600	83,6	50,5	0,66	62,2	0,81	34,0	0,49	41,9	0,60	26,3	0,42	32,5	0,52
57 x 240	37,4	20,3	0,69	27,8	0,94	12,2	0,56	16,7	0,77	7,9	0,56	10,8	0,77
57 x 300	46,7	26,4	0,68	35,1	0,90	16,6	0,53	22,1	0,71	11,7	0,50	15,5	0,66
57 x 350	54,5	31,4	0,67	41,0	0,88	20,2	0,52	26,4	0,68	14,7	0,47	19,2	0,62
57 x 400	62,3	36,4	0,67	46,8	0,86	23,8	0,51	30,6	0,65	17,7	0,45	22,8	0,58
63 x 240	41,3	22,5	0,69	30,7	0,94	13,5	0,56	18,5	0,77	8,7	0,56	11,9	0,77
63 x 300	51,7	29,2	0,68	38,8	0,90	18,4	0,53	24,4	0,71	12,9	0,50	17,2	0,66
63 x 350	60,3	34,7	0,67	45,3	0,88	22,4	0,52	29,2	0,68	16,3	0,47	21,2	0,62
63 x 400	68,9	40,3	0,67	51,8	0,86	26,3	0,51	33,8	0,65	19,6	0,45	25,2	0,58
63 x 450	77,5	45,8	0,66	58,1	0,84	30,2	0,50	38,4	0,64	22,8	0,44	29,0	0,56
63 x 500	86,1	51,3	0,66	64,4	0,83	34,2	0,50	42,9	0,62	26,1	0,43	32,7	0,54
63 x 600	103,3	62,3	0,66	76,9	0,81	42,0	0,49	51,8	0,60	32,5	0,42	40,1	0,52
69 x 240	45,3	24,6	0,69	33,7	0,94	14,8	0,56	20,3	0,77	9,5	0,56	13,0	0,77
69 x 300	56,6	31,9	0,68	42,5	0,90	20,1	0,53	26,8	0,71	14,1	0,50	18,8	0,66
69 x 350	66,0	38,0	0,67	49,6	0,88	24,5	0,52	32,0	0,68	17,8	0,47	23,3	0,62
69 x 400	75,4	44,1	0,67	56,7	0,86	28,8	0,51	37,1	0,65	21,4	0,45	27,6	0,58
75 x 200	41,0	21,4	0,69	30,0	0,98	12,1	0,59	17,0	0,83	6,7	0,65	9,4	0,91
75 x 240	49,2	26,7	0,69	36,6	0,94	16,1	0,56	22,0	0,77	10,3	0,56	14,2	0,77
75 x 300	61,5	34,7	0,68	46,2	0,90	21,9	0,53	29,1	0,71	15,4	0,50	20,4	0,66
75 x 350	71,8	41,3	0,67	54,0	0,88	26,6	0,52	34,7	0,68	19,4	0,47	25,3	0,62
75 x 400	82,0	47,9	0,67	61,6	0,86	31,3	0,51	40,3	0,65	23,3	0,45	29,9	0,58
75 x 450	92,3	54,5	0,66	69,2	0,84	36,0	0,50	45,7	0,64	27,2	0,44	34,5	0,56
75 x 500	102,5	61,1	0,66	76,7	0,83	40,7	0,50	51,1	0,62	31,0	0,43	39,0	0,54
75 x 600	123,0	74,2	0,66	91,5	0,81	50,0	0,49	61,7	0,60	38,7	0,42	47,7	0,52

*Table 2: Max shear force capacity V_k [kN] of **LVL-X** beams with different notch depths and inclination, distance x from the support line to the edge of the notch $x = 100mm$.*

Notch depth ($h-h_{ef}$)		50 mm				100 mm				150 mm			
Beam size (b x h) [mm]	V_k without notch [kN]	V_k with notch											
		i = 0 [kN]	k_v	i = 3 [kN]	k_v	i = 0 [kN]	k_v	i = 3 [kN]	k_v	i = 0 [kN]	k_v	i = 3 [kN]	k_v
45 x 200	27,0	14,1	0,69	19,8	0,98	8,0	0,59	11,2	0,83	4,4	0,65	6,2	0,91
45 x 240	32,4	17,6	0,69	24,1	0,94	10,6	0,56	14,5	0,77	6,8	0,56	9,3	0,77
45 x 300	40,5	22,9	0,68	30,4	0,90	14,4	0,53	19,1	0,71	10,1	0,50	13,4	0,66
45 x 350	47,3	27,2	0,67	35,5	0,88	17,5	0,52	22,9	0,68	12,7	0,47	16,6	0,62
45 x 400	54,0	31,6	0,67	40,6	0,86	20,6	0,51	26,5	0,65	15,3	0,45	19,7	0,58
45 x 450	60,8	35,9	0,66	45,6	0,84	23,7	0,50	30,1	0,64	17,9	0,44	22,7	0,56
45 x 500	67,5	40,2	0,66	50,5	0,83	26,8	0,50	33,6	0,62	20,4	0,43	25,7	0,54
45 x 600	81,0	48,9	0,66	60,3	0,81	32,9	0,49	40,6	0,60	25,5	0,42	31,4	0,52
51 x 200	30,6	16,0	0,69	22,4	0,98	9,1	0,59	12,7	0,83	5,0	0,65	7,0	0,91
51 x 240	36,7	19,9	0,69	27,3	0,94	12,0	0,56	16,4	0,77	7,7	0,56	10,6	0,77
51 x 300	45,9	25,9	0,68	34,5	0,90	16,3	0,53	21,7	0,71	11,5	0,50	15,2	0,66
51 x 350	53,6	30,8	0,67	40,3	0,88	19,9	0,52	25,9	0,68	14,4	0,47	18,9	0,62
51 x 400	61,2	35,8	0,67	46,0	0,86	23,4	0,51	30,1	0,65	17,4	0,45	22,3	0,58
51 x 450	68,9	40,7	0,66	51,6	0,84	26,9	0,50	34,1	0,64	20,3	0,44	25,8	0,56
51 x 500	76,5	45,6	0,66	57,2	0,83	30,4	0,50	38,1	0,62	23,2	0,43	29,1	0,54
51 x 600	91,8	55,4	0,66	68,3	0,81	37,3	0,49	46,0	0,60	28,9	0,42	35,6	0,52
57 x 240	41,0	22,3	0,69	30,5	0,94	13,4	0,56	18,4	0,77	8,6	0,56	11,8	0,77
57 x 300	51,3	29,0	0,68	38,5	0,90	18,2	0,53	24,3	0,71	12,8	0,50	17,0	0,66
57 x 350	59,9	34,5	0,67	45,0	0,88	22,2	0,52	29,0	0,68	16,1	0,47	21,1	0,62
57 x 400	68,4	40,0	0,67	51,4	0,86	26,1	0,51	33,6	0,65	19,4	0,45	25,0	0,58
63 x 240	45,4	24,6	0,69	33,7	0,94	14,8	0,56	20,3	0,77	9,5	0,56	13,0	0,77
63 x 300	56,7	32,0	0,68	42,6	0,90	20,2	0,53	26,8	0,71	14,2	0,50	18,8	0,66
63 x 350	66,2	38,1	0,67	49,7	0,88	24,5	0,52	32,0	0,68	17,8	0,47	23,3	0,62
63 x 400	75,6	44,2	0,67	56,8	0,86	28,9	0,51	37,1	0,65	21,5	0,45	27,6	0,58
63 x 450	85,1	50,3	0,66	63,8	0,84	33,2	0,50	42,1	0,64	25,1	0,44	31,8	0,56
63 x 500	94,5	56,3	0,66	70,7	0,83	37,5	0,50	47,1	0,62	28,6	0,43	35,9	0,54
63 x 600	113,4	68,4	0,66	84,4	0,81	46,1	0,49	56,9	0,60	35,7	0,42	44,0	0,52
69 x 240	49,7	27,0	0,69	36,9	0,94	16,2	0,56	22,2	0,77	10,4	0,56	14,3	0,77
69 x 300	62,1	35,0	0,68	46,6	0,90	22,1	0,53	29,4	0,71	15,5	0,50	20,6	0,66
69 x 350	72,5	41,7	0,67	54,5	0,88	26,9	0,52	35,1	0,68	19,5	0,47	25,5	0,62
69 x 400	82,8	48,4	0,67	62,2	0,86	31,6	0,51	40,7	0,65	23,5	0,45	30,2	0,58
75 x 200	45,0	23,5	0,69	32,9	0,98	13,3	0,59	18,7	0,83	7,3	0,65	10,3	0,91
75 x 240	54,0	29,3	0,69	40,2	0,94	17,7	0,56	24,2	0,77	11,3	0,56	15,5	0,77
75 x 300	67,5	38,1	0,68	50,7	0,90	24,0	0,53	31,9	0,71	16,9	0,50	22,4	0,66
75 x 350	78,8	45,4	0,67	59,2	0,88	29,2	0,52	38,1	0,68	21,2	0,47	27,7	0,62
75 x 400	90,0	52,6	0,67	67,6	0,86	34,4	0,51	44,2	0,65	25,6	0,45	32,9	0,58
75 x 450	101,3	59,8	0,66	75,9	0,84	39,5	0,50	50,2	0,64	29,8	0,44	37,9	0,56
75 x 500	112,5	67,0	0,66	84,2	0,83	44,7	0,50	56,1	0,62	34,1	0,43	42,8	0,54
75 x 600	135,0	81,5	0,66	100,5	0,81	54,9	0,49	67,7	0,60	42,5	0,42	52,4	0,52

2. Design of LVL edgewise loaded beams with unreinforced holes

Holes are openings with a clear dimension d ≥ h/10 with h, being the height of the beam or d ≥ 80mm.
According to ÖNORM B 1995-1-1:2015 [1] the application of unreinforced circular and rectangular holes is restricted to service class 1 and 2.

In general, it is not allowed to carry out on the building site openings not planned in design. For holes, a verification is necessary.

2.1 Geometric boundary conditions

In the current European standard for the design of timber structures EN 1995-1-1 [2] no explicit rules for the verification of holes in beams (loaded in bending) are given. Nevertheless, rules for the handling of this important topic are defined in a few National Annexes of the mentioned standard.

Until more specific rules are determined for Stora Enso LVL by experimental tests, relevant rules for reinforced holes (and notches) can be found in National Annexes to EN 1995-1-1 (e. g. ÖNORM B 1995-1-1).

In Figure 2 and Figure 3, the geometric boundary conditions regarding holes in beams are shown.

The rules given in the further sections of this chapter are only valid, for unreinforced holes and if the following geometric boundary conditions are respected.

General boundary condition:

- $l_V \geq h$
- $l_A \geq 0.5 \cdot h$

Additionally for circular holes:

- $h_d = d \leq 0.7 \cdot h$
- When the hole centre is situated at the neutral axis:
  $h_{ro} \geq 0.15 \cdot h$ and $h_{ru} \geq 0.15 \cdot h$
- When the hole centre is situated eccentrically to the neutral axis (eccentricity) :
  $h_{ro} \geq 0.25 \cdot h$ and $h_{ru} \geq 0.25 \cdot h$
- $l_z \geq max \begin{cases} 0.50 \cdot h \\ 2.0 \cdot d \end{cases}$

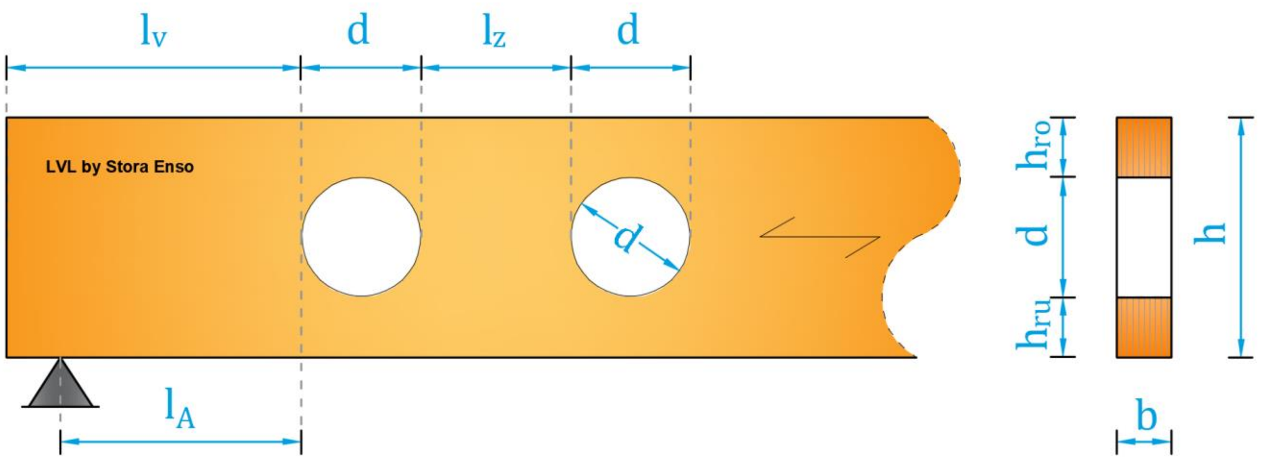

Figure 2: Definitions of geometric dimensions related to circular holes

Additionally for rectangular holes: The radius of curvature at each corner shall be at least 15 mm.

- $h_d \leq 0.3 \cdot h$
- $a \leq 1.5 \cdot h$
- $h_{ro} \geq 0.35 \cdot h$ and $h_{ru} \geq 0.35 \cdot h$
- $l_z \geq 1.5 \cdot h$

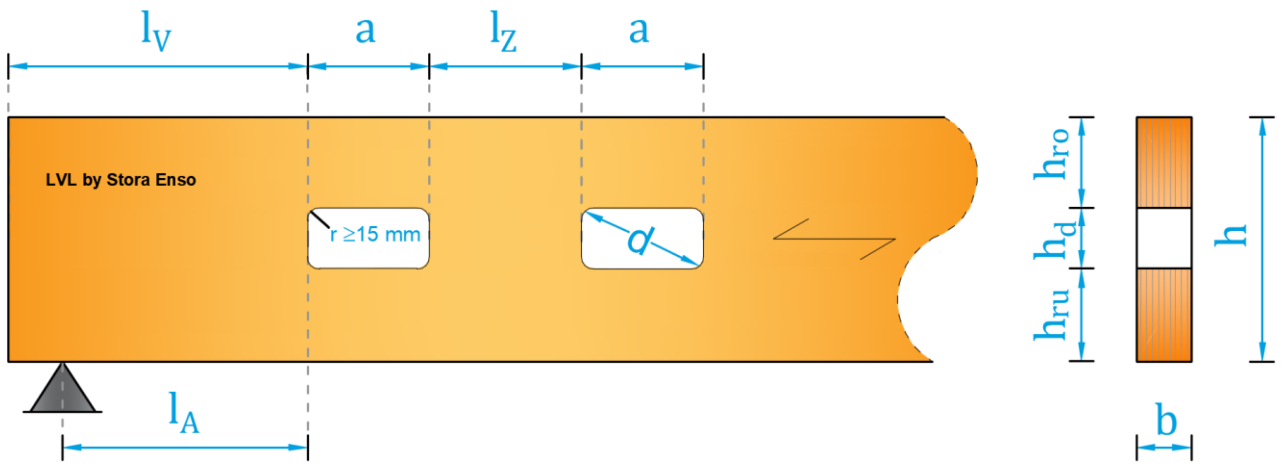

Figure 3: Definitions of geometric dimensions related to rectangular holes.

with

h Depth of the LVL beam [mm] ;
l_z Distance between two holes [mm];
h_d Diameter or height of the circular opening [mm];
a Length of the rectangular opening [mm].

2.2 Size and location of the holes

Beams with circular holes (LVL-S and LVL-X) loaded in bending

Geometrical limitations for circular holes in LVL-S and LVL-X by Stora Enso beams.

BEAM HEIGHT	MIN DISTANCE FROM THE BEAM END	MIN DISTANCE FROM THE SUPPORT	MIN DISTANCE BETWEEN HOLES	Center of the hole on neutral axis		Center of the hole not on neutral axis	
				MAXIMUM DIAMETER OF THE HOLE	DISTANCE FROM THE EDGES OF THE BEAM	MAXIMUM DIAMETER OF THE HOLE	DISTANCE FROM THE EDGES OF THE BEAM
h [mm]	L_V min [mm]	L_A min [mm]	L_Z min [mm]	d [mm]	h_{ro} and hr_u min [mm]	d [mm]	h_{ro} and h_{ru} min [mm]
200	200	100	280	140	30	100	50
240	240	120	336	168	36	120	60
300	300	150	420	210	45	150	75
350	350	175	490	245	52,5	175	87,5
400	400	200	560	280	60	200	100
450	450	225	630	315	67,5	225	112,5
500	500	250	700	350	75	250	125
600	600	300	840	420	90	300	150

Beams with rectangular holes (LVL-S and LVL-X) loaded in bending

Geometrical limitations for rectangular holes in LVL-S and LVL-X by Stora Enso beams.

BEAM HEIGHT	MIN DISTANCE FROM THE BEAM END	MIN DISTANCE FROM THE SUPPORT	MIN DISTANCE BETWEEN HOLES	MAXIMUM LENGTH OF TWO HOLE	MAXIMUM HEIGHT OF THE HOLE	DISTANCE FROM THE EDGES OF THE BEAM
h [mm]	L_V min [mm]	L_A min [mm]	L_Z min [mm]	a max [mm]	h_d max [mm]	h_{ro} and hr_u min [mm]
200	200	100	300	300	60	70
240	240	120	360	360	72	84
300	300	150	450	450	90	105
350	350	175	525	525	105	122,5
400	400	200	600	600	120	140
450	450	225	675	675	135	157,5
500	500	250	750	750	150	175
600	600	300	900	900	180	210

As a conservative approach in the design of unreinforced holes the initiation of the first crack is recommended to be considered as the “ultimate” load and stress level accordingly. The difference between the load level at the occurrence of the 1st crack and the maximum load has to be seen as a “buffer” for the missing interaction of stresses (e. g. simultaneously acting stresses due to tensile stresses perpendicular to the grain and shear stresses) as well as loading effects from temperature and moisture content (shrinkage / swelling) in the vicinity of the hole not considered explicitly in the verification.

The following equations and design steps for unreinforced holes are based on the report from holz.bau forschungs gmbh [4]. The equations for the determination of the shear factor k_τ considering the stress concentrations at the contour of the circular and rectangular openings shall be used. This method is also based on a multitude of tests on LVL beams by Stora Enso with openings [5]. This includes alternatives to the method in the standard [6] for the verification of the tensile stresses perpendicular to grain which makes it possible to justify bigger ratios $\frac{h_d}{h}$ as given there.

Approach of Ardalany

The underlaying mechanical model is based on a beam on elastic foundation assuming that the lower part of the cracked beam is infinitely stiff in bending according to the approach of Ardalany [4].

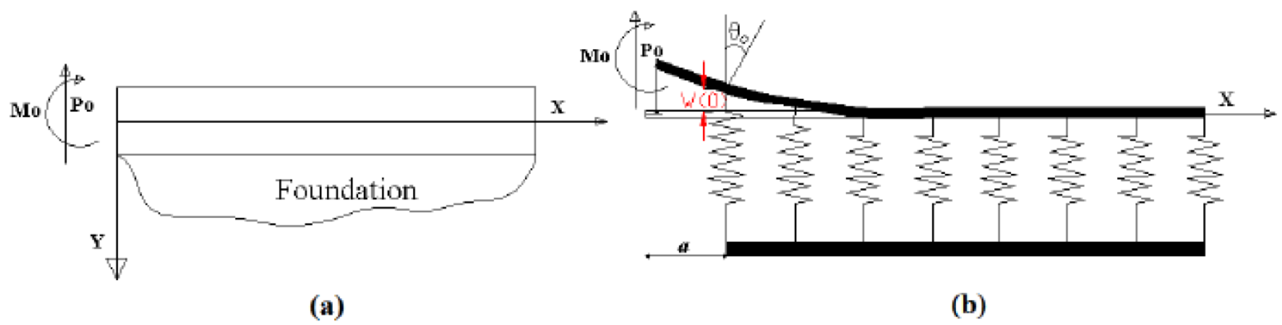

Figure 4 : Model of beam on elastic foundation: (a) beam on elastic foundation, (b) schematization of a beam on springs as elastic foundation, [7].

2.3 Verification of tension force perpendicular to grain (approach of Ardalany)

2.3.1 due to pure shear

The tension force perpendicular to grain for loadings in pure shear can be computed as follows:

$$F_{cr,t,90,V} = \frac{b \cdot f_{t,90}}{\sqrt{4 \cdot \lambda^2 + \frac{6}{5} \cdot \frac{K \cdot b}{G \cdot A}}} \qquad \text{Eq 6}$$

with

$$\lambda = \sqrt[4]{\frac{K \cdot b}{4 \cdot E \cdot I}} \qquad \text{Eq 7}$$

$$K = \frac{1}{2} \cdot \frac{f_{t,90}{}^2}{G_{I,f}}$$

The total shear resistance of the hole is twice this force as follows:

$$F_{cr,V} = 2 \cdot F_{cr,t,90,V} \qquad \text{Eq 8}$$

$F_{cr,t,90,V}$	Shear resistance of the beam section for pure shear (at crack initiation), splitting force [N];
$F_{cr,V}$	Total shear resistance of the beam section for pure shear [N] ;
K	Spring stiffness in a beam on elastic foundation [N/mm³] ;
$G_{I,f}$	Fracture energy in mode I (opening) [N/mm] (see chapter 2.3.4);
$f_{t,90}$	Tensile strength perpendicular to grain [N/mm²];
b	Width of the beam [mm] ;
E	Modulus of elasticity [N/mm²] ;
I	Moment of inertia $I = \frac{b \cdot h_{cr}{}^3}{12}$ [mm⁴] ;
h_{cr}	Height of a portion of a beam above potential crack surface [mm];
	- for circular opening : $h_{cr} = \frac{h}{2} - \frac{h_d}{2} \cdot \cos\alpha$, with $\alpha = 45°$
	- for rectangular opening : $h_{cr} = \frac{h}{2} - \frac{h_d}{2}$
λ	Parameter for beam on elastic foundation [1/mm] ;
G	Shear modulus of the beam section [N/mm²] ;
A	Shear area ($A = b \cdot h_{cr}$) [mm²] .

2.3.2 due to pure bending

With the denotations used in standards, the local moment in the upper part of the beam on elastic foundation at crack initiation is as follows:

$$M_{cr,t,90} = \frac{b}{2 \cdot \lambda^2} \cdot f_{t,90} \qquad \text{Eq 9}$$

The total moment is composed two parts:

a. Constant (rectangular) stress distribution

$$\sigma_N = \sigma_M \cdot \frac{h_{cr} + h_d \cdot \cos\alpha}{h_{cr}} \qquad \text{Eq 10}$$

with the resultant compression force

$$N = b \cdot \sigma_M \cdot (h_{cr} + h_d \cdot \cos\alpha) \qquad \text{Eq 11}$$

b. Triangular stress distribution

The triangular stresses are given by:

$$\sigma_{cr,t,90,M} = \frac{M_{cr,t,90}}{W} \qquad \text{Eq 12}$$

Considering the moment of both portions of the beam (upper and lower portion) as well as from the resultant axial forces, the total moment $M_{cr,M}$ is given. Due to the different lever arm of circular and rectangular holes it is defined by:

- **for circular holes:**

$$M_{cr,M} = 2 \cdot M_{cr,t,90} + 2 \cdot \sigma_{cr,t,90,M} \cdot (h_{cr} + h_d \cdot cos\,\alpha) \cdot (h - h_{cr}) \qquad \text{Eq 13}$$

- **for rectangular holes:**

$$M_{cr,M} = 2 \cdot M_{cr,t,90} + 2 \cdot \sigma_{cr,t,90,M} \cdot (h_{cr} + h_d) \cdot (h - h_{cr}) \qquad \text{Eq 14}$$

where

b	Width of the beam [mm];
W	Cross section modulus $W = \frac{b \cdot h_{cr}^2}{6}$ [mm³];
h_{cr}	Height of a portion of a beam above potential crack surface [mm];
$\sigma_{cr,t,90,M}$	Stress due to bending moment [N/mm²];
$M_{cr,t,90}$	Moment resistance of the section [N·mm];
$M_{cr,M}$	Total resistance moment of the beam section for pure bending [N·mm].

2.3.3 Beam subjected to combined shear and bending moment (Splitting)

In general, combined actions form shear and bending moment occur in the beam. Thus an interaction equation has to be taken into account. The following empirical relationship shall be fulfilled:

$$\left(\frac{V_{cr}}{F_{cr,V}}\right) + \left(\frac{M_{cr}}{M_{cr,M}}\right)^2 = 1 \qquad \text{Eq 15}$$

where

M_{cr}	Design bending moment [N·mm];
V_{cr}	Design shear force at the location of the hole [N].

2.3.4 Fracture energy rate $G_{I,f}$ in mode I (opening) for LVL by Stora Enso

The determination of the fracture energy rate $G_{I,f}$ described in [4] is based on a test configuration of CIB-W18 standard draft proposed by Larsen and Gustafsson [8].

The experimentally determined values for LVL by Stora Enso are:

Mean value:	$G_{I,f,mean} = 0.875\ N/mm$
Characteristic value:	$G_{I,f,k} = 0.625\ N/mm$

Since the fracture energy value $G_{I,f}$ is a material parameter used in ULS verification, the modification factor K_{mod} (considering the moisture content and duration of load of the members) as well as a partial safety factor γ_M have to be considered for the computation of the design value $G_{I,f,d}$.

2.4 Verification of shear stresses for circular and rectangular holes in beams

In addition to the tensile stresses at the circumference (contour) of the hole, also the shear stresses have to be verified. In a first approximation these stresses can be determined applying the equation from the Beam Theory for the net cross section, but it is obvious that due to the redistribution of stresses in the vicinity of the hole stress peaks will occur.
By considering these concentration peaks in the design, the maximum shear stress at the contour of the hole can be multiplied by the factor for the shear stresses k_τ applicable for circular and rectangular holes.

The shear stress at the hole location should satisfy the following expression:

$$\tau_d = k_\tau \cdot 1{,}5 \cdot \frac{V_d}{b \cdot (h - h_d)} \leq f_{v,d} \qquad \text{Eq 16}$$

Since the redirection of stresses is expected to be smoother for circular holes and thus lead to minor pronounced stress peak at the contour of the hole, different k_τ factors shall be applied for each shape.

The following equations were determined by means of linear elastic FEM-simulations and shall be applied:

Rectangular holes

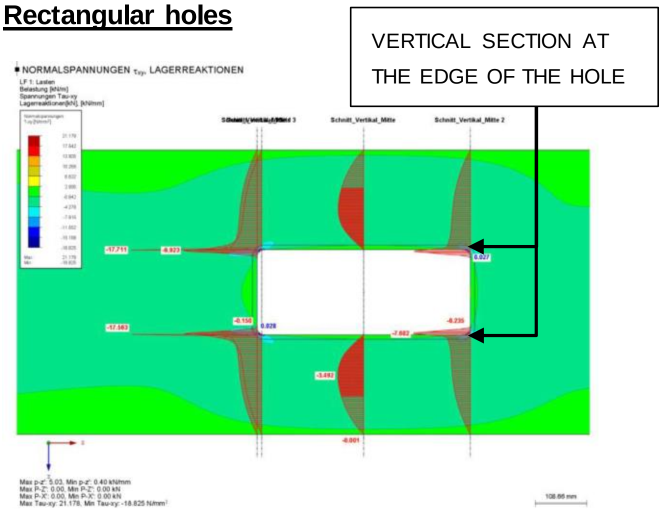

Figure 5: Shear stress distribution at the contour of a rectangular hole

For the computation of the maximum shear stresses, the shear factor k_τ at the corners of rectangular holes shall be determined according to [4] and [6].
as follows:

$$k_\tau = 1{,}85 \cdot \left(1 + \frac{a}{h}\right) \cdot \left(\frac{h_d}{h}\right)^{0{,}2} \qquad \text{Eq 17}$$

with: $0.1 \leq \frac{a}{h} \leq 1.0$ and $0.1 \leq \frac{h_d}{h} \leq 1.0$

The maximum shear stress value should be determined in the vertical section at the edge of the hole closer to the supports.

Circular holes

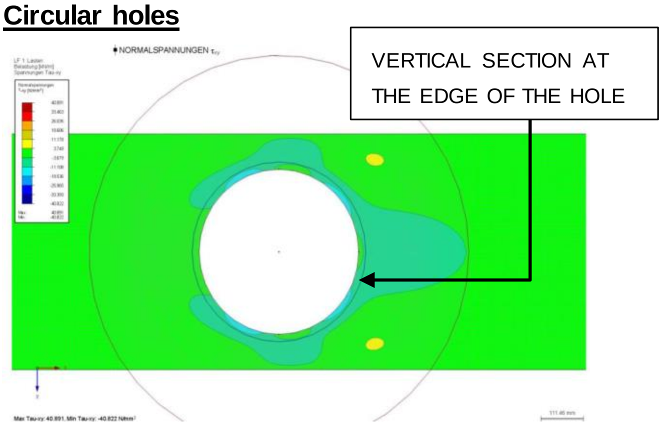

Figure 6: Shear stress distribution at the contour of a circular hole

For the computation of the maximum shear stresses, the shear factor k_τ of circular holes shall be determined as follows:

$$k_\tau = 0{,}62 \cdot \left[4{,}00 - \left(\frac{h_d}{h}\right)\right] \qquad \text{Eq 18}$$

Remark:

(Compared to the currently given equation in ÖNORM B 1995-1-1:2015 [6] this equation given by Stora Enso leads to value for k_τ that are about 1/3 lower for circular holes.)

2.5 Verification of longitudinal stresses - Bending

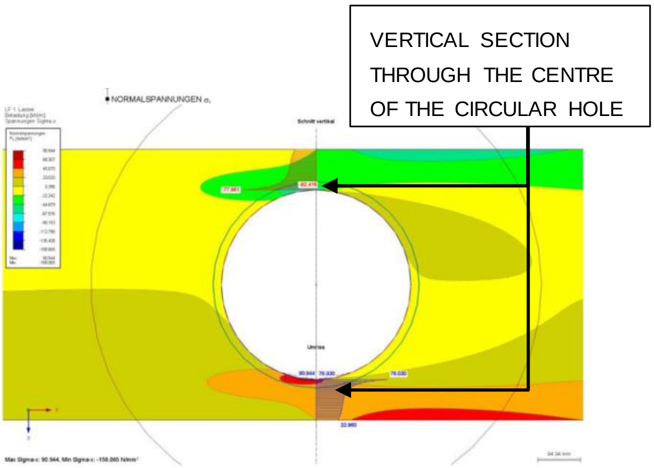

Figure 7: Longitudinal stresses at the contour of the hole and the edge of the beams

For circular holes:

While the longitudinal stresses for hd/h ratios up to ≈ 0.30 are greater at the edge of the beam (see Figure 6), for higher hd/h values strongly increasing stresses at the circumference in the vertical section through the centre of the circular hole occur (see in Figure 7).

Thus, if $\frac{h_d}{h}$ ratios ≤ 0.7 shall be applied, in addition to the verification of the longitudinal stresses at the edge of the beam, given e. g. in the standard [6] , also the longitudinal stresses at the contour in the vertical section through the centre of the circular hole have to be verified (see Figure 7) .

For rectangular holes:

Similar to circular holes also at the contour, in particular at the corners of rectangular holes, pronounced stress peaks of the longitudinal stresses occur.

The bending stress at the hole location presented in Figure 5 for rectangular, and in Figure 6 and Figure 7 for circular holes (depending on the $\frac{h_d}{h}$ ratio) should satisfy the following expression:

$$\frac{\frac{M_d}{W_n} + \frac{M_{o,d}}{W_o}}{f_{m,d}} \leq 1 \qquad \text{Eq 19}$$

and

$$\frac{\frac{M_d}{W_n} + \frac{M_{u,d}}{W_u}}{f_{m,d}} \leq 1 \qquad \text{Eq 20}$$

where

$$M_{o,d} = \frac{A_o}{A_u + A_o} \cdot V_d \cdot \frac{a}{2} \qquad \text{Eq 21}$$

$$M_{u,d} = \frac{A_u}{A_u + A_o} \cdot V_d \cdot \frac{a}{2} \qquad \text{Eq 22}$$

$$A_o = b \cdot h_{ro} \qquad \text{Eq 23}$$

$$A_u = b \cdot h_{ru} \qquad \text{Eq 24}$$

$$W_o = \frac{b \cdot {h_{ro}}^2}{6} \qquad \text{Eq 25}$$

$$W_u = \frac{b \cdot {h_{ru}}^2}{6} \qquad \text{Eq 26}$$

with

M_d	Design value of the bending moment at the edge of the opening [N.mm];
W_n	Effective cross section modulus of the beam at the position of the opening [mm³];
V_d	Design value of the transversal force at the edge of the opening [N];
$f_{m,d}$	Design value for the edgewise bending strength of the beam [N/mm²];
$h_{ro}; h_{ru}$	Remaining heights of the net cross section [mm]; According to the figures Figure 2 and Figure 3.

For circular holes it is sufficient to verify the bending stresses from the beam effect at the edges under consideration of the net cross section.

The bending stress at the location of a circular hole has to be verified by the equations:

$$\frac{\frac{M_d}{W_n}}{f_{m,d}} \leq 1 \qquad \text{Eq 27}$$

The verification of the resistance in tension perpendicular to the grain can be the most critical condition to fulfil the design of holes in LVL-S beams. LVL-X beams, on the other hand, offer a significant advantage for beams with holes, as the cross veneers act as reinforcement around the holes preventing cracking due to tension stresses perpendicular to the grain.

Remark:

It is critically mentioned that in the known design standards no interaction of stresses, i.e. tensile stresses perpendicular to grain and shear stresses as well as longitudinal stresses within the verification process is required, although they are simultaneously acting at the contour of the hole.

3. References

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