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TIMBER ENGINEERING - VSM196

LECTURE 9 –

TAPERED, CURVED AND
PITCHED GLULAM BEAMS

SPRING 2020

Topic

- Tapered, curved and pitched glulam beams

- [DoTS: Chapter 3.3]

Content

- Background and finger joints
- Pitched and curved glulam beams
- Stresses - distribution
- Failures of glulam structures

- Design examples D1 & D2

Based on lectures by Prof. Roberto Crocetti, LTH

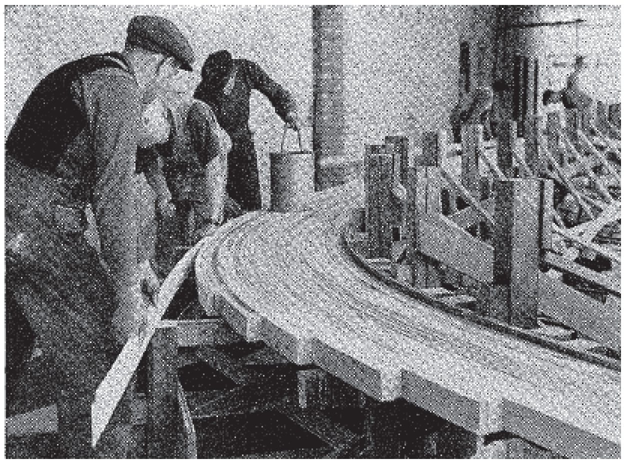
Intended Learning Outcomes of this lecture

- You understand the benefits of curved and tapered beams
- You can identify the distribution of different stresses in such beams
- You can calculate the relevant stresses and verify the strength
- You can choose the adequate geometry of beams for different situations

Background

“Old fashion technique” of glulam

- Arches
- I-cross section were used to improve the performance of the structure!



- Lamellas were nail-glued to each other by means of nails and casein glue

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“Old fashion technique” of glulam

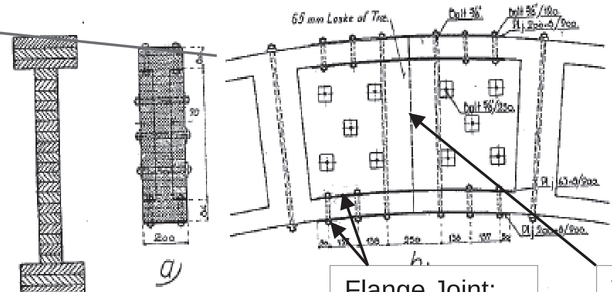


Fig. 190

Flange Joint:
plates $t = 8$mm

Web Joint:
Glulam

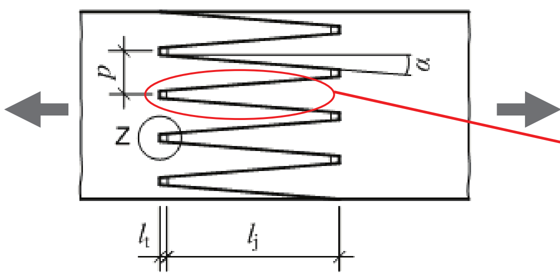
- Web stiffeners were applied at regular intervals along the arch length. The joints between lamellas were always placed between two web stiffeners. A bolt was always inserted at the stiffeners, in a hole through the beam depth

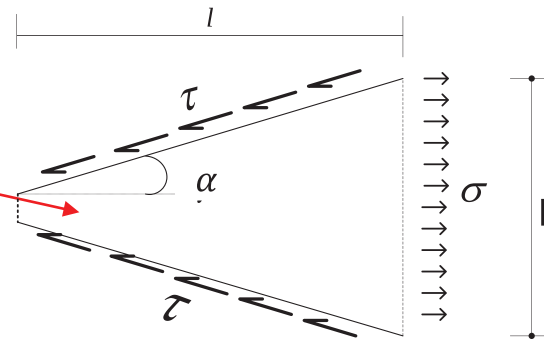
Finger jointing

Source: Gerhard Fink

Finger joint

- What is the reasonable relationship l/p ?





- The joint should be stronger than the base material. Therefore:

$$\sigma \cdot p \leq \left(2 \cdot \tau \cdot \frac{l}{\cos \alpha}\right) \cdot \cos \alpha \Rightarrow \frac{\sigma}{\tau} \leq \frac{2 \cdot l}{p}$$

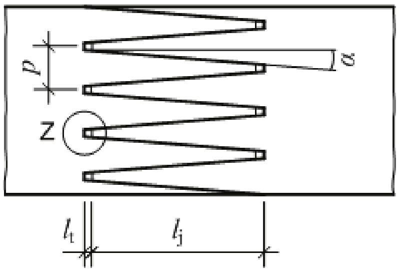
- The ratio of tensile strength to shear strength is approx. $f_t/f_v \approx 4$ (C27)

$$\frac{2 \cdot l}{p} \geq 4 \Rightarrow \frac{l}{p} \geq 2{,}0$$

Finger joint

- Finger joint geometries of industrially most used finger joints

Profile	Profile geometry			
	l	p	b_t	l/p
A	15	3,8	0,42	3,9
B	20	6,2	1,0	3,2
C	20	5,0	0,5	4
D	32	6,2	1,0	5,2



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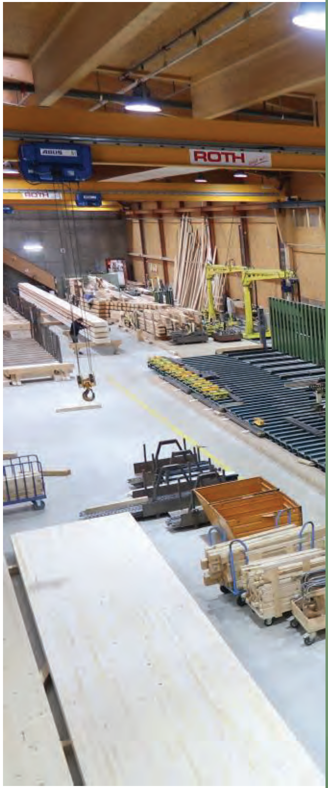
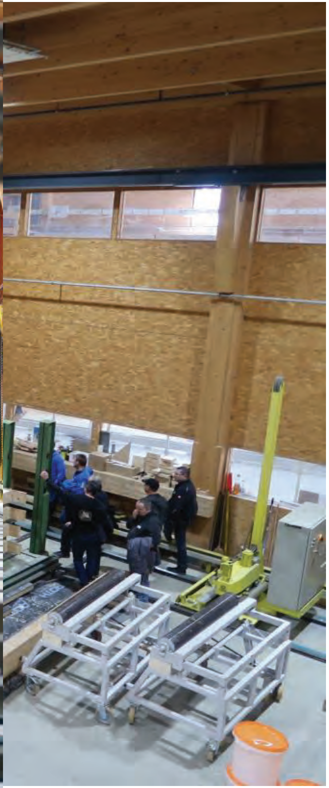
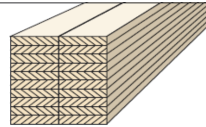
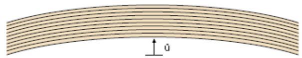
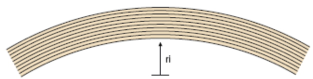
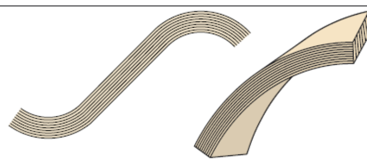
Assembly and pressing

Variety in geometry

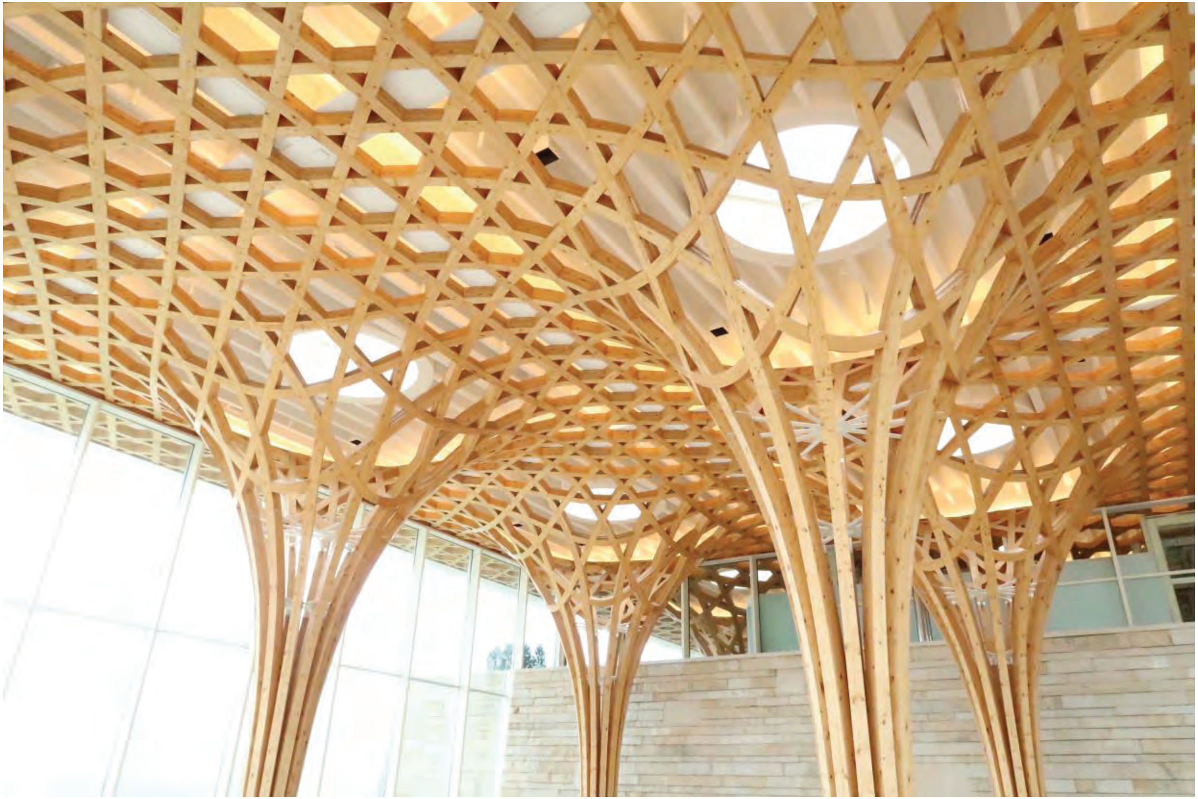




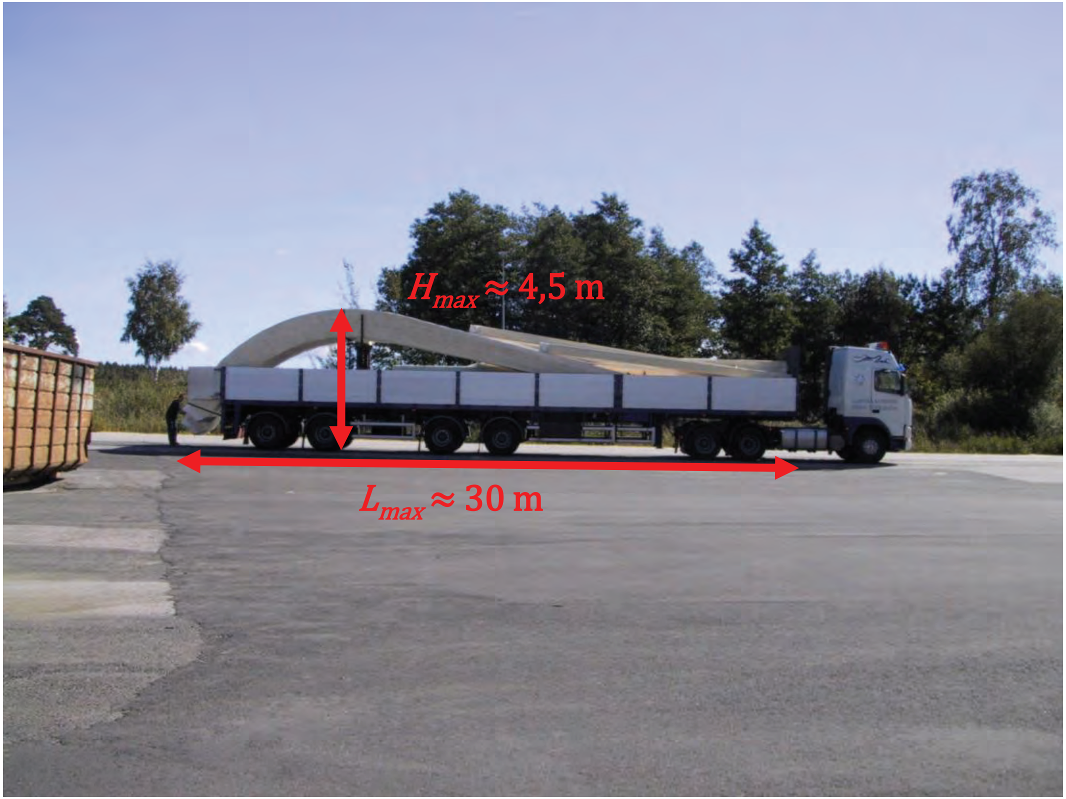
Some other shapes of glulam elements

Double or multiple glued beams		■ for widths larger than 28 cm ■ general finger-jointed joint = resorcinol gluing
Pre-cambered beams		■ pre-cambered to l/200 or l/300 ■ simple camber for single-span beams ■ pre-camber for multiple-span or cantilever beams
Sloped beam with straight bottom chord		■ Transverse stress reinforcement with threaded rods ■ Beam lay-up: combined non-symmetrically
Curved beams		■ any radii desired with more than 1 m inner radius ■ Lamination thickness > 5 mm ■ Beam lay-up: combined non-symmetrically
Sloped beam with arched bottom chord (boomerang)		■ up to 20° roof slope ■ Transverse stress reinforcement with threaded rods ■ Beam lay-up: combined non-symmetrically
Free shapes		■ double curvatures, 2-axis curves ■ free shapes are formed by gluing ■ or custom joinery

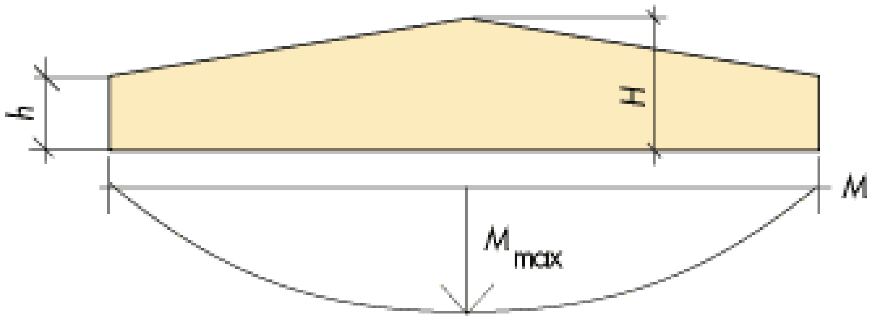
Some other shapes of glulam elements



Transport



Benefits of special geometries



- The shape of a symmetrical double pitched beam approximates to the moment diagram of a beam freely supported at each end.
- It is therefore more economic in material than a constant-depth beam.

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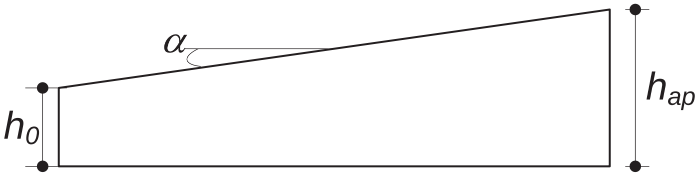
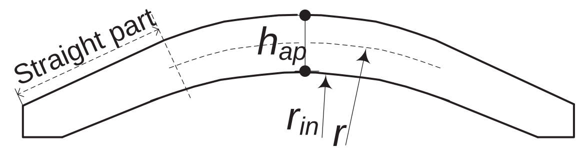
Pitched cambered beams with overlap purlins

Tapered, curved and pitched glulam



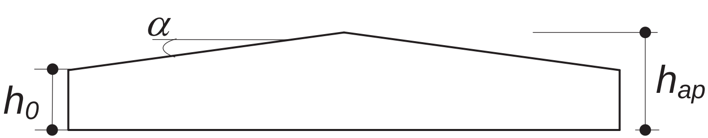
(a)

- Single tapered beam



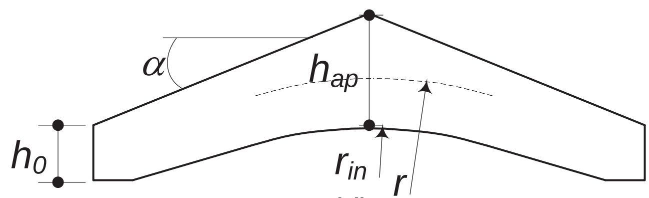
(c)

- Curved beam



(b)

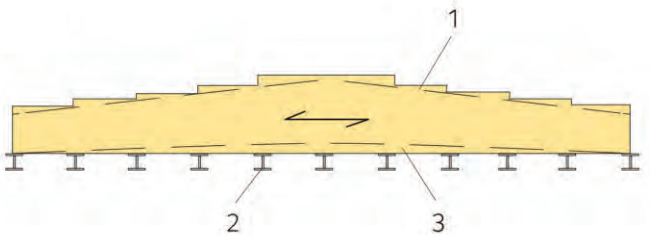
- Double tapered beam



(d)

- Pitched cambered beam

Structural component with varying sectional height



(1) Trimming

(2) Pressure distributing base

(3) Possible camber

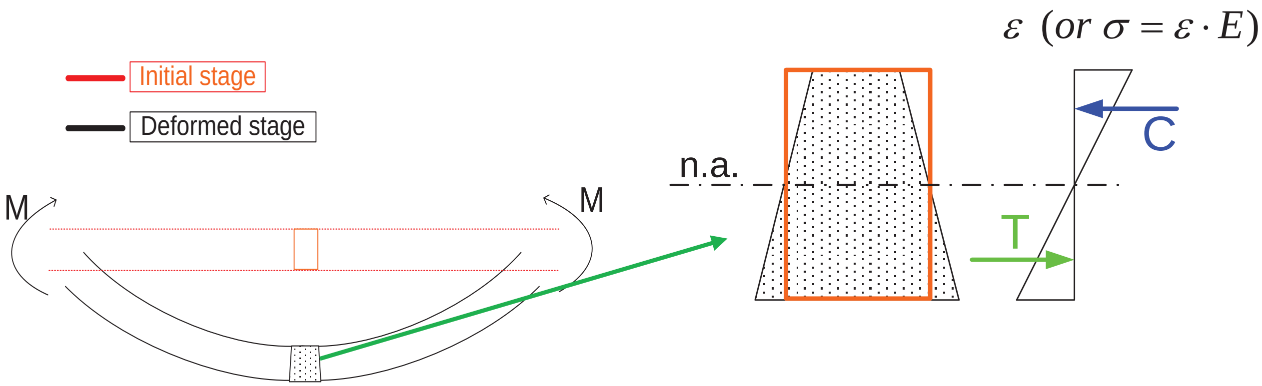
Issues to be investigated

Some specific issues related to tapered, curved and pitched cambered beams

- Bending stress distribution in the cross section
- Position of maximum bending stress
- Effect of sawn taper cuts
- Stress distribution along the span
- Failure criteria and bending of laminations
- Tensile stress perpendicular to the grain at the apex
- Volume effect

Distribution of bending stress

Deformation of a straight beam



- According to the Bernoulli's principle, plane section will remain plane after deformation. The neutral axis is located in the middle of the cross section.
- Equilibrium is respected (T=C) being the “triangle of compression stresses” identical to the “triangle of tension stresses”

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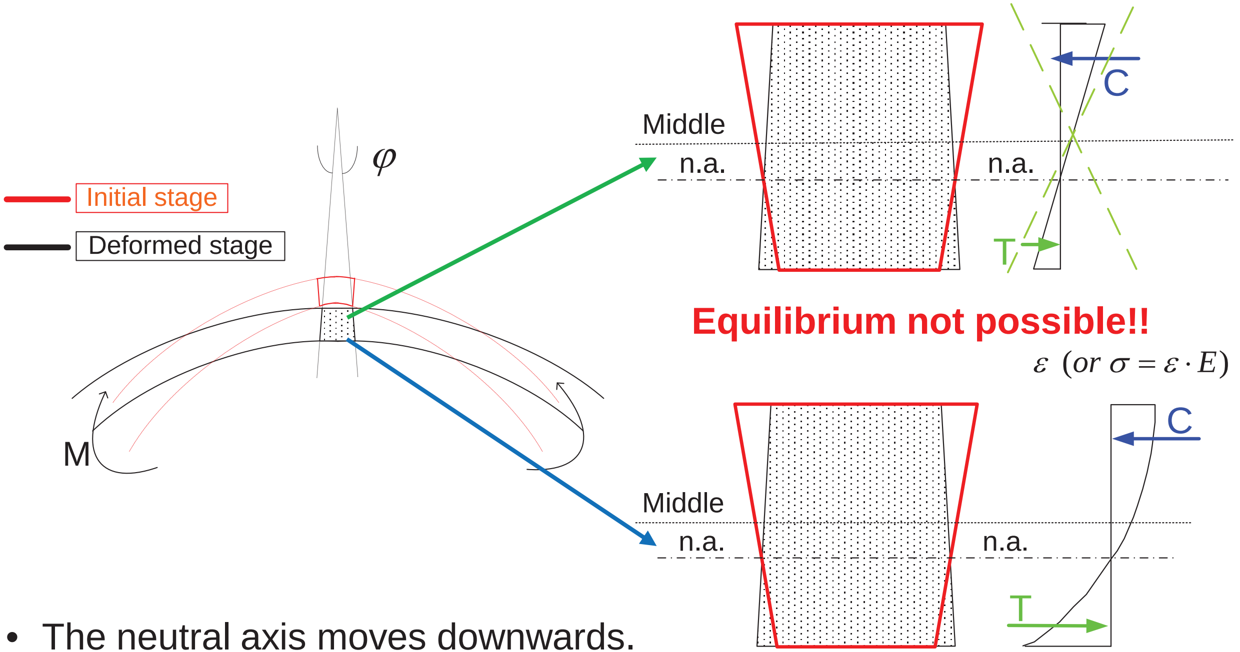
Deformation of a curved (or tapered) beam

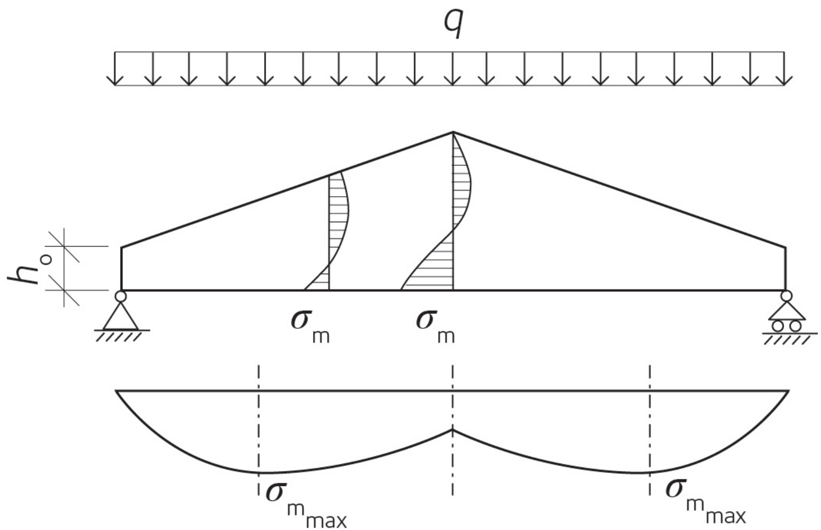


- The neutral axis moves downwards.
- Equilibrium is possible only if the stress distribution is non linear (hyperbolic)
- The maximum stress is achieved at the inner fibre (smaller radius)

Position of maximum bending stress

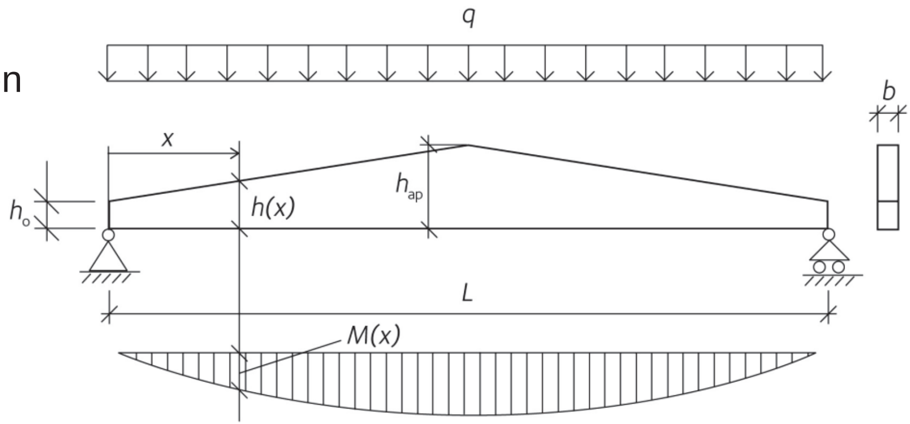
Position of maximum bending stress

- Where is the location maximum bending stress σ_m ?



Position of maximum bending stress

- Where is the location maximum bending stress σ_m ?

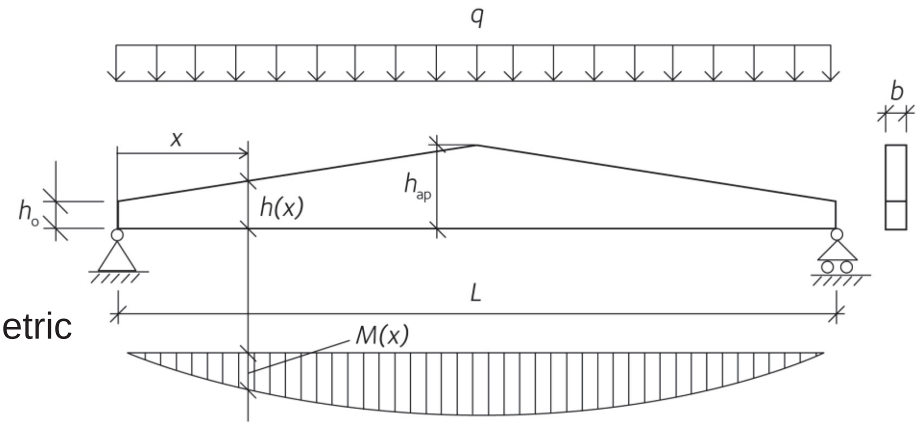


- Find x_0 !

- The function $\sigma(x)$ has a maximum at the point where its derivate is zero:

$$\frac{d}{dx}\sigma(x) = 0 \Rightarrow \frac{d}{dx}\frac{M(x)}{W(x)} = 0$$

Position of maximum bending stress



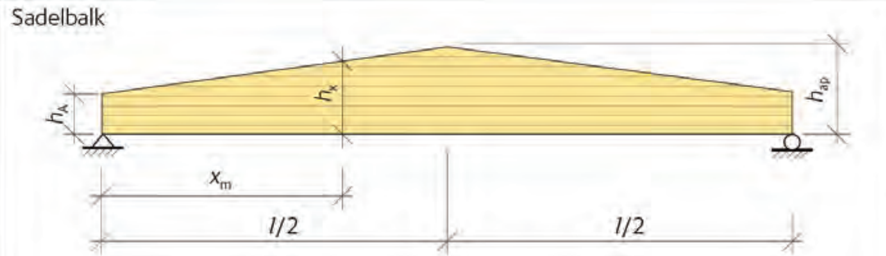
- For a double symmetric tapered or pitched cambered beam:

$$M(x) = q_d \left(\frac{L}{2} \cdot x - \frac{x^2}{2} \right) \qquad W(x) = b \cdot \frac{h(x)^2}{6} = \frac{b}{6} \cdot \left(h_0 + x \cdot \frac{h_{ap} - h_0}{0{,}5 \cdot L} \right)^2$$

- The maximum is to be found where the derivative of $\sigma(x)$ equals 0

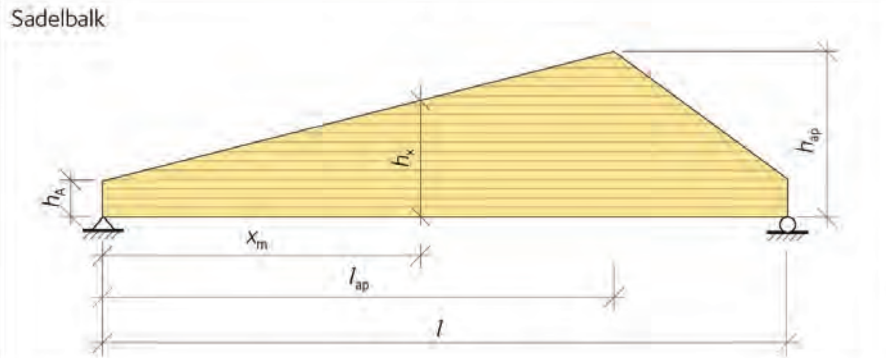
$$\frac{d}{dx} \frac{M(x)}{W(x)} = 0 \Rightarrow \qquad x_0 = \frac{L \cdot h_0}{2 \cdot h_{ap}}$$

Position of maximum bending stress



$$x_m = \frac{l \cdot h_A}{2 \cdot h_{ap}}$$

$$h_x = h_A \cdot \left(2 - h_A / h_{ap}\right)$$

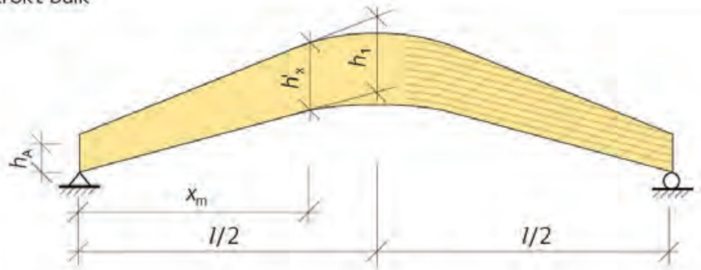


$$x_m = \frac{l_{ap}}{h_{ap}/h_A + 2 \cdot l_{ap}/l - 1}$$

$$h_x = h_A + \frac{x_m}{l_{ap}} \cdot \left(h_{ap} - h_A\right)$$

Position of maximum bending stress

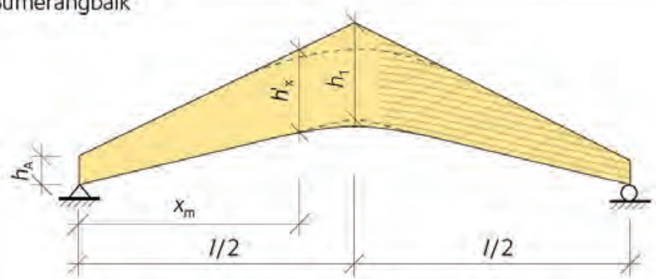
Krökt balk



$$x_m = \frac{l \cdot h_A}{2 \cdot h_1}$$

$$h'_x = h_A \cdot \left(2 - h_A / h_1\right)$$

Bumerangbalk

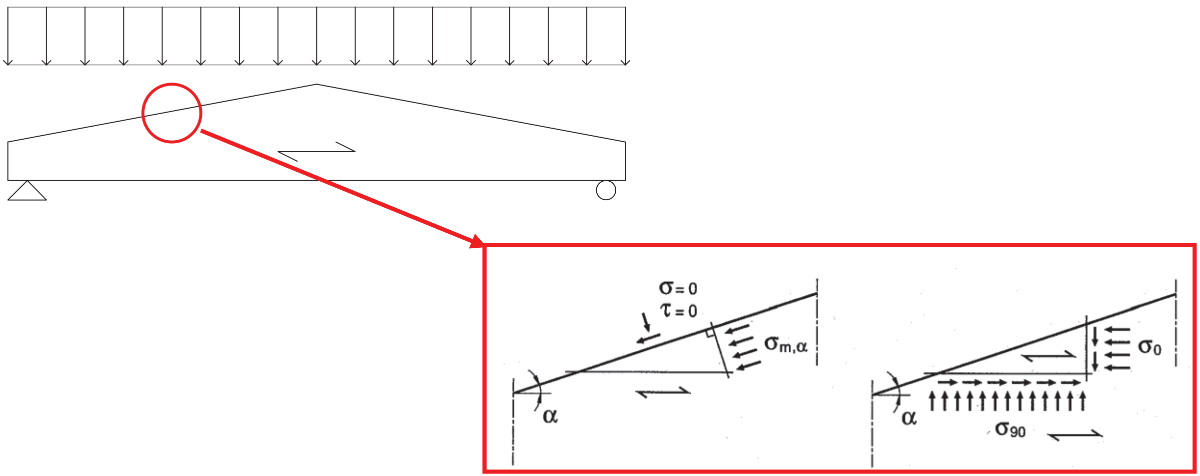


$$x_m = \frac{l \cdot h_A}{2 \cdot h_1}$$

$$h'_x = h_A \cdot \left(2 - h_A / h_1\right)$$

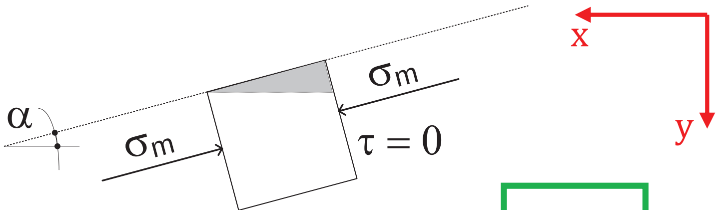
Effect of sawn cut

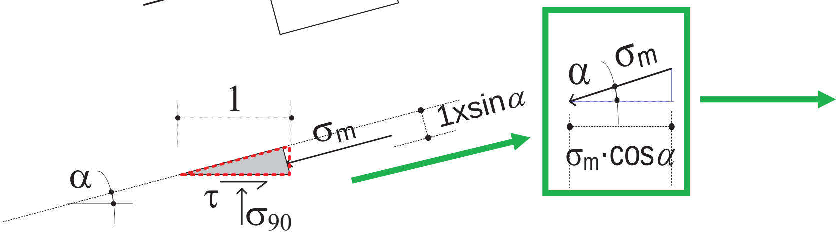
Effect of sawn taper cuts



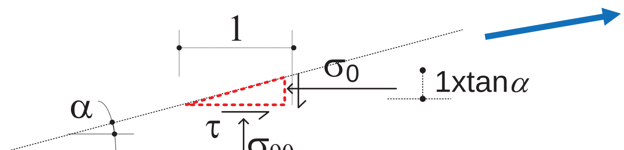
- The bending stresses σ_m are parallel to the tapered side.
- This generates:
  - compression ⊥ grain, if the tapered side is compressed (fig. above)
  - tension ⊥ grain, if the tapered side is in tension

Equilibrium considerations





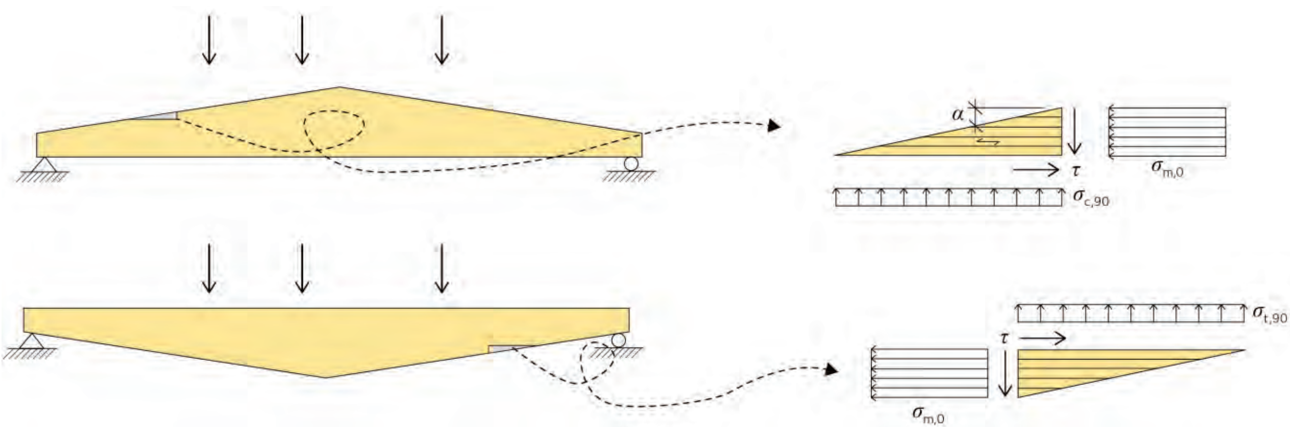
$$\left\{\begin{aligned} &\Sigma x = 0 \\ &\tau \cdot 1 = (\sigma_m \cos\alpha)\cdot(1\cdot\sin\alpha) \Rightarrow \\ &\tau = \sigma_m \cdot \cos\alpha \cdot \sin\alpha \end{aligned}\right.$$



$$\left\{\begin{aligned} &\Sigma x = 0 \\ &\tau \cdot 1 = \sigma_0(\tan\alpha) \Rightarrow \\ &\sigma_m \sin\alpha \cdot \cos\alpha \cdot 1 = \sigma_0(1\cdot\tan\alpha) \\ &\sigma_0 = \sigma_m \cos^2\alpha \\ &\Sigma y = 0 \\ &\tau \cdot 1 \cdot \tan\alpha = \sigma_{90} \cdot 1 \Rightarrow \\ &\sigma_m \sin\alpha \cdot \cos\alpha \cdot 1 \cdot \tan\alpha = \sigma_{90} \cdot 1 \\ &\sigma_{90} = \sigma_m \sin^2\alpha \end{aligned}\right.$$

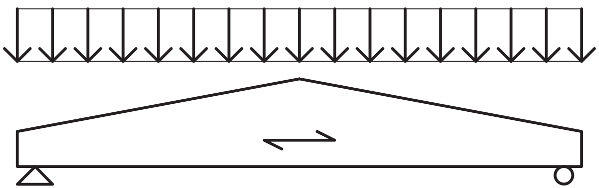
DoTS, p. 3.27 and Eqs. 3.42-3.44

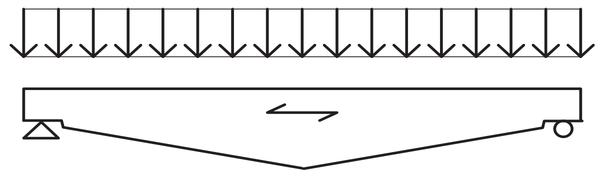
Effect of sawn taper cuts



Effect of sawn taper cuts

- The reduction in strength depends on the tapering, being in the compression or in the tension side of the beam



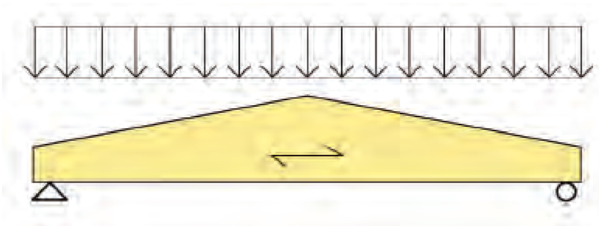


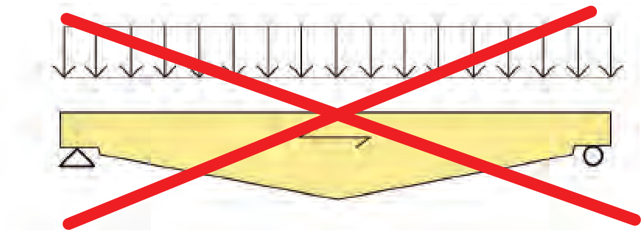
- Compression ⊥ grain at the tapered edge

- Tension ⊥ grain at the tapered edge

- Taperig slopes larger than 15° on the compression side and 5° on the tension side should be avoided! In order to reduce the possibility of crack initiation, a board can be nail-glued on the tapered side.

Effect of sawn taper cuts

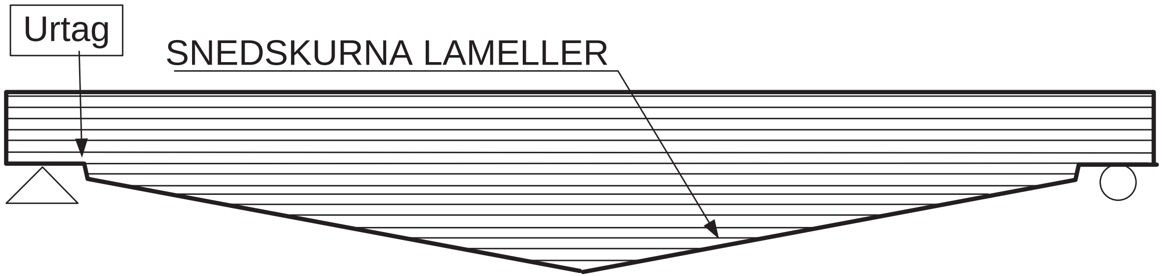




- Compression perpendicular to the grain occurs at the tapered edge
- Tension perpendicular to the grain occurs at the tapered edge (upside down tapered beam)

Effect of sawn taper cuts

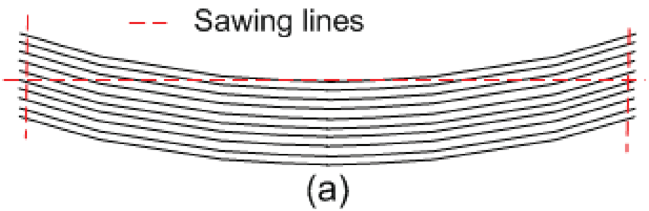
- Be careful if you design a beam like this!

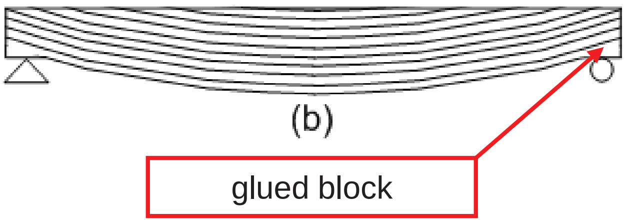


- Sawn taper cuts at the tension side mean tension perpendicular to the grain. Such stresses increase with increasing slopes and are even more dangerous in case of repetitive changes in moisture content.

Alternative

- This is a significantly better beam!





- Gluing of the laminations
- The “fish belly” beam

Effect of variable height on stress distribution

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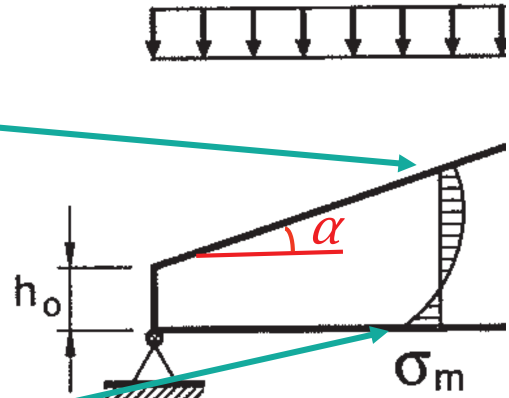
Tapered beams

Theory: effect of variable height (old version of EC5)

- At the tapered side, “sawn grain”

$$\sigma_{m,\alpha,d} := (1 - \tan^2(\alpha))\frac{M_{x0}}{W_{x0}}$$



- At the side with ”continuous grain”

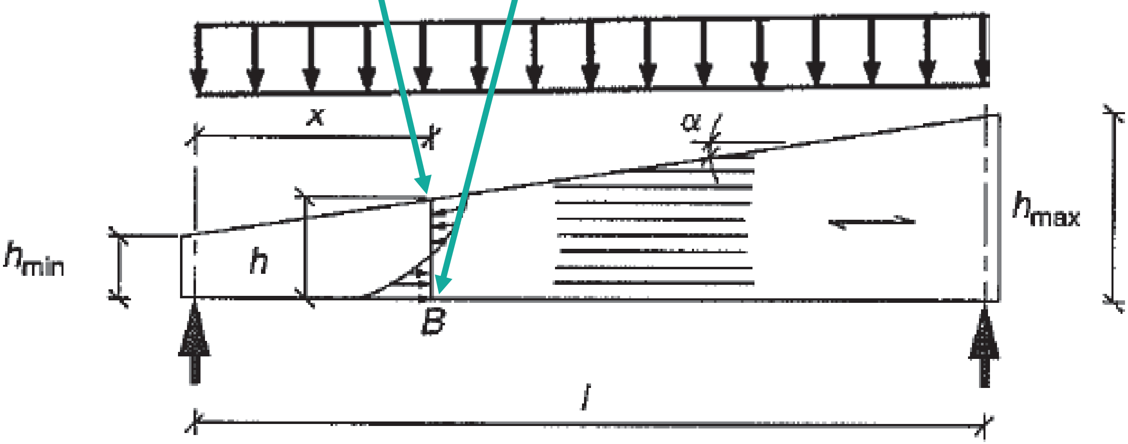
$$\sigma_{m,0,d} := (1 + \tan^2(\alpha))\frac{M_{x0}}{W_{x0}}$$

- Not used anymore in EC5!

Tapered beams

- Definition in current EC5!

$$\sigma_{m,\alpha,d} := \sigma_{m,0,d} = \frac{6M_d}{bh^2}$$



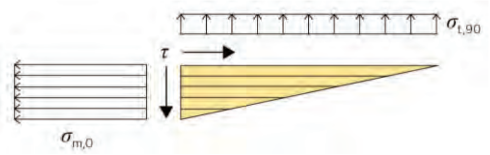
Tapered beams

Current EC5: reduction of strength at tapered edge:

- $\sigma_{m,\alpha,d}$ and $\sigma_{m,0,d}$ are the design bending stresses at an angle to grain and at the straight edge, respectively

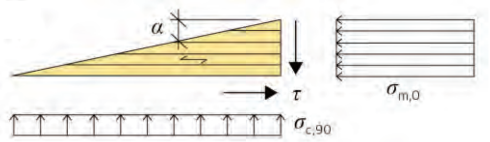
$$\sigma_{m,\alpha,d} \leq k_{m,\alpha} f_{m,d}$$

- For tensile stresses ∥ tapered edge



$$k_{m,\alpha} = \frac{1}{\sqrt{1 + \left(\frac{f_{m,d}}{0{,}75 f_{v,d}} \tan\alpha\right)^2 + \left(\frac{f_{m,d}}{f_{t,90,d}} \tan^2\alpha\right)^2}}$$

- For compressive stresses ∥ edge

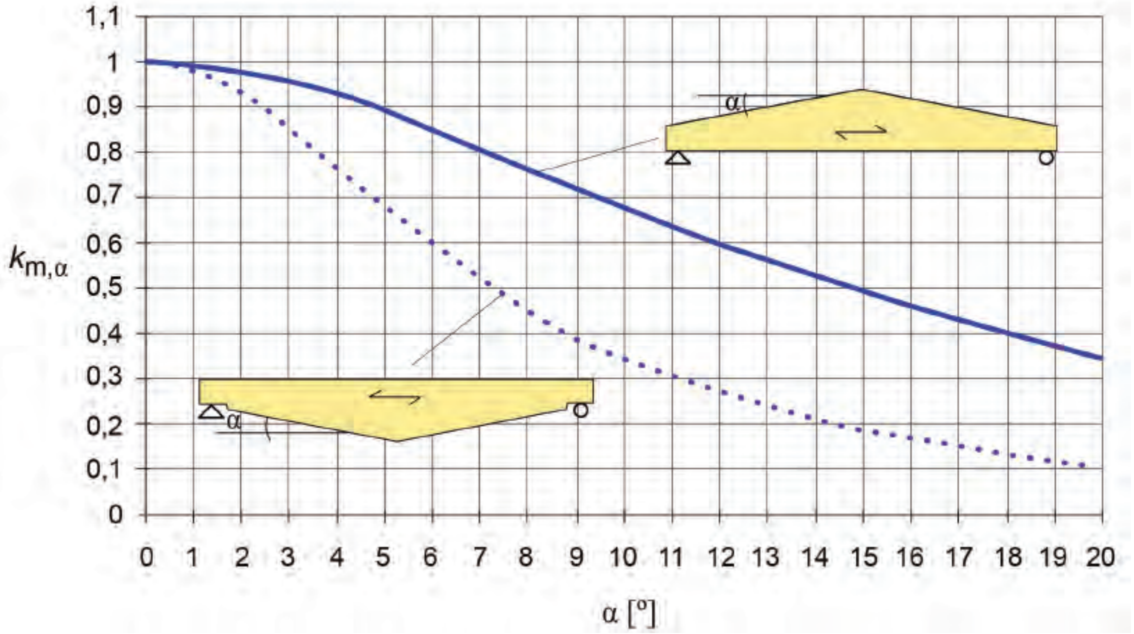


$$k_{m,\alpha} = \frac{1}{\sqrt{1 + \left(\frac{f_{m,d}}{1{,}5 f_{v,d}} \tan\alpha\right)^2 + \left(\frac{f_{m,d}}{f_{c,90,d}} \tan^2\alpha\right)^2}}$$

ref. EC5: Eqs: 6.38 - 6.40

Pitch cambered beams

- Values of $k_{m,\alpha}$ according to EC 5 for different slopes of the tapered edge; Glulam class GL30c. Service class 1; Load duration: medium term

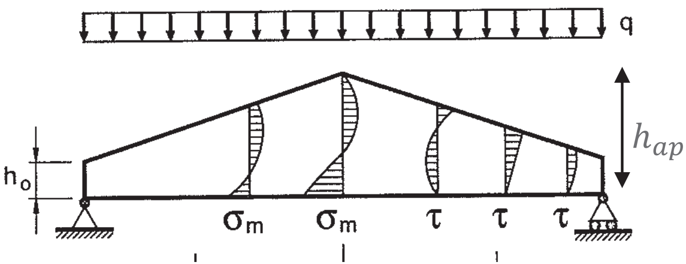


Example: Tapered beams with cantilever

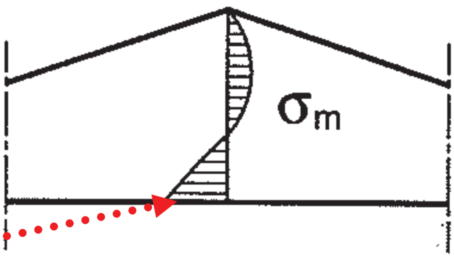
Tapered beam

EC5:

- Bending stresses in the apex



$$\sigma_{md} = k_l \frac{6 \cdot M_{ap,d}}{b \cdot h_{ap}^2}$$

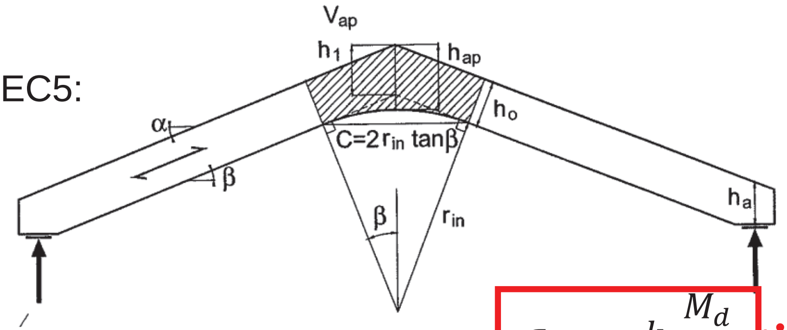


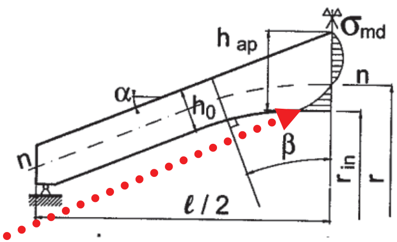
$$k_l = 1 + 1{,}4 \cdot \tan\alpha + 5{,}4 \cdot \tan^2\alpha$$

ref. EC5: Eqs: 6.42 and 6.44

Pitched cambered beam at the apex

EC5:





$$\boxed{\sigma_{m,d} = k_l \frac{M_d}{W}}$$

$$k_l = k_1 + k_2\left(\frac{h_{ap}}{r}\right) + k_3\left(\frac{h_{ap}}{r}\right)^2 + k_4\left(\frac{h_{ap}}{r}\right)^3$$

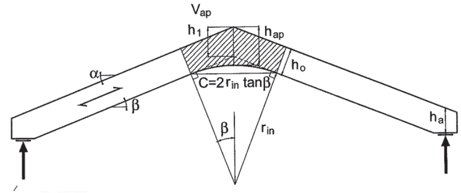
$$\begin{cases} k_1 = 1 + 1{,}4\tan(\alpha) + 5{,}41{,}4\tan^2(\alpha) \\ k_2 = 0{,}35 - 8\tan(\alpha) \\ k_3 = 0{,}6 + 8{,}3\tan(\alpha) - 7{,}8\tan^2(\alpha) \\ k_4 = 6\tan^2(\alpha) \end{cases}$$

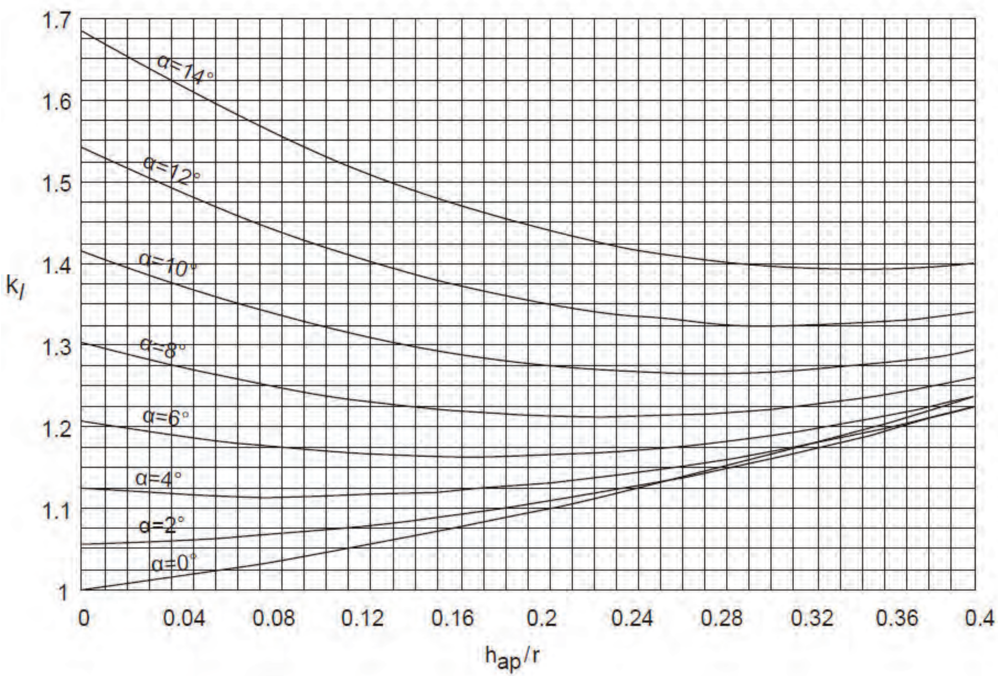
- For curved beams with constant cross section, the slope should be assumed: $\alpha = 0$

ref. EC5: Eqs: 6.42 and 6.43-6.47

Pitched cambered beam at the apex

- Factor k_l for different radius and slope of grain



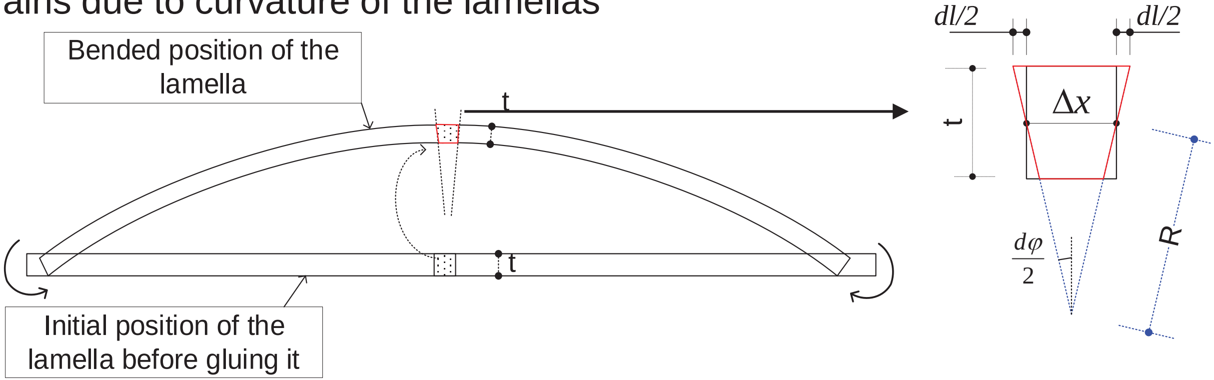


Effect of internal stresses in lamellas

Problem: Bending of laminations during manufacturing

Bending of laminations with thickness t

- Strains due to curvature of the lamellas



- Large stresses during glulam production!

$$\begin{cases} \dfrac{dl}{2} = \dfrac{t}{2} \cdot \dfrac{d\phi}{2} \\ \Delta x = R \cdot d\phi \end{cases} \longrightarrow \frac{dl}{\Delta x} = \frac{t}{2 \cdot R}$$

$$\sigma = \varepsilon \cdot E = \frac{dl}{\Delta x} \cdot E = \frac{E \cdot t}{2 \cdot R}$$

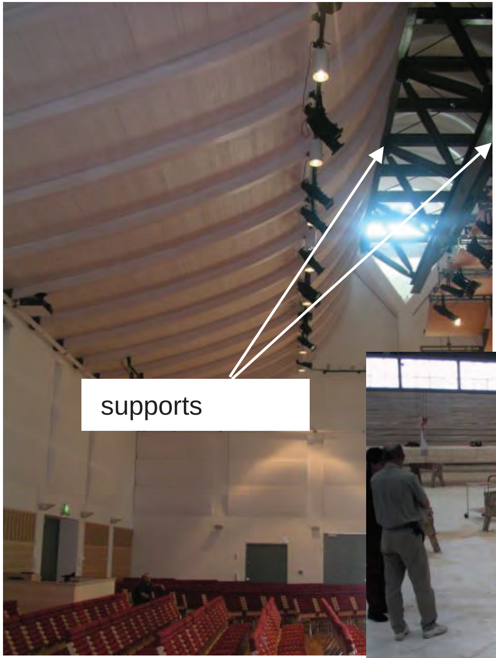
Bending of laminations during manufacturing

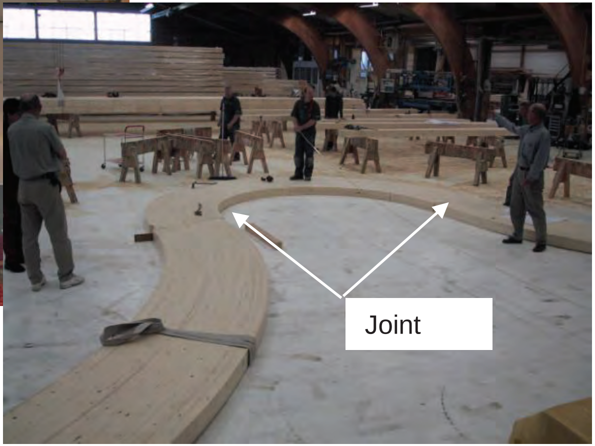
- Example:
  - $E = 10'000 N/m^2$
  - $t = 33mm$
  - $R = 8m$

$$\sigma = \frac{E \cdot t}{2 \cdot R} = \frac{10000}{2} \cdot \frac{33}{8000} = 20.6\ N/mm^2!$$

- However, these stresses are not so large in reality, due to plastic deformation and relaxation, i.e. creep, especially during production where there is some moisture from the glue

Example: Dunkers house - Helsingborg





- Radius: 1.5 m
- Thickness of lamellas = 10 mm!

$$\sigma = \frac{E \cdot t}{2 \cdot R} = \frac{12000}{2} \cdot \frac{10}{1500} = 40\ N/mm^2!$$

Failure criteria

- The bending stresses shall satisfy the following conditions:

$$\sigma_m \leq k_r f_m$$

- k_r takes into account the strength reduction due to high eigenstresses built into the laminations during production

Bending of laminations, EC5

- According to EC5, the bending strength should be reduced by a factor k_r, if the ratio r/t is too large

$$k_r \coloneqq \begin{cases} 1 & \text{for} \quad \dfrac{r_{in}}{t} \geq 240 \\ 0{,}76 + 0{,}01\dfrac{r_{in}}{t} & \text{for} \quad \dfrac{r_{in}}{t} < 240 \end{cases}$$

$$f_{m,curved} \coloneqq k_r \cdot f_m$$

- For example, a beam with $r_{in} = 5m$

$$\frac{r_{in}}{t} = \frac{5000}{33.3} = 150.1 \leq 240$$

$$k_r = 0.76 + 0.001 \cdot \frac{r_{in}}{t} = 0.76 + 0.001 \cdot \frac{5000}{33.3} = 0.91$$

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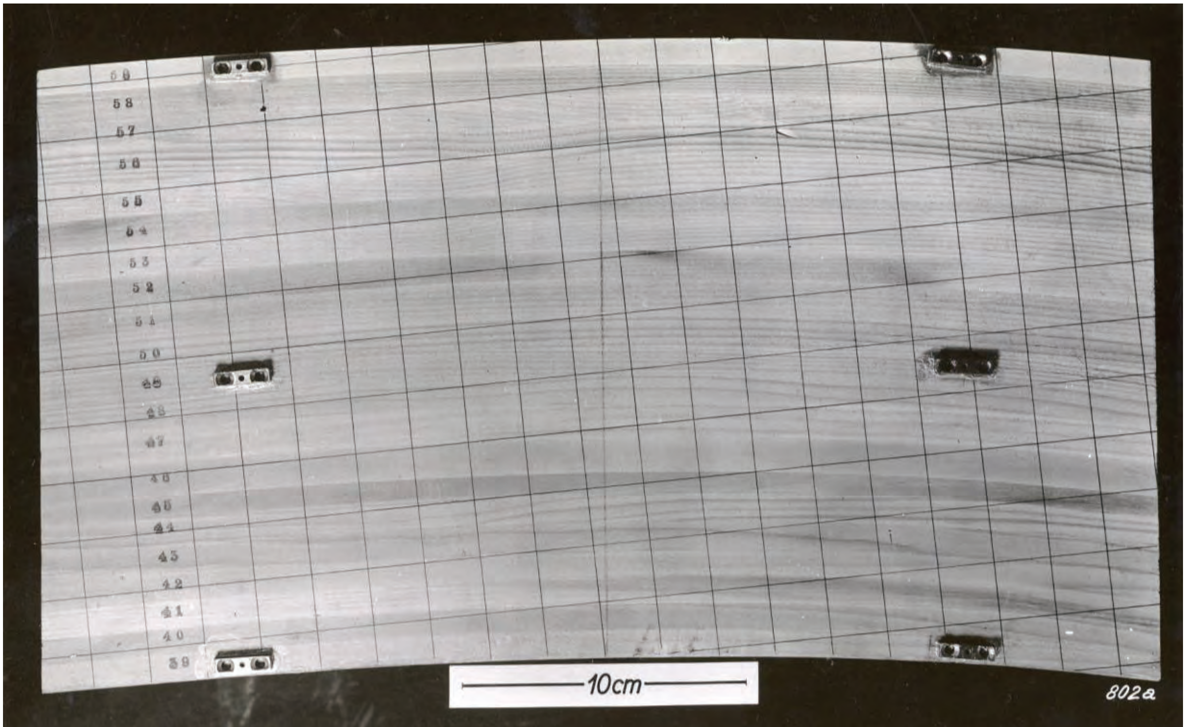
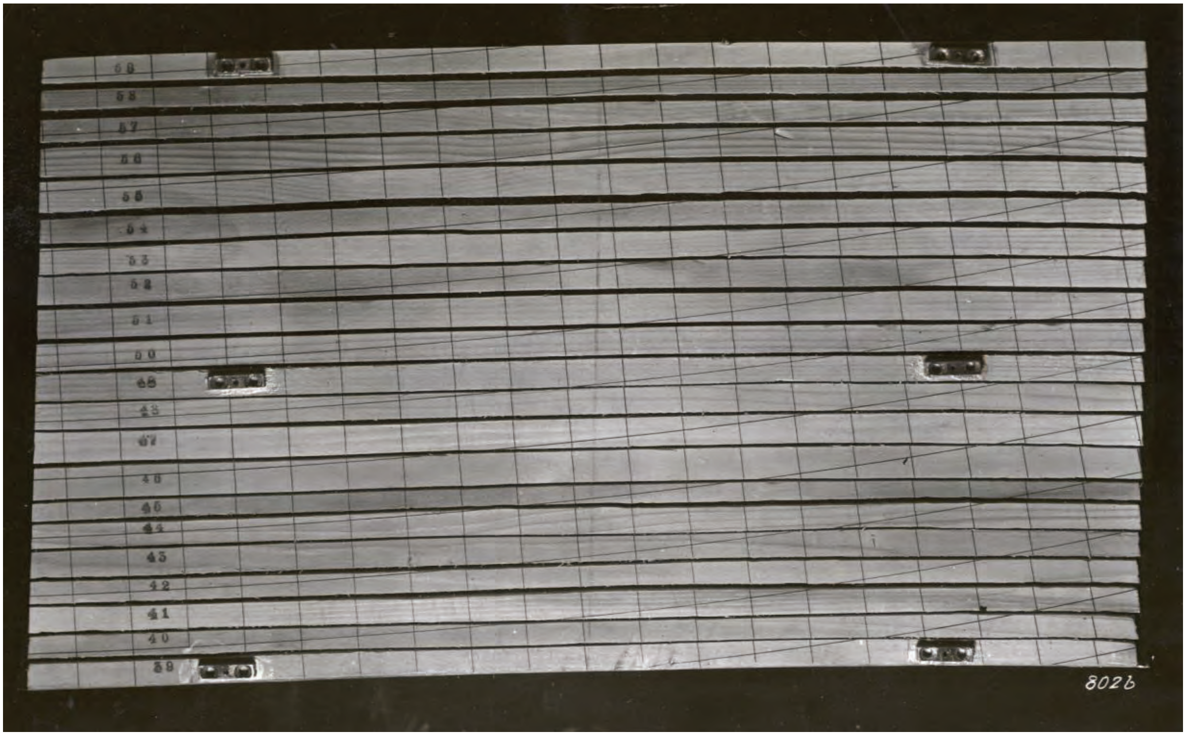
Internal stresses in curved beams



Internal stresses in curved beams

- 20% plastic deformation after 5 years (80% elastic deformation)



Tension perpendicular to grain stresses

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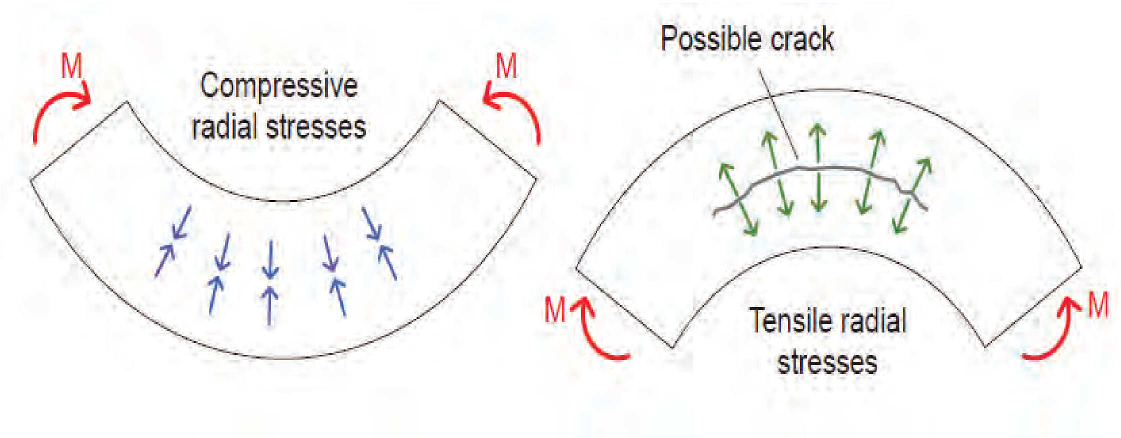
Pitch cambered beams

Tensile stress perpendicular to the grain

- Bending moments in curved members cause radial stresses perpendicular to the grain.
- These stresses have been one of the major cause of structural collapses of timber structures!

Curved beams in bending

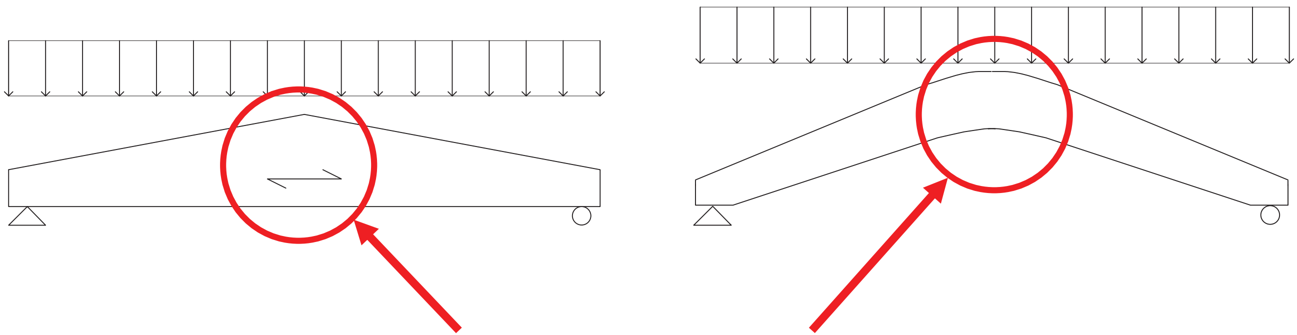
- A bending moment is applied to a beam that is initially curved in the plane of bending,



- When the applied bending moment tends to straighten the glulam member, the laminations try to move apart.
- Radial tensile stresses occur between laminations!

Tensile stress perpendicular to the grain

- Apex zones of tapered and pitch cambered beams



- Zones, where tension perpendicular to the grain occurs!

- The steeper the slope, the higher the tension perpendicular to the grain

Curved glulam beam with cross-section: b x h

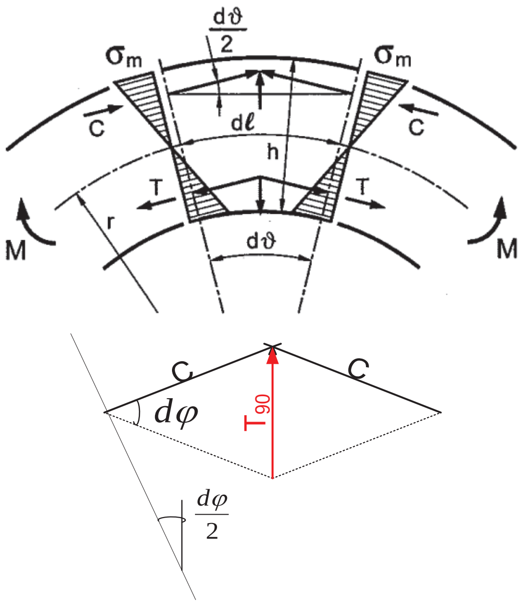
- Forces

$$C = -T = \frac{1}{2} \cdot \left(\sigma_m \cdot b \cdot \frac{h}{2} \right) \qquad dl = r d\vartheta$$

- Equilibrium

$$T_{90} = 2 \cdot C \cdot \sin\left(\frac{d\vartheta}{2}\right) \approx 2 \cdot C \cdot \frac{\vartheta}{2} = C\vartheta$$

$$T_{90} = \frac{1}{2} \cdot \left(\sigma_m \cdot b \cdot \frac{h}{2} \right) \cdot \frac{dl}{r}$$



- Tension perp. to the grain stress

$$\sigma_{90} = \frac{T_{90}}{b \cdot dl} = \frac{h}{4 \cdot r} \cdot \sigma_m$$

$$\sigma_{90} = \frac{h}{4 \cdot r} \cdot \frac{M}{W} \qquad \text{with} \qquad W = {bh^2}/{6} \qquad \Rightarrow \qquad \boxed{\sigma_{90} = 1.5 \frac{M}{bhr}}$$

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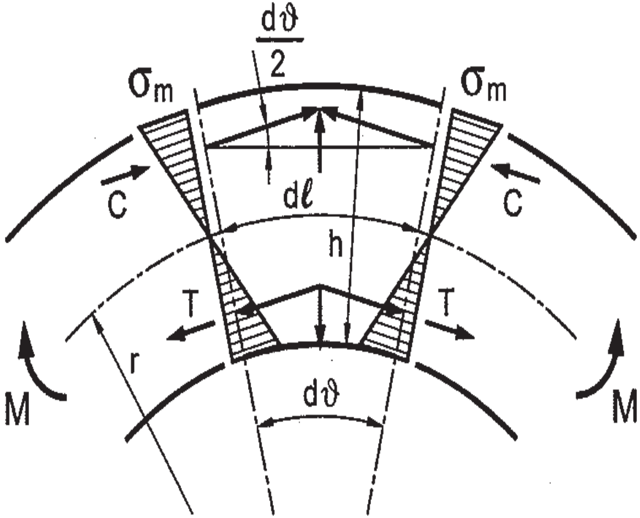
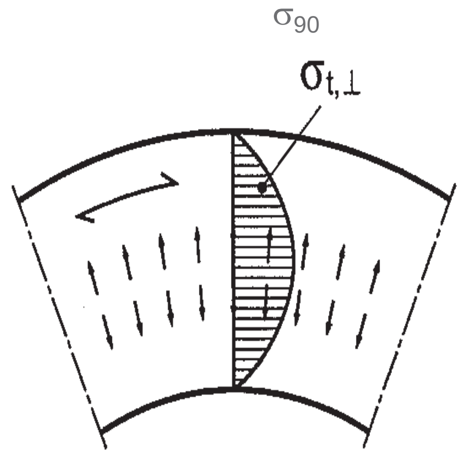
Tensile stress perpendicular to the grain

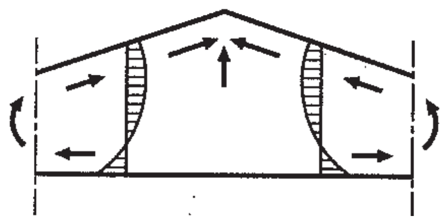
- Curved beams

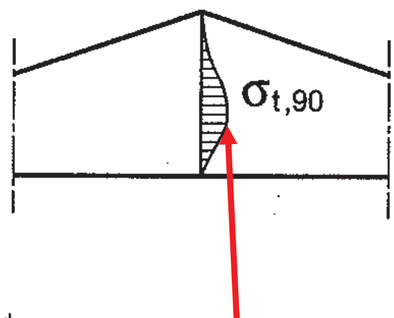


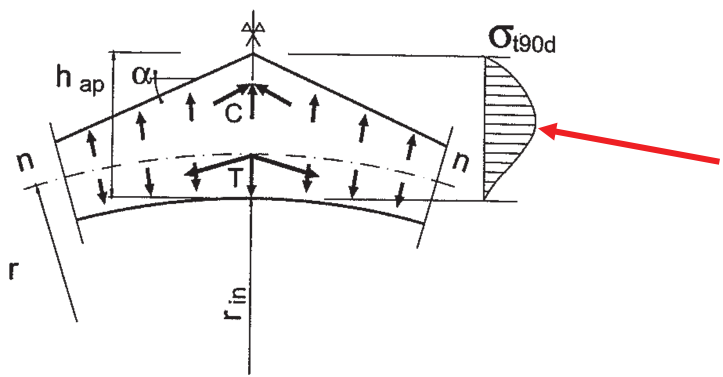


Tensile stress perpendicular to the grain

- Apex zones of tapered and pitch cambered beams



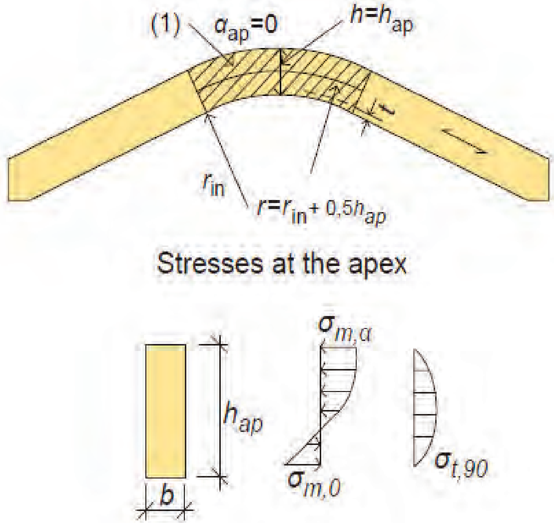


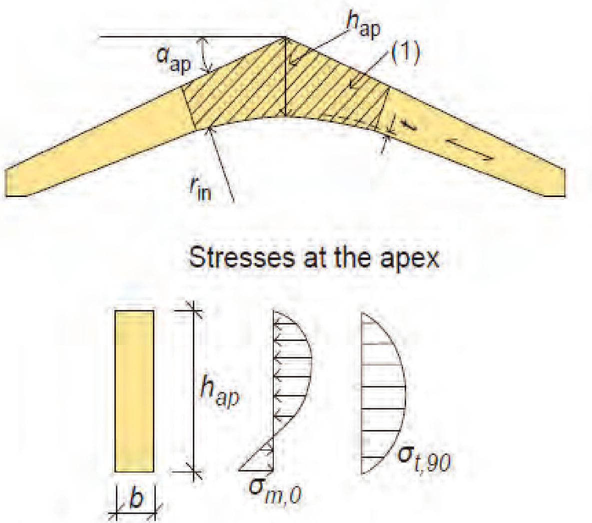


Tapered beam &
pitched cambered beams

Curved and pitch cambered beams

- Comparison





Curved and pitch cambered beams

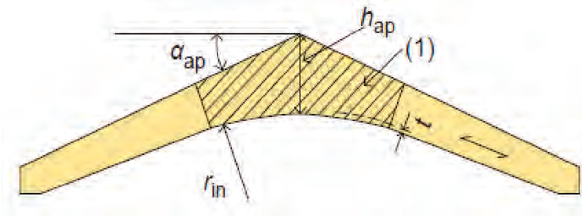
EC5:

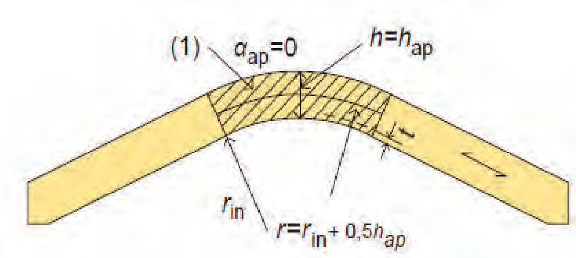
- Tensile stresses perpendicular to grain

$$\sigma_{t,90,d} = k_p \frac{M_d}{W}$$

$$k_p = k_5 + k_6\left(\frac{h_{ap}}{r}\right) + k_7\left(\frac{h_{ap}}{r}\right)^2$$

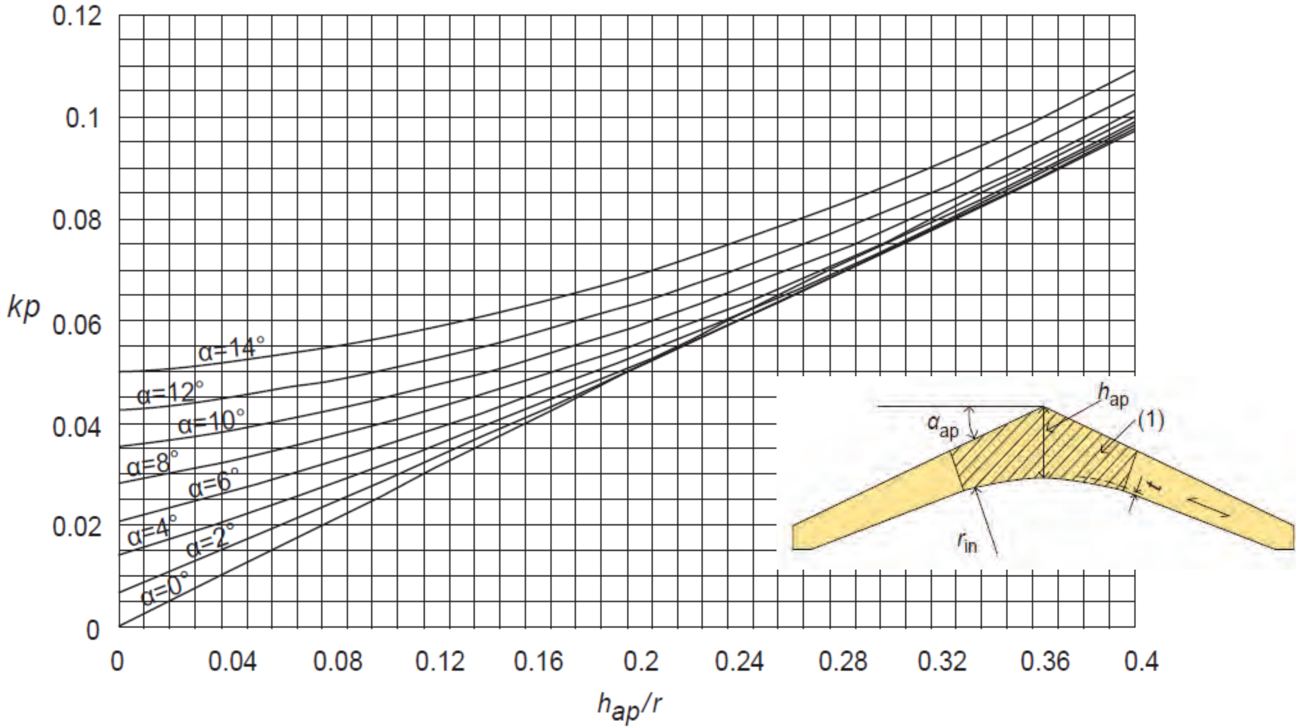
$$\begin{cases} k_5 = 0{,}2\tan(\alpha_{ap}) \\ k_6 = 0{,}25 - 1{,}5\tan(\alpha_{ap}) + 2{,}6\tan^2(\alpha_{ap}) \\ k_7 = 2{,}1\tan(\alpha_{ap}) - 4\tan^2(\alpha_{ap}) \end{cases}$$





ref. EC5: Eqs: 6.54 and 6.56-6.59

Factor k_p for different radius and slope of grain




Toggenburger

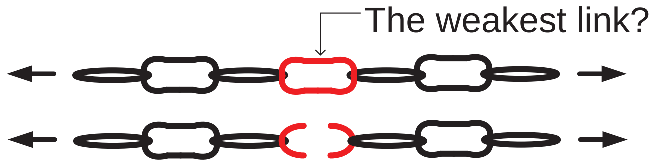
Failure criteria

- The tensile strength perpendicular to the grain are very sensitive to:
  - moisture variation
  - volume effect

Volume effect

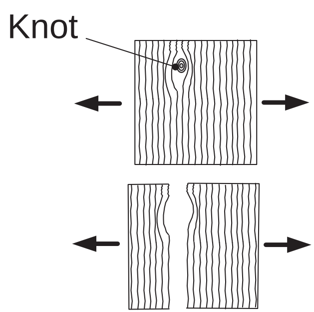
- The longer the chain….

…the bigger the possibility that the chain has a ”weak link”



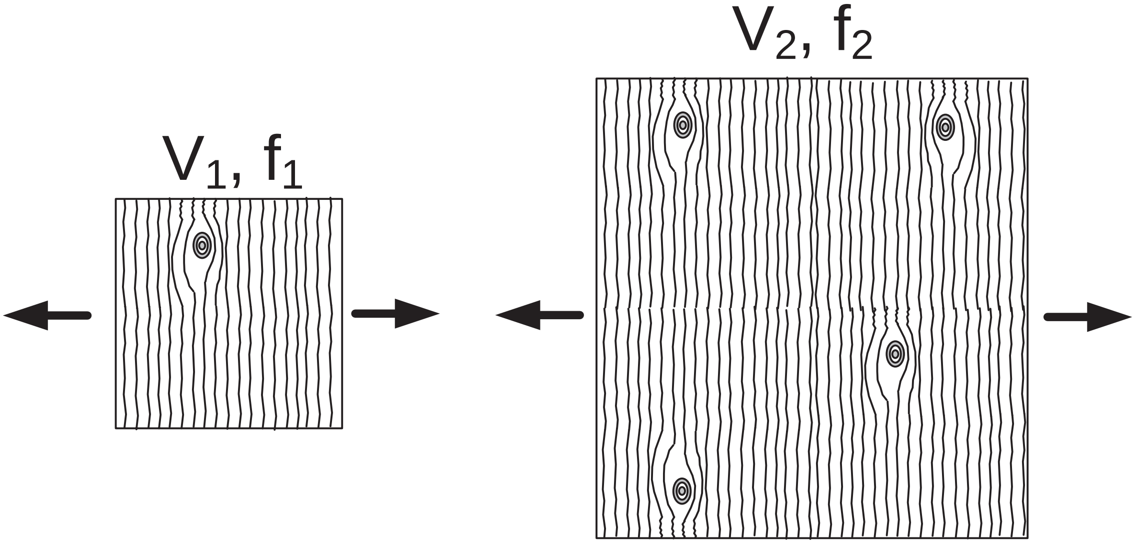
- The larger the volume of wood …

…the larger is the possibility that the volume contains a defect (e.g. a knot)



Volume effect

- By means of the Weibull's theory for brittle failures, a relationship between the strength of two specimens can be obtained

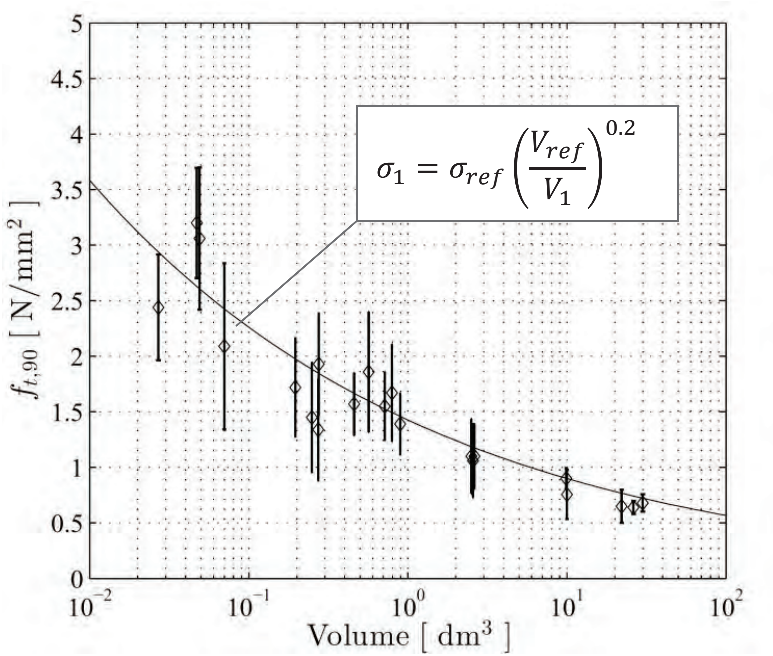


$$\frac{f_2}{f_1} = \left(\frac{V_1}{V_2}\right)^{\frac{1}{k}} \Rightarrow f_2 = f_1 \left(\frac{V_1}{V_2}\right)^{\frac{1}{k}} \qquad k \approx 5$$

(from laboratory tests)

Volume effect

- Strength in tension perpendicular to the grain as a function of the loaded volume



Tensile strength perpendicular to the grain, EC5

EC5: Design for tension perpendicular to grain in beams

$$\sigma_{t,90,d} \leq k_{dis} \cdot k_{vol} \cdot f_{t,90,d}$$

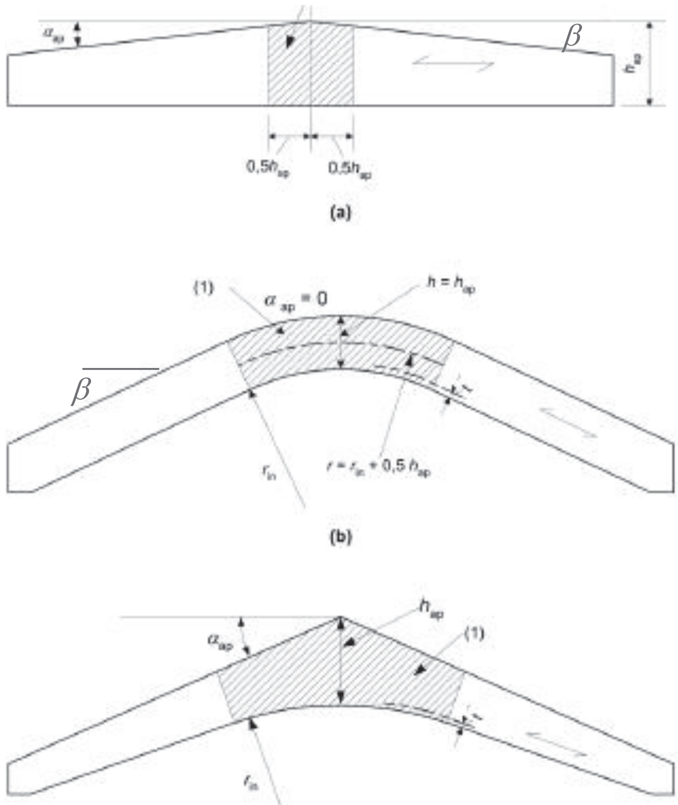
- k_{dis} is a factor which takes into account the effect of the stress distribution in the apex zone.

$$k_{dis} = \begin{cases} 1{,}4 & \text{for double tapered and curved beams} \\ 1{,}7 & \text{for pith cambered beams} \end{cases}$$

$$k_{vol} = \begin{cases} 1{,}0 & \text{for solid timber} \\ \left(\dfrac{0{,}01m^3}{V}\right)^{0{,}2} & \text{for glued laminated timber and LVL with veneers parallel to the beam axis} \end{cases}$$

- Values of k_{dis} and V for beams loaded by uniformly-distributed load can be taken from Table.

Shaded area for apex zone (1) and loaded volume V



ref. EC5: Figure 6.9

Tension perpendicular to the grain

- Distribution factor for volume effect for different stress configuration and loaded volume V

$$k_{dis}k_{vol}f_{t,90,d} = k_{dis}\left(\frac{0{,}01m^3}{V}\right)^{0.2} f_{t,90,d}$$

Curved beam with constant cross-section	$k_{dis} = 1{,}4$	$V = \frac{\beta\pi}{180}\, b\,(h_{ap}^2 + 2r_{in}h_{ap}) \leq \frac{2}{3}V_b$
Double tapered beam	$k_{dis} = 1{,}4$	$V = bh_{ap}^2\,(1 - \frac{\tan\alpha}{4}) \leq \frac{2}{3}V_b$
Pitched cambered beam	$k_{dis} = 1{,}7$	$V = b\left(\sin\alpha\cos\alpha\,(r_{in} + h_{ap})^2 - r_{in}^2\frac{\pi\alpha}{180}\right) \leq \frac{2}{3}V_b$

Table 1 Factor k_{dis} and volume V for different types of beams.

ref. EC5: Eqs: 6.50 - 6.52

Dangerous cracks in a pitched cambered beam

Re: Aicher

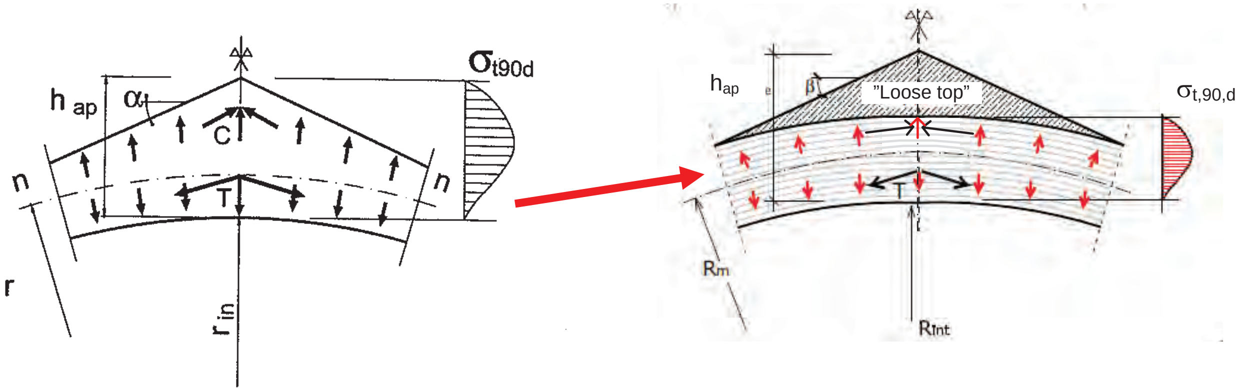
Failure of a pitched cambered beam

Re: Aicher

Tension perpendicular to the grain

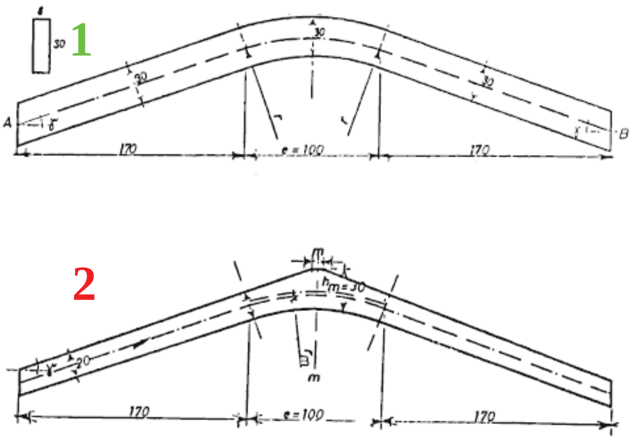
Methods to reduce the risk of cracking:

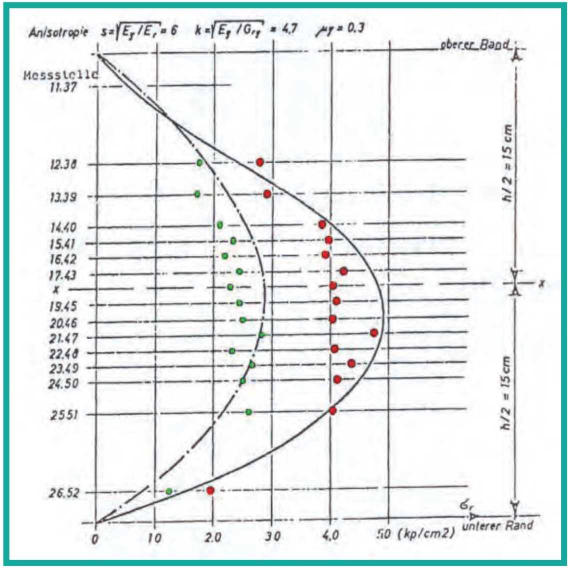
1) Leave a non-glued “hat” at the apex zone



Tension perpendicular to the grain

- Beams without and with apex



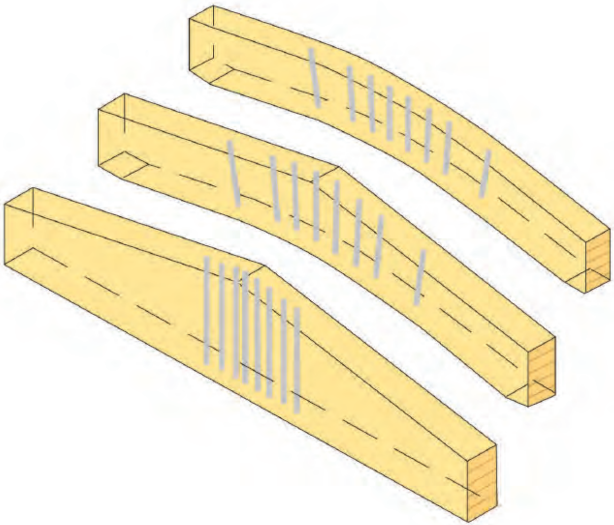


1: experimental; theory

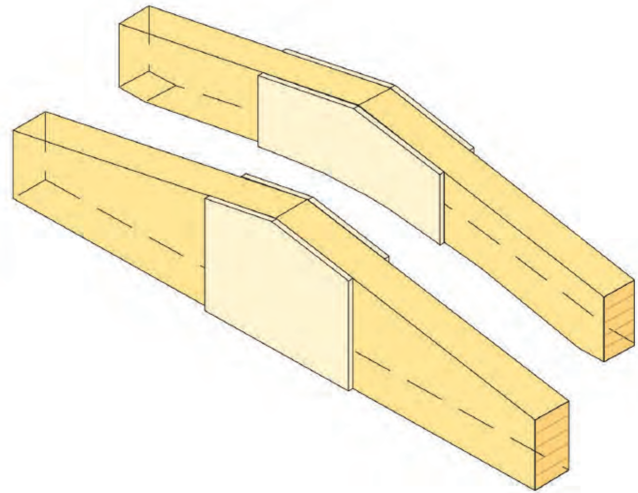
2: experimental; theory

Tension perpendicular to the grain

Methods to reduce the risk of cracking:



2) By means of glued-in rods or self-tapping screws



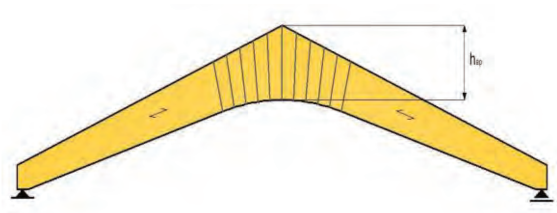
3) By means of plywood sheets glued on each side of the beam at the apex zone

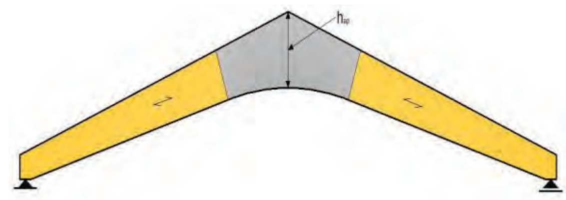
Reinforcement against tension perpendicular to the grain

Pitched camber beams

- The design tensile stress, $\sigma_{t,90,d}$

$$\sigma_{t,90,d} = k_p \frac{6M_{ap,d}}{b \cdot h_{ap}^2}$$

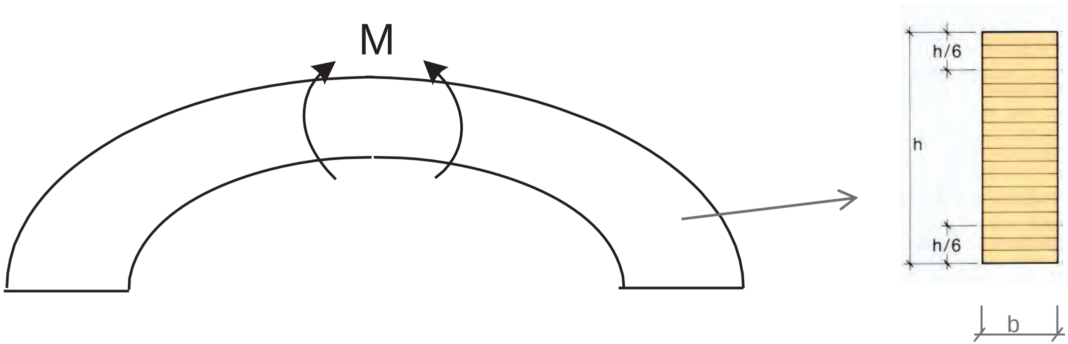




1. The load to be carried by discrete connectors, such as screws or glued in rods, is the total of all tensile stresses on an area equal to the connector spacing by the beam width.
2. The capacity of the connectors is determined by the withdrawal capacity and the tensile strength.

Rehearsal question

- A curved glulam beam with radius r (cross-section b x h), see figure, is loaded by bending moment and there is a risk that the beam can split due to stresses perpendicular to the grain. Derive the expression for these stresses by assuming that the bending stresses in the apex zone are linearly distributed.

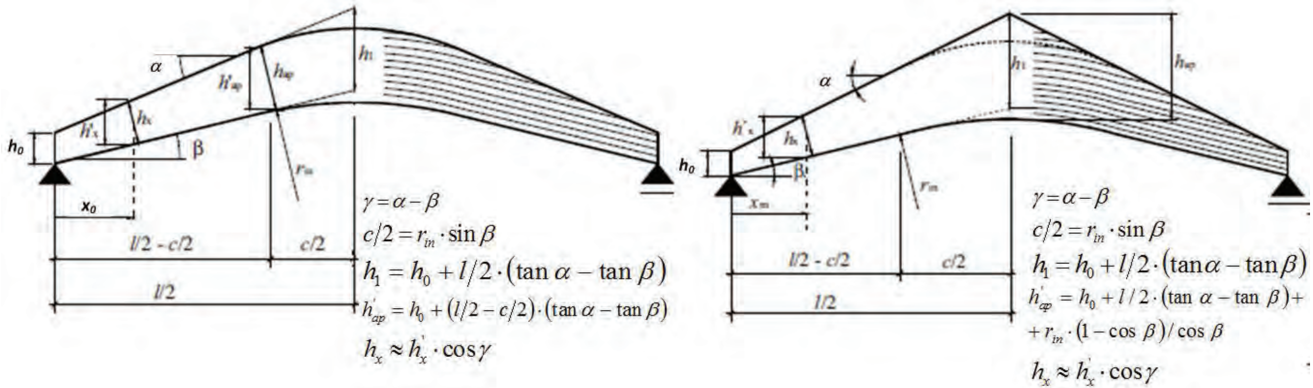


Preliminary design of simply-supported curved and pitched cambered beams subjected to uniformly distributed load

- Geometric parameters for preliminary design

Type of beam	Breadth b	Depth at the support h_0	Depth at the apex h_{ap}	Radius of curvature r
Curved	l/140 to l/120	≥ l/30	≈l/17	≥ 10m
Pitched cambered	l/100 to l/80	≥ l/30	≈l/13	≥ 10m

Preliminary design of simply-supported curved and pitched cambered beams subjected to uniformly distributed load

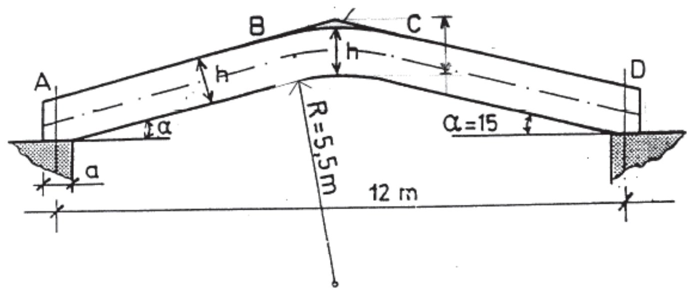


- The first step is to determine the depth of the beam at the position of maximum bending stress, i.e. at $x = x_0$ from the support.
- As for the case of tapered beams it is assumed therefore, that the location of x_0 is at $l/4$ from the support.

$$h'_{x0} = \frac{3 \cdot l}{4} \cdot \sqrt{\frac{q_d}{b \cdot (0{,}9 \cdot f_{m,d})}}$$

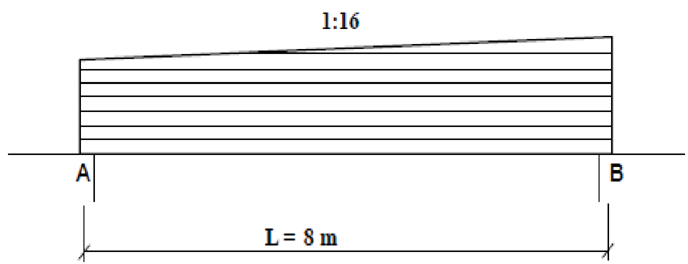
Example: D1. Pitched-cambered glulam beams

- The roof of a church close to Hofors (Sweden) will be renewed. The plan is to use pitched cambered glulam beams as roof trusses.
  - Check the maximum bending and shear stresses in ULS.
  - Design the length of its supports (a) ULS.
- The glulam beam has strength class GL32c and is built up of 36 lamellas of 33,3 mm thickness each. The width of the beam (b) is 190 mm. The span of the beams is 12m and their spacing is 4m.
- The load of the roof sheeting and the purlins may be assumed to 0,4 kN/m^2 (horizontally, characteristic value). The snow load may be assumed to 2,5 kN/m^2 (characteristic value). The only load case to check is: self-weight (roof sheeting + beam) + snow load. Service class 1 may be assumed. Assume that the apex part is active! The beam can be assumed to be anchorage against lateral torsional buckling.



Example: D2. Single-tapered glulam beams

- The roof of a school close to Gävle in Sweden will be renewed. Single tapered glulam beams are used in the roof. Design these beams (choose the width b, to the nearest 5 mm). The glulam has strength class GL32c, the depth of the beams at the support A is $h_0 = 0{,}2m$. The inclination of the roof is 1:16.
- The span of the beams is 8 m, and the spacing between the beams is 3m. The load of the roof sheeting and the purlins may be assumed to 0.4 kN/m^2 (characteristic value). The snow load is 2.5 kN/m^2 (characteristic value). The only load case to check is snow load + self-weight (roof sheeting + beam). Service class 1. Assume that the load is of medium term duration class.
- Assume that the maximum stress condition occurs at the point $x = L/(1 + \frac{h_1}{h_s})$.



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