DESIGN OF GLULAM BEAMS

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This paper describes the design of glulam beams according to EUROCODE 5. The essential peculiarities that must be considered are specified.
The most important are:
- size effect for bending and production requirements for finger joints;
- non linear stress distributions parallel to grain and stresses perpendicular to grain depending on the size of stressed volume and load configuration in case of curved, cambered and double tapered beams

GENERAL

Glulam structures are widespread nowadays substituting in many cases traditional constructions made of solid timber. This may be explained by the fact that in comparison with solid timber, glulam has some advantages, which are based on the production process of glulam beams (Figure 1):

> Boards are glued together by means of finger joints to get an endless lamellae, from which lamellaes of the desired length are cut off. These lamellaes are put one upon the other, glued together and thus yield the finished glulam beam.

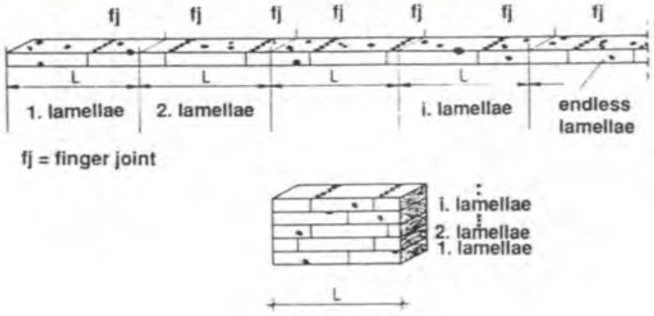

Figure 1: Production of glulam beams

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According to this production process knots are spread all over the beam so that glulam represents a more homogeneous material than solid timber (lamination effect). Furthermore, glulam has a lower moisture content. Due to these improvements, glulam shows in most cases higher characteristic MOE- and strength values.

Besides nearly unlimited beam sizes and -shapes, the lamination quality may be adapted to the occurring stresses (combined glulam). For this case, lamellaes of a higher quality Q_1 may be used in the outer zones and a lower quality Q_2 in the inner zone (Figure 2). The outer zones usually amount 1/6 of the beam depth.

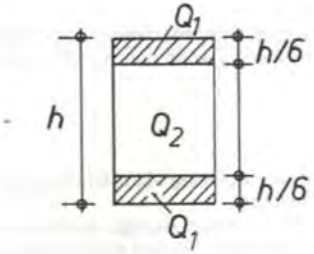

Figure 2: Combined glulam: beam set-up with different lamination qualities

During the design of glulam beams with different lamination qualities the question arises, which lamination quality is decisive for the different stress cases:

- In case of bending with stress peaks in the outer laminations the bearing capacity of glulam beams is determined by the strength of these laminations. The calculation of characteristic bending strength values for glulam can therefore be based on the charecteristic tensile strength values of the outer laminations;
- In case of shear and tension perpendicular to grain, the most stressed inner laminations are decisive;
- In case of mere tension or compression parallel to grain, all beam zones are almost equally stressed. Therefore the strength values for glulam are influenced by all beam zones.

DESIGN

In this chapter the different beam shapes mentioned in EUROCODE 5 will be presented and the most important peculiarities, that must be considered during design, will be explained.

The describing factors will be noted as k_{xxx} or k_{yyy}. The factors k_{xxx} are specified in EUROCODE 5 by the same nomenclature. The other factors k_{yyy} are directly specified by an equation (formulae) and do therefore not appear explicitly in EUROCODE 5. That is why they are written in ilalic letters.

Straight beams

Straight beams are mainly stressed in bending. That is why only this type of loading will be treated.

Many beam tests showed that bending strength of glulam beams depends on both strength of boards and strength of finger joints in the outer tension laminations. Therefore the production of high quality glulam affords the guaranty of high quality boards and high quality finger joints. There is no sense of grading knot-free boards while producing bad finger joints. In this case every test beam will fail in the area of finger joints.

How can high quality glulam actually be produced? To answer this question it is certainly helpful to look at the strength determining factors of the two parameters boards and finger joints:

- The strength of boards depends on knot-size, wood density and MOE, whereas
- the strength of finger joints is determined by wood density, MOE and production dependend factors.

This shows that

- high quality glulam is only possible with a grading of the laminations on the basis of wood density and/or MOE, and that furthermore
- besides a certain wood quality, certain minimum strength requirements for finger joints are indispensable. These minimum requirements concern the production of finger joints and must therefore be fulfilled by the glulam factories.

The bending stresses shall satisfy the following condition:

$$\sigma_{m,d} = M/W \leq k_{size} \cdot f_{m,d} \qquad \text{eq(1)}$$

with

k_{size} = factor taking into account the effect of beam size (length, depth)

$\sigma_{m,d}$ is the design value of the occurring bending stress and $f_{m,d}$ is the design value of resistance.

Size effect The factor k_{size} is new for most European countries and considers the fact that the strength of glulam beams decreases with increasing length and depth. This effect may be explained as follows: the increase of beam size leads to a higher number of built-in boards, i.e., to an increase of the amount of used wood and thus a higher number of weak parts (knots and finger joints). But: the more defects occur, the higher the probability will be that the beam fails at a lower load. The amount of the factor k_{size} still is subject of discussion.

Production requirement If a certain characteristic bending strength $f_{m,k,glulam}$ is used in design, the glulam factories must demonstrate that they are able to produce glulam of this strength class. For this the characteristic bending strength $f_{m,k,fj}$ of their produced finger joints shall satisfy the following condition:

$$f_{m,k,fj} \geq k_{fj} \cdot f_{m,k,glulam} \qquad \text{eq(2)}$$

with

$k_{fj} = 1,0 \ldots 1,25$

The final value for k_{fj} is not yet fixed.

Tapered beams

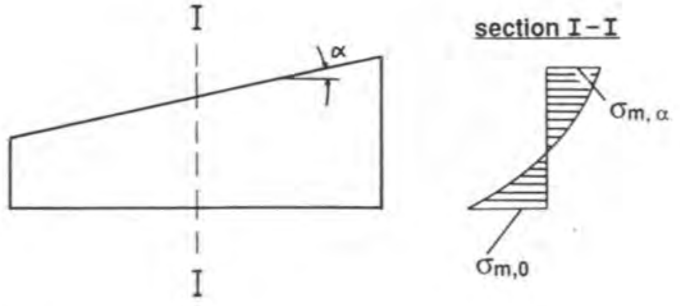

Figure 3: Tapered beam

In case of tapered beams (Figure 3), the occurring bending stresses shall satisfy the following conditions:

$$\sigma_{m,\alpha,d} = k_{\sigma,1} \cdot M/W \leq k_f \cdot f_{m,d} \qquad \text{eq(3)}$$

$$\sigma_{m,0,d} = k_{\sigma,2} \cdot M/W \leq f_{m,d} \quad (\cdot\, k_{size}\,?) \qquad \text{eq(4)}$$

with

$k_{\sigma,1}$ and $k_{\sigma,2}$ = factors taking into account the non-linear stress distribution; depending on α

k_f = factor taking into account the strength reduction at the inclined margin due to the interaction of stresses (shear stresses, stresses parallel and perpendicular to grain); depending on α and type of stress (tension, compression)

In analogy with straight beams, the influence of beam size must also be considered here. In view of the actual discussion it is mentioned in brackets with a question mark.

Double tapered beams

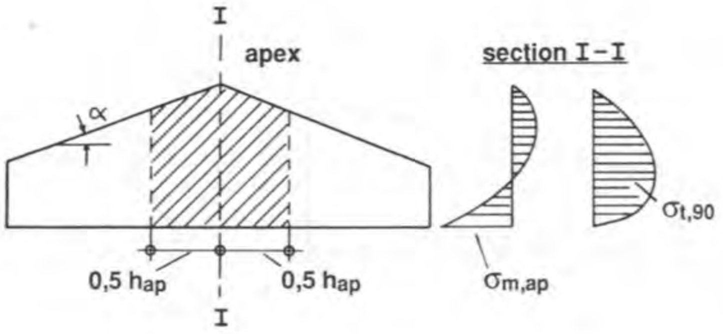

Figure 4: Double tapered beams

In case of double tapered beams (Figure 4), two peculiarities are worth to be mentioned, which are due to the apex:

- Bending stresses at the apex differ very much from the linear M/W - distribution;
- Stresses perpendicular to grain occur due to the deviation of forces at the apex zone.

The bending stress $\sigma_{m,ap}$ and the stress perpendicular to grain $\sigma_{t,90}$ shall satisfy the following conditions:

$$\sigma_{m,ap,d} = k_{\sigma,3} \cdot M/W \leq f_{m,d} \quad (\cdot\, k_{size}\,?) \qquad \text{eq(5)}$$

$$\sigma_{t,90,d} = k_{\sigma,4} \cdot M/W \leq k_{dis} \cdot k_{vol} \cdot f_{t,90,d} \qquad \text{eq(6)}$$

with

$k_{\sigma,3}$ = factor taking into account the non-linear stress distribution; depending on α
$k_{\sigma,4}$ = factor for calculating the stress perpendicular to grain on the basis of bending stress; depending on α
k_{dis} = factor taking into account the effect of stress distribution along the beam; depending on load configuration (uniformly distributed load, single loads)
k_{vol} = factor taking into account the effect of the size of stressed volume (volume effect); depending on volume of the apex zone (shaded area)

$\sigma_{m,d}$ is again the design value of bending stress, $\sigma_{t,90,d}$ is the design value of tensile stress perpendicular to grain, $f_{m,d}$ amd $f_{t,90,d}$ are the corresponding design values of resistance.

Curved beams with constant depth

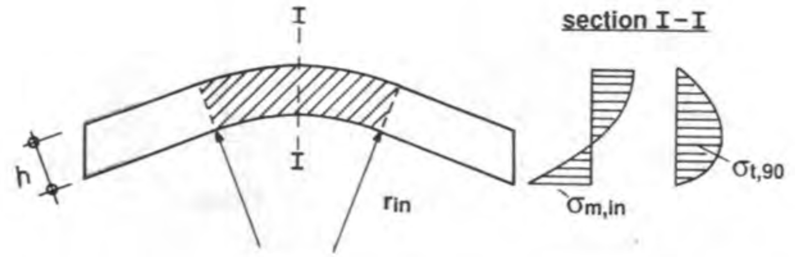

Figure 5: Curved beams with constant depth

In case of curved beams with constant depth (Figure 5), non-linear bending stress distributions and stresses perpendicular to grain occur in the curved part of the beam. These stresses shall satisfy the following conditions:

$$\sigma_{m,in,d} = k_{in} \cdot M/W \leq k_r \cdot f_{m,d} \quad (\cdot\, k_{size}\,?) \qquad \text{eq(7)}$$

$$\sigma_{t,90,d} = k_{\sigma,5} \cdot M/W \leq k_{dis} \cdot k_{vol} \cdot f_{t,90,d} \qquad \text{eq(8)}$$

with

k_{in} = factor taking into account the non-linear stress distribution; depending on r_{in} and beam depth h
k_r = factor taking into account the strength reduction due to bending of the laminations; depending on r_{in} and lamination thickness t
$k_{\sigma,5}$ = factor for calculating the stress perpendicular to grain on the basis of bending stress; depending on r_{in} and h
k_{dis} = factor taking into account the effect of stress distribution along the beam; depending on load configuration (uniformly distributed load, single loads)
k_{vol} = factor taking into account the effect of the size of stressed volume (volume effect); depending on volume of the curved part (shaded area)

Cambered beams

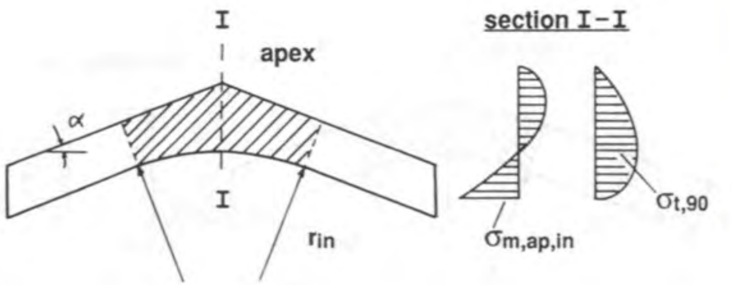

Figure 6: Cambered beams

Also in case of cambered beams (Figure 6), non-linear bending stresses and stresses perpendicular to grain occur in the curved part of the beam. In comparison with curved beams with constant depth, the bending stresses at the innermost fibres as well as the stresses perpendicular to grain are much higher. This may be explained by the additional effect of the apex.

The occurring stresses shall satisfy the following conditions:

$$\sigma_{m,ap,in,d} = k_m \cdot k_{in} \cdot M/W \leq k_r \cdot f_{m,d} \quad (\cdot\, k_{size}\,?) \qquad \text{eq(9)}$$

$$\sigma_{t,90,d} = k_t \cdot k_{\sigma,6} \cdot M/W \leq k_{dis} \cdot k_{vol} \cdot f_{t,90,d} \qquad \text{eq(10)}$$

with

$k_m \cdot k_{in}$ = factors taking into account the non-linear stress distribution; depending on α, r_{in} and beam depth h

k_r = factor taking into account the strength reduction due to bending of the laminations; depending on r_{in} and lamination thickness t

$k_t \cdot k_{\sigma,6}$ = factors for calculating the stress perpendicular to grain on the basis of bending stress; depending on α, r_{in} and beam depth h

k_{dis} = factor taking into account the effect of stress distribution along the beam; depending on load configuration (uniformly distributed load, single loads)

k_{vol} = factor taking into account the effect of the size of stressed volume (volume effect); depending on volume of the curved part (shaded area)

The factors k_{dis} and k_{vol} are more "moderate" than in case of curved beams with constant depth and thus reduce - at least partly - the effect of higher stress peaks at the apex.