Eurocodes – Background and Applications
EN 1995 – Tension Perpendicular to Grain

Dipl.-Ing. Philipp Dietsch

Technische Universität München
Chair of Timber Structures and Building Construction
Univ.-Prof. Dr.-Ing. Stefan Winter
Timber – Strength Classes

<table>
<thead>
<tr>
<th>Strength properties (in N/mm²)</th>
<th>Poplar and softwood species</th>
<th>C14</th>
<th>C16</th>
<th>C18</th>
<th>C20</th>
<th>C22</th>
<th>C24</th>
<th>C27</th>
<th>C30</th>
<th>C35</th>
<th>C40</th>
<th>C45</th>
<th>C50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>f_{m,k}</td>
<td></td>
<td>14</td>
<td>16</td>
<td>18</td>
<td>20</td>
<td>22</td>
<td>24</td>
<td>27</td>
<td>30</td>
<td>35</td>
<td>40</td>
<td>45</td>
<td>50</td>
</tr>
<tr>
<td>Tension parallel</td>
<td></td>
<td>8</td>
<td>10</td>
<td>11</td>
<td>12</td>
<td>13</td>
<td>14</td>
<td>16</td>
<td>18</td>
<td>21</td>
<td>24</td>
<td>27</td>
<td>30</td>
</tr>
<tr>
<td>f_{t,0,k}</td>
<td></td>
<td>0.4</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>Tension perpendicular</td>
<td></td>
<td>16</td>
<td>17</td>
<td>18</td>
<td>19</td>
<td>20</td>
<td>21</td>
<td>22</td>
<td>23</td>
<td>25</td>
<td>26</td>
<td>27</td>
<td>29</td>
</tr>
<tr>
<td>f_{c,0,k}</td>
<td></td>
<td>2.0</td>
<td>2.2</td>
<td>2.2</td>
<td>2.3</td>
<td>2.4</td>
<td>2.5</td>
<td>2.6</td>
<td>2.7</td>
<td>2.8</td>
<td>2.9</td>
<td>3.1</td>
<td>3.2</td>
</tr>
<tr>
<td>Compression parallel</td>
<td></td>
<td>1.7</td>
<td>1.8</td>
<td>2.0</td>
<td>2.2</td>
<td>2.4</td>
<td>2.5</td>
<td>2.8</td>
<td>3.0</td>
<td>3.4</td>
<td>3.8</td>
<td>3.8</td>
<td>3.8</td>
</tr>
</tbody>
</table>

Stiffness properties (in kN/mm²)

<table>
<thead>
<tr>
<th>Mean modulus of elasticity parallel</th>
<th>E_{0,mean}</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>9.5</th>
<th>10</th>
<th>11</th>
<th>11.5</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean modulus of elasticity 5% parallel</td>
<td>E_{0,05}</td>
<td>4.7</td>
<td>5.4</td>
<td>6.0</td>
<td>6.4</td>
<td>6.7</td>
<td>7.4</td>
<td>7.7</td>
<td>8.0</td>
<td>8.7</td>
<td>9.4</td>
<td>10.0</td>
<td>10.7</td>
</tr>
<tr>
<td>Mean modulus of elasticity parallel</td>
<td>E_{90,mean}</td>
<td>0.23</td>
<td>0.27</td>
<td>0.30</td>
<td>0.32</td>
<td>0.33</td>
<td>0.37</td>
<td>0.38</td>
<td>0.40</td>
<td>0.43</td>
<td>0.47</td>
<td>0.50</td>
<td>0.53</td>
</tr>
<tr>
<td>Mean shear modulus</td>
<td>G_{mean}</td>
<td>0.44</td>
<td>0.5</td>
<td>0.56</td>
<td>0.59</td>
<td>0.63</td>
<td>0.69</td>
<td>0.72</td>
<td>0.75</td>
<td>0.81</td>
<td>0.88</td>
<td>0.94</td>
<td>1.00</td>
</tr>
</tbody>
</table>

\[ f_{t,90,k} \approx \frac{1}{30} f_{t,0,k} \]

\[ f_{v,k} \approx \frac{1}{10} f_{m,k} \]

[EN 338]
Double tapered, curved and pitch cambered Beams

Distribution of Tension Perpendicular to Grain Stresses

\[ \sigma_{t,90} \]

\[ r_{in} \]
Double tapered, curved and pitch cambered Beams

Distribution of Shear Stresses
Double tapered, curved and pitch cambered Beams

Distribution of high Shear and Tension Perpendicular to Grain Stresses

Shear

Interaction

Tension perp. to grain

\[ \frac{\tau}{\tau_{cr}} \]

\[ \frac{\sigma_{c,90,d}}{f_{c,90,d}} \]

\[ \frac{\sigma_{t,90,d}}{f_{t,90,d}} \]

(Kirchanschöring, MPA BAU)

(Neuburg on the Danube, MPA BAU)

[SIA 265]
Double tapered, curved and pitch cambered Beams

Brittle materials – Size Effect

„A member under tension stress is only as strong as the weakest link“

The strength of a brittle material is a function of its volume under uniform stress.

\[
\frac{f_i}{f_j} = \left(\frac{V_j}{V_i}\right)^m
\]
Double tapered, curved and pitch cambered Beams in EC 5

6.4.3 Double tapered, curved and pitched cambered beams

(6) In the apex zone the greatest tensile stress perpendicular to the grain, \( \sigma_{t,90,d} \), should satisfy the following expression:

\[
\sigma_{t,90,d} \leq k_{\text{dis}} k_{\text{vol}} f_{t,90,d}
\]  \hspace{1cm} (6.50)

with

\[
k_{\text{vol}} = \begin{cases} 
1.0 & \text{for solid timber} \\
\left( \frac{V_0}{V} \right)^{0.2} & \text{for glued laminated timber and LVL with all veneers parallel to the beam axis} 
\end{cases}
\]  \hspace{1cm} (6.51)

\[
k_{\text{dis}} = \begin{cases} 
1.4 & \text{for double tapered and curved beams} \\
1.7 & \text{for pitched cambered beams} 
\end{cases}
\]  \hspace{1cm} (6.52)

where:

- \( k_{\text{dis}} \) is a factor which takes into account the effect of the stress distribution in the apex zone;
- \( k_{\text{vol}} \) is a volume factor;
- \( f_{t,90,d} \) is the design tensile strength perpendicular to the grain;
- \( V_0 \) is the reference volume of 0.01\( m^3 \);
- \( V \) is the stressed volume of the apex zone, in \( m^3 \), (see Figure 6.9) and should not be taken greater than 2\( V_b/3 \), where \( V_b \) is the total volume of the beam.

[EN 1995-1-1:2004; 6.4.3, p. 48ff]
Double tapered, curved and pitch cambered Beams in EC 5

6.4.3 Double tapered, curved and pitched cambered beams

(8) The greatest tensile stress perpendicular to the grain due to the bending moment should be calculated as follows:

\[ \sigma_{t,90,d} = k_p \frac{6 \, M_{ap,d}}{b \, h_{ap}^2} \]  \hspace{1cm} (6.54)

where:

- \( p_d \) is the uniformly distributed load acting on the top of the beam over the apex area;
- \( b \) is the width of the beam;
- \( M_{ap,d} \) is the design moment at apex resulting in tensile stresses parallel to the inner curved edge;

with:

\[ k_p = k_5 + k_6 \left( \frac{h_{ap}}{r} \right) + k_7 \left( \frac{h_{ap}}{r} \right)^2 \]  \hspace{1cm} (6.56)

\[ k_5 = 0.2 \, \tan \alpha_{ap} \]  \hspace{1cm} (6.57)

\[ k_6 = 0.25 - 1.5 \, \tan \alpha_{ap} + 2.6 \, \tan^2 \alpha_{ap} \]  \hspace{1cm} (6.58)

\[ k_7 = 2.1 \, \tan \alpha_{ap} - 4 \, \tan^2 \alpha_{ap} \]  \hspace{1cm} (6.59)

[EN 1995-1-1:2004; 6.4.3, p. 48ff]
Double tapered, curved and pitch cambered Beams in EC 5

6.4.3 Double tapered, curved and pitched cambered beams
Double tapered, curved and pitch cambered Beams

Strengthening Measures

Self-tapping screws with continuous threads or threaded rods

Plywood / Laminated Veneer Lumber
Double tapered, curved and pitch cambered Beams

Strengthening Measures – Screws or threaded Rods

Fritz Leonhardt, Vorlesungen über Massivbau
Double tapered, curved and pitch cambered Beams

Strengthening Measures – Plywood / Laminated Veneer Lumber glued to Timber Member

Strengthening measures (screws / plates) should be designed to carry full tension perpendicular to grain stresses and should cover the entire area under tension perp. to grain stresses (curved area)
Moisture Conditions

Ice-rink arena
(Ingolstadt, MPA BAU)

- 20 mm = 25.1%
- 55 mm = 18.9%
- 95 mm = 19.1%

Gymnasium with skylights
(Benediktbeuern, MPA BAU)

- 10 mm = 7.5%
- 70 mm = 10.5%
- 120 mm = 11.7%
Moisture Conditions – Cracks caused by Shrinking

In Glulam Beams – Crack Distribution enabled
Moisture Conditions – Cracks caused by Shrinking

In Glulam Beams – Crack Distribution enabled

(Benediktbeuern, MPA BAU)
Moisture Conditions – Cracks caused by Shrinking

In Combination with Fasteners – Crack Distribution impeded

→ reduction of applicable strength values or cross sections by e.g. $k_{cr}$

(Feldkirchen, Prof. Winter)
Notched Beams

Picture: Prof. H. Blaß, TH Karlsruhe

Chair of Timber Structures and Building Construction
Notched Beams in Concrete

→ Constant tensile strength in all directions

Fritz Leonhardt, Vorlesungen über Massivbau
Notched Beams in Timber

- Tensile strength changes with varying angle between load and grain

\[ f_{t,90,k} \approx 0.5 \]

\[ 10 \leq f_{t,0,k} \leq 21 \text{ [MN/m}^2]\]

\[ f_{t,90,k} \approx \frac{1}{30} f_{t,0,k} \]
Notched Beams in Timber

\[ \sigma_{t,90} \]

\[ f_{t,90} \]

\[ \sigma_{c,90} \]

\[ \tau \]

\[ \sigma_{t,90} \]
Notched Beams in Timber – Constructive Measures

\[ \sigma_{t,90} \]

\[ f_{t,90} \]

Chair of Timber Structures
and Building Construction
Notched Beams in Timber

6.5 Notched members

6.5.2 Beams with a notch at the support

It should be verified that

\[
\frac{1.5 \nu}{b h_c} \leq k_v f_{v,d}
\]  

(6.60)

where \( k_v \) is a reduction factor defined as follows:

For beams notched at the opposite side to the support (see Figure 6.11b)

\[
k_v = 1.0
\]  

(6.61)

For beams notched on the same side as the support (see Figure 6.11a)

\[
k_v = \min \left\{ \begin{array}{c}
1 \\
k_p \left( 1 + \frac{11 \nu}{\sqrt{h}} \right)
\end{array} \right. \\
\frac{\sqrt{h}}{\sqrt{h} \left( \sqrt{\alpha(1-\alpha)} + 0.8 \frac{\sqrt{h}}{\alpha} \frac{1}{\alpha - \alpha^2} \right)}
\]

[EN 1995-1-1:2004; 6.5.2, p. 52ff]
Notched Beams in Timber

6.5 Notched members

6.5.2 Beams with a notch at the support

where:

\( i \) is the notch inclination (see Figure 6.11a);
\( h \) is the beam depth in mm;
\( x \) is the distance from line of action of the support reaction to the corner of the notch;

\[
\alpha = \frac{h_{ef}}{h}
\]

\[
k_n = \begin{cases} 
4.5 & \text{for LVL} \\
5 & \text{for solid timber} \\
6.5 & \text{for glued laminated timber}
\end{cases}
\]

\[\text{[EN 1995-1-1:2004; 6.5.2, p. 52ff]}\]
Notched Beams in Timber – Strengthening Measures

\[ \sigma_{t,90} \]
\[ f_{t,90} \]
\[ \sigma_{c,90} \]

Example of reinforcement in concrete structures

Strengthening measure / reinforcement by self-tapping screws with continuous thread
Notched Beams in Timber – Strengthening Measures

Strengthening measure / reinforcement by glueing plywood / LVL to the sides of beam, glueline pressed by screws.
Cross Connections

Pictures: Prof. H. Blaß, TH Karlsruhe
Cross Connections

→ Pure Compression ($F_c$) Perpendicular to Grain

$F_c = F$

→ Tension and Compression Perpendicular to Grain

$F_c = 1 - \eta^* F; \quad F_t = \eta^* F$

→ Pure Tension ($F_t$) Perpendicular to Grain

$F_t = F$
Cross Connections – Influences on load-carrying Capacity

Load-carrying capacity depends on stressed volume and stress distribution / stress peaks and is therefore influenced by:

- Ratio between distance $b_e$ and beam depth $h$
- Fastener spacing in grain direction / length $a_r$
- Penetration thickness $t$
Cross Connections

8.1.4 Connection forces at an angle to the grain

(3) For softwoods, the characteristic splitting capacity for the arrangement shown in Figure 8.1 should be taken as:

\[ F_{90,Rk} = 14bw \left( \frac{h_c}{h} \right) \left( \frac{h_c}{h} \right) \]

where:

\[ w = \begin{cases} 
\max \left( \frac{w_{pl}}{100} \right)^{0.35} & \text{for punched metal plate fasteners} \\
1 & \text{for all other fasteners} 
\end{cases} \]

and:

- \( F_{90,Rk} \) is the characteristic splitting capacity, in N;
- \( w \) is a modification factor;
- \( h_c \) is the loaded edge distance to the centre of the most distant fastener or to the edge of the punched metal plate fastener, in mm;
- \( h \) is the timber member height, in mm;
- \( b \) is the member thickness, in mm;
- \( w_{pl} \) is the width of the punched metal plate fastener parallel to the grain, in mm.

[EN 1995-1-1:2004; 8.1.4, p. 59ff]
Cross Connections

8.1.4 Connection forces at an angle to the grain

See also STEP C2 „Tension perpendicular to the grain in joints“

[EN 1995-1-1:2004; 8.1.4, p. 59ff]
Cross Connections – Strengthening Measures

Self-tapping screws with continuous thread

Plywood / LVL, glued, pressed by screws

Critical area

Chair of Timber Structures and Building Construction
Openings

Pictures: Prof. H. Blaß, TH Karlsruhe
Openings
Openings
Openings - Constructive Measures

Place in center line of member, at distance from supports

Size – as small as possible (minimize reduction in cross section)

Round openings or chamfered corners (avoid stress peaks)
Openings - Strengthening Measures
Tension Perpendicular to Grain - Conclusion

- Tension perpendicular to grain strength very low
- Avoid tension perp. to grain stresses whenever possible
- Members with tension perp. to grain stresses are:
  - Double tapered, curved and pitch cambered beams
  - Notched members, members with holes or cross connections
- Tension perp. to grain stresses also develop with changing moisture content
- Possible reinforcements are: Self-tapping screws with continuous thread, drilled or glued-in rods, plywood / LVL...
- Proposal: reinforcements should be designed to carry full tension perp. to grain stresses (cracked tension perp. to grain zone)
Literature

- Timber Engineering – STEP 1, STEP 2; Centrum Hout; The Netherlands
- Erläuterungen zu DIN 1052:2004; DGFH; Germany (in German)
- CIB – W18 Proceedings; TH Karlsruhe; Germany
- Design of Structural Timber to EC5; Palgrave; GB
- Structural Timber Design to Eurocode 5; Blackwell Publishing; GB