Connections and connectors for timber structures – Part 2
Functional requirements:

“transfer axial forces, moments and shear forces from one structural member to an other, with acceptable deflection and rotations, and adequate safety at a reasonable cost”

Borg Madsen
List of functional requirements

• Strength
• Stiffness
• Failure mode (ductility!)
• ....

But also:

• Corrosive environment, fire resistance, easy of manufacturing, *simplicity of design*, etc
Ring and shear plate connectors (SV: Mellanläggsbrickskor)

Common sizes

<table>
<thead>
<tr>
<th>Diameter</th>
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<tbody>
<tr>
<td>D65</td>
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<tr>
<td>D80</td>
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<tr>
<td>D95</td>
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<tr>
<td>D126</td>
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<tr>
<td>D128</td>
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<tr>
<td>D160</td>
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<tr>
<td>D190</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Diameter</th>
<th>Bolt</th>
</tr>
</thead>
<tbody>
<tr>
<td>E65</td>
<td>M12</td>
</tr>
<tr>
<td>E80</td>
<td>M12</td>
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<tr>
<td>E95</td>
<td>M12</td>
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<tr>
<td>E128</td>
<td>M12</td>
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<tr>
<td>E160</td>
<td>M16</td>
</tr>
<tr>
<td>E190</td>
<td>M16</td>
</tr>
</tbody>
</table>

Approx design capacity // grain (GL28)

$R_{cd} = 13 \text{ kN} - 66 \text{ kN}$
• **Ring connectors** are only applied in timber-to-timber joints, normally in combination with a bolt

• **Shear plate connectors** may be applied in both timber-to-timber and steel-to-timber joints

**Empirical formulas for the design of such connectors are given by EC5**
Production

a) Bolt hole and connector groove are drilled into the wood (proper cutters are necessary!!). The hole is normally oversized, therefore the load is not transmitted by the bolt!

b) Connectors are placed into the groove

c) Timber members are put together and bolts are inserted into the holes and tightened
Load-carrying behaviour

Failure mode in tension // grain:
-Embedding (if end distance is rel. small) or
-shear (if end distance is rel. large)

Failure mode in tension 30° to 150° to the grain:
-Splitting

Failure mode in compression:
-Normally Embedding-Splitting failure
Advantages and disadvantages

+ high strength per unity area

- Very complicate manufacture and assembling
- Difficult to check if the ring or the shear plate has really been installed!
Toothed-plate connectors

Approx design capacity // grain (GL28)

\[ R_{cd} = 5 \text{ kN} - 28 \text{ kN} \]
• **Toothed-plate connectors** are applied into the timber by pressing together the members \( (\rho < 500 \text{ kg/m}^3) \)

• **Double-sided toothed plate** are used in timber-to-timber connections while **single-sided toothed** are used in steel-to-timber joints

**Empirical formulas for the design of such connectors are given by EC5**
Berg- och dalbana (Balder) – Liseberg, Göteborg
Production

a) Bolt hole drilled into the wood. The pressing of the teeth into the timber require considerable forces! Therefore, either hydraulic press or high strength bolt (with large washers) must be used.

b) After pressing, a mild steel bolt is inserted into the hole and tightened.
Load-carrying behaviour

• The failure of toothed plate connections normally is caused by an embedment failure of the wood under both the teeth and the bolt, eventually combined with bending of the teeth.
Load-carrying behaviour

• The failure of toothed plate connections normally is caused by an embedment failure of the wood under both the teeth and the bolt, eventually combined with bending of the teeth.

• Toothed-plate connectors show generally a plastic failure mode, which lead to a formation of a plastic hinge in the bolt. Therefore, not only the toothed-plate but also the bolt contribute to the load carrying capacity of the joint!
Advantages and disadvantages

+ Rather high strength per unity area

- Rather complicate manufacture and assembling
- Difficult to check if the toothed-plate has really been installed!
Punched metal plate fasteners or nail plates

- Thickness: 1-2 mm
- Developed in USA in the 1950’s
- Nails are stamped perpendicular to the plate
- The thickness of the timber members varies usually between 35mm and 70 mm

- Length of the nails: 8-15mm
- Size of the plate: 30 cm²-1 m²
The typical application is to connect truss elements in roof structures.

Transfers load in shear at the surface of two members.
Assembly of nail plates

In order to minimize the gap between members, the timber is planned at all four faces.

Then the plate is put in the right position and pressed to the timber by means of a hydraulic press.
Roof trusses: span lengths up to 25-30 m
Screw connections - Loading perpendicular to the screw axis

Traditional screws: coach screw

Threaded part: root diameter $d_1 = 0.7d$

- Diameter: 8mm-20 mm
- Predrilling required: “0.7d” and “d” for the two parts
- Time-consuming assembly!
Self tapping screws: continuous and limited threads

- Self-tapping screws with continuous threads
- Length up to 600 mm
- Diameter up to 12 mm

After Blaß
Screws loaded // to the screw axis: failure modes

- Withdrawal failure
- Push-in failure
- Tensile failure of the screw
Withdrawal failure

Shear failure 1: “extraction of a wooden cylinder”

Strength #1 ~ 2/3 (or 67 %) strength #2!
Compression failure

By buckling of the screws

By pushing-in of the screws
Tensile failure of the screw

After Blaß
Withdrawal capacity

\[ F_{ax,k,Rk} = \frac{n_{ef} f_{ax,k} d \ell_{ef} k_d}{1,2 \cos^2 \alpha + \sin^2 \alpha} \]

- \( F_{ax,k,Rk} \) is the characteristic withdrawal strength of the connection,
- \( n_{ef} \) is the effective number of screws,
- \( d \) is the outer diameter measured on the threaded part,
- \( \ell_{ef} \) is the point side penetration length of the threaded part minus one screw diameter.
- \( f_{v,ax,\alpha,k} \) is the characteristic withdrawal strength at an angle \( \alpha \) to the grain,

\[ f_{ax,k} = 0,52 \, d^{-0,5} \, \ell_{ef}^{-0,1} \, \rho_k^{0,8} \]

\[ k_d = \min\left\{ \frac{d}{8}, 1 \right\} \]

\[ n_{ef} = (n)^{0,9} \]
Withdrawal capacity: approximate estimation

\[ F_{ax,90,Rk} = \left( \pi \cdot d \cdot l_{ef} \right) \cdot f_{v,ax,0,k} \]

\( f_{v,ax,\alpha,k} \) is the characteristic withdrawal strength at an angle \( \alpha \) to the grain,

For \( \alpha=0 \) \( f_{v,ax,0,k} \) is 4-5 MPa, (say 4.5 MPa)
Inclined screws

After Blaß
Gamla formeln!

Använd:

\[ F_{\text{utdragskapacitet}} = \frac{P_{\text{utdragskapacitet}}}{1.2 \cos^2 \alpha + \sin^2 \alpha} \]

stålbrott

utdragskapacitet

\[ R = \frac{16.6 \cdot 0.26}{2} = 14.8 \text{ kN} \]

\[ \frac{R}{E} = \frac{16.6}{E} + \frac{0.26}{E} \cdot \frac{1}{2} \]

\[ \{ h \times (x-0.8)(10-0.8)(x+0.8) \} \]

\[ f_{y} = 410 \text{ kN/m}^2 \]

\[ f_{g} = 900 \text{ kN/m}^2 \]

\[ l = 800 \text{ mm} \]

\[ \text{Shank diameter} d = 8 \text{ mm} \]
Inclined screws

Truss action

After Blaß
\[ R = F_{x,t} \cos 45^\circ + F_{x,c} \cos 45^\circ = \]
\[ = 16.16 \left( \frac{\sqrt{2}}{2} + \frac{\sqrt{2}}{2} \right) = 23.5 \text{ km} \]
Glued-in rods
Some applications

Frame corners
Some applications

Moment resistant beam joint

Column-to-foundation joint
Manufacture

• Drill a hole, approximately 1 mm larger than the bolt diameter
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• Inject the glue (which should be quite liquid) and check that the volume of the glue is the same as that of the drilled hole
Manufacture

- Drill a hole, approximately 1 mm larger than the bolt diameter
- Inject the glue (which should be quite liquid) and check that the volume of the glue is the same as that of the drilled hole
- Insert the threaded rod, common diameters $d = 12\text{mm-24mm}$
Inserting glued-in roads // grain in a horizontal plane

- The glue has to be injected under some pressure to avoid voids that would reduce the strength of the joint.
Adhesives

- Phenol-resorcinol (some authors claim that this adhesive should be used carefully, due to the fact that it tends to shrink during hardening, thus reducing the strength of the joint)

- Two-component polyurethane

- Two-components epoxy
Strength of axially loaded rods

• The strength is the same **both in tension and in compression**

• **Volkersen theory** (1953) applies, i.e. the strength is influenced by: (1) difference in stiffness between steel and wood, (2) the glue length of the rod, (3) the stiffness of the bond between rod and wood

• **The density** of the timber has negligible influence on the axial strength of the rod

• **The angle between road and grain direction** on the axial strength of the rod has no consistent effect on the axial strength of the rod
Volkersen theory

Lap joint (assumed: $EA_1=EA_2$)

$$\tau(x) = \tau_m \frac{\rho}{2} \frac{\cosh \left( \frac{\rho x}{\ell} \right)}{\sinh \left( \frac{\rho}{2} \right)}$$

After S. Aicher
Parameters affecting the bond stress distribution

<table>
<thead>
<tr>
<th>Components with equal stiffness $EA$</th>
<th>Components with different stiffness</th>
<th>Components with equal stiffness</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Components with equal stiffness $EA$" /></td>
<td><img src="image2" alt="Components with different stiffness" /></td>
<td><img src="image3" alt="Components with equal stiffness" /></td>
</tr>
<tr>
<td>Bond with high stiffness</td>
<td>Bond with low stiffness</td>
<td>Short glued length</td>
</tr>
</tbody>
</table>

- $F$: force
- $l_g$: glued length of the bolt
- $d$: bolt diameter
Influence of the rod slenderness and type of glue

After S. Aicher


\[ \lambda = \frac{L}{d} \]

\[ d = \text{const.} = 16 \text{ mm} \]

bond shear stress $\tau$  

slip $\delta$  

[mm]
Load-carrying capacity

• Depend on both (1) the withdrawal capacity and (2) the tensile strength of the steel and (3) the tensile strength of the timber net area
Load-carrying capacity

- Depend on both (1) the withdrawal capacity and (2) the tensile strength of the steel and (3) the tensile strength of the timber net area
- It depends also on the fracture energy (G) of the joint.
Load-carrying capacity

• Depend on both (1) the withdrawal capacity and (2) the tensile strength of the steel and (3) the tensile strength of the timber net area.
• It depends also on the fracture energy ($G$) of the joint.
• However, in order to make the design relatively simple, instead of $G$, another parameter, i.e. the “brittleness factor” $\omega$ is used. If $\omega$ is small – i.e. a “short joint” - then failure of the joint will solely depend on the strength of the materials. If $\omega$ is large – i.e. a long joint – the shear stresses are not uniformly distributed, thus the joint has a lower strength.
Design according to Swedish type approval

\[ R_{ld} = \min \left\{ \frac{0.6 \cdot f_{bu,k} \cdot A_s}{\gamma_{m,steel}} \cdot \frac{\pi \cdot d \cdot l_i \cdot f_{ax,k} \cdot \tanh \omega}{\omega} \cdot k_{mod} \cdot k_1}{\gamma_{m,timber}} \right\} \]

Tensile failure of the rod

Failure of the bond line

- \( f_{bu,k} \)  = Tensile strength of the steel (N/mm²)
- \( A_s \)  = Root Area of the rod (mm²)
- \( d \)  = Diameter of the (mm)
- \( l_i \)  = Glued length (mm)
- \( f_{ax,k} \)  = withdrawal parameter: 5,5 N/mm²
- \( \omega \)  = brittleness parameter
- \( \gamma_m \)  = partial coefficient for material
- \( k_{mod} \)  = modification factor (duration of the load and moisture content)
- \( k_1 \)  = 1,0 för service class 0 och 1; 0,8 for service class 2
Design according to Swedish type approval

\[ R_{td} = f_{t,0,d} A_{eff} \]

Tensile failure of the wood
Design according to Swedish type approval

**Glued-in rods transversally loaded**

- The same rules as for dowel-type connections applies

- For rods loaded ⊥ grain, use the same embedding strength as for dowel/bolts with the same diameter

- For rods loaded // grain use 10% of the embedding strength of a a dowel/bolt with the same diameter

- For rods loaded at angles $0^\circ < \alpha < 90^\circ$, interpolate!
Multiple shear steel-to-timber joints
Olympic hall in Hamar, 1994 L=71m, The lower chord is designed for a tensile load $F_d=7000\text{kN}$
Tynset bridge, Norway main span 71m
The static system is a 2-hinges arch. The shape is such that prevalently compression forces occur in the lower and up chord (no significant bending moments). However, tension occurs in some diagonals.
Universeum - Göteborg
Manufacturing

If possible, the major part of the manufacture should take place at the factory. The drilling of holes and inserting of dowels requires high precision.

Flisa Bridge, truss beam with L=90m
Manufacturing

1. Steel plates - with identical hole patterns as the slotted-in plates – are placed at each node. The holes in the plates are threaded.

2. Tubes, with threaded ends are screwed on such plates. The inner diameter of the tubes is the same as the diameter of the drill.

3. In this way, the hole in the slotted-in plates cannot be missed!

Shows the drilling method:
Use of pattern plates and guide tube
Toward a safe design of dowelled connections

• When several dowels in a row - along the direction of the load - are present, sometimes brittle failure may occur, even though the distance prescribed by the building code are adopted.
When several connectors in a row are present, a method to reduce the risk of brittle failure is to arrange the connection in such a manner so to achieve large deformations before failure occurs!
This can be achieved, for example by…

….Choosing a spacing between slotted-in plates such to induce yielding of the dowel/bolt before collapse of the connection.
What mode of failure do we wish to occur?

This is a rather good one!
One of these 2 failures should occur!

\[ \sum q_h = 0 \]
The question is:

what is the optimum spacing to be chosen in order to ensure a plastic behaviour of the connection?
“Wooden parts between 2 steel plates”

\[
\begin{aligned}
R_{am} - q_h \cdot x_p &= 0 \\
\frac{q_h \cdot x_p^2}{2} - 2 \cdot M_{pl} &= 0
\end{aligned}
\]

\[x_p = 2 \cdot \sqrt{\frac{M_{pl}}{q_h}} \rightarrow t_2 \geq 2 \cdot x_p = 4 \cdot \sqrt{\frac{M_{pl}}{q_h}}\]

\[R_{am} = q_h \cdot x_p = 2 \cdot \sqrt{M_{pl} \cdot q_h}\]
According to EC5, the resistance of the joint should be increased by 15%:

\[ R_{am} = 1,15 \cdot 2,0 \cdot \sqrt{M_{pl} \cdot q_h} \]

Since:
\[ R_{am} = q_h \cdot x_p \]

this means that \( x_p \) and thus even \( t_2 \) should also be increased by 15%!

\[ t_2 \geq 2 \cdot x_p = 4 \cdot 1,15 \cdot \sqrt{\frac{M_{pl}}{q_h}} \]
“External wooden parts” – 1 plastic hinge

\[ \begin{aligned}
R_{as} + q_h \cdot x - q_h \cdot (t_1 - x) &= 0 \rightarrow R_{as} = 2q_h \cdot x - q_h \cdot t \\
q_h \cdot (t_1 - x) \cdot \left[ \frac{(t_1 - x)}{2} + x \right] - q_h \cdot \frac{x^2}{2} + M_{pl} &= 0
\end{aligned} \]

\[ x = \sqrt{\frac{t_1^2}{2} + \frac{M_{pl}}{q_h}} \]

In order to achieve a plastic hinge:

\[ t_1 \geq x \Rightarrow t_1 \geq 2 \cdot \sqrt{\frac{M_{pl}}{q_h}} \]

**Exactly as in EC5!**
"External wooden parts" – 2 plastic hinges

\[ R_{as} - q_h \cdot x_p = 0 \]
\[ q_h \cdot \frac{x_p^2}{2} - 2 \cdot M_{pl} = 0 \quad \rightarrow \quad x_p = 2 \cdot \sqrt{\frac{M_{pl}}{q_h}} \quad \rightarrow \quad t_1 \geq x_p = 2 \cdot \sqrt{\frac{M_{pl}}{q_h}} \]

\[ R_{am} = q_h \cdot x_p = 2 \cdot \sqrt{M_{pl} \cdot q_h} \]
Again, according to EC5, the resistance of the joint should be increased by 15%:

\[ R_{am} = 1,15 \cdot 2,0 \cdot \sqrt{M_{pl} \cdot q_h} \]

Since : \[ R_{am} = q_h \cdot x_p \]

this means that \( x_p \) and thus even \( t_2 \) should also be increased by 15%!

\[ t_1 \geq x_p = 2 \cdot 1,15 \cdot \sqrt{\frac{M_{pl}}{q_h}} \]
\[ 2 M \rho e - \frac{f_h}{g} x^2 = 0 \]

\[ X = 2 \sqrt{\frac{M \rho e}{f_h}} \]

\[ X = 1.15 \times \left( 2 \sqrt{\frac{M \rho e}{f_h}} \right) \]

TAKING INTO ACCOUNT \( \dot{m}, \dot{m}_1 \) and \( \dot{m}_2 \) (EC)
External - case 2

\[ R_{\text{left}}(x) \]

\[ \frac{g_h}{g_h} \left( \frac{x}{2} + \frac{x}{2} \right) \]

\[ - \frac{g_h x}{2} + M_p c = 0 \]

\[ \Rightarrow x = \sqrt{\frac{M_p c}{g_h}} \]

\[ D F = 0 = R_{\text{left}}(x) + g_h x - g_h \left( \frac{x}{2} \right) \to \]

\[ \Rightarrow R_{\text{left}} = g_h \left( 2x - t_1 \right) = \]

\[ = g_h t \left( \sqrt{2 + \frac{2M_p c}{g_h t^2}} - t_1 \right) \]

**External - case 2**

\[ \Sigma F = 0 \Rightarrow R_{\text{left}}(x) - g_h x - 0 \]

\[ 2M_p x - g_h x^2 = 0 \]

\[ \Rightarrow x = \frac{2M_p}{g_h} \]

EC5 \[ \Rightarrow x = \frac{1}{15} \times 2\sqrt{M_p/g_h} \]

**Strength of the connection**

\[ R_k = 2 \left( R_{\text{left}} + R_{\text{right}} \right) \]

But first check

1. \[ t_f > \frac{X_0}{X_0} \]
2. \[ t_f > 2x \]
**EXAMPLE**

**MATERIAL** GLULAM ⇒ \( f_g = 410\ \text{kN/m}^3 \)

**STEEL** S355 ⇒ \( f_u = 400\ \text{MPa} \), \( d = 12\ \text{mm} \)

**LOADING**:

\[
\begin{align*}
\phi_{10} & = 0.982 (1 - 0.01 \times 12) \\
\phi_{10} & = 0.82 \\
\end{align*}
\]

\[
\begin{align*}
\phi_{10} \cdot f_{10} & = 0.82 \\
f_{10} & = 410 \times 0.82 \\
f_{10} & = 355 \ \text{N/m} \\
\end{align*}
\]

**INTERNAL PART**

\[
\begin{align*}
t & = 2 \left( \frac{M_{pe}}{f_u} \right)^{0.6} \\
 & = 2 \left( \frac{94013}{355} \right)^{0.6} \\
 & = 2 \times (1.15 \times 2) \\
\end{align*}
\]

**EXTERNAL PART**

\[
\begin{align*}
t & \geq \frac{f_{10} \cdot M_{pe}}{2} \\
t & \geq \frac{410 \times 355}{2} \\
t & \geq 7600 \ \text{mm} \\
\end{align*}
\]

\[
\begin{align*}
2 \sqrt{\frac{M_{pe}}{f_{10}}} & = 2 \sqrt{94013/355} \\
& = 33 \ \text{mm} \\
\end{align*}
\]

\( t = 20 \Rightarrow x = 22 \ \text{m} \)

\( t = 21 \Rightarrow x = 22 \ \text{m} \)

\( t = 25 \Rightarrow x = 25 \)
When you have many fasteners, remember to check the load carrying capacity of the wooden part that is left!!

Ballerup Bicycle velodrome Denmark
Two trusses, L=72 m collapsed on January 2003, no one was injured

Now snow on the roof, when collapse occurred!!
Why?

- The cross section was not reduced for bolts and slotted-in plates
- Moment due to the stiff connection not taken into account
- The effective number of fasteners (in a row) was disregarded
- …and perhaps some others
Block shear failure

For steel-to-timber connections subjected to a force component parallel to grain near the end of the timber member, block shear failure should be checked.
In joints with several fasteners, there can a risk for block shear failure!

Two steel plates

One steel plate
Check for block shear failure

For failure modes (e,f,j,l,k,m)

$$A_{\text{net},t} = \sum_i l_{t,i} \cdot t_1$$

For all the others failure modes

$$A_{\text{net},v} = \begin{cases} 
\sum_i l_{v,i} \cdot t_1 \\
\frac{1}{2} \left( \sum_i l_{t,i} + 2t_{ef} \right)
\end{cases}$$

$$F_{bs,Rk} = \max \left\{ 1,5 A_{\text{net},t} f_{t0k}, 0,7 A_{\text{net},v} f_{vk} \right\}$$

where:

- $t_i$:
- $l_{t,i}$: thickness
- $l_{v,i}$: length
- $f_{t0k}$: nominal stress
- $f_{vk}$: ultimate stress
- $A_{\text{net},t}$: net area
- $A_{\text{net},v}$: net area
- $F_{bs,Rk}$: block shear force