CHALMERS
UNIVERSITY OF TECHNOLOGY

TIMBER ENGINEERING - VSM196

LECTURE 11 –

JOINTS – AXIALLY LOADED NAILS/SCREWS

SLS DESIGN

SPRING 2020

Topic

- Joints – axially loaded nails/screws
- Mechanical and glued connections, SLS design

- [DoTS: Chapter 4]

Content

- Axially loaded fasteners
- Moment resisting connections
- Design for SLS

- Design examples H3

Intended Learning Outcomes of this lecture

- You know different fasteners with for axial load-transfer
- You can calculate the axial load-carrying capacity of different fasteners
- You can determine the actions on fasteners in moment resisting connections
- You can calculate the deformation and slip of connections

Overview

Axially loaded fasteners

- We talk about the tensile (anchorage) capacity of fasteners.

- Tensile capacity of fasters can be provided by using:
  - Annular rings

Axially loaded fasteners

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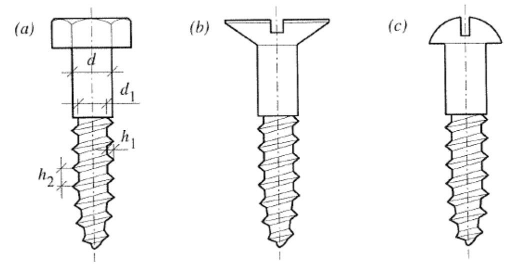
- Tensile capacity of fasters can be provided by using:
  - Annular rings
  - Threading (screws)
    a) coach screw
    b) countersunk head screw
    c) round head screw



Typical wood screws: (a) coach screw (b) countersunk head (c) round head.

Axially loaded fasteners

- We talk about the tensile (anchorage) capacity of fasteners.

- Tensile capacity of fasters can be provided by using:
  - Annular rings
  - Threading (screws)
  - Nuts and washers on the head side
  - Nuts and washers on the point side

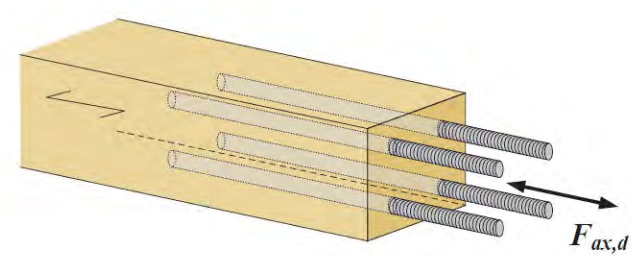
Throughout **bolts**
with washers and nuts

Diameter 6 - 30 mm
Length up to 500 mm

Axially loaded fasteners

- We talk about the tensile (anchorage) capacity of fasteners.

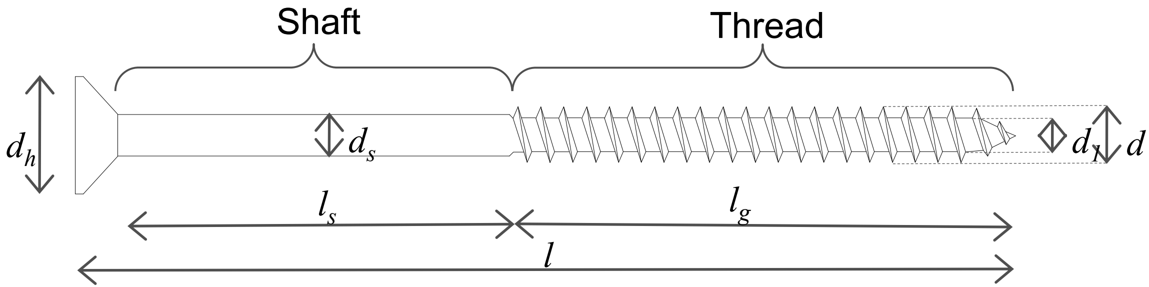
- Tensile capacity of fasters can be provided by using:
  - Annular rings
  - Threading (screws)
  - Nuts and washers on the head side
  - Nuts and washers on the point side
  - Bonded-in rods



Source: Henkel AG

Screws

Screws - general

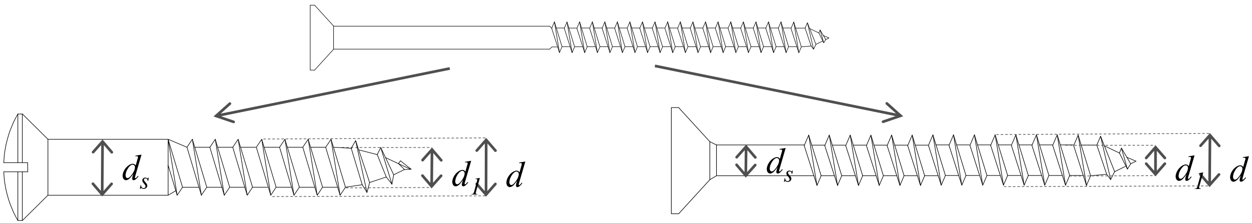


EN 14592

2.4 mm ≤ d ≤ 24 mm

- d Diameter; Outer thread diameter
- d_1 Inner thread diameter
- d_s Diameter of the shaft part
- d_h Head diameter of screws
- l Length
- l_g Length of the threaded part
- l_s Length of the shaft

Screws – production method



Lag screws

- Thread cut into the wire (DIN 7998):

  $d_s = d$

  $d_1/d = 0.7 - 0.75$

- Mostly low carbonated steel

Self-tapping screw

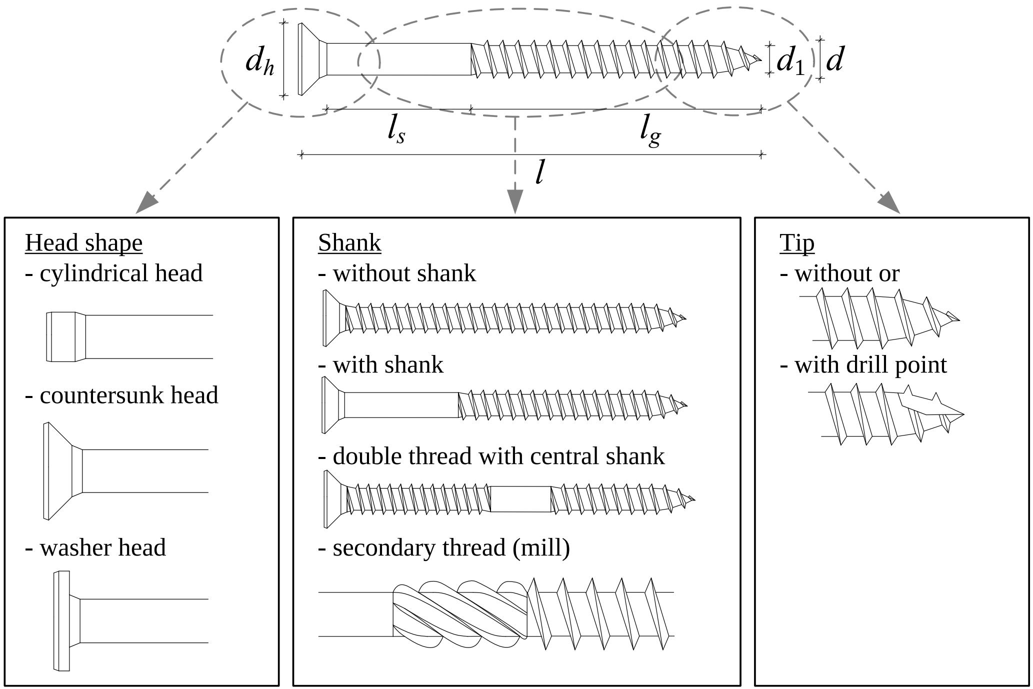
- Thread forged or rolled from the wire:

  $d_s \approx d_1$

  $0.6 \leq d_1/d \leq 0.6$

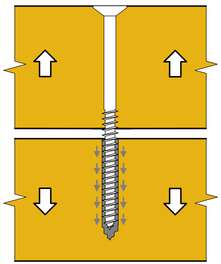
- Large diversity of screw heads, thread, screw tip etc.
- Mostly high carbonated steel

Self-tapping screws

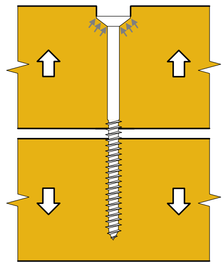


Failure modes situations

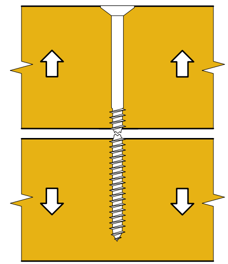
- Axial failure modes
  - Withdrawal



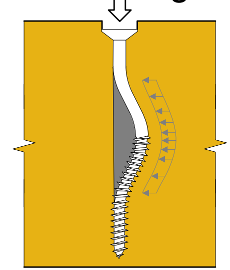
  - Head pull-trough



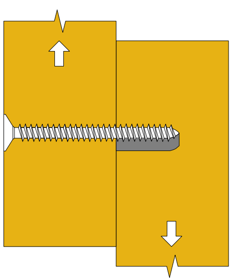
  - Tension



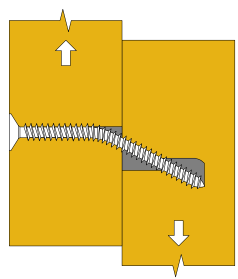
  - Buckling



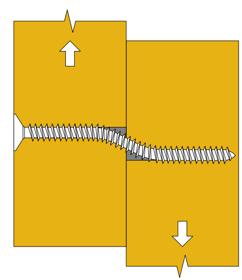
- Lateral failure modes (Johansen theory, European Yield Model)
  - Embedment failure



  - Combined failure



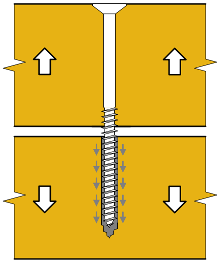
  - Ductile failure



Withdrawal

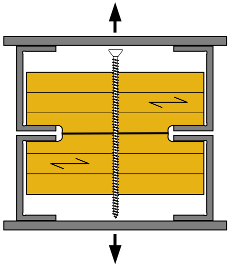
- Withdrawal capacity

$$F_{ax,k,Rk} = f_{ax,k} d l_{ef}$$



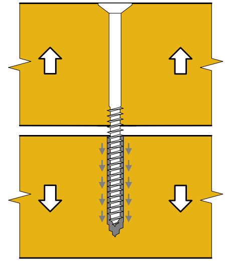
- Withdrawal parameter (EN 1382)

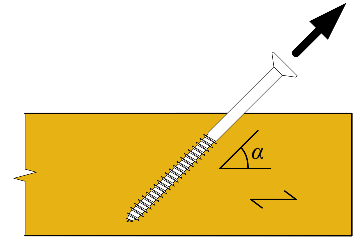
$$f_{ax} = \frac{F_{\max}}{d l_{ef}}$$



Bejtka, I and Blaß, H. J. (2002), CIB-W18/39-7-2.

Withdrawal





- Withdrawal resistance
  - EN 1995-1-1(2008)
    - General values for $\alpha \geq 30°$
    - Effective penetration depth $l_{ef} \geq 6d$
    - 6 mm $\leq d \leq 12$ mm
    - $0.6 \leq d_1/d \leq 0.75$

$$F_{ax,k,Rk} = \frac{n_{ef} f_{ax,k} d l_{ef} k_d}{1.2 \cos^2 \alpha + \sin^2 \alpha}$$

$$f_{ax,k} = 0.52 d^{-0.5} l_{ef}^{-0.1} \rho_k^{0.8} \qquad k_d = \min \begin{cases} d/8 \\ 1 \end{cases} \qquad n_{ef} = n^{0.9}$$

- Product specific values

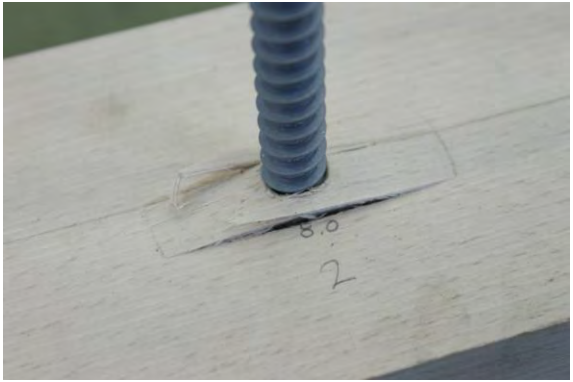
$$F_{ax,\alpha,Rk} = \frac{n_{ef} f_{ax,k} d l_{ef}}{1.2 \cos^2 \alpha + \sin^2 \alpha} \left(\frac{\rho_k}{\rho_a} \right)^{0.8}$$

Bejtka, I and Blaß, H. J. (2002), CIB-W18/39-7-2.

Withdrawal failure

- Case 1
- Screw parallel to the grain

- Case 2
- Screw perpendicular to the grain

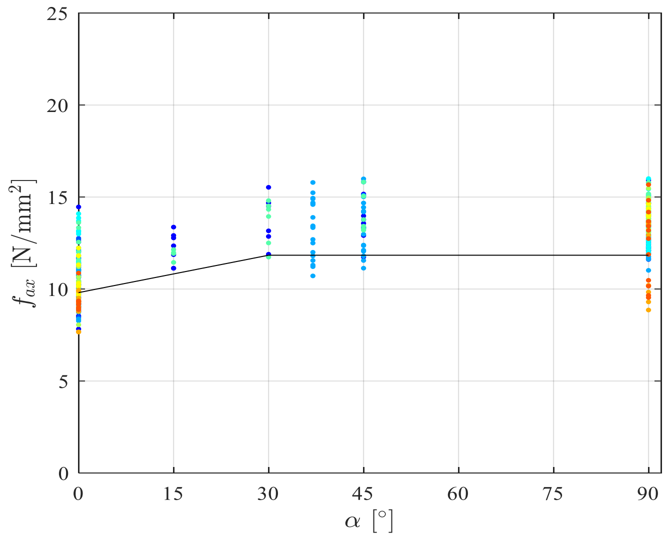


Withdrawal failure

- Case 1
- Screw parallel to the grain

- Case 2
- Screw perpendicular to the grain

Test results

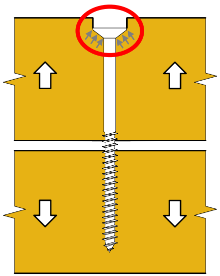


Head pull-through resistance

- EN 1995-1-1 (2008)

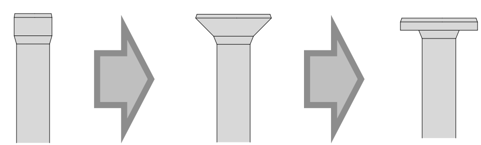
$$F_{ax,\alpha,Rk} = n_{ef} f_{head,k} d_h^2 \left(\frac{\rho_k}{\rho_a}\right)^{0.8}$$

  - d_h diameter of the screw head
  - ρ_k, ρ_a char. und reference density for $f_{head,k}$ according to EN 14592



- the characteristic pull-through parameter $f_{head,k}$ strongly depends on the shape of the screw head!

For higher head pull-trough resistance use whashers or plate heads!

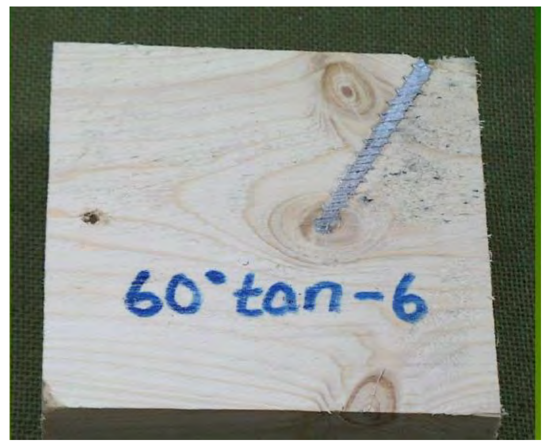


Tensile failure of the screw

- EN 1995-1-1 (2008)
  - characteristic tensile resistance
    (head tear-off or tensile capacity of shank)

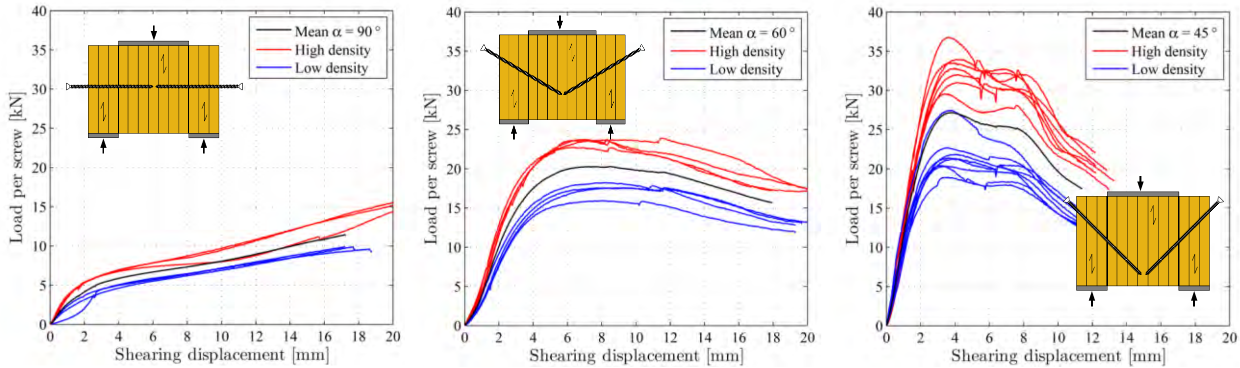
$$F_{t,Rk} = n_{ef} f_{tens,k}$$

- $f_{tens,k}$ characteristic tensile capacity



Inclined screws

- Influence of the screw inclination

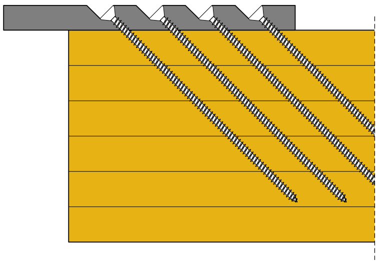


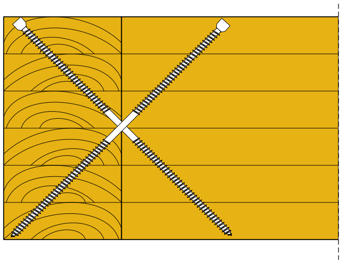
Incline screw to achieve

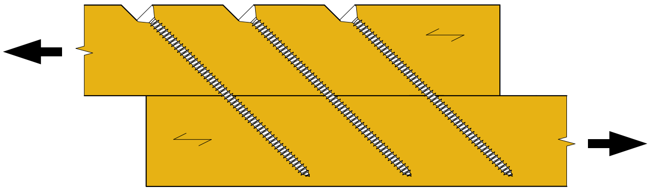
- High strength
- High stiffness

Inclined screws

- Self-tapping screws with inclination
- Shear connection







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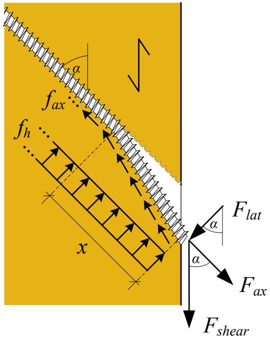


- Interaction of lateral and withdrawal capacity
  - Bejtka and Blass:

$$R = R_{ax}(\mu \sin \alpha + \cos \alpha) + R_{lat}(\sin \alpha - \mu \cos \alpha)$$

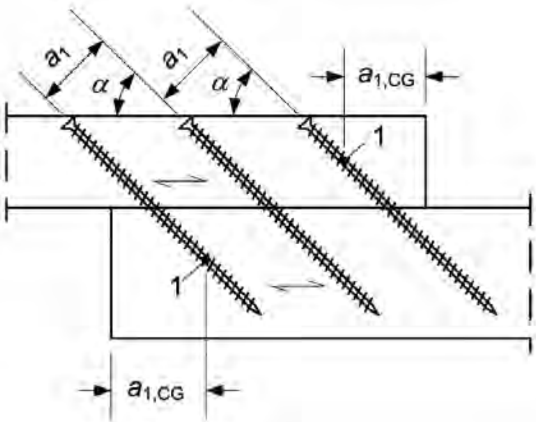
- Joint stiffness
  - Tomasi et al.

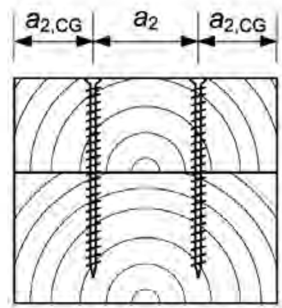
$$K_{ser} = K_{ax} \cos \alpha \,(\cos \alpha + \mu \sin \alpha) + K_{lat} \sin \alpha \,(\sin \alpha - \mu \cos \alpha)$$

Spacing and distances of screws

Table 8.6 – Minimum spacings and end and edge distances for axially loaded screws

Minimum screw spacing in a plane parallel to the grain a_1	Minimum screw spacing perpendicular to a plane parallel to the grain a_2	Minimum end distance of the centre of gravity of the threaded part of the screw in the member $a_{1,CG}$	Minimum edge distance of the centre of gravity of the threaded part of the screw in the member $a_{2,CG}$
$7d$	$5d$	$10d$	$4d$





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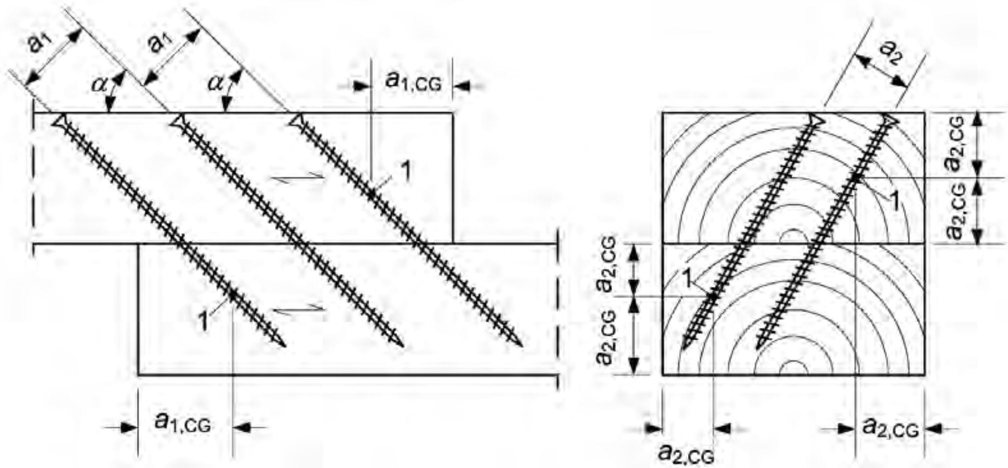


Inclined screws

- Applications

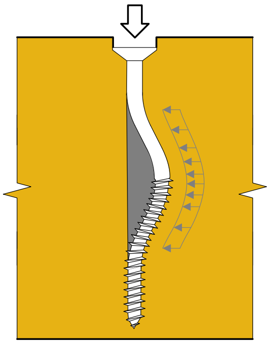
Source: Wiehag

Buckling

- Pushing-in of the screws

- Buckling of the screws

Screws under compression loading



- Buckling with elastic bedding

$$F_{ax,c,Rk} = k_c f_{y,k} \pi \frac{d_1^2}{4}$$

  - buckling factor

$$k_c = \frac{1}{k + \sqrt{k^2 - \lambda_{rel}^2}} \leq 1$$

$$k = 0.5\left[1 + 0.49(\lambda_{rel} - 0.2) + \lambda_{rel}^2\right]$$

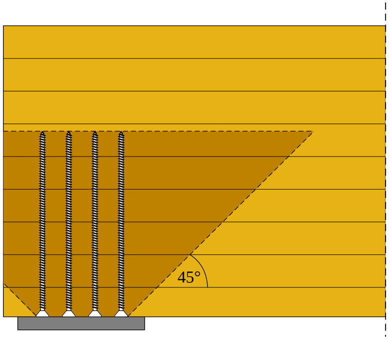
  - relative slenderness

$$\lambda_{rel} = \sqrt{\frac{N_{pl,k}}{N_{ki,k}}}$$

  - plastic and critical load

$$N_{pl,k} = f_{y,k} \pi \frac{d_1^2}{4} \qquad N_{ki,k} = (1{\sim}2)\sqrt{c_h E_k \pi \frac{d_1^4}{64}}$$

  - bedding coefficient $c_h = \dfrac{(0.22 + 0.014d)\rho}{1.17 \sin \alpha^2 + \cos \alpha^2}$



Bejtka, I and Blaß, H. J. (2006), Self-tapping screws as reinforcements in beam supports, CIB-W18/39-7-2.

Nails

Axial capacity of nails

- The tensile capacity depends on:
  - The roughness along the nail, f_{ax}
  - The anchorage capacity of nail head, f_{head}
- For smooth nails

$$f_{ax,k} = 20 \cdot 10^{-6} \rho_k^2$$

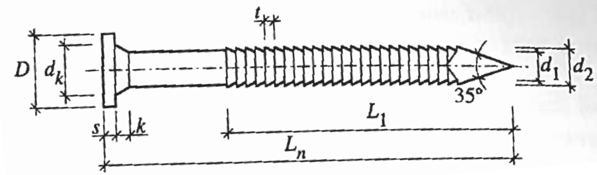
$$f_{head,k} = 70 \cdot 10^{-6} \rho_k^2$$

ρ_k [kg/m^3]
f_{ax}, f_{head} [N/mm^2]

- Minimum penetration of $8d$
- Providing that the penetration length is at least $12d$, if less it is multiplied by $\left(t_{pen}/4d - 2\right)$

EC5, Eq. 8.25, 8.26

Axial capacity of nails



- The tensile capacity depends on:
  - The roughness along the nail, f_{ax}
  - The anchorage capacity of nail head, f_{head}
- For annular ring shanked nails

$$f_{ax,k} = 65 \cdot 10^{-6} \rho_k^2$$

ρ_k [kg/m³]
f_{ax} [N/mm²]
$L_1 = 2/3\, L_n$

  - Minimum penetration of $6d$
  - Providing that the penetration length is at least $8d$, if less it is multiplied by $\left(t_{pen}/2d - 3\right)$

EC5, Eq. 8.25, 8.26

Axial capacity of nails

- Other than smooth nails

$$F_{ax} = \min \begin{cases} f_{ax,k} \cdot d \cdot t_{pen} \\ f_{head,k} \cdot d_{head}^2 \end{cases}$$

EC5, Eq. 8.23

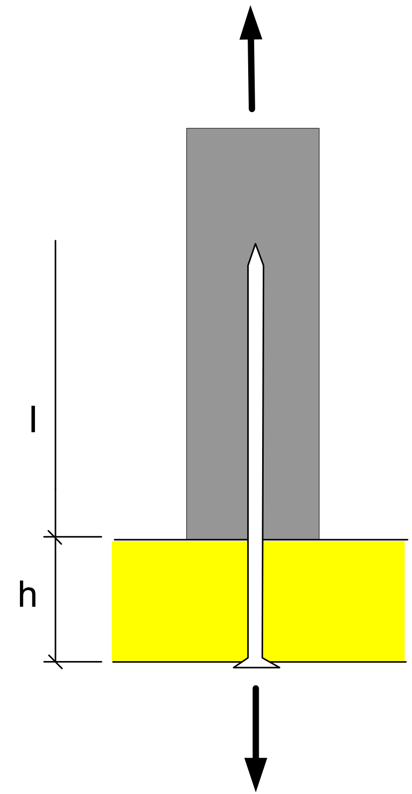
- Smooth nails

$$F_{ax} = \min \begin{cases} f_{ax,k} \cdot d \cdot t_{pen} \\ f_{ax,k} \cdot d \cdot t_{headside} + f_{head,k} \cdot d_{head}^2 \end{cases}$$

EC5, Eq. 8.24

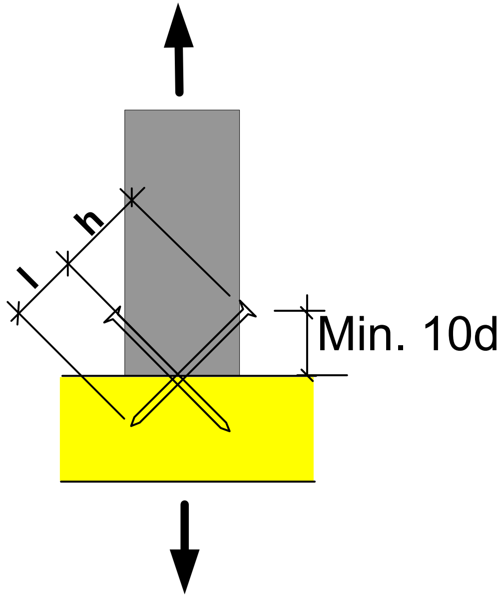
Axially loaded nails

- Penetration length l should be as a minimum $12d$ for smooth nails and $8d$ for other nails



Axially loaded nails

- Slant nailing



Do not trust smooth nails in tension! Timber might dry, shrink, crack

Bolts

Bolts – axial capacity

- The withdrawal capacity depends on anchorage capacity of washers and nuts and the strength of bolt

$$F_{ax,washer,k} = 3 \cdot f_{c,90,k} \cdot A_{washer}$$

- Strength class

Bolt class	4.6	5.6	6.8	8.8	10.9
f_{yb} (N/mm^2)	240	300	480	640	900
f_{ub} (N/mm^2)	400	500	600	800	1000

Bolts – axial capacity

(1) The axial load-bearing capacity and withdrawal capacity of a bolt should be taken as the lower value of:

– the bolt tensile capacity;

– the load-bearing capacity of either the washer or (for steel-to-timber connections) the steel plate.

(2) The bearing capacity of a washer should be calculated assuming a characteristic compressive strength on the contact area of $3{,}0f_{c,90,k}$.

(3) The bearing capacity per bolt of a steel plate should not exceed that of a circular washer with a diameter which is the minimum of:

– $12t$, where t is the plate thickness;

– $4d$, where d is the bolt diameter.

General

Combined loading

- If the fastener is subjected to combined effect of shear and tension then:

- Smooth nails

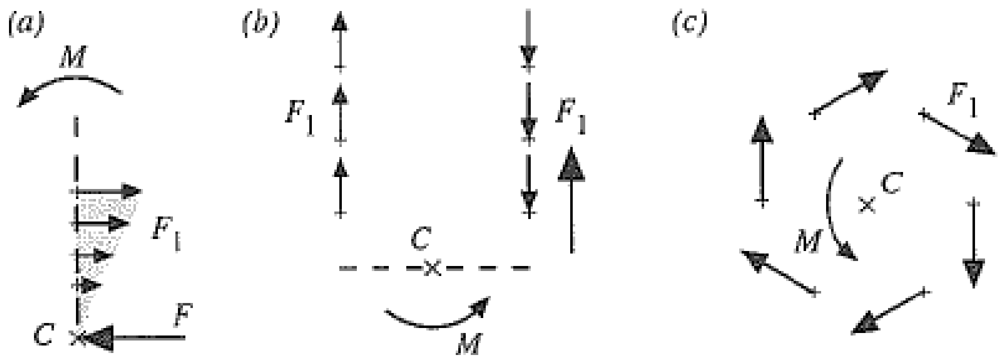
$$\frac{F_{ax,Ed}}{F_{ax,Rd}} + \frac{F_{v,Ed}}{F_{v,Rd}} \leq 1 \qquad \text{Eq. 8.27}$$

- Other than smooth nails and screws

$$\left(\frac{F_{ax,Ed}}{F_{ax,Rd}}\right)^2 + \left(\frac{F_{v,Ed}}{F_{v,Rd}}\right)^2 \leq 1 \qquad \text{Eq. 8.28}$$

Moment resisting connections

Moment resisting connections



Force diagrams on the fasteners in moment-resisting joints.

Moment resisting connections - Procedure

1. Translate the force to center of gravity of joint
2. The vertical component of the force will be equally taken by each fastener, $F_{yi} = F/n$
3. The force due to moment in each fastener will be

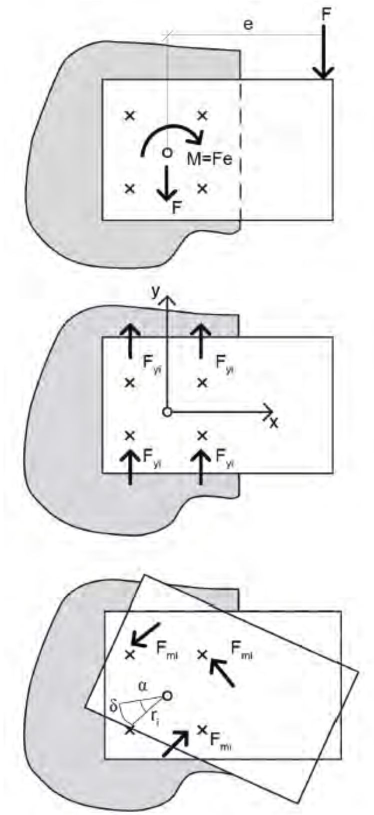
$$I_P = \sum r_i^2 = \sum (x_i^2 + y_i^2) \qquad F_{mi} = K \cdot \alpha \cdot r_i = \frac{M \cdot r_i}{I_p}$$

$$F_{mxi} = -\frac{M \cdot y_i}{I_p} \qquad F_{myi} = -\frac{M \cdot x_i}{I_p}$$

4. Vector summation gives

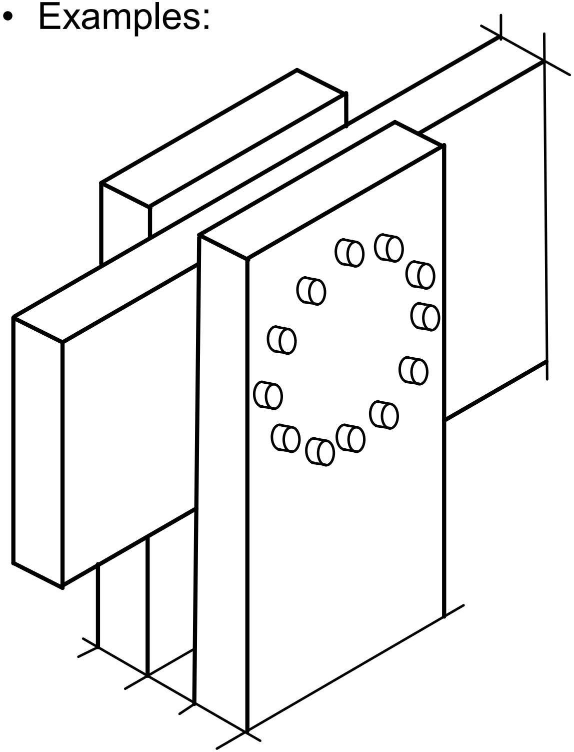
$$F_i = \sqrt{(F_{xi} + F_{mxi})^2 + \left(F_{yi} + F_{myi}\right)^2}$$

- Which should be compared with strength of a single fastener



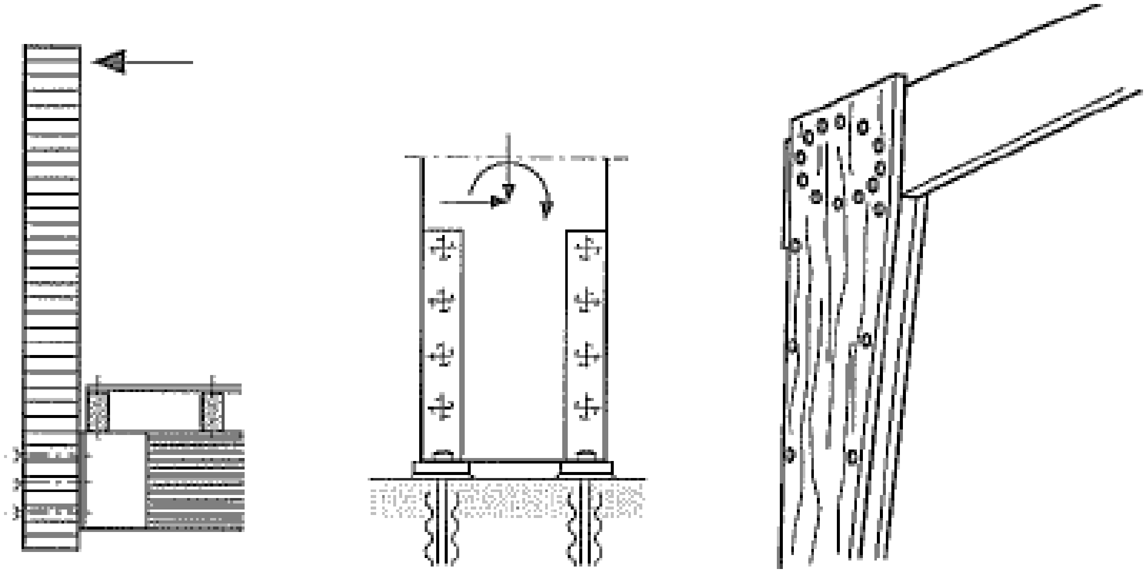
Moment resisting connections

- Examples:



Moment resisting connections

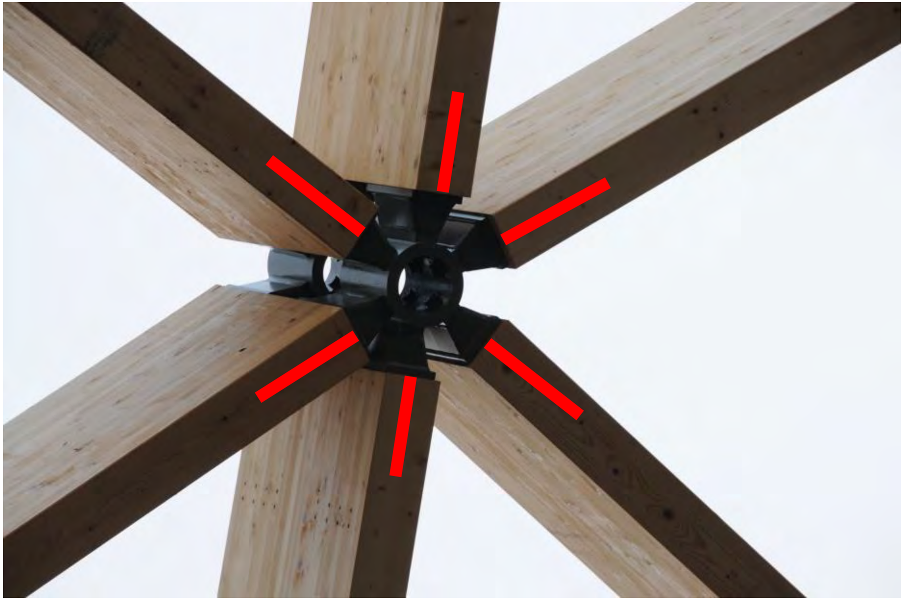
- Examples:



(a) (b) (c)

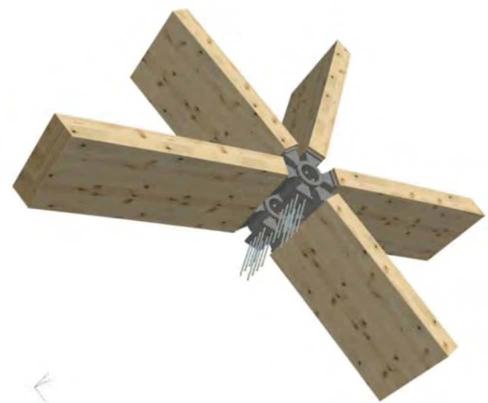
Bonded-in rods/ Glued-in rods

Bonded-in rods



Bonded-in rods

Pictures: Häring AG



Bonded-in rods

Materials

- Timber
  - Glued laminated timber Glulam
  - Laminated veneer lumber LVL
  - Cross laminated timber CLT
- Adhesive
  - Tested according to prEN 17334
  - PUR
  - Epoxy
- Rods
  - Metric Threaded Rods
  - Ribbed Rods

Bonded-in rods

Failure modes:

- tension failure of the rod
- compression (buckling) failure of the rod
- failure of the adhesive in the bondline and its bond to rod and timber
- shear failure of the timber adjacent to the bondline
- splitting of the timber departing from the Bonded-in-rods
- timber failure of the member in the surrounding of the glued-in-rod

Bonded-in rods

- Axial resistance of the bonded-in rod

$$F_{ax,Rd} = min\begin{cases} F_{ax,rod,Rd} \\ F_{ax,b,Rd} \end{cases}$$

- with

$$F_{ax,rod,Rd} = \min\begin{cases} \dfrac{1}{\gamma_{M,0}} A_s f_{y,k} \\ \dfrac{1}{\gamma_{M,2}} 0.9 A_s f_{u,k} \end{cases}$$

Resistance of the rod

$$F_{ax,b,Rd} = \frac{k_{mod}}{\gamma_M} \pi d l_{b,eff} f_{k,1,k}$$

Resistance of the bondline

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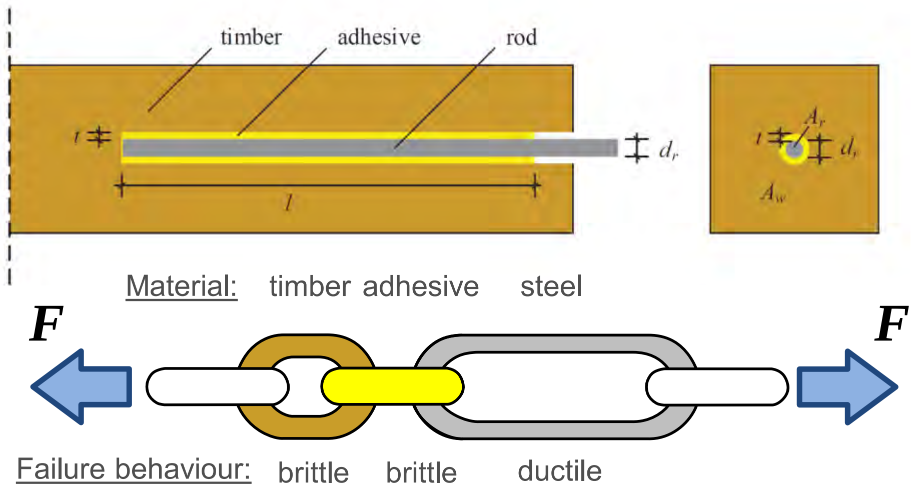
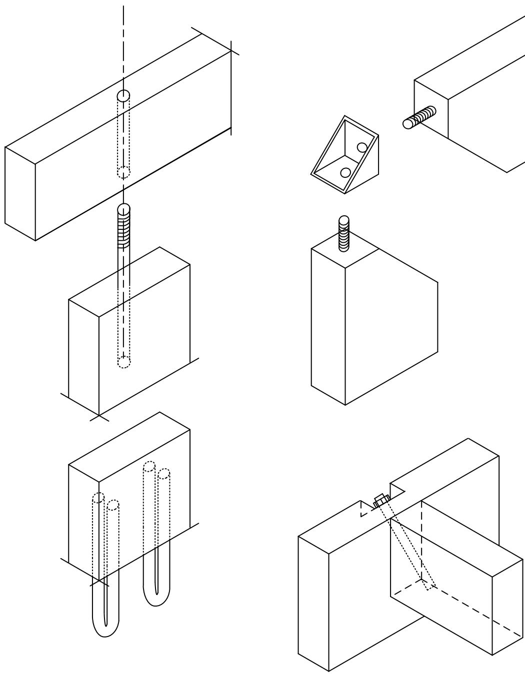
Bonded-in rods

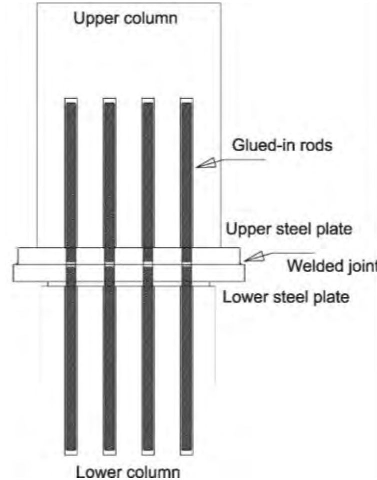


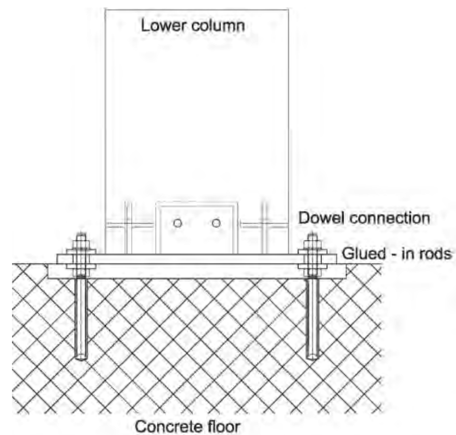
- Failure modes
  - Steel ➡ low variability
  - Adhesive ➡ high variability
  - Timber ➡ high variability

Bonded-in rods

- Examples

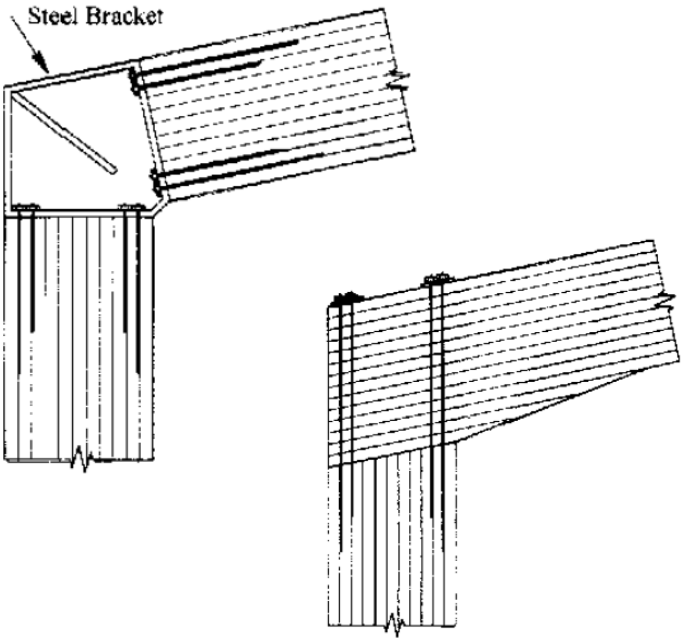






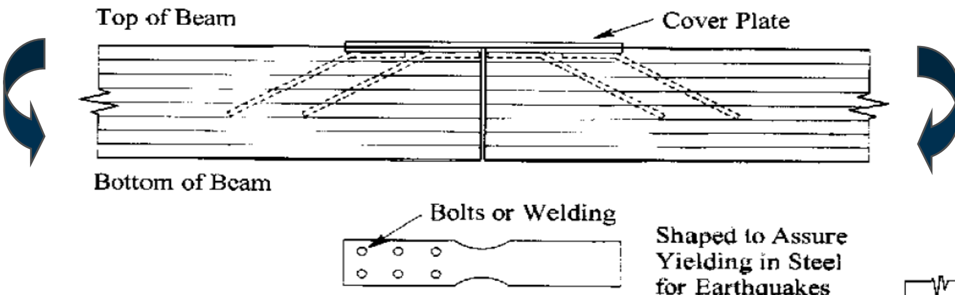
Bonded-in rods

- Examples
    - Frame corners

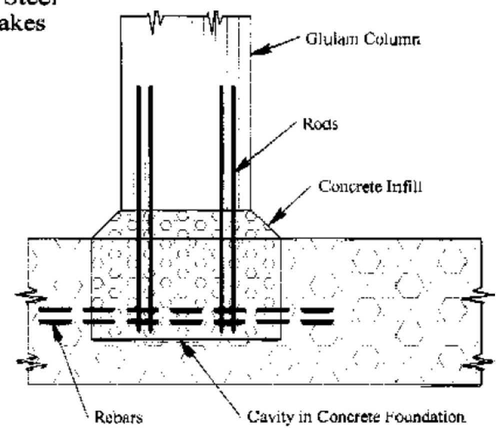


Bonded-in rods

- Examples



Moment resistant beam joint



Column-to-foundation joint

Bonded-in rods

Production

- Check steel strength of rods!
- Follow requirements and processing guidelines of the adhesive producers!
- Check excess or loss of adhesive during bonding process
- Clean cut surface of pre-drilled holes. Not burned!
- Clean pre-drilled holes from saw dust and drilling chips
- Use spacers to insured centering of the rods in the holes
- Tighten nuts uniformly for connections with several bonded-on rods
- Use torque-limiting wrench for tightening of the nuts to limit the tensile load applied to the rods

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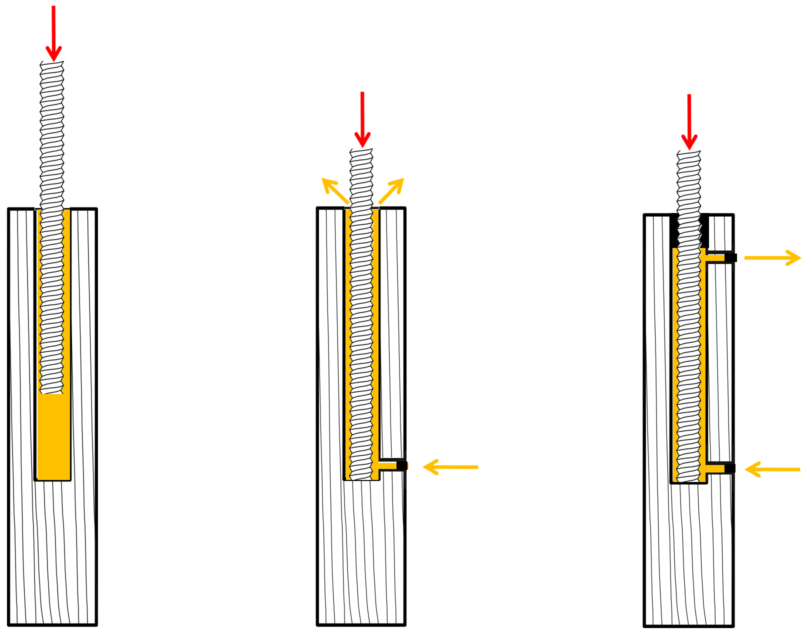
Bonded-in rods

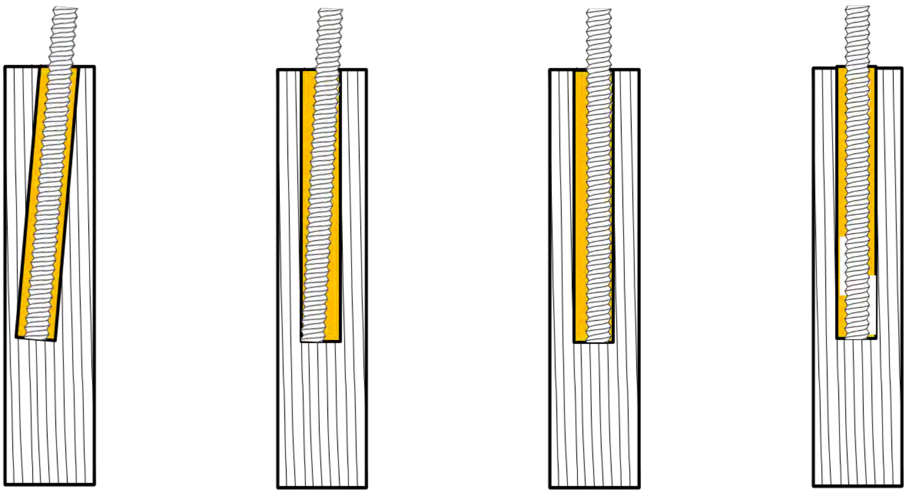
- Production



Source: R. Wiedmann, R. Steiger

Bonded-in rods

- Possible errors!



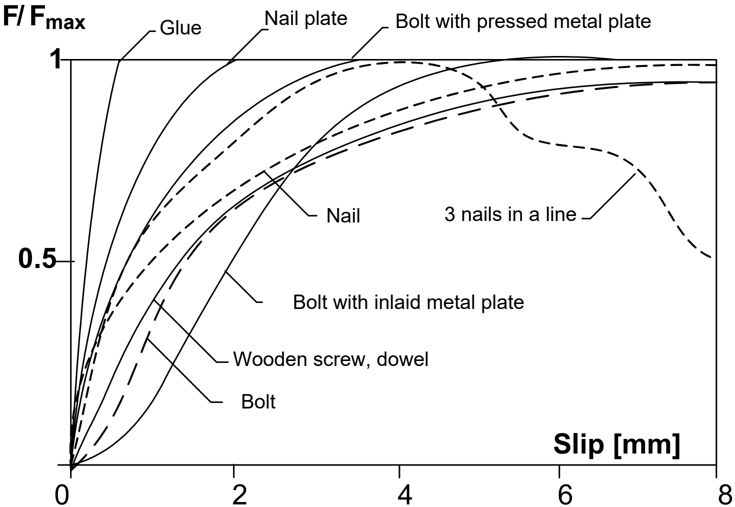
Source: R. Wiedmann, R. Steiger

Serviceability limit states/ Stiffness of joints

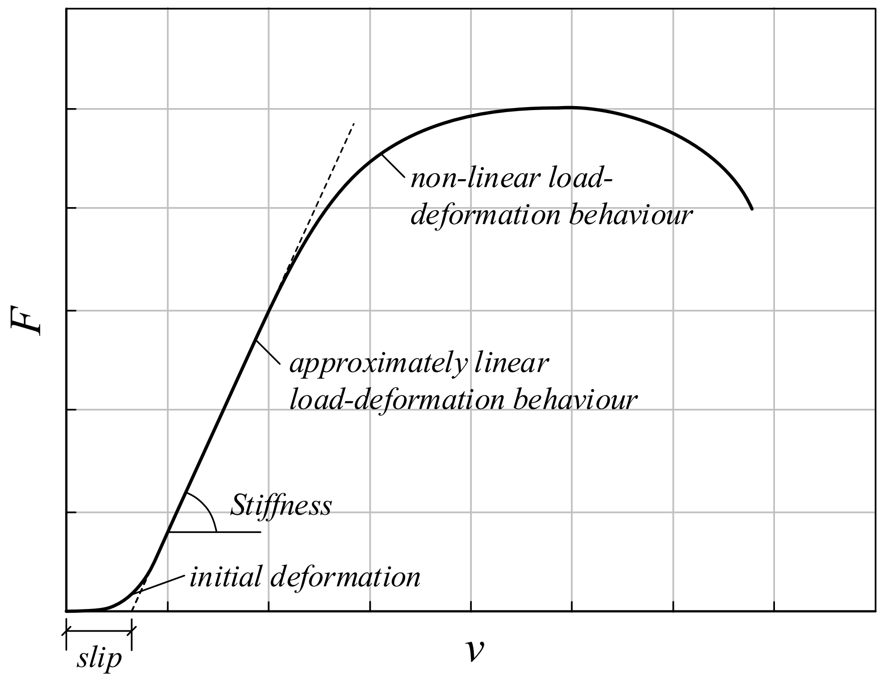
Typical load-slip curves of connections

The stiffness of timber joints depends on:

- Type of joint
- Strength and quality of the parts
- Grain direction
- Load level
- Load duration and creep



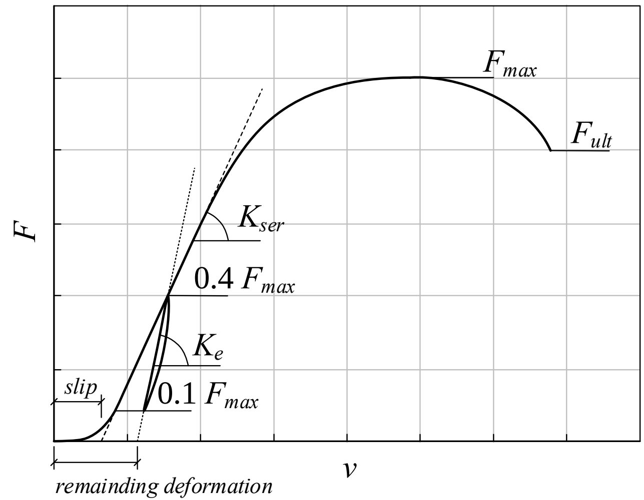
Typology of the load-deformation curve



Derivation of EC5 equations

- Stiffness according to EN 26891

$$K_{ser} = \frac{0.4F_{max}}{\frac{4}{3}(v_{04} - v_{01})}$$



- Deformation according to EC5

$$u_{inst} = \frac{F_d}{K_{ser}}$$

Slip-Modulus of fasteners

Type of fastener	K_{ser}
• Nails:	
- Without pre-drilling	$\rho_m^{1,5} d^{0,8}/30$
- With pre-drilling	$\rho_m^{1,5} d/23$
• Screws	$\rho_m^{1,5} d/23$
• Bolts	$\rho_m^{1,5} d/23$
• Dowels	$\rho_m^{1,5} d/23$

Calculation of deformation of connections

7.1 Joint slip

(1) For joints made with dowel-type fasteners the slip modulus K_{ser} per shear plane per fastener under service load should be taken from Table 7.1 with ρ_m in kg/m³ and d or d_c in mm. For the definition of d_c, see EN 13271.

NOTE: In EN 26891 the symbol used is k_s instead of K_{ser}.

Table 7.1 – Values of K_{ser} for fasteners and connectors in N/mm in timber-to-timber and wood-based panel-to-timber connections

Fastener type	K_{ser}
Dowels Bolts with or without clearance[a] Screws Nails (with pre-drilling)	$\rho_m^{1,5} d/23$
Nails (without pre-drilling)	$\rho_m^{1,5} d^{0,8}/30$
Staples	$\rho_m^{1,5} d^{0,8}/80$
Split-ring connectors type A according to EN 912 Shear-plate connectors type B according to EN 912	$\rho_m d_c/2$
Toothed-plate connectors: – Connectors types C1 to C9 according to EN 912 – Connectors type C10 and C11 according to EN 912	 $1{,}5\rho_m d_c/4$ $\rho_m d_c/2$
[a] The clearance should be added separately to the deformation.	

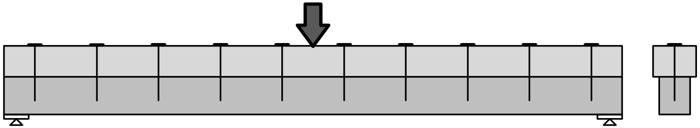
(2) If the mean densities $\rho_{m,1}$ and $\rho_{m,2}$ of the two jointed wood-based members are different then ρ_m in the above expressions should be taken as

$$\rho_m = \sqrt{\rho_{m,1}\rho_{m,2}} \tag{7.1}$$

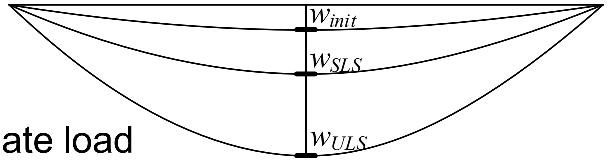
(3) For steel-to-timber or concrete-to-timber connections, K_{ser} should be based on ρ_m for the timber member and may be multiplied by 2,0.

Example: combined beam

- initial deformation (self-weight)
  - slip of the connections



Deflection:

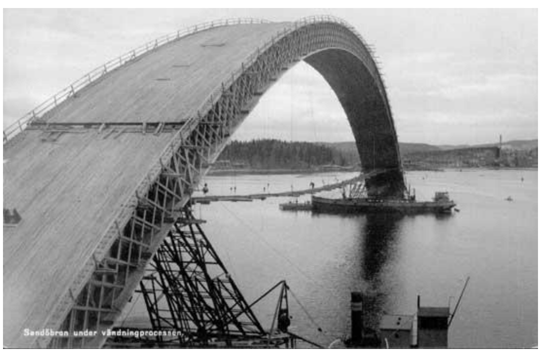


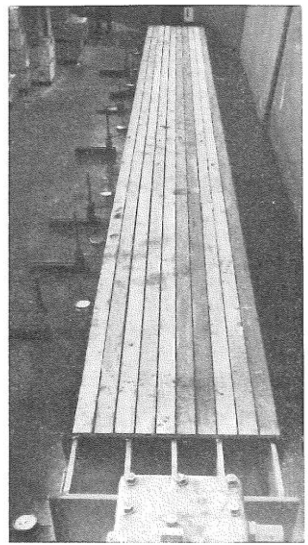
- serviceability limit state (SLS)
  - K_{ser} of linear-elastic range between 10% and 40% of ultimate load

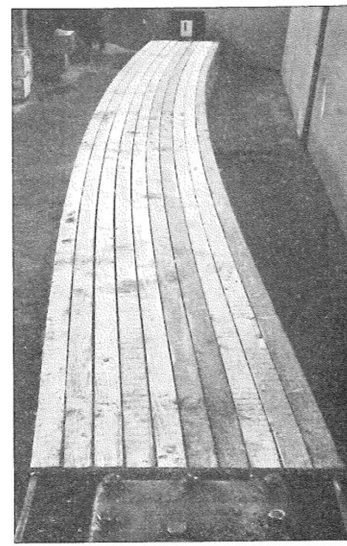
- ultimate limit state (ULS)
  - $K_u := 2/3 K_{ser}$

Look back in history: Collapse due to low connection stiffness

- Collapse of the Sandö-Bridge formwork in 1939







Examples H3

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