TIMBER CONNECTIONS

by

Dr. Ad Leijten

TU-Eindhoven

The Netherlands

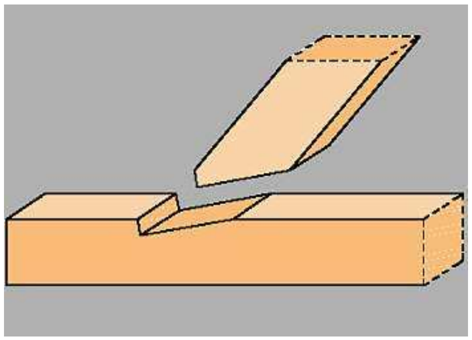
Former PT-member

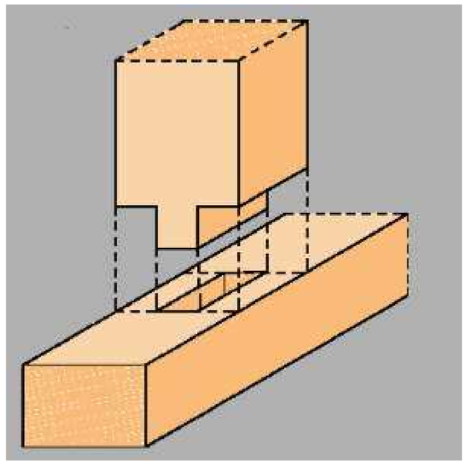
We can not escape connections

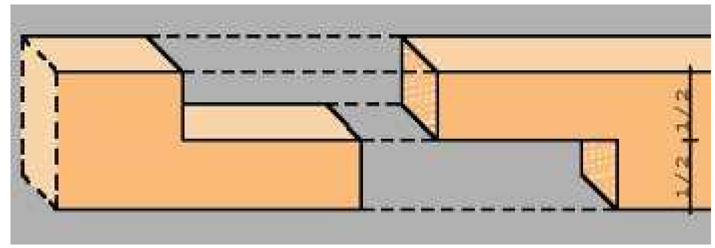
THE WEAKEST LINK

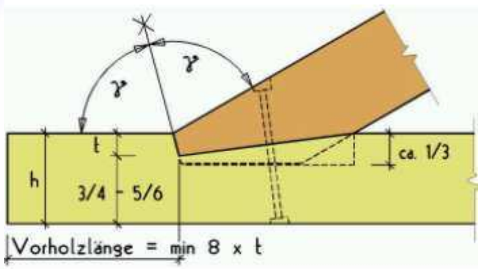
What kind of connections do we use?

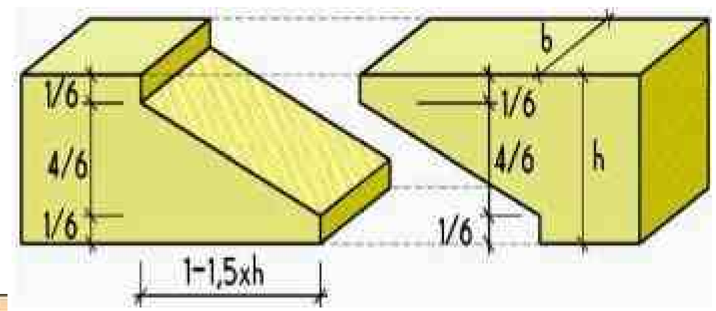
Carpenter connections (not in Eurocode 5)

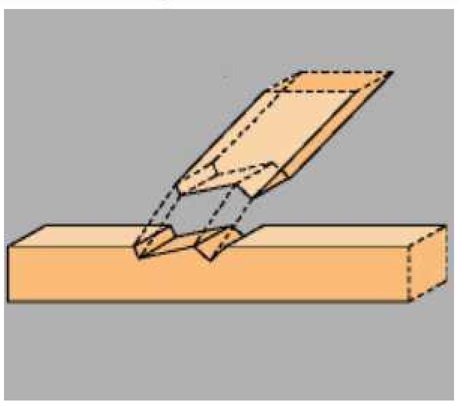


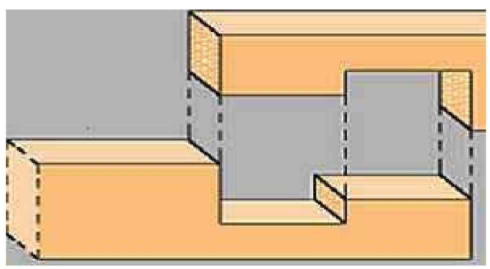


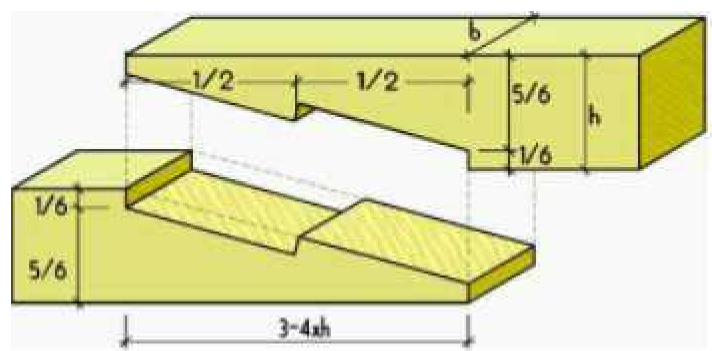












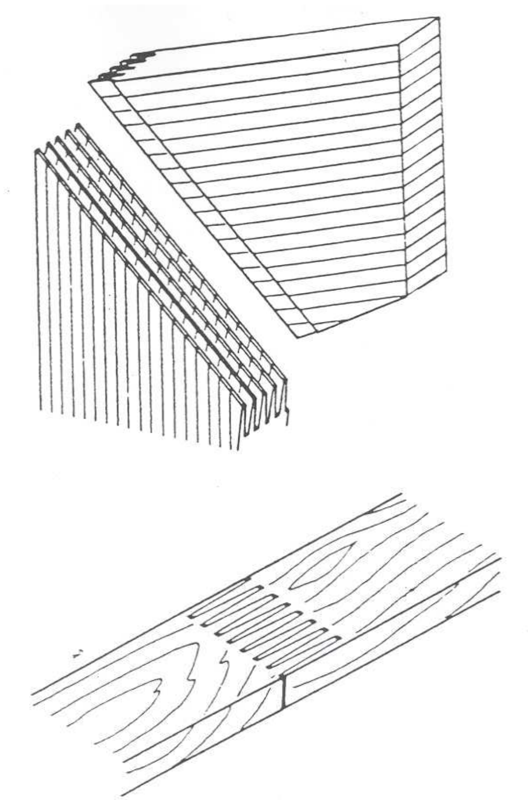
National regulations apply

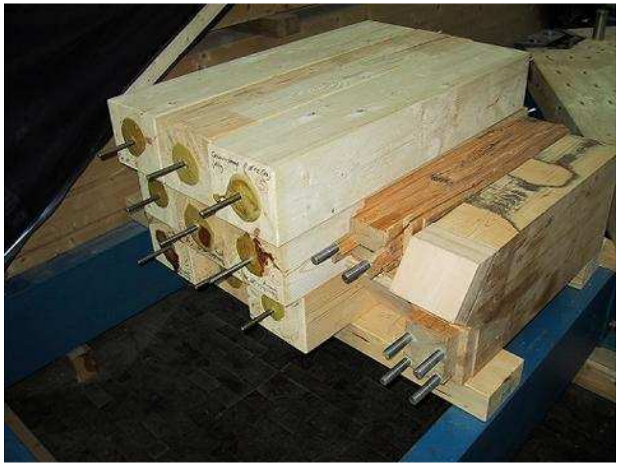




Carpenter connections → compression forces

Glued connections (not in Eurocode 5)





Structural Finger joints **Glued in steel rods**

National regulations apply

What do we find in Eurocode 5

Section 8: Connections with metal fasteners

Mechanical connections with

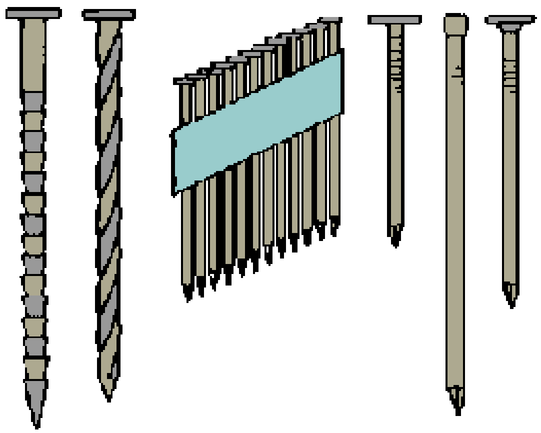
Dowel type fasteners

- Nails, staples,
- punched metal plates,
- screws,
- dowels and bolts

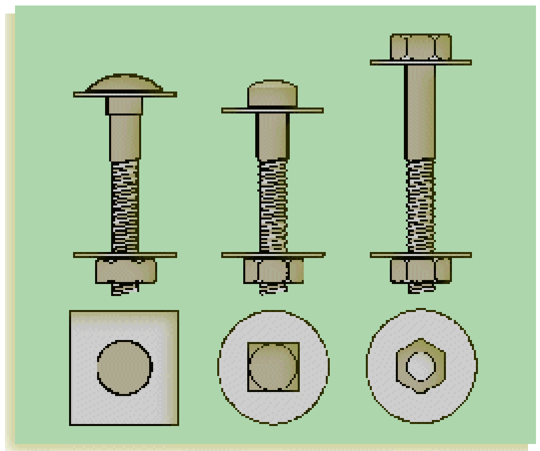
Connectors

- Shear plates

- Split-rings

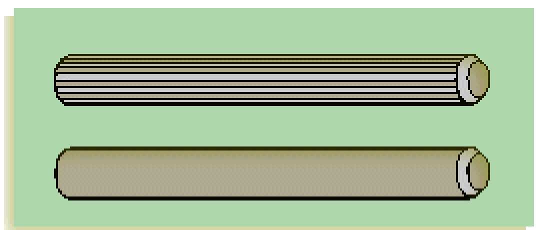


Nails < 8 mm (EN14592)
definition profiled nails



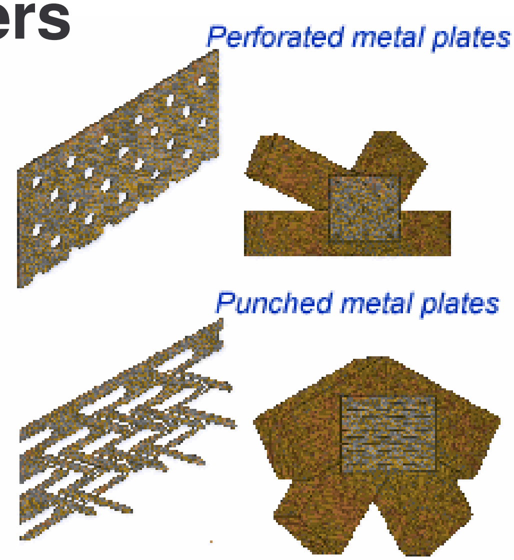
Bolts > 8 mm

Screws



Dowels > 6 mm

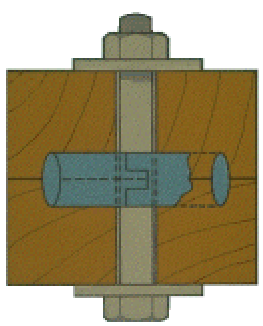
Punched metal plate fasteners



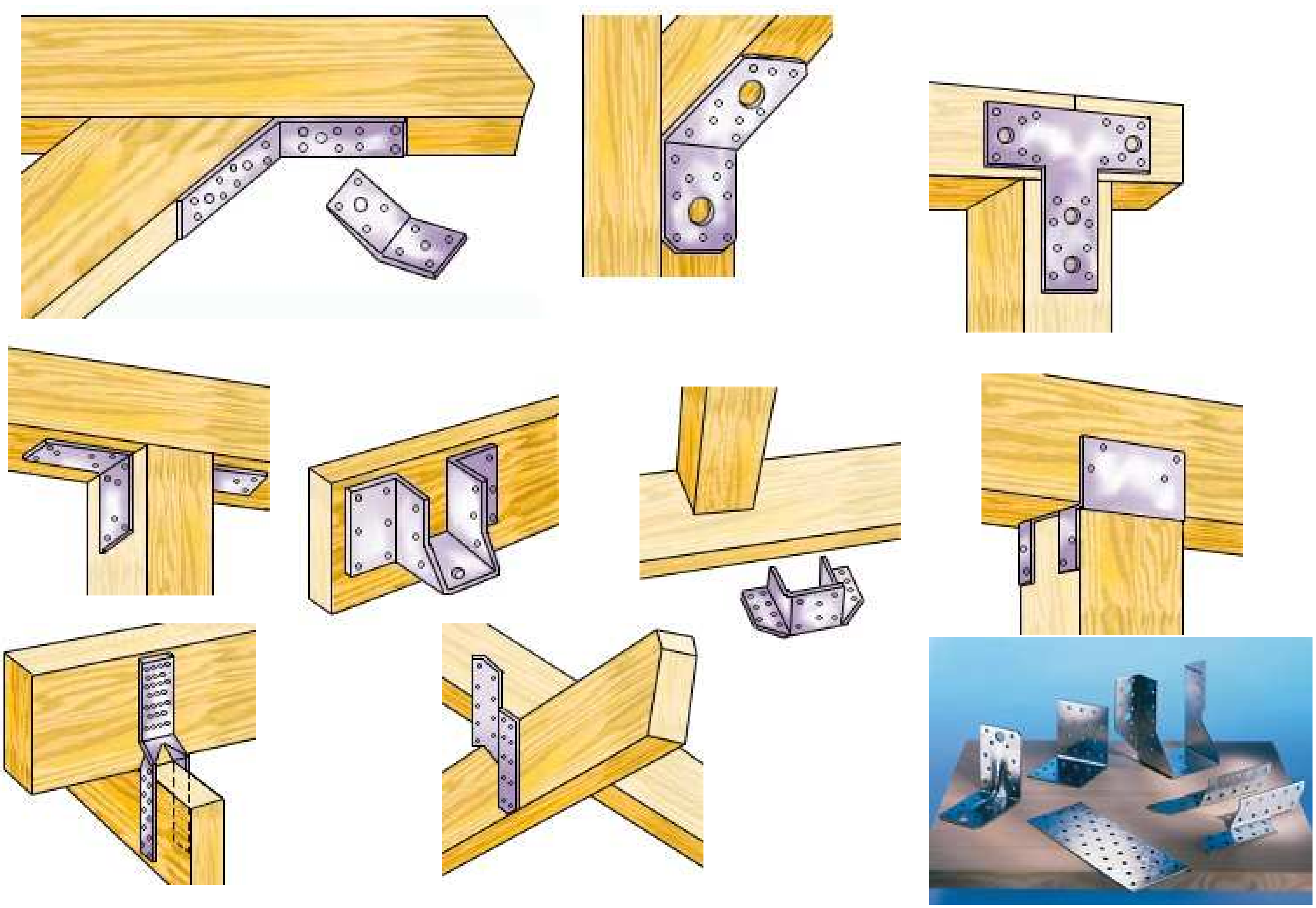
Split-ring connectors

64- 104 mm diameter

Bolts M12 to M20



Steel – to – timber



Eurocode 5 allows:

Design by testing:

EN 1075 – tests punched metal plates connections

EN 1380 – tests nails,screws,dowels,bolted conn.

EN 1381 - tests on stapled connections.

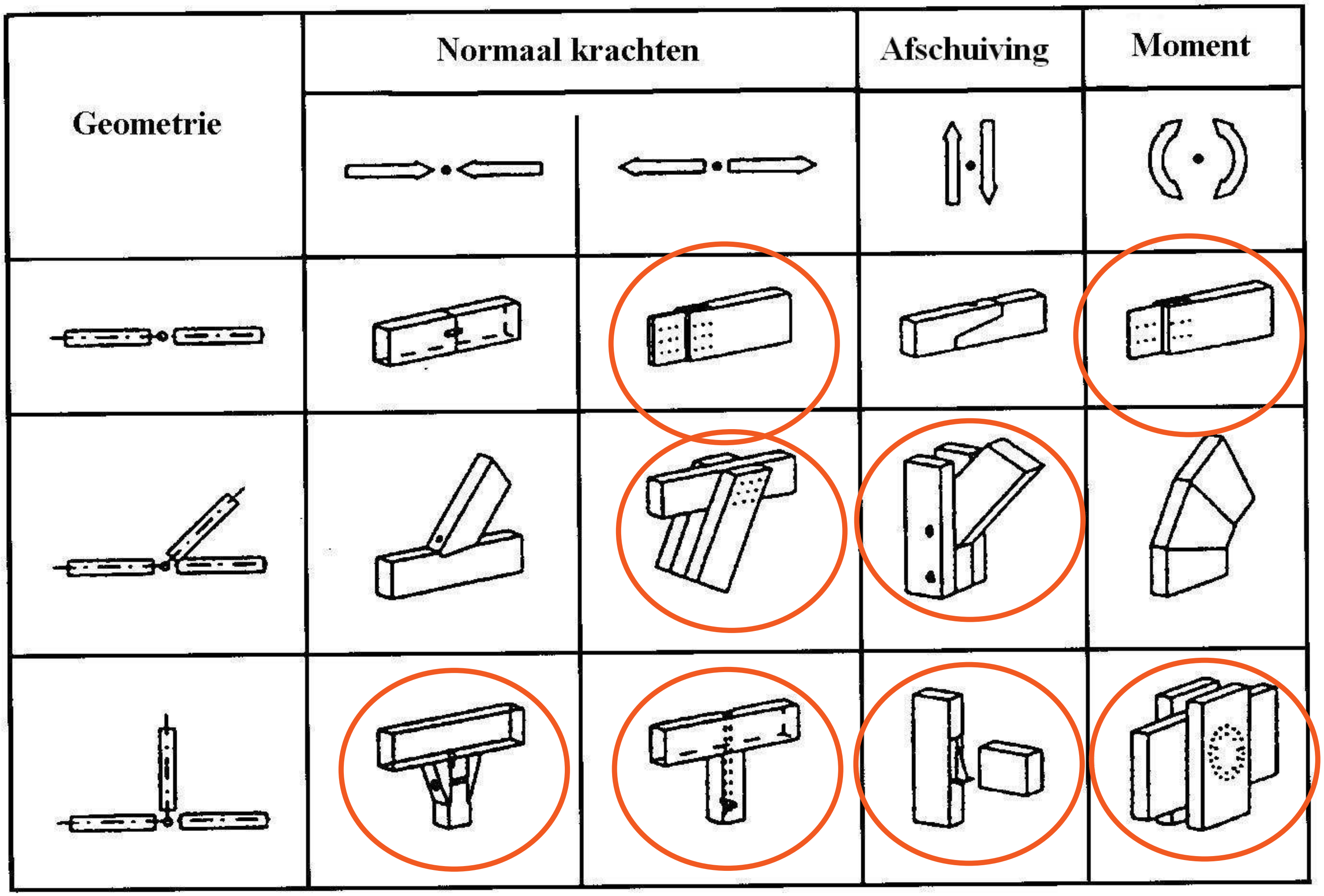
EN 26891 – Specimen density selection.

EN 28970 – Test procedure for connection tests.

Design by calculation

- Model provided in EN1995-1-1

Design by calculation - covers



Fastener spacing requirements

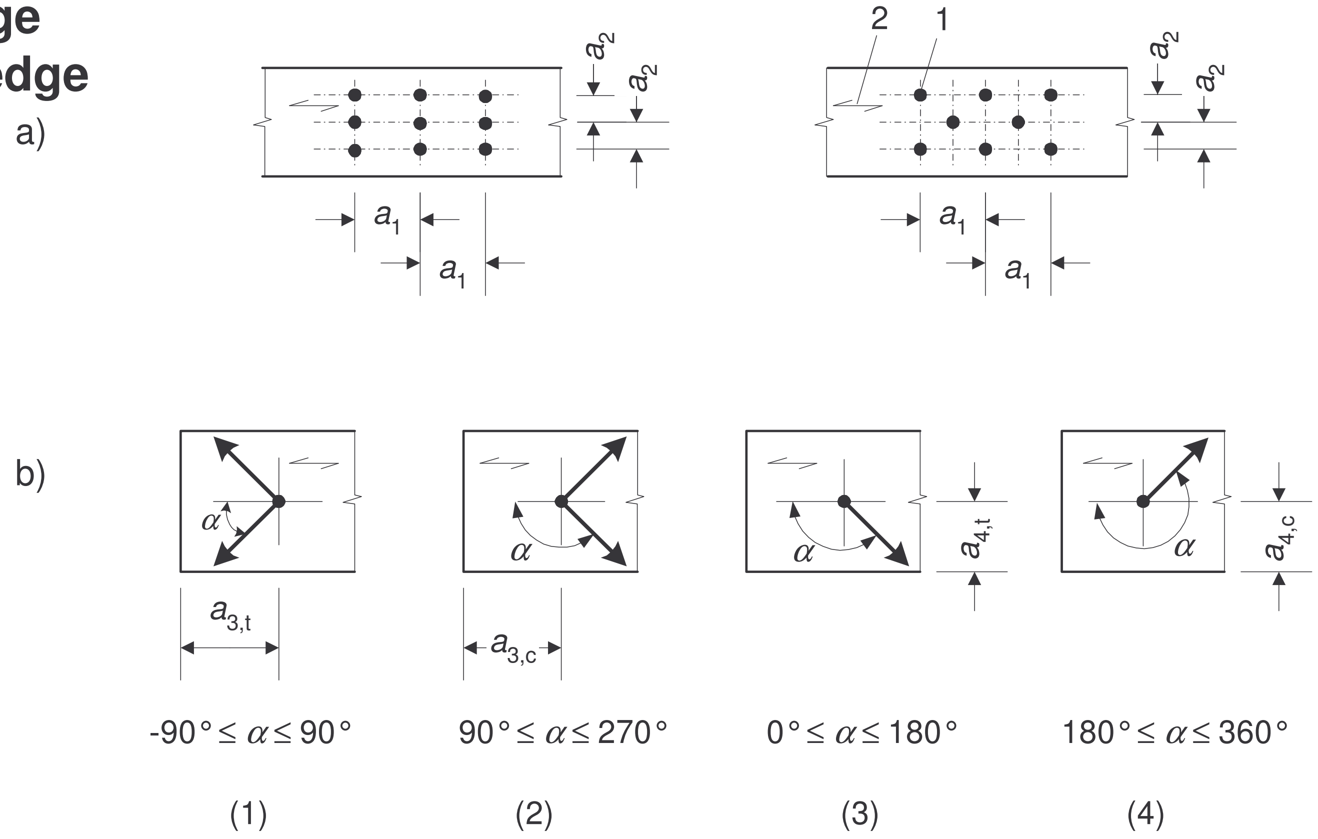
Key:

(1) Loaded end

(2) Unloaded end

(3) Loaded edge

(4) Unloaded edge

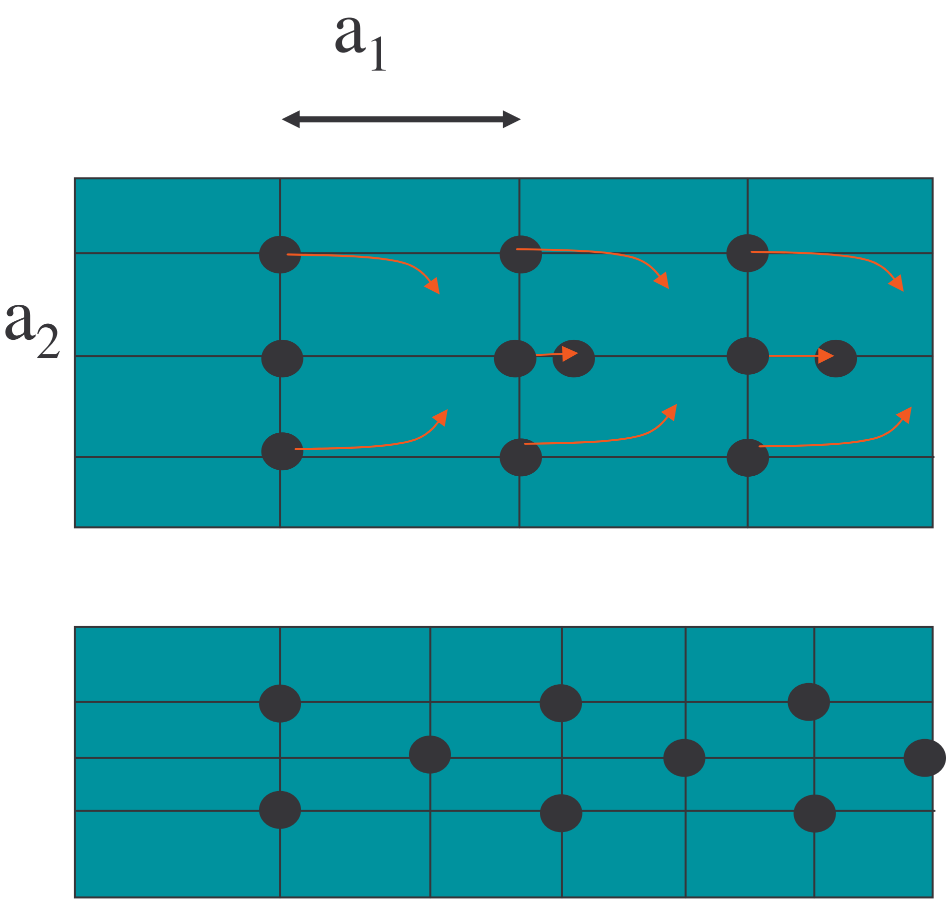


Fastener spacing requirements (bolts)

Spacing and end/edge distances (see Figure 8.7)	Angle	Minimum spacing or distance
a_1 (parallel to grain)	$0^\circ \leq \alpha \leq 360^\circ$	$(4 + \lvert \cos \alpha \rvert)\ d$
a_2 (perpendicular to grain)	$0^\circ \leq \alpha \leq 360^\circ$	$4\ d$
$a_{3,t}$ (loaded end)	$-90^\circ \leq \alpha \leq 90^\circ$	max (7 d; 80 mm)
$a_{3,c}$ (unloaded end)	$90^\circ \leq \alpha < 150^\circ$ $150^\circ \leq \alpha < 210^\circ$ $210^\circ \leq \alpha \leq 270^\circ$	max([1 + 6 sin α) d; 4d) $4\ d$ max([1 + 6 sin α) d; 4d)
$a_{4,t}$ (loaded edge)	$0^\circ \leq \alpha \leq 180^\circ$	max([2 + 2 sin α) d; 3d)
$a_{4,c}$ (unloaded edge)	$180^\circ \leq \alpha \leq 360^\circ$	$3\ d$

Spacing requirements determine timber dimensions

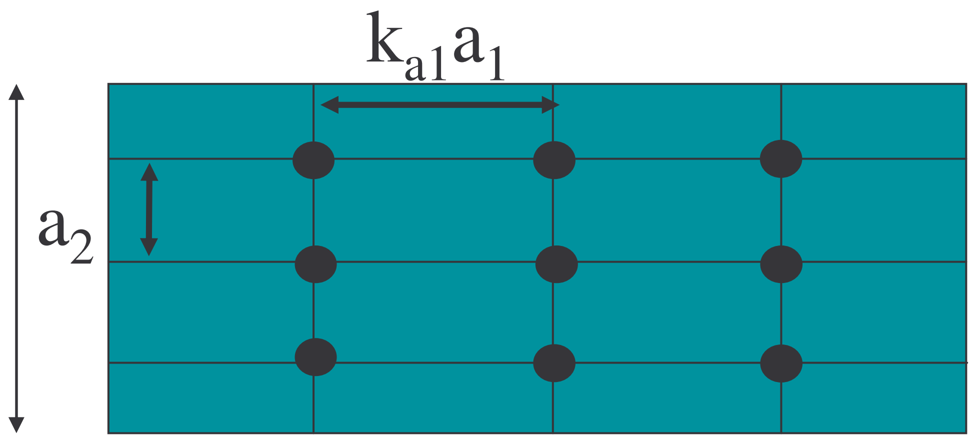
Decrease member width ?

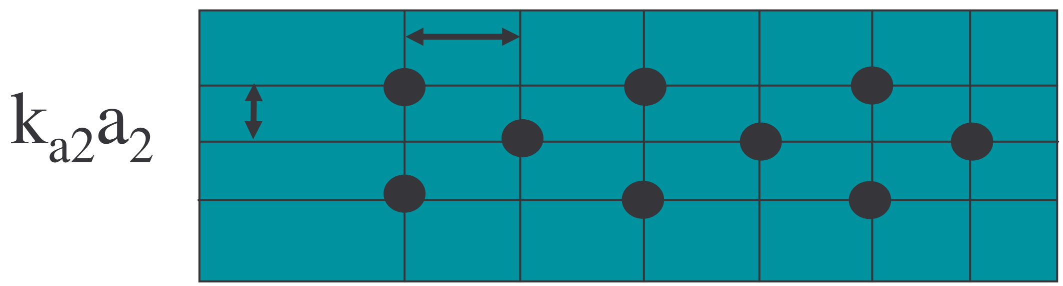


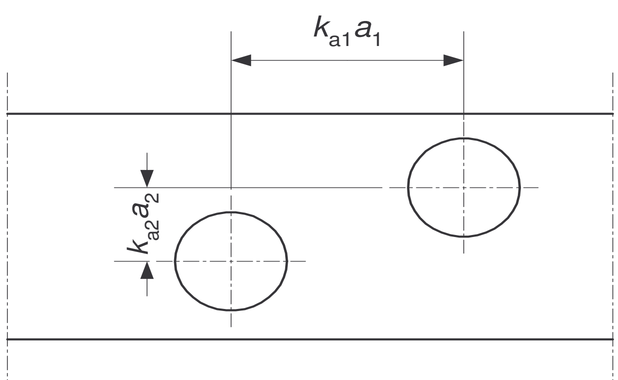
Spacing requirements determine timber dimensions

Only for connectors

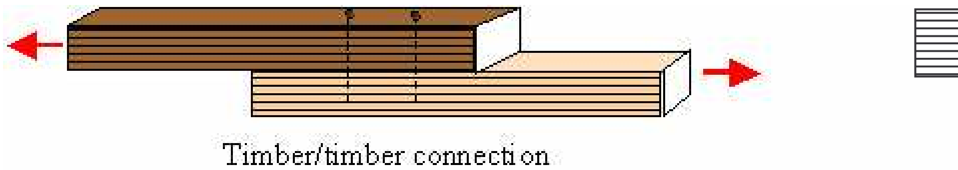
Split-rings and shear plates

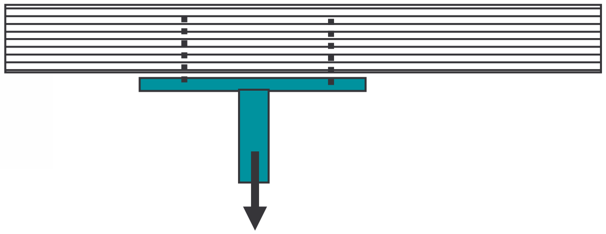






$$(k_{a1})^2 + (k_{a2})^2 \geq 1 \qquad \text{with} \qquad \begin{cases} 0 \leq k_{a1} \leq 1 \\ 0 \leq k_{a2} \leq 1 \end{cases}$$





Laterally loaded   axially loaded

The strength capacity model for

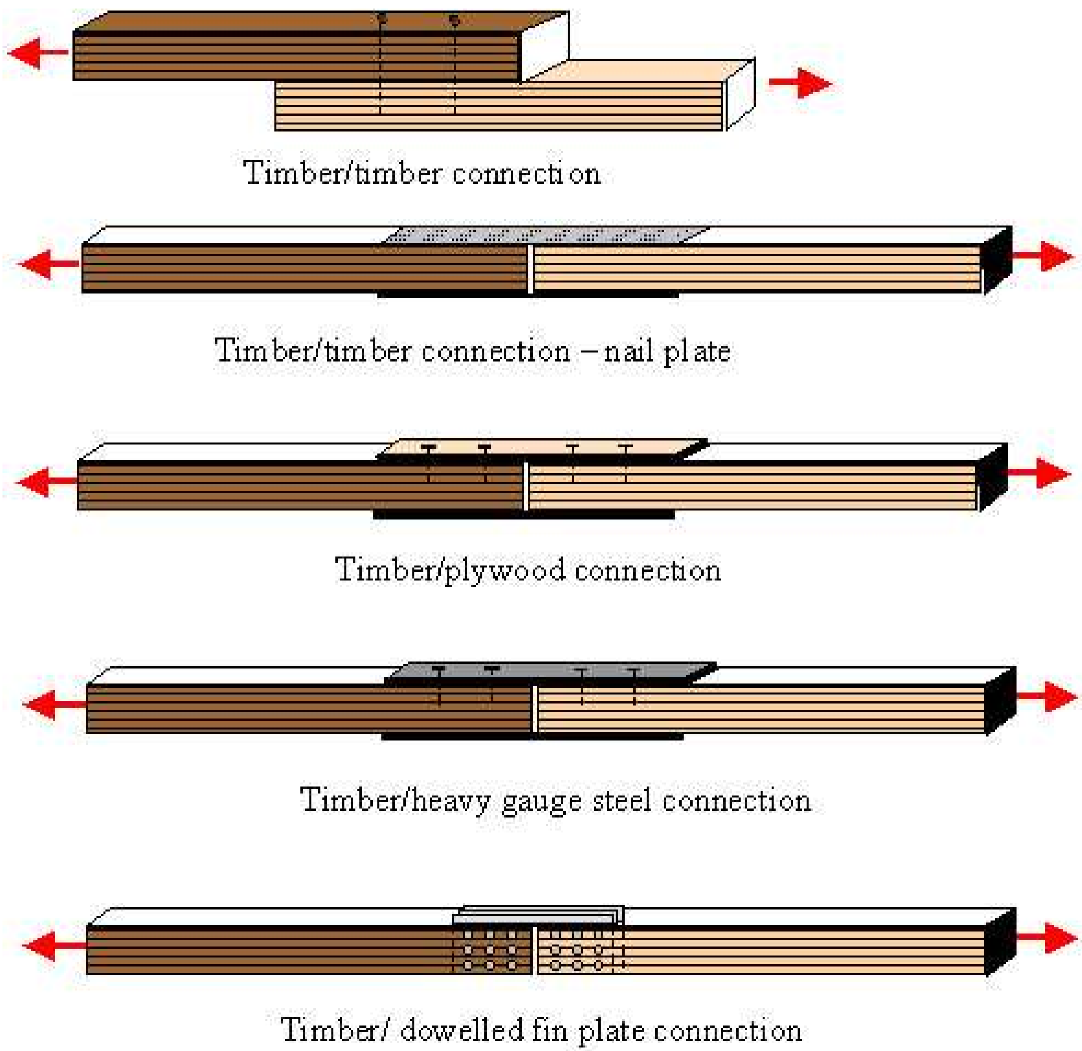
laterally loaded dowel-type-fasteners

(based on Johansen (1949)

Background:

-Structural Education Timber Program (STEP 1)(1994)

-Timber Engineering; Thelandersson & Larsen (2003)   **ISBN 0-470-84469-8**

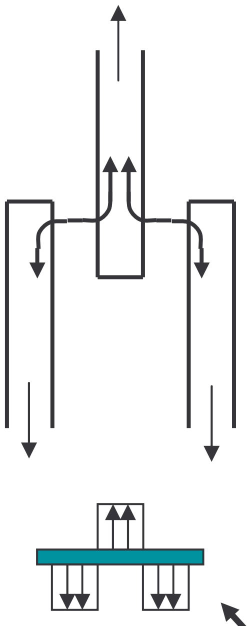


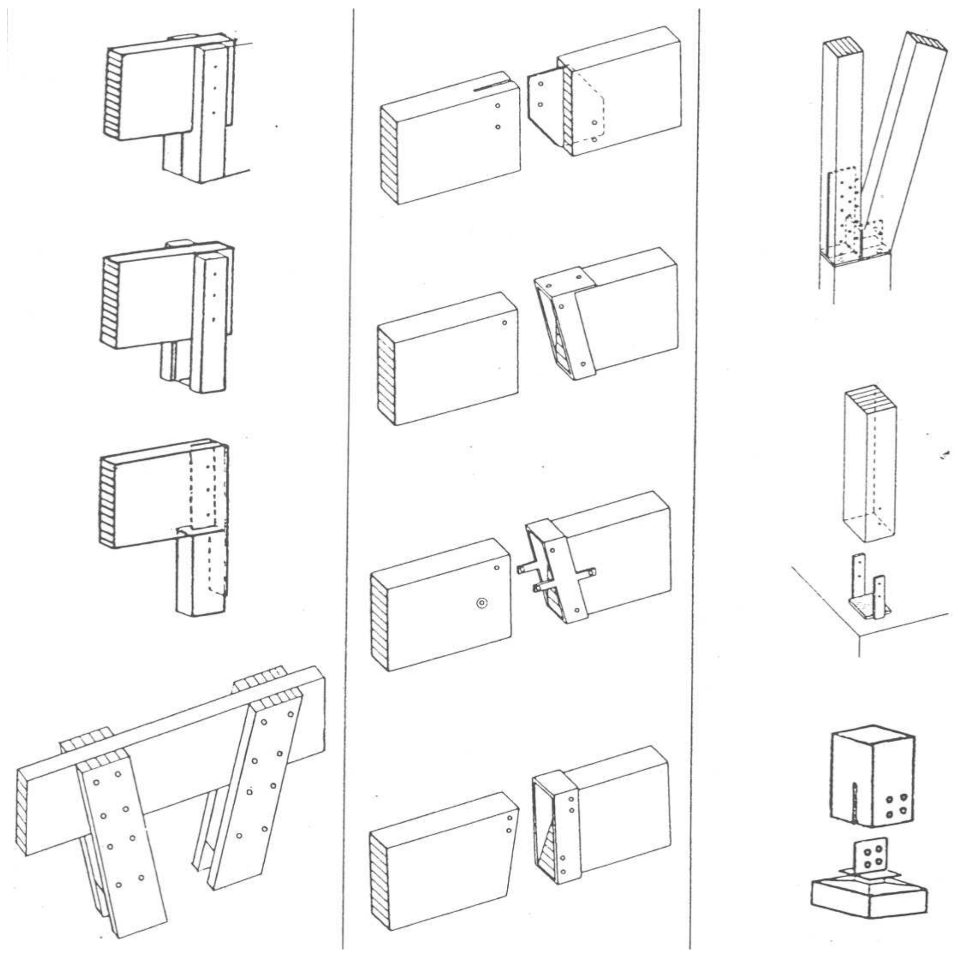
single shear

fasteners

multiple shear

Double shear

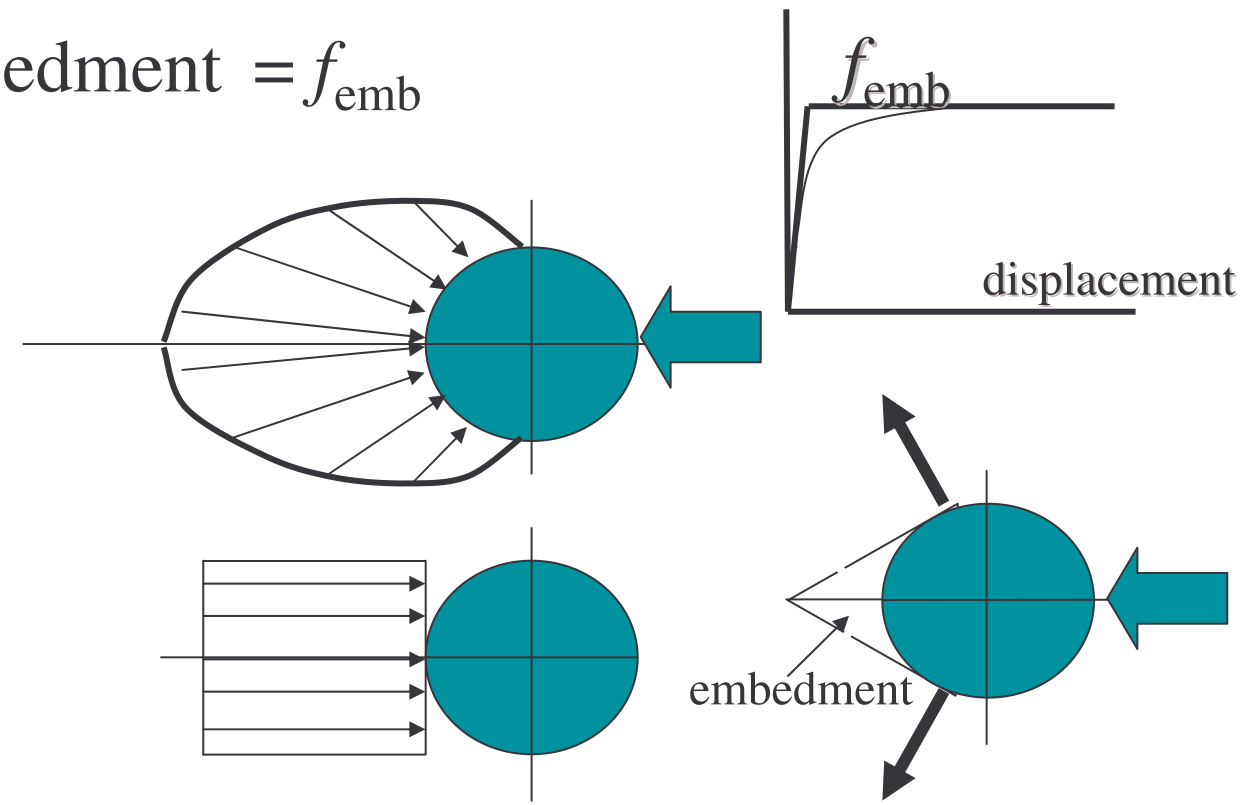




Embedment stresses

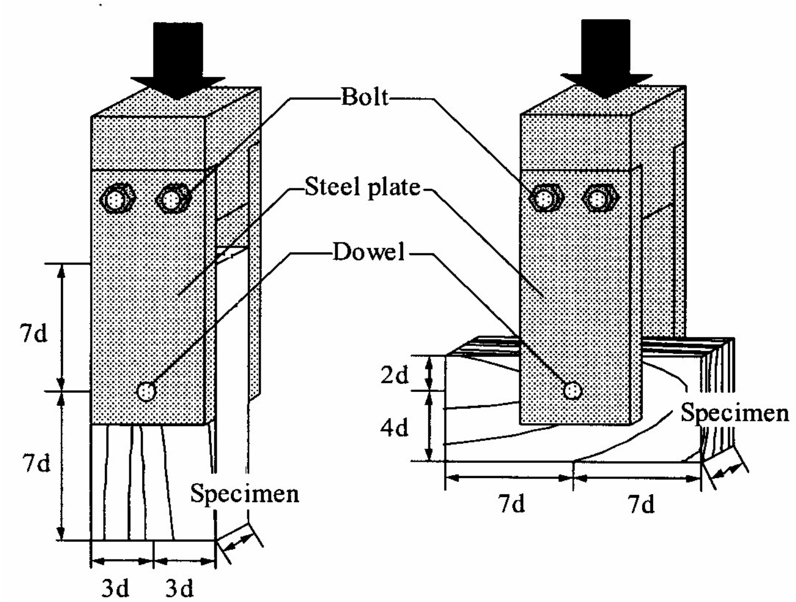
Starting point for strength model - Embedment strength

Embedment $= f_{emb}$



Idealised $f_{emb} = f_v$

Determination of embedment strength –EN 383



Eurocode 5 Design clause embedment strength

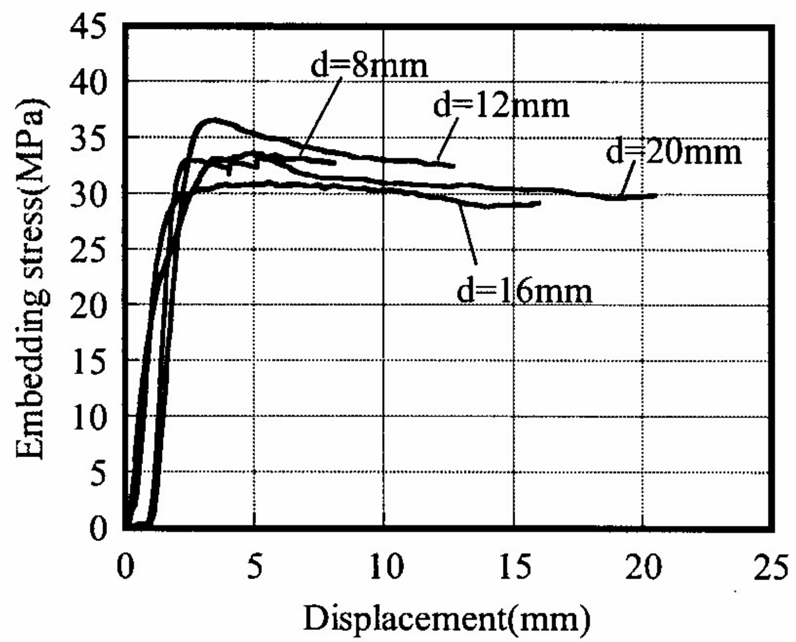
Nails (not pre-drilled) $f_{h,k} = 0,082\,\rho_k\,d^{-0,3}$ N/mm^2

Nails pre-drilled

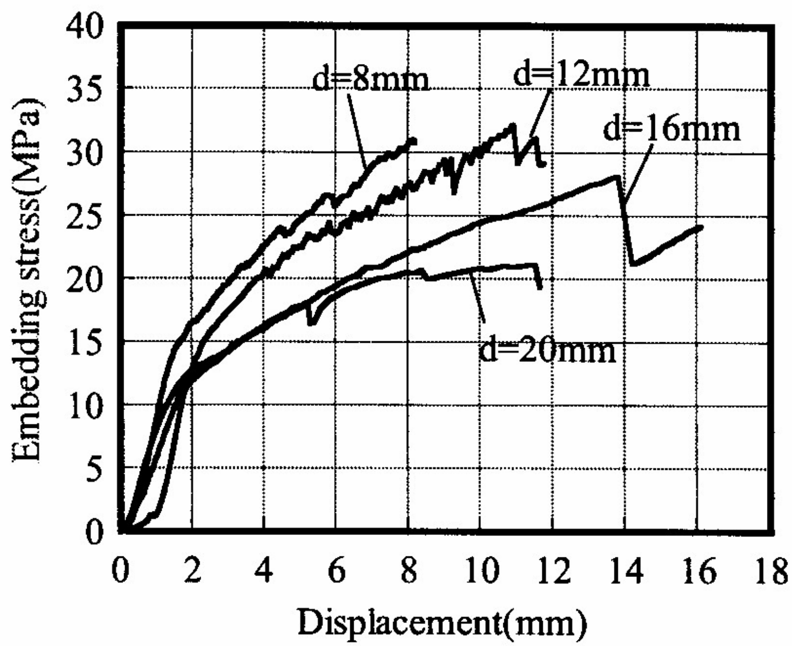
Bolts/dowels

$$f_{h,k} = 0,082\,(1 - 0,01\,d)\,\rho_k \quad \text{N/mm}^2$$

Parallel



Perpendicular

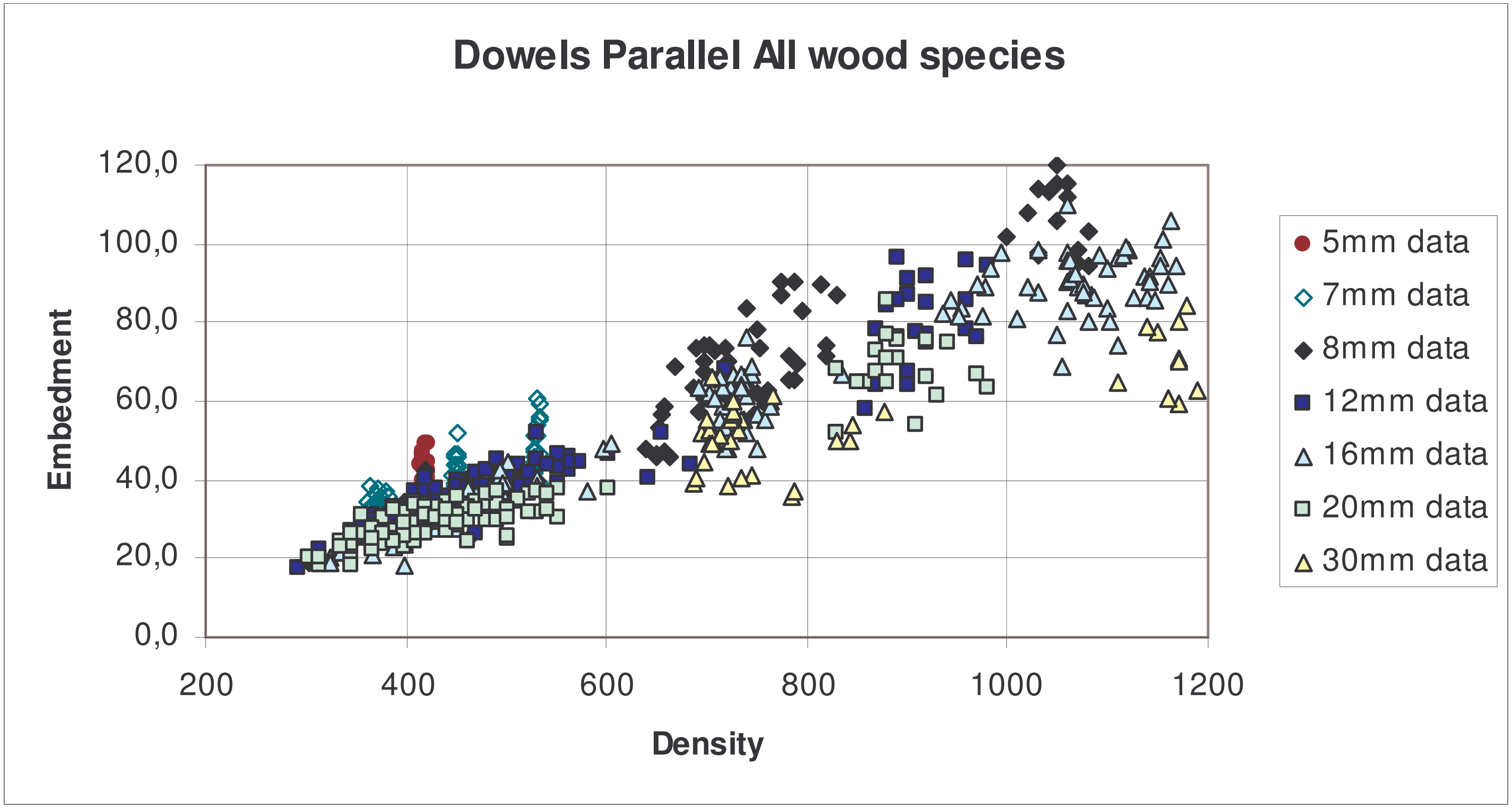


Taken from Sawata and Yasumura (2002).

Background: Whale L. and Smith, I. The derivation of design clauses for nailed and bolted joint in Eurocode 5, In Proceedings of paper CIB-W18 paper 19-7-6/ Florenze 1986

Yasumura, M. and Sawata, K., Determination of embedment strength of wood for dowel-type-fasteners. In: Journal of Wood Science, nr. 48, 2002, Japan Wood Research Society, Inst. Of Wood Techn, Akita, Japan

Embedment test - parallel to grain



Background: Leijten, A.J.M. & Köhler, J.& A Jorissen, Review of Probability Data for Timber Connections with Dowel-Type Fasteners; In Proceedings of CIB-W18, paper 37-7-12, Edinburgh, UK, September 2004

Re-evaluation parallel to grain embedment results for future consideration in EC5?

Nails (pre-drilled)

Coniferous

$$f_{h;0} = 0,0104\rho^{1,35}d^{-0,27}$$

Bolts and dowels

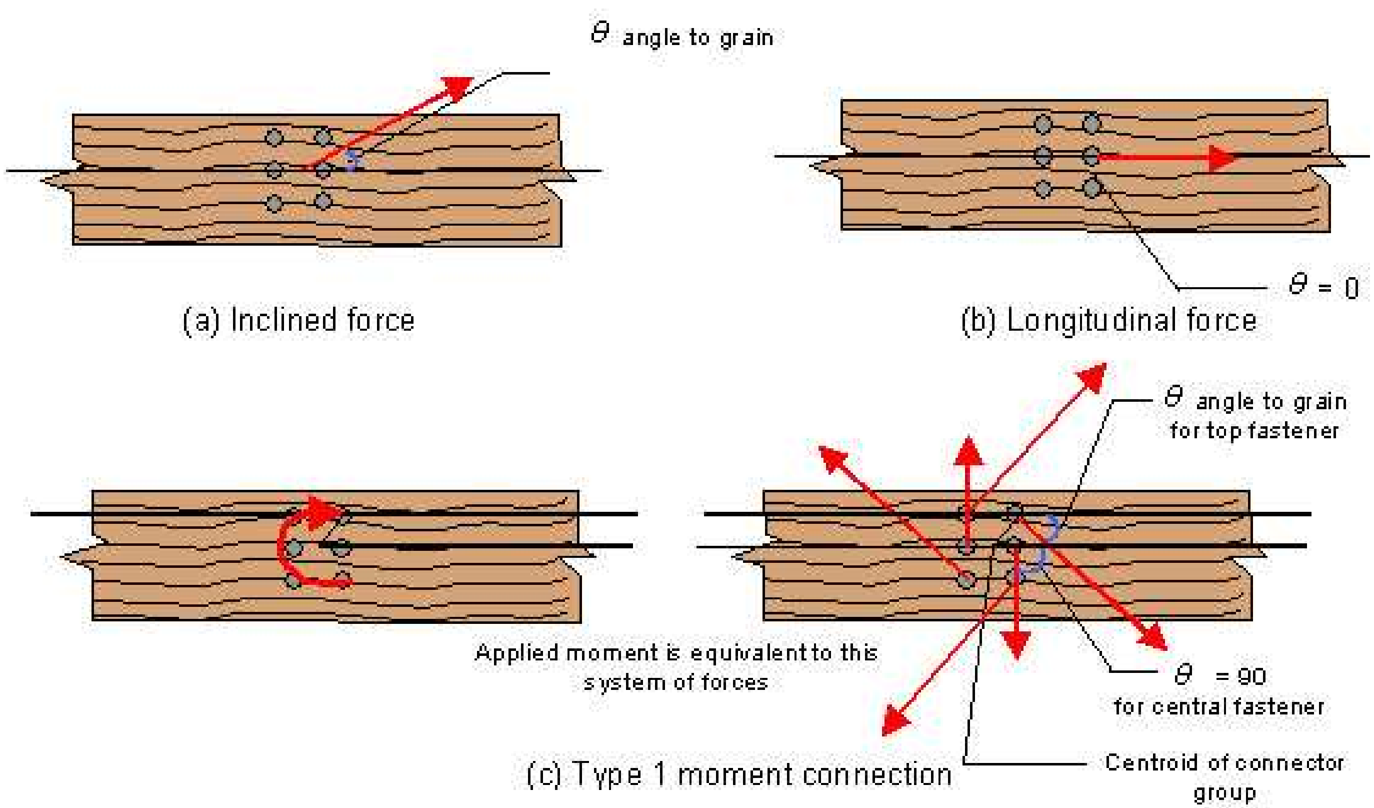
Coniferous

$$f_{h;0} = 0,097\rho^{1,07}d^{-0,25}$$

Decideous

$$f_{h;0} = 0,087\rho^{1,09}d^{-0,25}$$

Embedment - perpendicular to grain



Embedment – at angle to grain

Bolts/dowel:

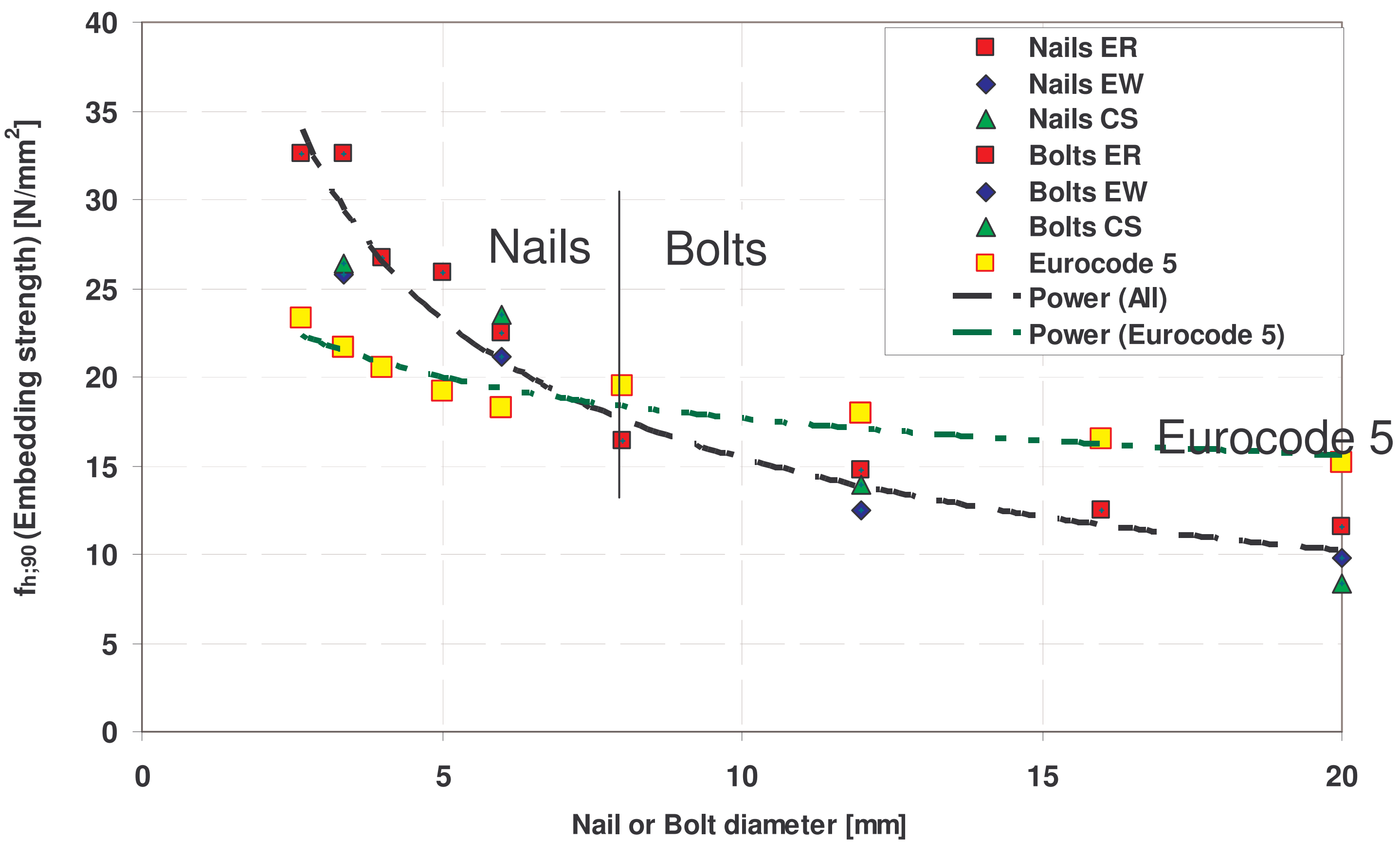
$$f_{\mathrm{h,0,k}} = 0,082\,(1 - 0,01\,d)\,\rho_{\mathrm{k}}$$

$$f_{\mathrm{h,\alpha,k}} = \frac{f_{\mathrm{h,0,k}}}{k_{90}\sin^2\alpha + \cos^2\alpha}$$

$$k_{90} = \begin{cases} 1,35 + 0,015\,d & \text{for softwoods} \\ 0,90 + 0,015\,d & \text{for hardwoods} \end{cases}$$

Coniferous: Embedment test - perpendicular to grain

Embedding strength, based on average values embedding tests
(European Whitewood (EW), European Redwood (ER), Canadian Spruce Pine Fir (CS))



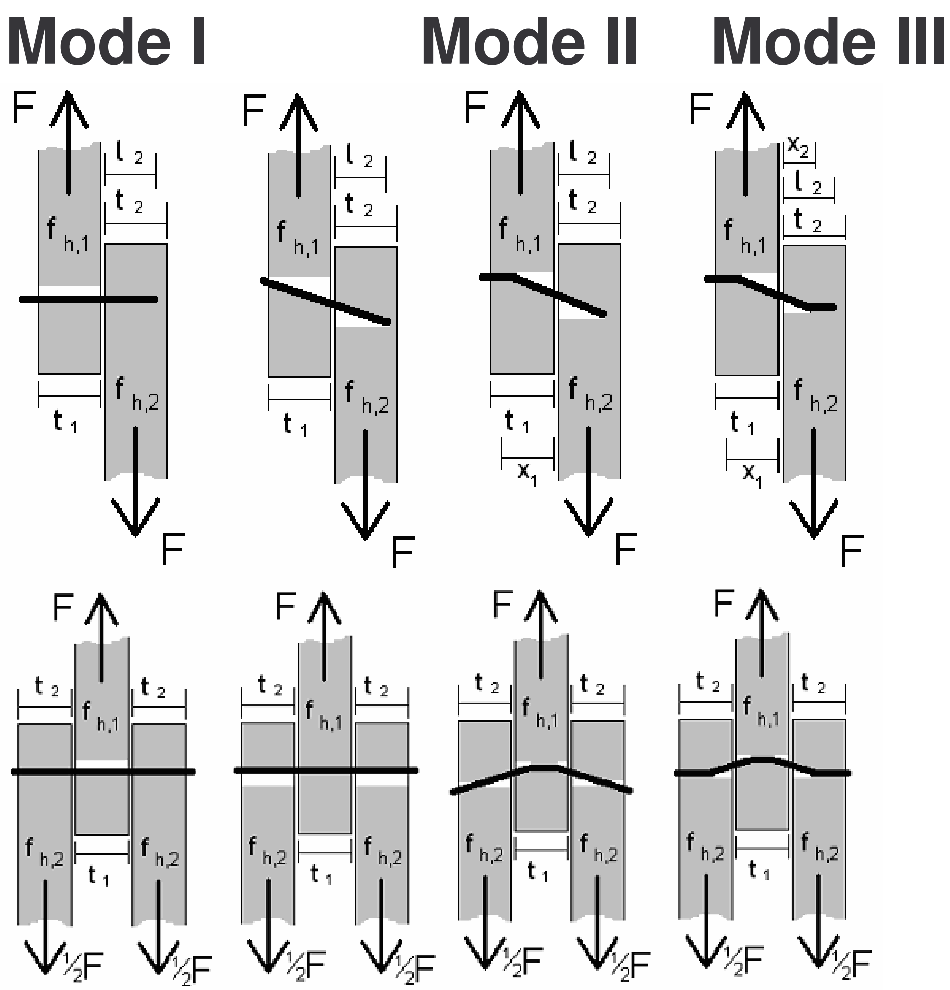
Needs adjustment in future EC5

Embedment rules

Nails in:

Plywood	$f_{\mathrm{h,k}} = 0{,}11\,\rho_{\mathrm{k}}\,d^{-0{,}3}$
Hardboard	$f_{\mathrm{h,k}} = 30\,d^{-0{,}3}t^{0{,}6}$
Particleboard & OSB	$f_{\mathrm{h,k}} = 65\,d^{-0{,}7}\,t^{0{,}1}$

Taken from DIN 1052



Some failure modes of single shear fasteners

Some failure modes of double shear fasteners

Equations for every failure mode

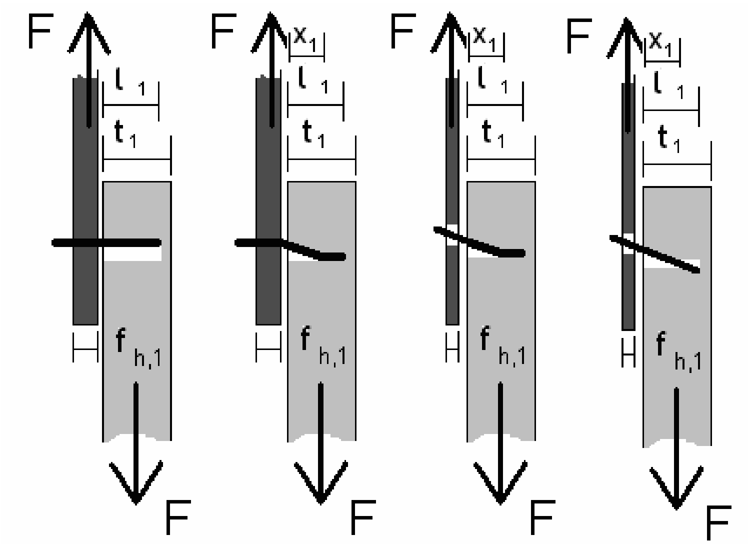
Fasteners in single shear

$$F_{\mathrm{v,Rk}} = \min \begin{cases} f_{\mathrm{h,1,k}} t_1 d & \text{(a)} \\ f_{\mathrm{h,2,k}} t_2 d & \text{(b)} \\ \dfrac{f_{\mathrm{h,1,k}} t_1 d}{1+\beta}\left[\sqrt{\beta + 2\beta^2\left[1+\dfrac{t_2}{t_1}+\left(\dfrac{t_2}{t_1}\right)^2\right]+\beta^3\left(\dfrac{t_2}{t_1}\right)^2} - \beta\left(1+\dfrac{t_2}{t_1}\right)\right] & \text{(c)} \\ \dfrac{f_{\mathrm{h,1,k}} t_1 d}{2+\beta}\left[\sqrt{2\beta(1+\beta)+\dfrac{4\beta(2+\beta)M_{\mathrm{y,Rk}}}{f_{\mathrm{h,1,k}}\, d\ \ t_1^2}} - \beta\right] & \text{(d)} \\ \dfrac{f_{\mathrm{h,1,k}} t_2 d}{1+2\beta}\left[\sqrt{2\beta^2(1+\beta)+\dfrac{4\beta(1+2\beta)M_{\mathrm{y,Rk}}}{f_{\mathrm{h,1,k}}\, d\ \ t_2^2}} - \beta\right] & \text{(e)} \\ \sqrt{\dfrac{2\beta}{1+\beta}}\sqrt{2M_{\mathrm{y,Rk}}\, f_{\mathrm{h,1,k}}\, d} + \dfrac{F_{\mathrm{ax,Rk}}}{4} & \text{(f)} \end{cases}$$

Equations for every failure mode

Fasteners in double shear

$$F_{\mathrm{v,Rk}} = \min \begin{cases} f_{\mathrm{h,1,k}} t_1 d & \text{(g)} \\ 0{,}5 f_{\mathrm{h,2,k}} t_2 d & \text{(h)} \\ \dfrac{f_{\mathrm{h,1,k}} t_1 d}{2+\beta}\left[\sqrt{2\beta(1+\beta)+\dfrac{4\beta(2+\beta)M_{\mathrm{y,Rk}}}{f_{\mathrm{h,1,k}} d\ t_1^2}}-\beta\right] & \text{(j)} \\ \sqrt{\dfrac{2\beta}{1+\beta}}\sqrt{2M_{\mathrm{y,Rk}} f_{\mathrm{h,1,k}} d} & \text{(k)} \end{cases}$$



Some failure modes of single shear fasteners steel to wood connections

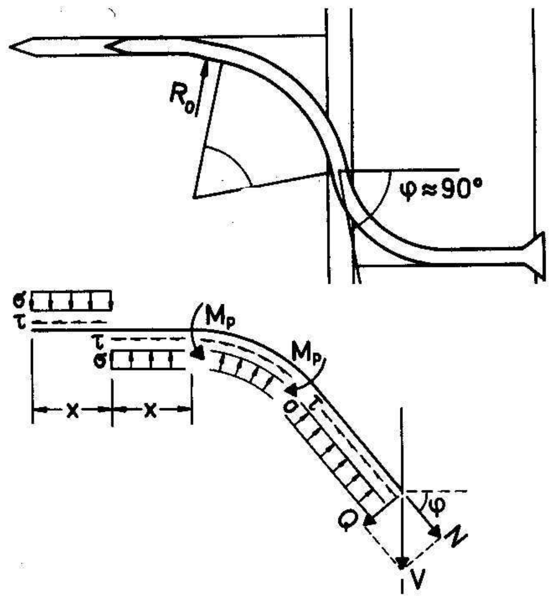
thick steel plate t > d = fastener diameter

thin steel plate t < 0,5d

Test results still higher than Johansen equations

Cord effect:

Only valid for
Mode II and III



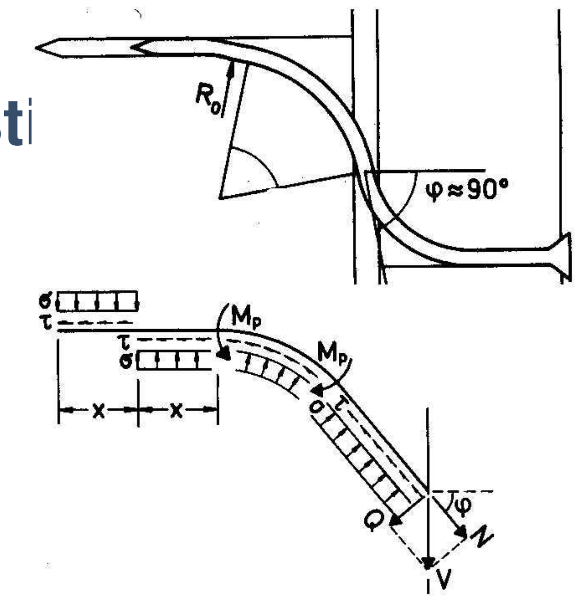
Requires knowledge about withdrawal
Theory for nails 15% extra

Background: Kuipers, J. Van der Put, T.A.C.M., Betrachtungen zum Bruchmechanismus von Nagel verbindungen, In: Ingenieuholzbau in Forschung und Praxis, J. Ehlebeck and G. Steck, editors, Bruderverlag Karlsruhe 1982

Test results still higher than Johansen equations

Cord effect:

F_{ax}/4 = withdrawal capacity/4 = esti



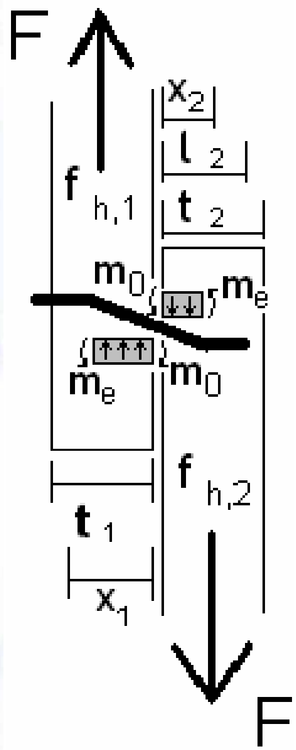
% are estimates

Maximum	
Nails	15%
Grooved nails	50%
Screws	100%
Bolts	25%
Dowels	0%

Fasteners in double shear

$$F_{v,Rk} = \min \begin{cases} f_{h,1,k} t_1 d & \text{(g)} \\ 0,5 f_{h,2,k} t_2 d & \text{(h)} \\ \dfrac{f_{h,1,k} t_1 d}{2+\beta}\left[\sqrt{2\beta(1+\beta)+\dfrac{4\beta(2+\beta)M_{y,Rk}}{f_{h,1,k}d\ t_1^2}}-\beta\right]+\dfrac{F_{ax,Rk}}{4} & \text{(j)} \\ \sqrt{\dfrac{2\beta}{1+\beta}}\sqrt{2M_{y,Rk}f_{h,1,k}d}+\dfrac{F_{ax,Rk}}{4} & \text{(k)} \end{cases}$$

Test results still higher than Johansen equations



Mode III

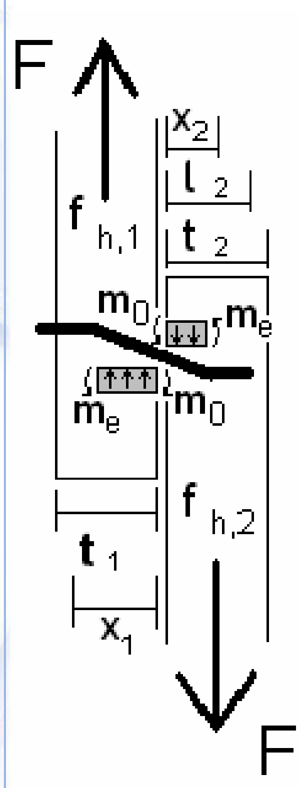
theory $$F = \sqrt{\frac{2\cdot\delta}{1+\delta}}\cdot\sqrt{2\cdot M_s\cdot f_{h,1}\cdot d_{schroef}}$$

Design value $$F_d = F_k\cdot\frac{k_{\mathrm{mod}}}{\gamma_m} = F_k\cdot\frac{0{,}9}{1{,}3} = 0{,}69\cdot F_k$$

***Ms* = yield bending moment steel fastener**

Partial material factor of timber γ_m
applied to *Ms* !!
Better seperate:

Mode III



Taking both γ_m - seperately

$$F_d = \sqrt{\frac{4\delta}{1+\delta}} \cdot \sqrt{\frac{M_{e,k}}{y_{m,s}} \cdot d_{schroef} \cdot \frac{f_{h,1,k}}{y_{m,h}} \cdot k_{\text{mod}}}$$

$$F_d = \sqrt{\frac{4\delta}{1+\delta}} \cdot \sqrt{\frac{M_{e,k}}{1{,}1} \cdot d_{schroef} \cdot \frac{f_{h,1,k}}{1{,}3} \cdot 0{,}9}$$

$$F_d = 0{,}79 \cdot \sqrt{\frac{4\delta}{1+\delta}} \cdot \sqrt{M_{e,k} \cdot d_{schroef} \cdot f_{h,1,k}}$$

$$F_d = 0{,}79 \cdot F_k$$

$$factor = \frac{0{,}79 \cdot F_k}{0{,}69 \cdot F_k} = 1{,}15$$

For Mode II factor is 1,05

Fasteners in double shear

$$F_{\mathrm{v,Rk}} = \min \begin{cases} f_{\mathrm{h,1,k}} t_1 d & \text{(g)} \\ 0{,}5 f_{\mathrm{h,2,k}} t_2 d & \text{(h)} \\ 1{,}05 \dfrac{f_{\mathrm{h,1,k}} t_1 d}{2+\beta}\left[\sqrt{2\beta(1+\beta) + \dfrac{4\beta(2+\beta) M_{\mathrm{y,Rk}}}{f_{\mathrm{h,1,k}} d \; t_1^2}} - \beta\right] + \dfrac{F_{\mathrm{ax,Rk}}}{4} & \text{(j)} \\ 1{,}15 \sqrt{\dfrac{2\beta}{1+\beta}} \sqrt{2 M_{\mathrm{y,Rk}} f_{\mathrm{h,1,k}} d} + \dfrac{F_{\mathrm{ax,Rk}}}{4} & \text{(k)} \end{cases}$$

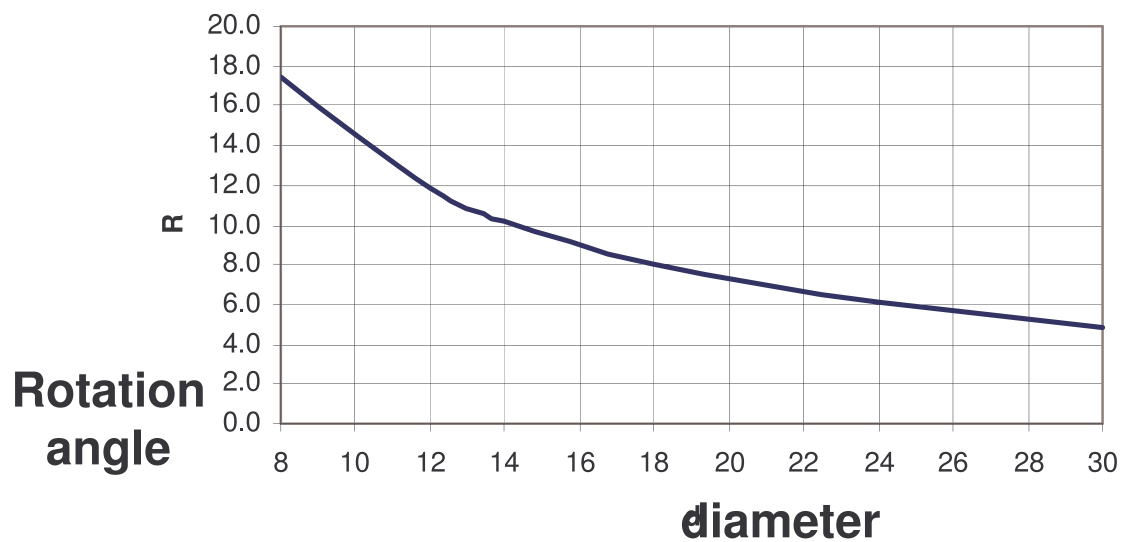
Eurocode 5 equations

Yield moment of dowel type fasteners

Large diameter bolts and dowels

Small rotation at failure → No full plastic yielding

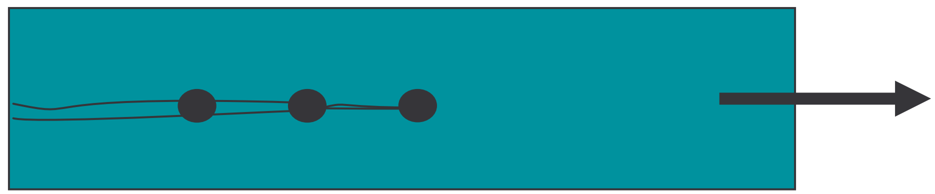
$$M_{y,Rk} = 0,3\, f_{u,k}\, d^{2,6}$$



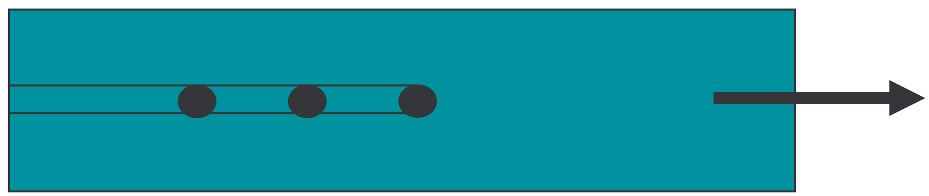
Background: Jorissen, A.J.M. Blass, H.J., the fastener yield strength in bending, In: Proceedings of CIB-W18 paper 31-7-6, 1998

Failure of multiple of fasteners in a row

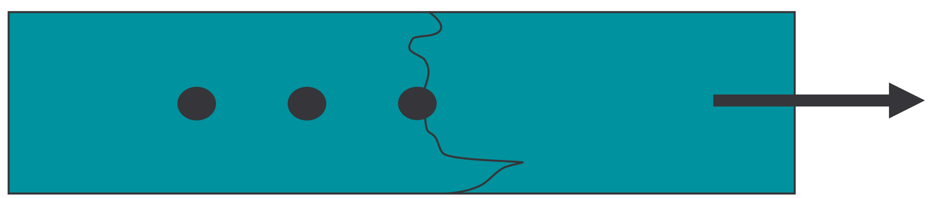
Splitting



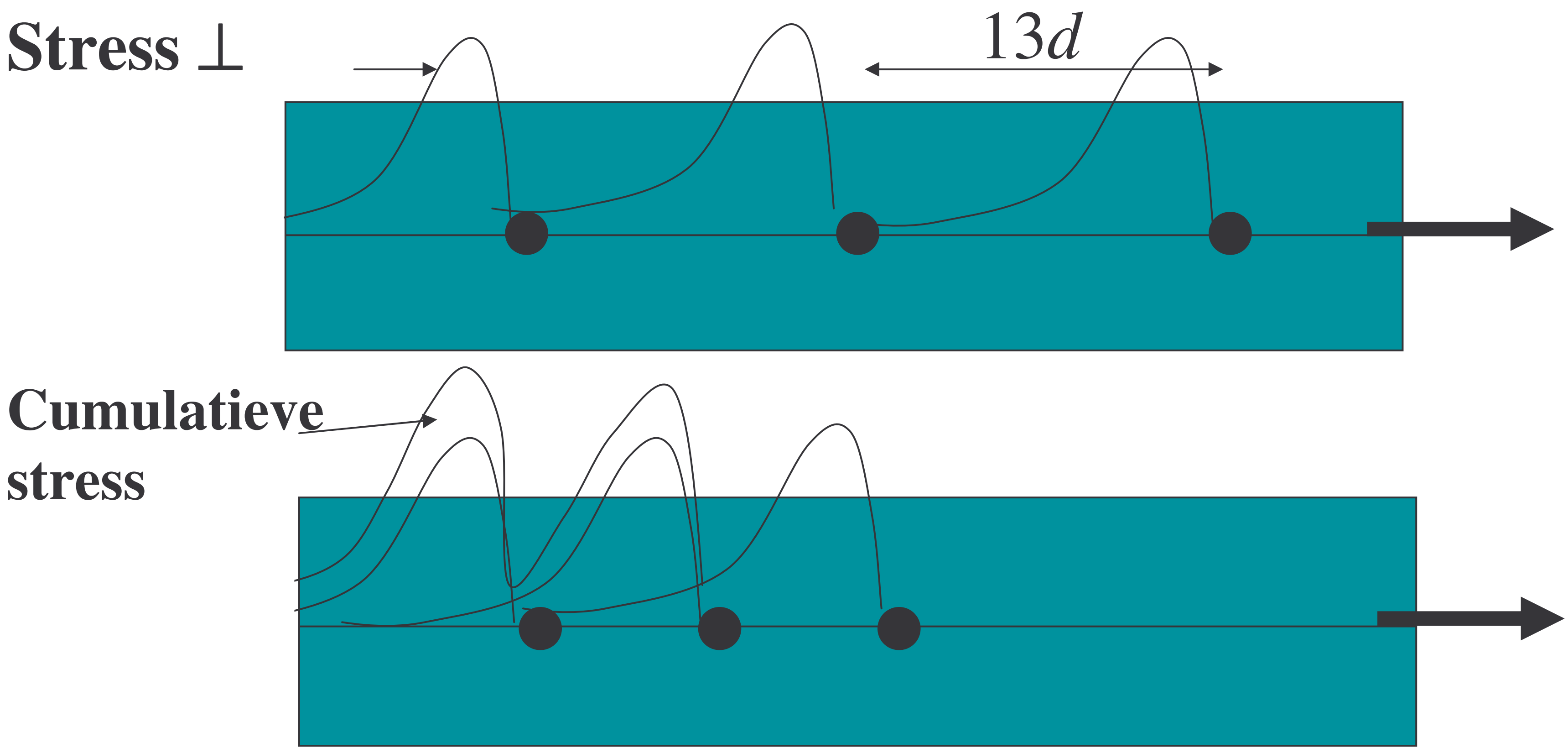
Shear



Tensile



Failure of multiple of fasteners in a row
Caused by group effect
→ Only for load component in grain direction



Failure of multiple of fasteners in one row

Caused by group effect→ effective number

Nails:

Empirical (Gehri)

$$n_{\text{ef}} = n^{k_{\text{ef}}}$$

Spacing[a]	k_{ef}		
	Not predrilled	Predrilled	
$a_1 \geq 14d$	1,0	1,0	
$a_1 = 10d$	0,85	0,85	
$a_1 = 7d$	0,7	0,7	
$a_1 = 4d$	-	0,5	

[a] For intermediate spacings, linear interpolation of k_{ef} is permitted

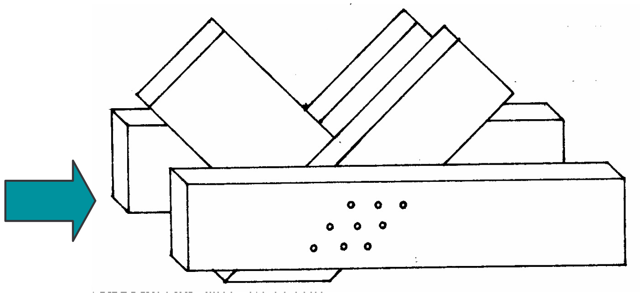
Bolts & dowels:

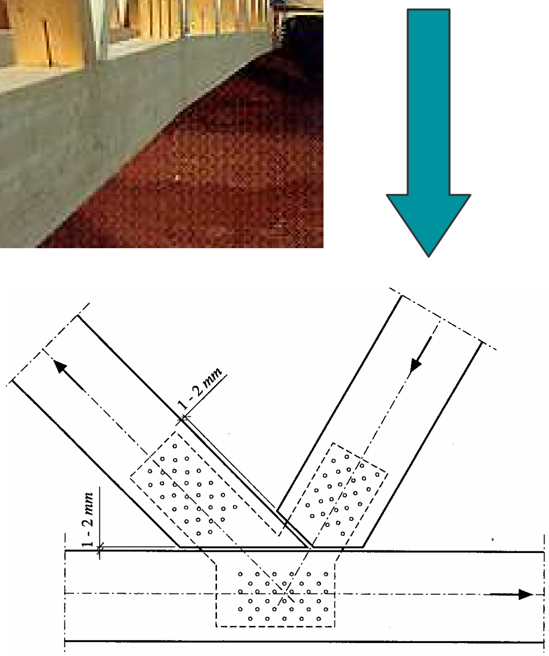
Fracture mechanics

$$n_{ef} = n^{0,9} \sqrt[4]{\frac{a_0}{13d}}$$

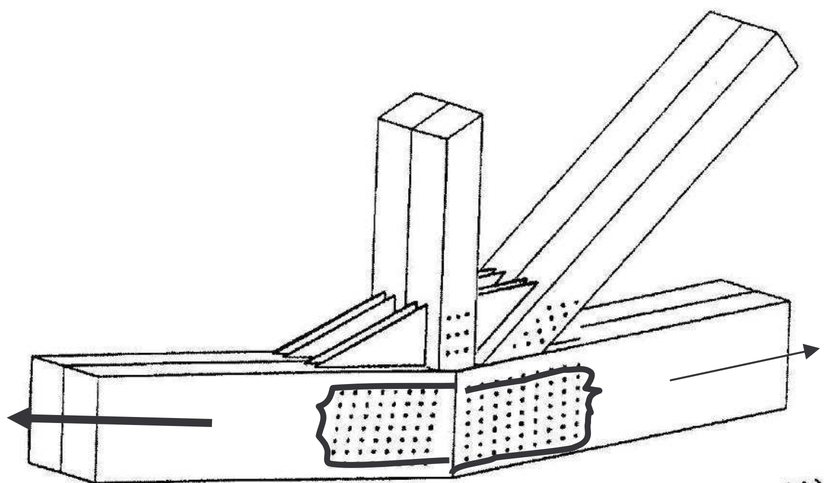
Background:
Double shear timber connections with dowel type fasteners, A.J.M. Jorissen, ISBN 90-407-1783-4, DUP Delft, 1998

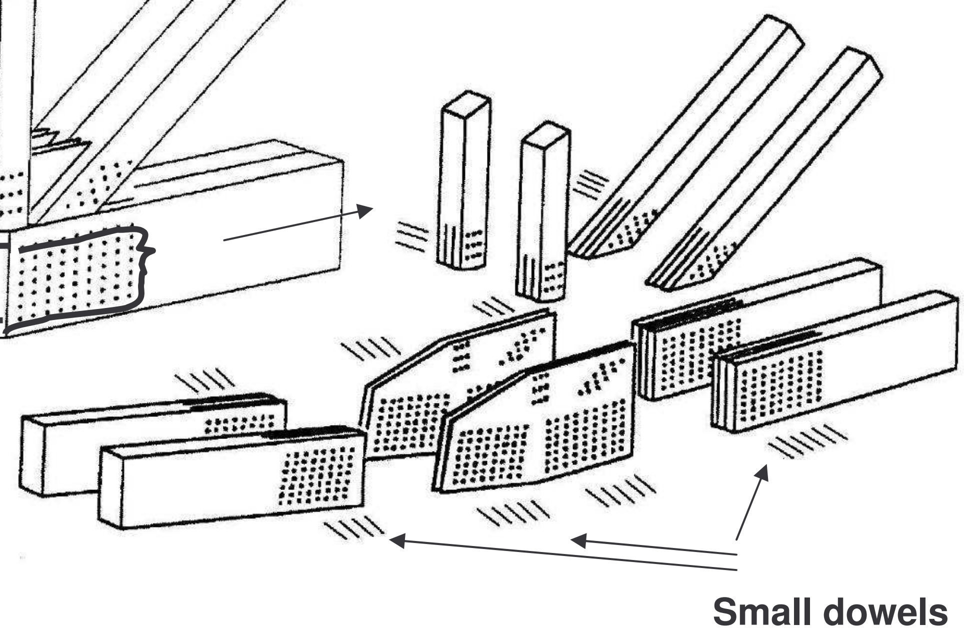
Be careful with cheese connections

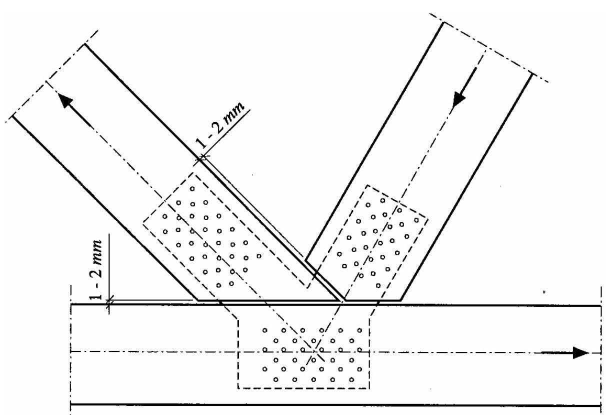




Steelplate – in – timber

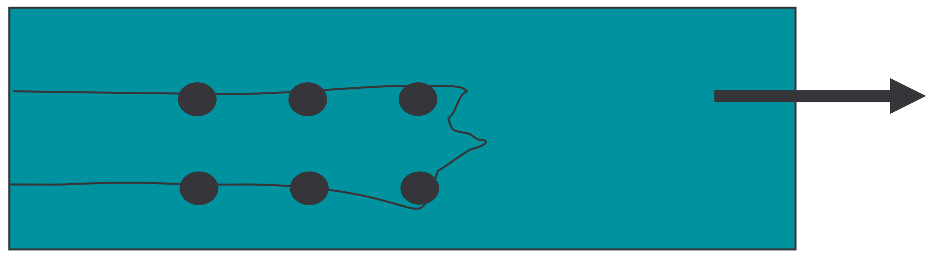




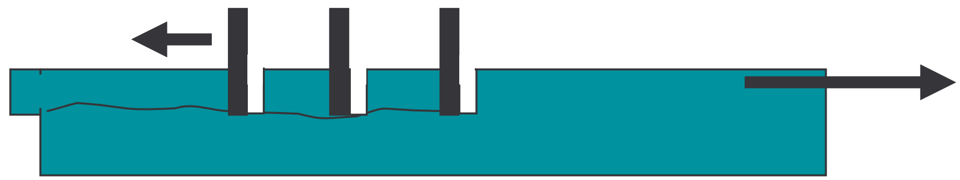


Failure at fastener perimeter (Prof.Racher, Fr.)

Block shear:
Full penetration



Plug shear
Partial penetration



Tensile or shear failure, which happens first?

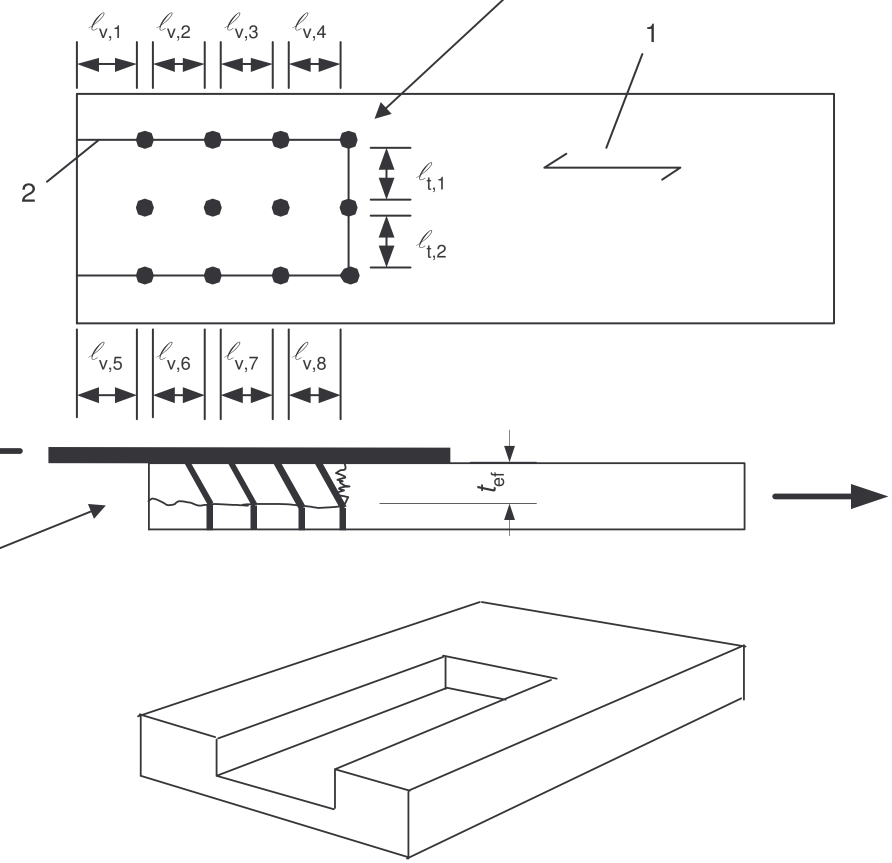
Literature: Johnson, H, Stehn, L, A Linear Fracture Mecanics Evaluation of Plug Shear Failure,In Proc of 8th world conf on Timber Engineering WCTE 2004, Finland

$$F_{\mathrm{bs,Rk}} = \max \begin{cases} 1{,}5\, A_{\mathrm{net,t}}\, f_{\mathrm{t,o,k}} \\ 0{,}7\, A_{\mathrm{net,v}}\, f_{\mathrm{v,k}} \end{cases}$$

Tensile failure

Shear fracture

Correlation parameters



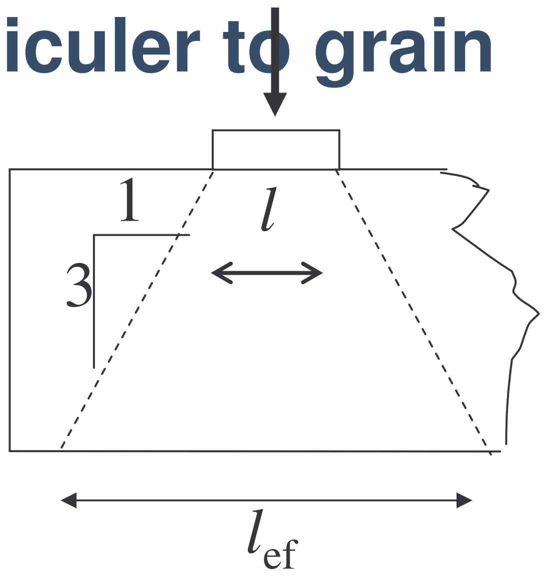
Fasteners keep straight

Not correct in EC5

see previous sheet

Amendment A1:
Contains:

New design rules for:
compressive strength perpendiculer to grain
Present rules unsafe



Amendment A1

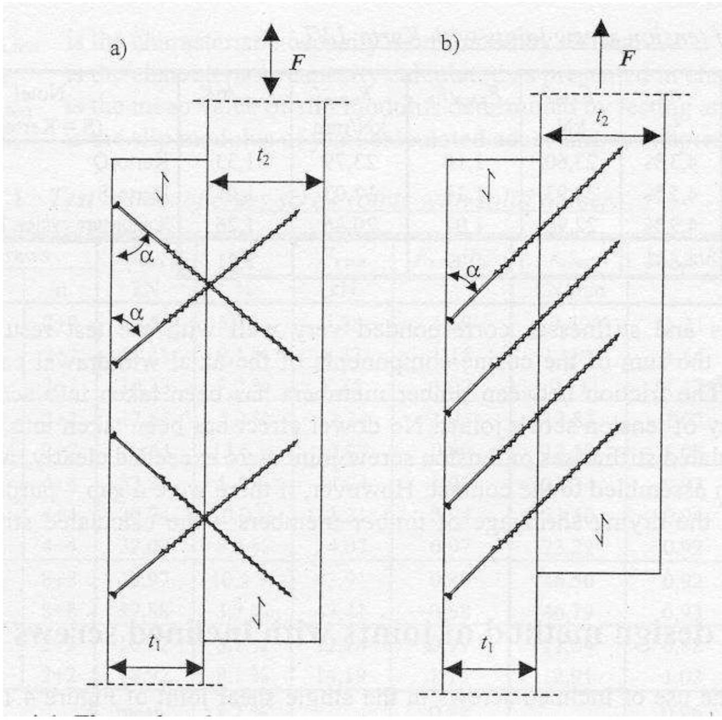
Addition
Axially loaded screws

Traditional screws
Diameter thread=smooth shank
Not very effective

- not hardened
- low bending moment
- >8mm requires predrilled holes

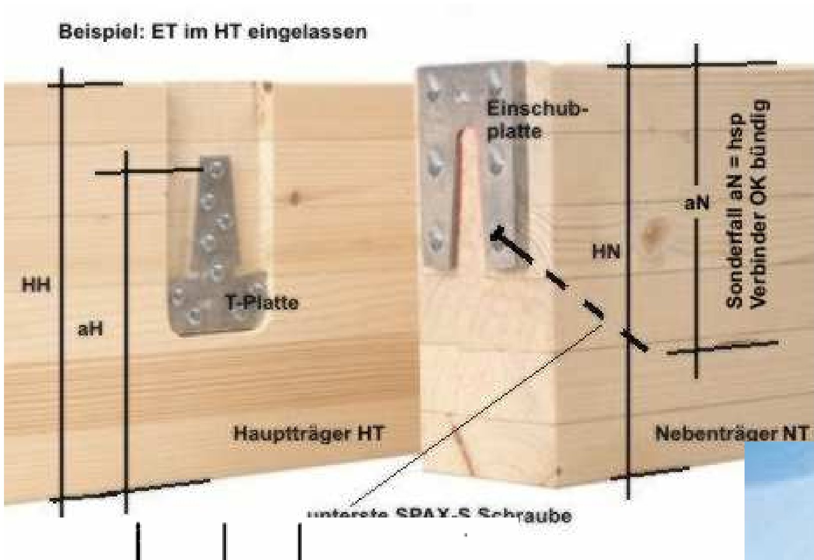
Amendment A1

Addition
Axially loaded screws



Very effective
hardened
self tapping
high axial stiffness

Background:
Blaß, HJ; Bejtka, I: Self-tapping screws as reinforcements in connections with dowel-type fasteners. In: Proceedings. CIB-W18 Meeting, Karlsruhe, Germany 2005. Paper 38-7-4
Blass H.J. Joints with dowel-type-fasteners, In: Timber Engineering Thelanderson and Larsen, editors, Wiley & Sons (2003):


Beispiel: ET im HT eingelassen
Einschub-
platte
aN
Sonderfall aN = hsp
Verbinder OK bündig
HN
HH
aH
T-Platte
Hauptträger HT
Nebenträger NT
unterste SPAX-S Schraube

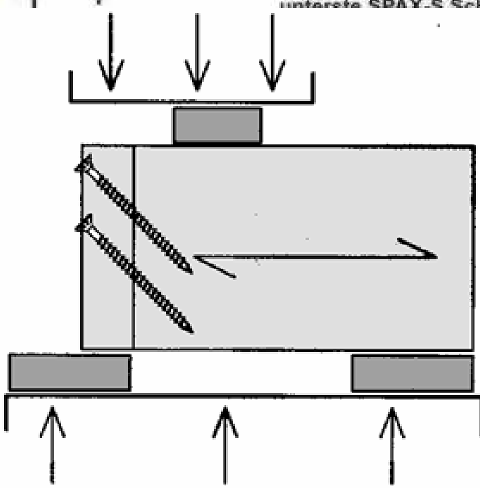



Bild 3


OV - Vollgewinde von 120 - 220 mm
Zul.-Nr. Z-9.1-610
40 mm
60 mm
80 mm
100 mm

Some examples

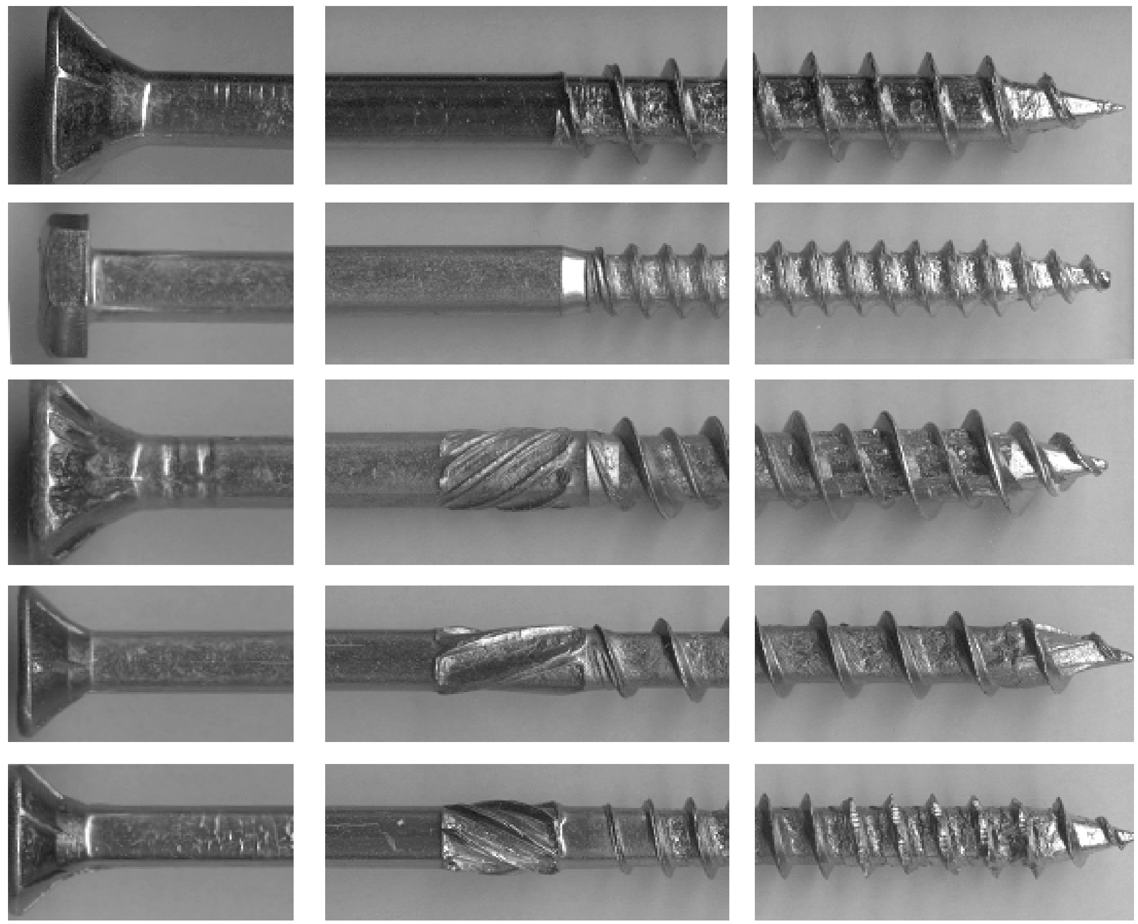
Spax

Leg or coach screw

Rapid

Heco

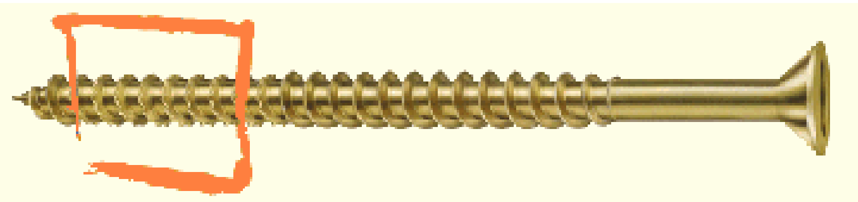
Tecfi



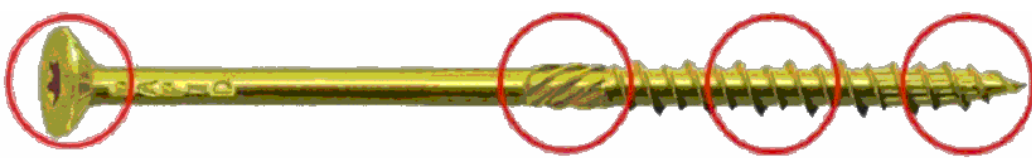
Some examples

Spax-S

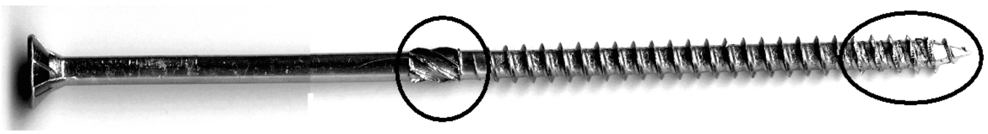
Heco Topix/Fix



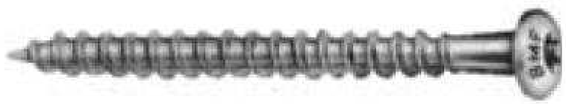
Rapid Komprex



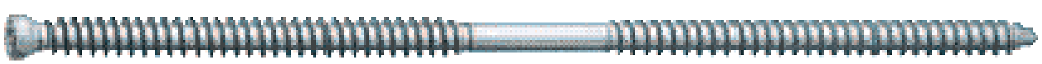
Tecfi Woodpecker



BMF Torx



SFS WT



Check:

- Withdrawal failure
- Tear-off failure of the head
- Pull through of the head
- Tensile failure of the screw
- Torsional capacity
- Group effect (n_{eff} number of effective fasteners)

-Withdrawal: Code proposals in EU countries

Eurocode 5 = (1)

(1) $$R_{ax,a,k} = \left(\pi \cdot d \cdot l_{ef}\right)^{0,8} \cdot \frac{3,6 \times 10^{-3} \rho_k^{1,5}}{\sin^2 a + 1,5 \cdot \cos^2 a}$$

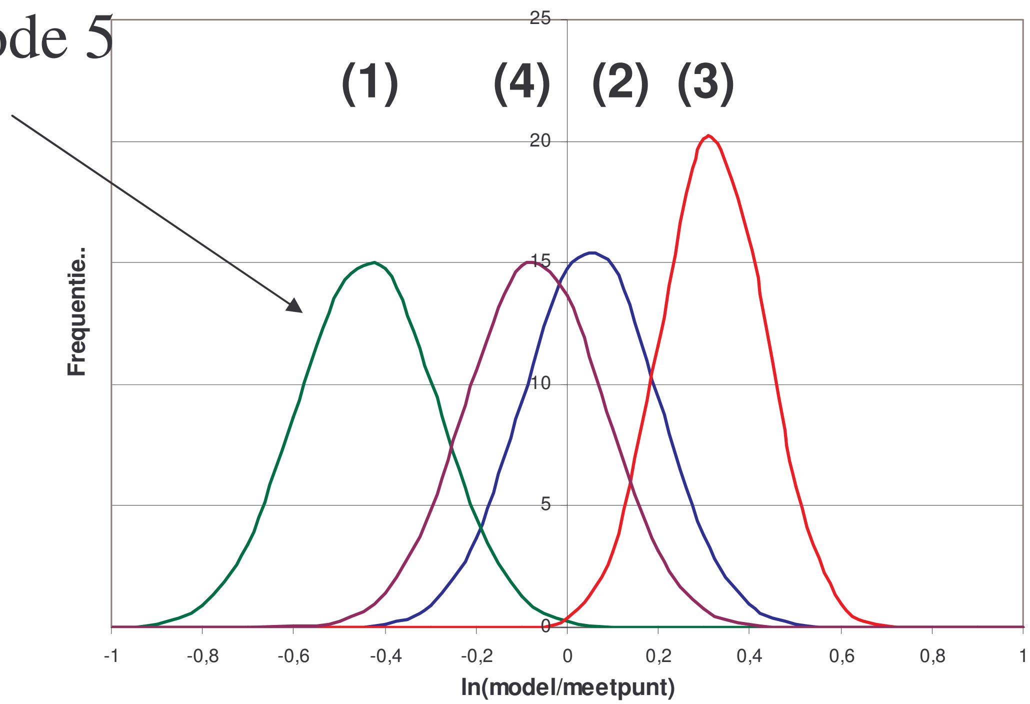
(2) $$R_{ax;k} = \frac{60 \times 10^{-6} \rho_k^{2}}{\sin^2 a + \frac{4}{3} \cdot \cos^2 a} \cdot d \cdot l_{ef}$$

(3) $$R_{ax,k} = \left(1,5 + 0,6 \cdot d_{nom}\right) \cdot \left(l_{hec} - d_{nom}\right) \cdot \sqrt{\rho}$$

(4) $$R_{ax,k} = 1,7 \cdot \left(\pi \cdot d_1 \cdot l_{ef}\right)^{0,8} \cdot \frac{3,0 \times 10^{-3} \cdot \rho_k}{\sin^2 a + 1,5 \cdot \cos^2 a}$$

Model uncertainty – evaluation of test results

Eurocode 5



Current EC5 design rule unsafe

New proposal in Amendment A1:

Requirement
Screws as defined in EN 14592

$$R_{ax,a,k} = n_{ef} \frac{0{,}52\sqrt{d}\,.l_{ef}^{0{,}9} \cdot \rho_k{}^{0{,}8}}{\sin^2 a + 1{,}2 \cdot \cos^2 a}$$

6 mm ≤ d ≤ 12 mm

All other screws:

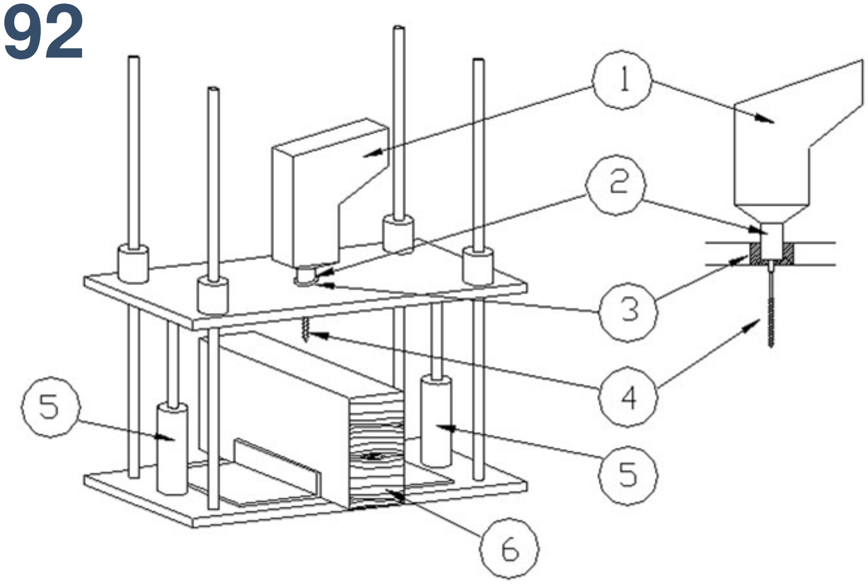
$$R_{ax,a,k} = n_{ef} \frac{f_{ax}.d.l_{ef}}{\sin^2 a + 1{,}2 \cdot \cos^2 a}\left(\frac{\rho_k}{\rho_a}\right)^{0{,}8}$$

Parameters determined by tests EN 14592 (EN 1382)

- Head tear off
- Axial screw strength:
  Determine by tests:
  EN 14592

$$R_{ax} = A \cdot f_{ax}$$

- Torsional capacity
  EN 14592



Head pull through
EN 14592
Test standard EN 1383

$$R_{ax} = A \cdot f_a$$

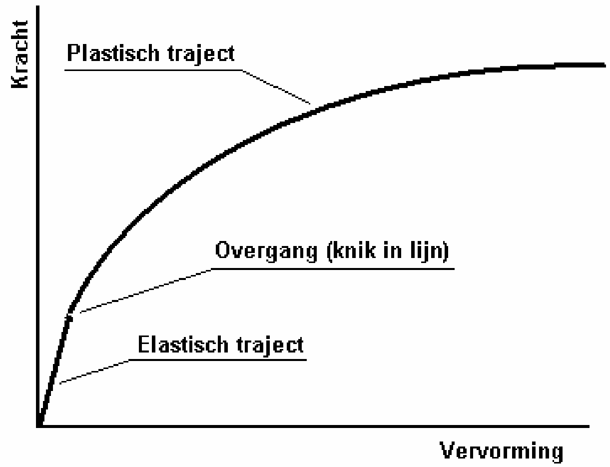
Eurocode 5:

$$R_k = \pi \cdot \left(\left(\tfrac{1}{2} \cdot d_k\right)^2 - \left(\tfrac{1}{2} \cdot d_s\right)^2 \right) \cdot 3{,}0 \cdot f_{c,90,k}$$

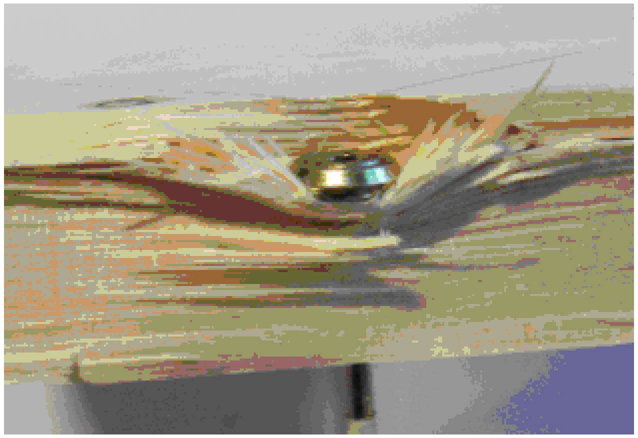
Zulassung Germany 9.1-235:

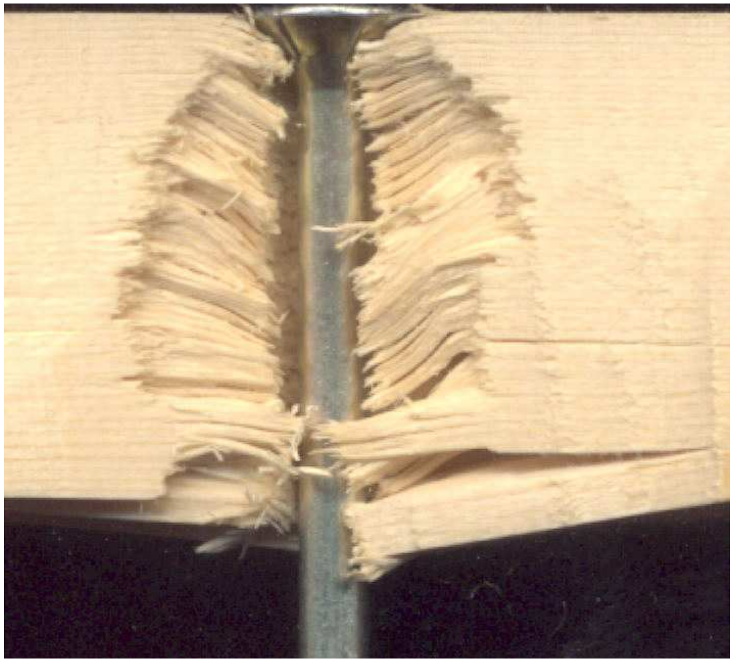
$$N_k = 16{,}0 \cdot d_k^{\;2}$$

In the absents of information Clause 8.5.2. bolt washers

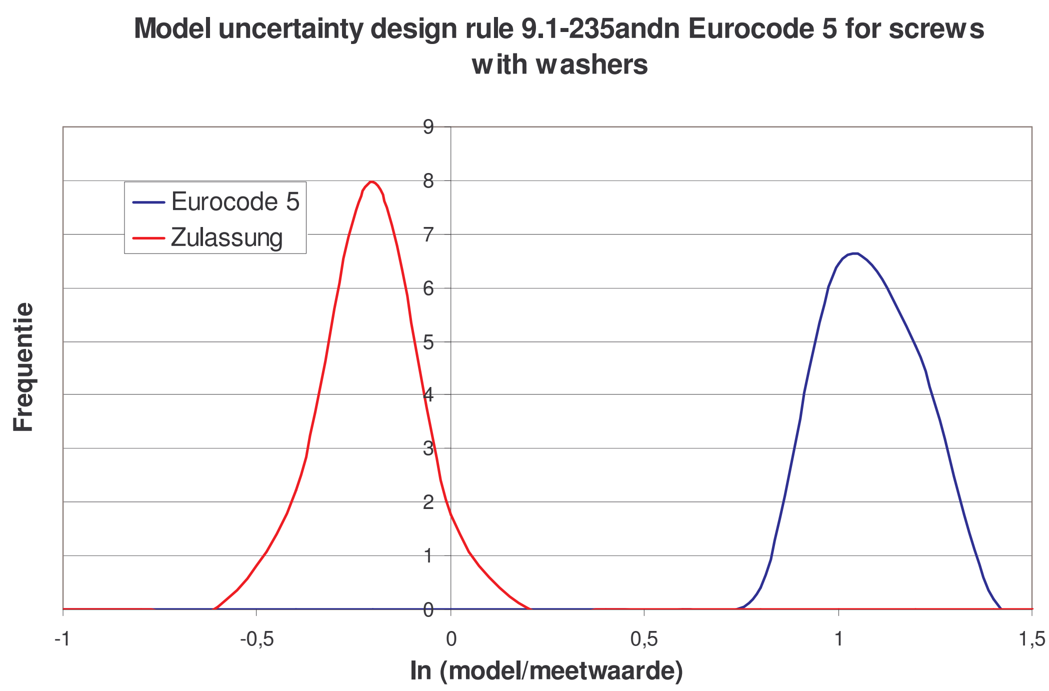


- short elastisch behaviour
- Large non-elastic traject



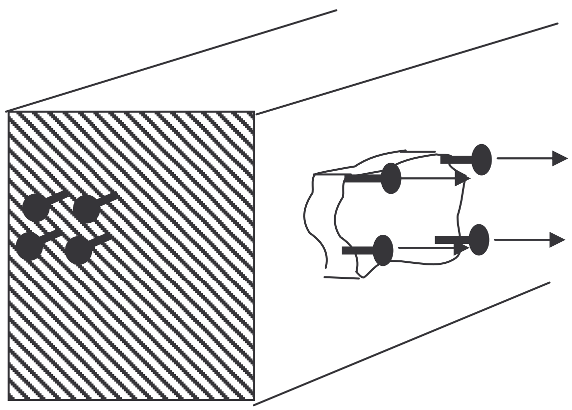


EN1995-1-1: Section 8 - Connections

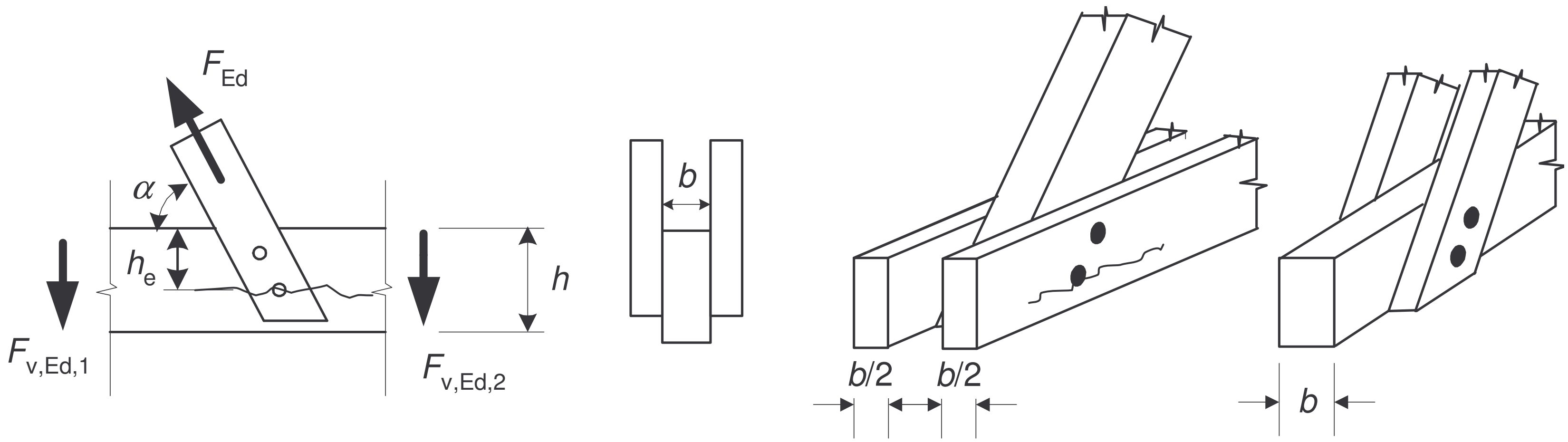


- **Group (tear out) effect:**
  Due to a lack of background information
  Based on test by Gehri (empirical):

$$n_{\mathrm{ef}} = n^{0,9}$$



Splitting by perpendicular to grain forces



a)

b)

Design clause 8.1.4 (3) is formulated as a maximum shear force criterion on either side of the connection

Background: Leijten A.J.M. & Vander Put T.A.C.M, Evaluation of Perpendicular to Grain Failure of Beams caused by Concentrated Loads of Joints, In: Proceedings of CIB-W18, paper 33-7-7, Delft, 2000.

Splitting by perpendicular to grain forces

Design clause 8.1.4 (3) is formulated as a maximum shear force criterion on either side of the connection

$$F_{90,\mathrm{Rk}} = 14\, b\, w \sqrt{\frac{h_\mathrm{e}}{\left(1 - \frac{h_\mathrm{e}}{h}\right)}}$$

Fracture mechanics background

14 is calibration parameter

w = (political factor)

$$w = \begin{cases} \max \begin{cases} \left(\frac{w_\mathrm{pl}}{100}\right)^{0,35} \\ 1 \end{cases} & \text{for punched metal plate fasteners} \\ 1 & \text{for all other fasteners} \end{cases}$$

Splitting by perpendicular to grain forces

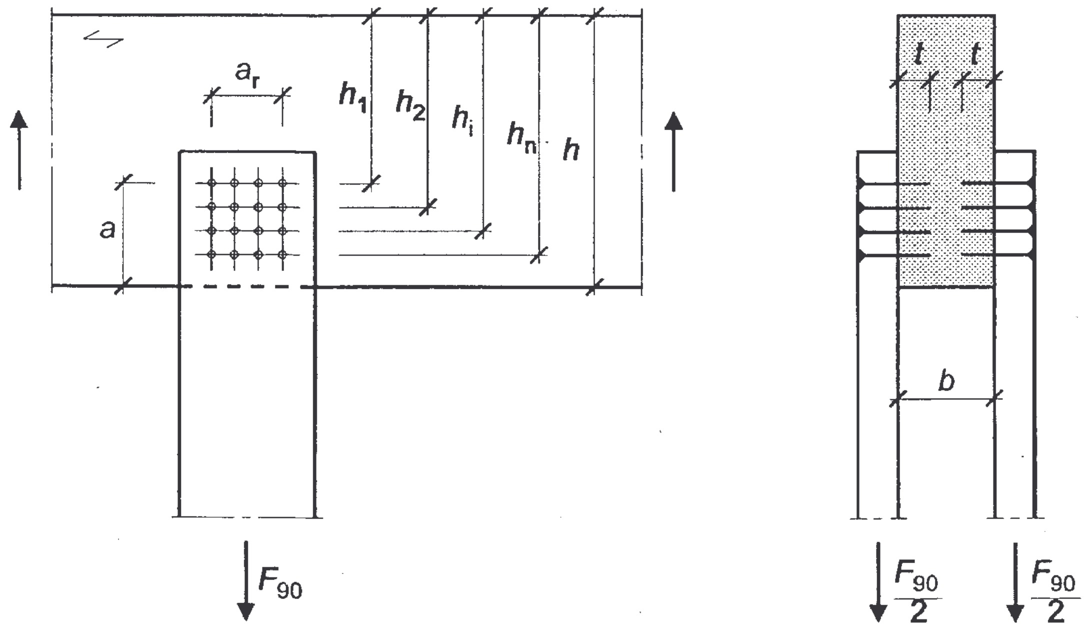
Some empirical models consider

Fastener spacing

$$F_{90,\mathrm{k}} = k_{\mathrm{s}} k_{\mathrm{r}} \left(6.5 + \frac{18a^2}{h^2} \right) (t_{\mathrm{ef}} h)^{0.8} f_{\mathrm{t,90,k}}$$

$$k_s = max \begin{cases} 1 \\ 0.7 + \dfrac{1.4a}{h} \end{cases}$$

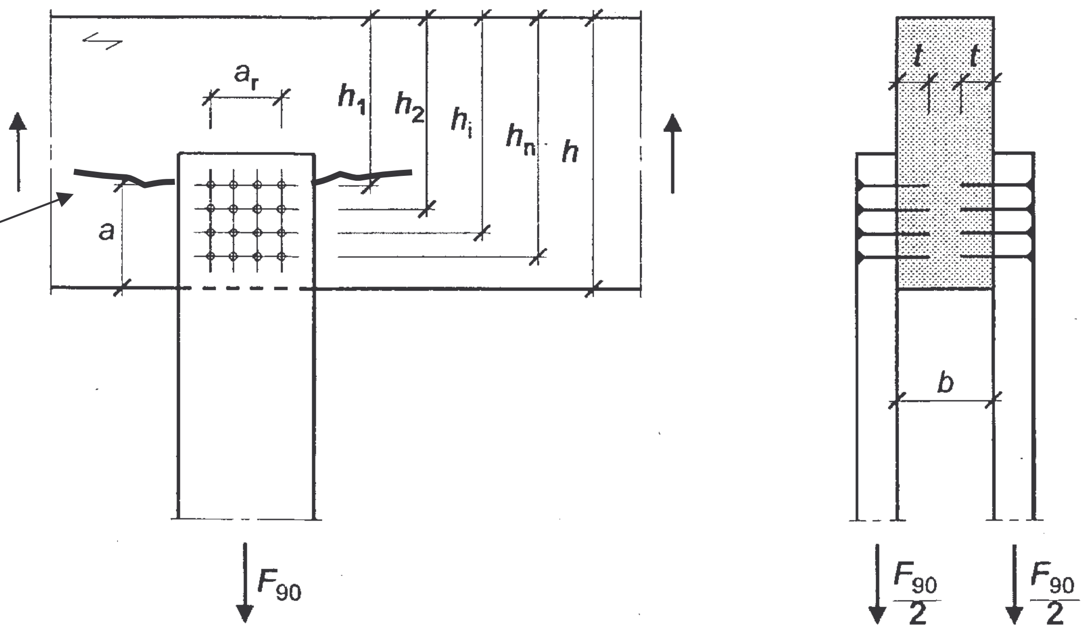
$$k_r = \frac{n}{\sum_{i=1}^{n} \left(\dfrac{h_1}{h_i} \right)^2}$$



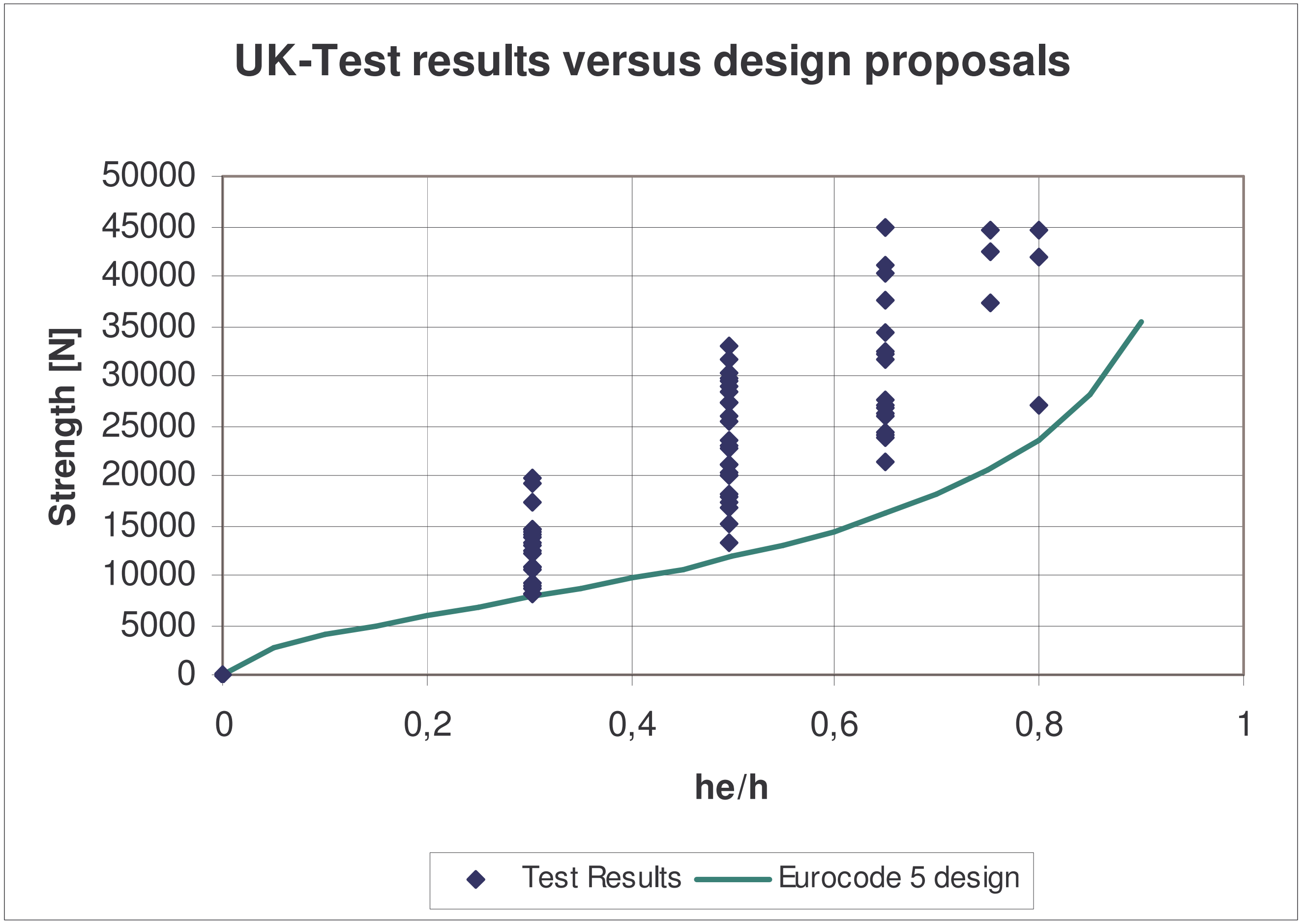
Splitting by perpendicular to grain forces

Fracture mechanical model

Consider energy balance after crack appearance

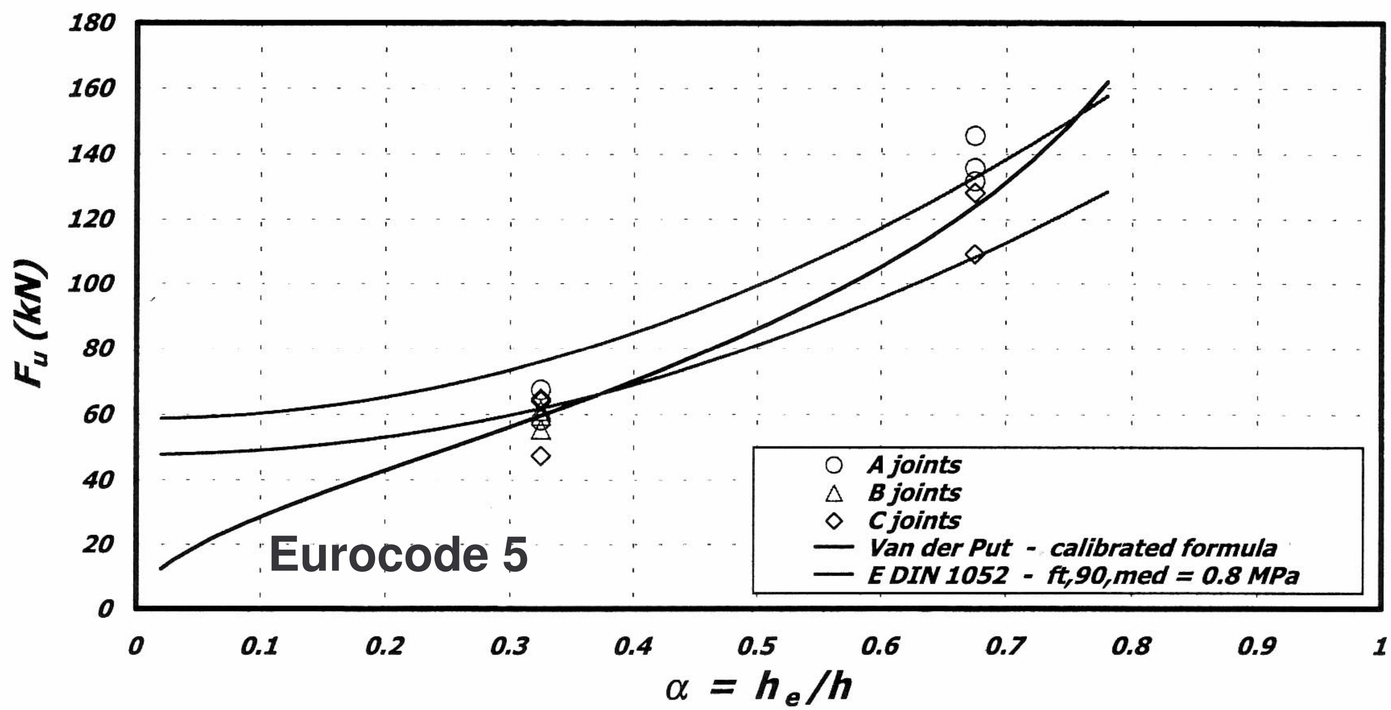


Splitting by perpendicular to grain forces



Punched metal plate fasteners

Comparison between models

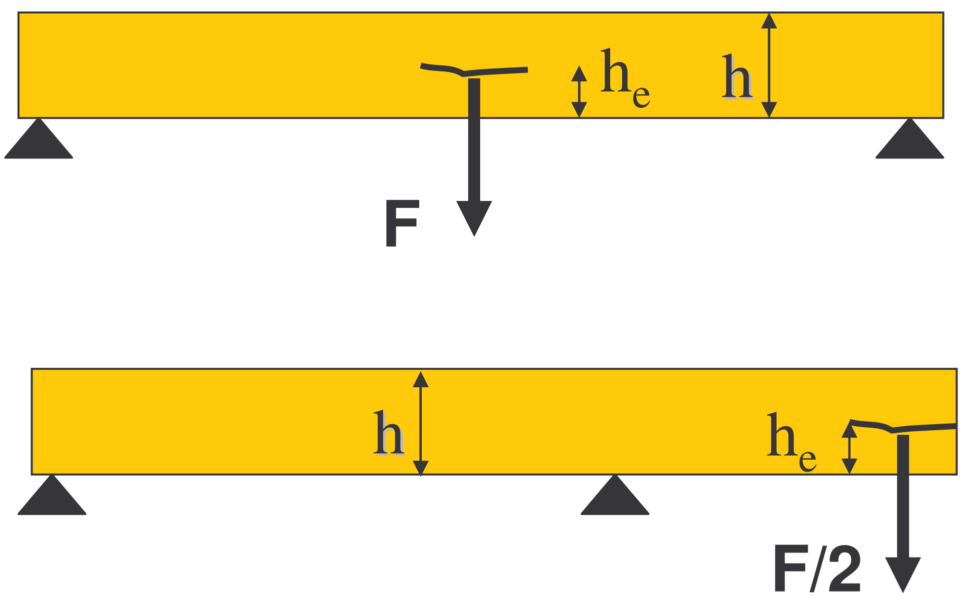


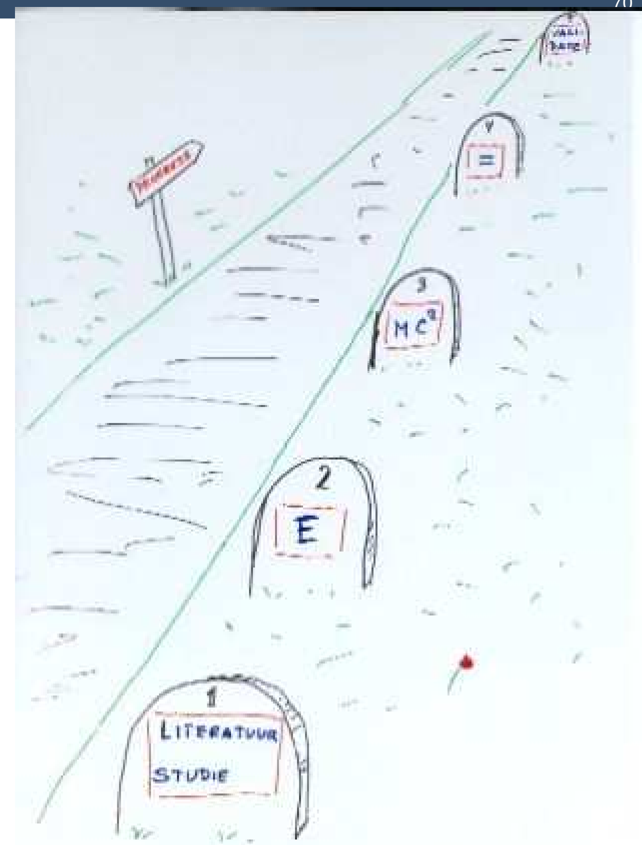
Splitting by perpendicular to grain forces

Assumed governing failure mechanism is shear
Not by tensile stresses perpendicular to grain

For loaded edges
>0,7 h → no splitting

Simply supported
→max F
Cantilever beam
→ max F/2





Frequently heard:

Not found in Eurocode

We don’t know everything

Research in progress
Future changes and additions are expected