

TIMBER CONNECTIONS

by

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Former PT-member

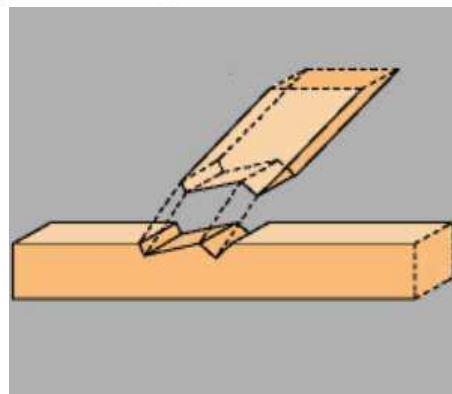
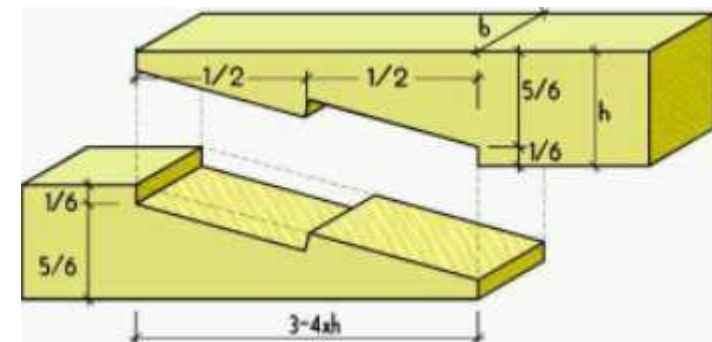
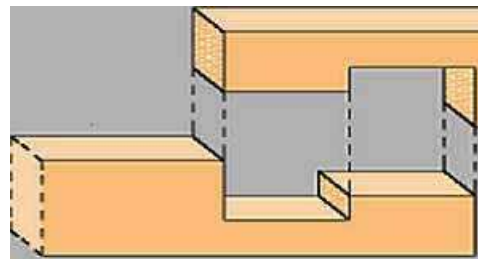
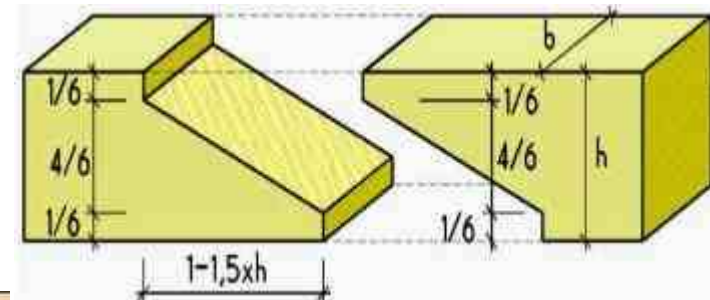
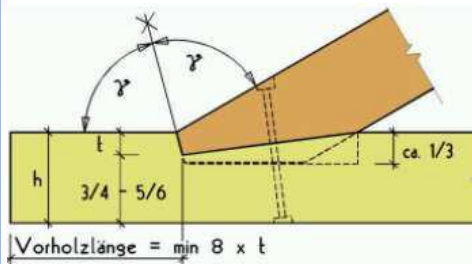
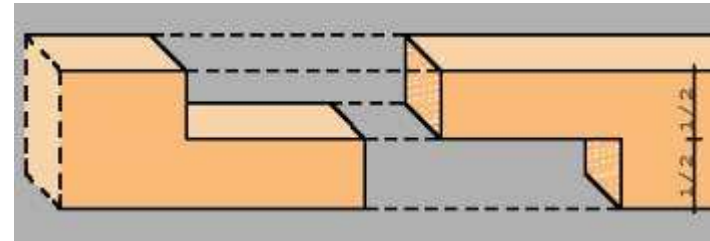
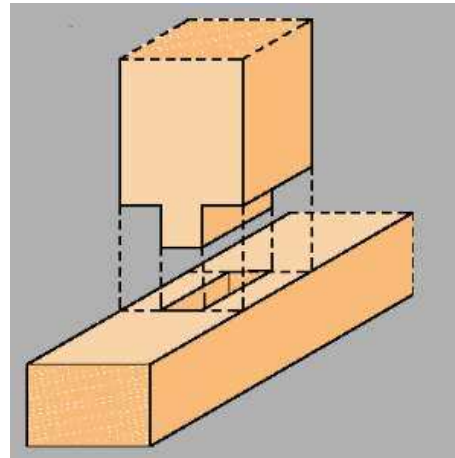
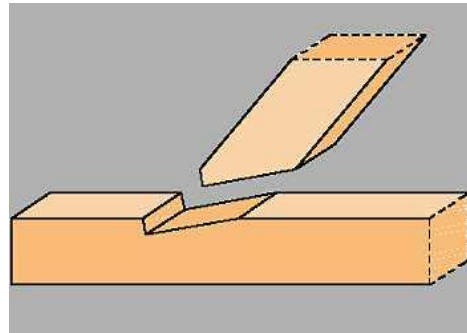


We can not escape connections

THE WEAKEST LINK

What kind of connections do we use?

Carpenter connections (not in Eurocode 5)

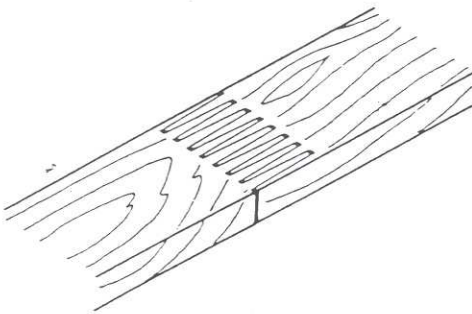
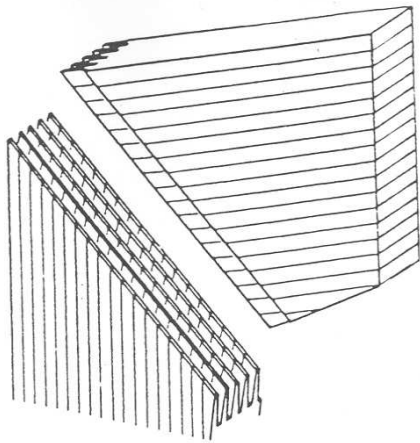


National regulations apply

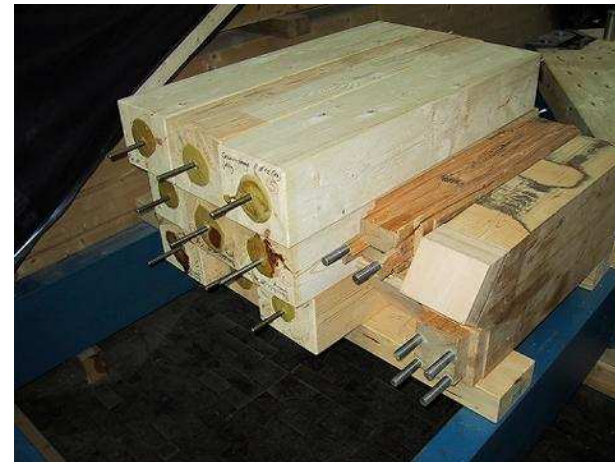


Carpenter connections → compression forces

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

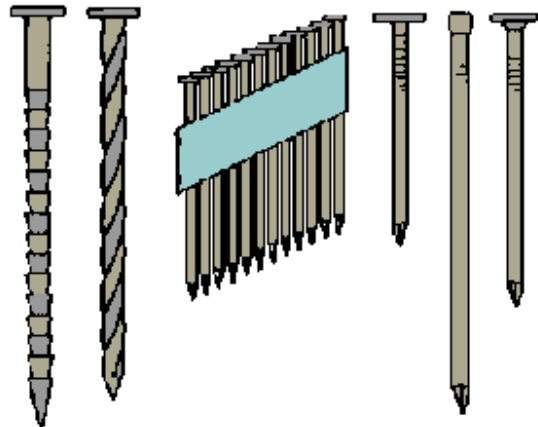
Mechanical connections with

Dowel type fasteners

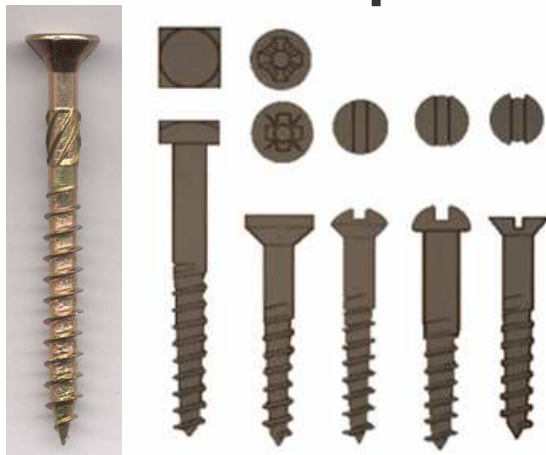
- Nails, staples,
- punched metal plates,
- screws,
- dowels and bolts

Connectors

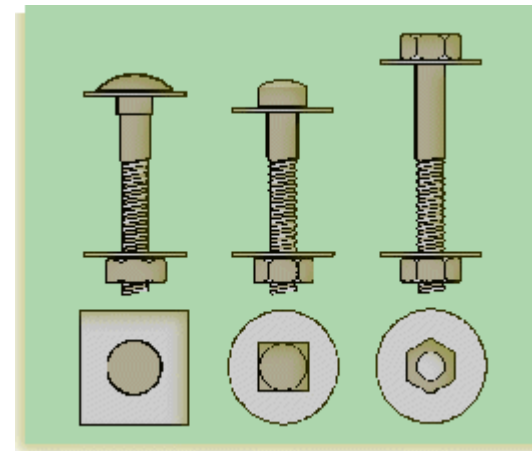
- **Shear plates**
- **Split-rings**



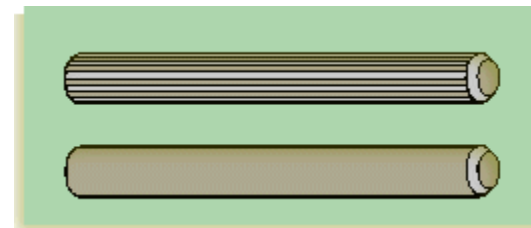
Nails < 8 mm (EN14592)
definition profiled nails



Screws

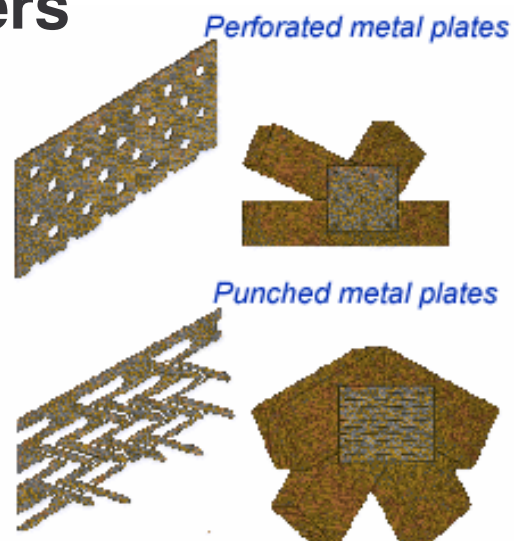


Bolts > 8 mm



Dowels > 6 mm

Punched metal plate fasteners

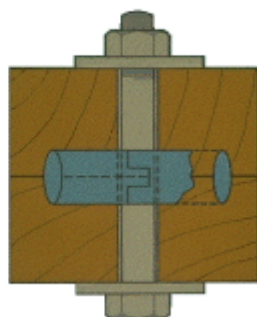


Split-ring connectors

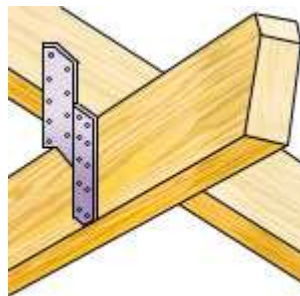
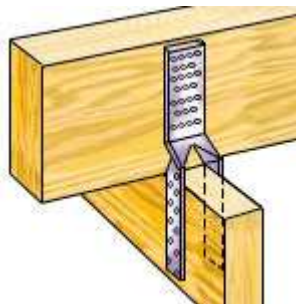
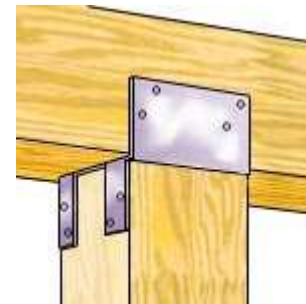
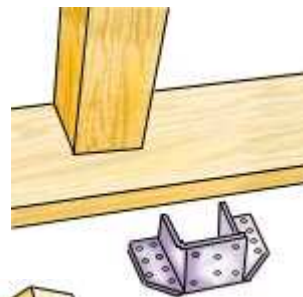
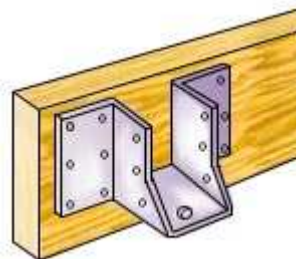
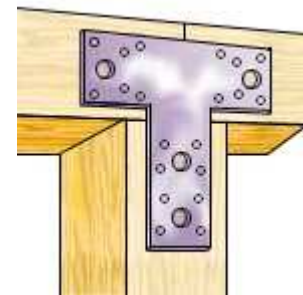
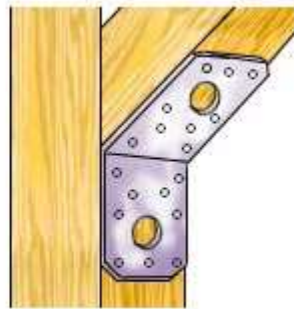
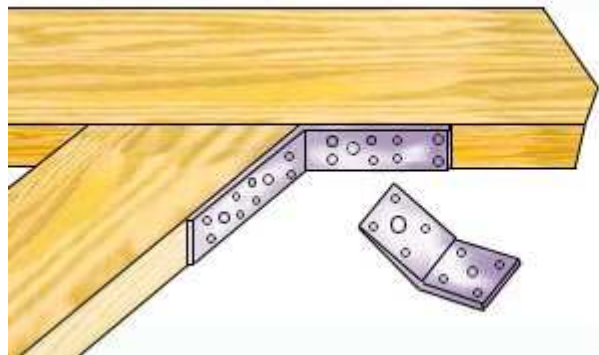
64- 104 mm diameter



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.



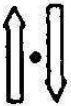
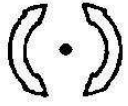


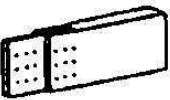

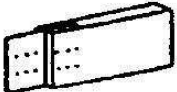

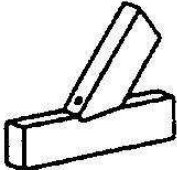


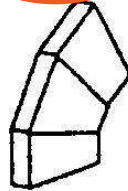
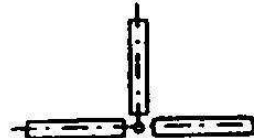
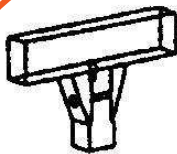
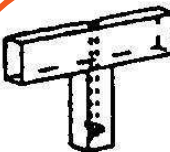
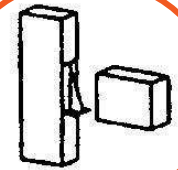
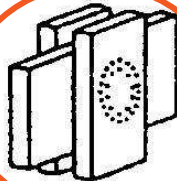
EN 26891 – Specimen density selection.

EN 28970 – Test procedure for connection tests.

Design by calculation

- Model provided in EN1995-1-1

Design by calculation - covers

Geometrie	Normaal krachten		Afschuiving	Moment
				
				
				
				

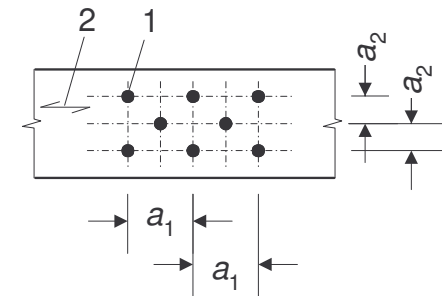
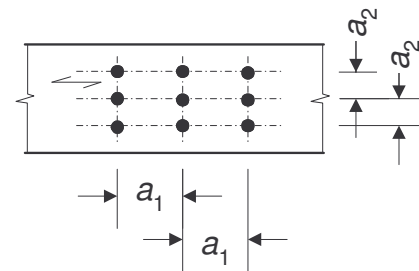


Fastener spacing requirements

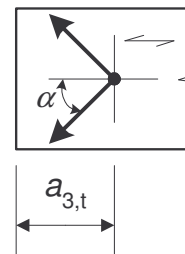
Key:

- (1) Loaded end
- (2) Unloaded end
- (3) Loaded edge
- (4) Unloaded edge

a)

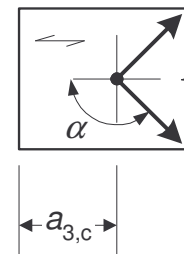


b)



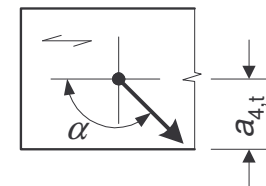
$$-90^\circ \leq \alpha \leq 90^\circ$$

(1)



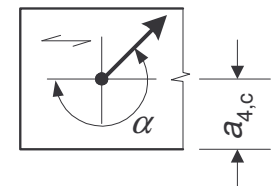
$$90^\circ \leq \alpha \leq 270^\circ$$

(2)



$$0^\circ \leq \alpha \leq 180^\circ$$

(3)



$$180^\circ \leq \alpha \leq 360^\circ$$

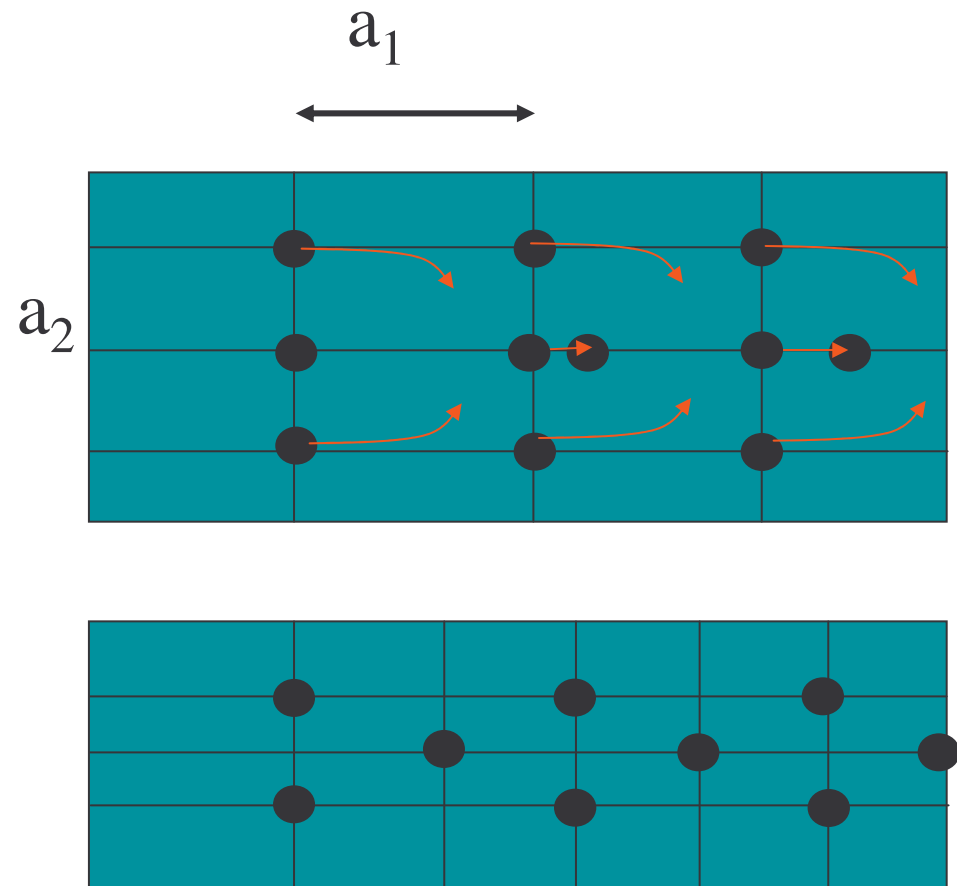
(4)

Fastener spacing requirements (bolts)

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

Spacing requirements determine timber dimensions

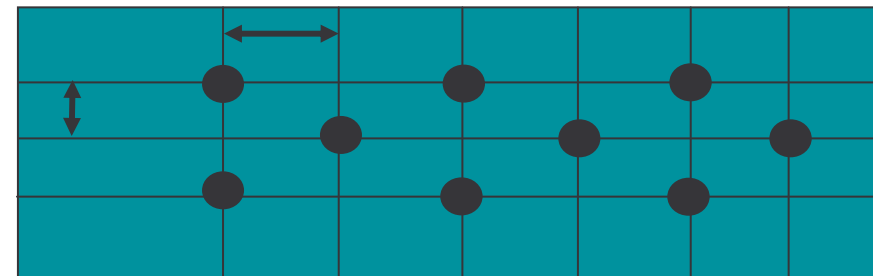
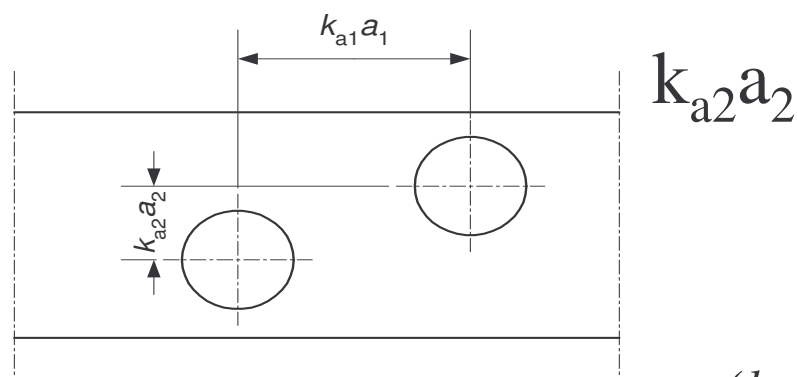
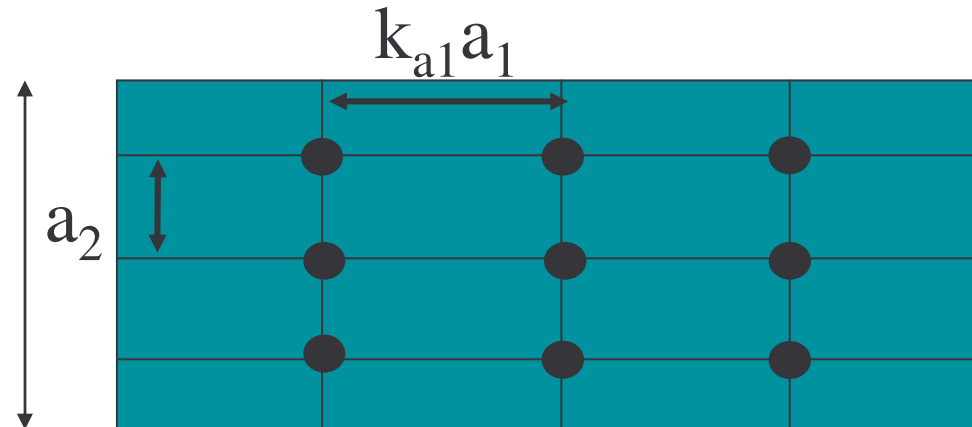
**Decrease member
width ?**



Spacing requirements determine timber dimensions

Only for connectors

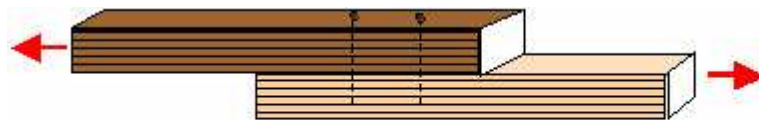
Split-rings and
shear plates



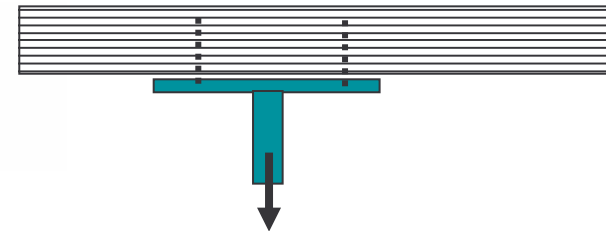
$$(k_{a1})^2 + (k_{a2})^2 \geq 1$$

with

$$\begin{cases} 0 \leq k_{a1} \leq 1 \\ 0 \leq k_{a2} \leq 1 \end{cases}$$



Timber/timber connection



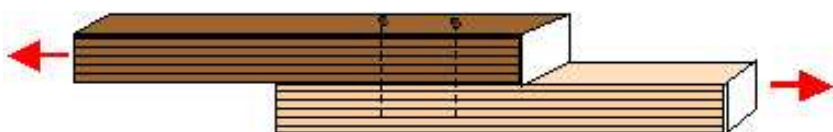
Laterally loaded axially loaded

**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



Timber/timber connection



Timber/timber connection – nail plate



Timber/plywood connection



Timber/heavy gauge steel connection

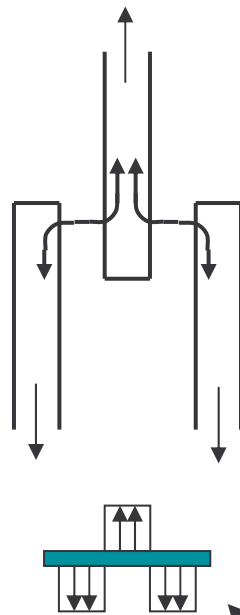


Timber/ dowelled fin plate connection

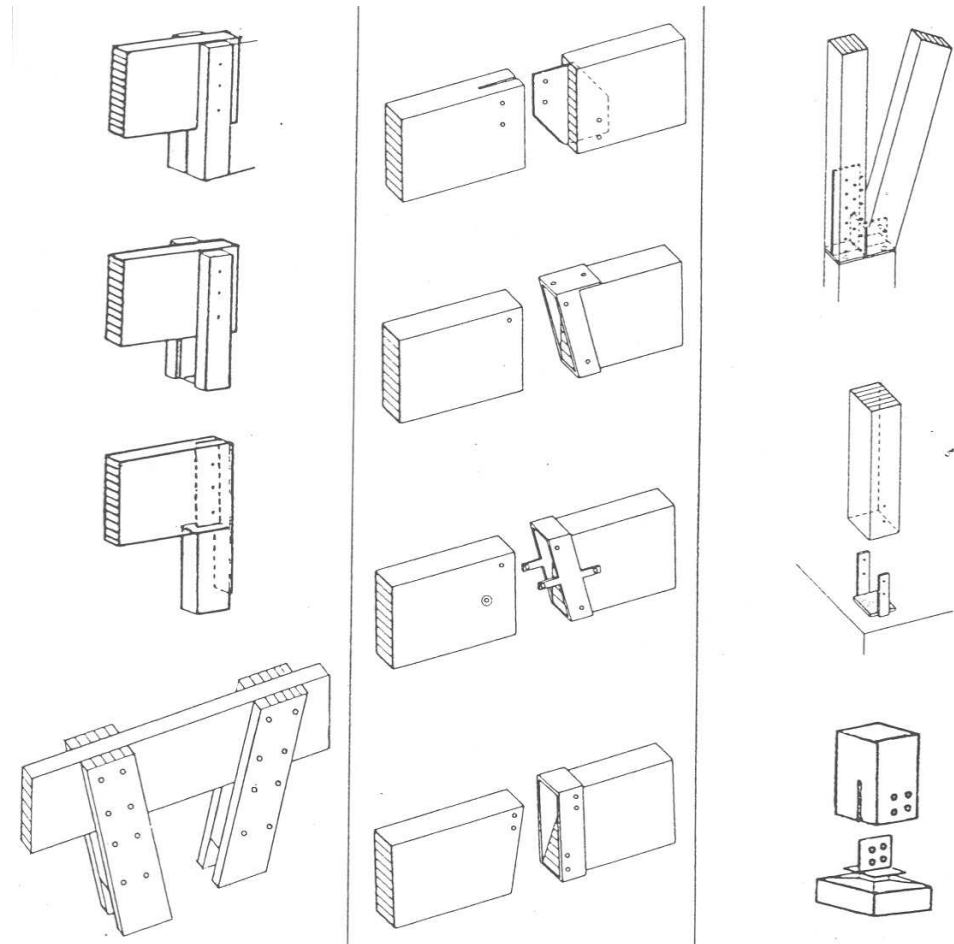
**single shear
fasteners**

multiple shear

Double shear

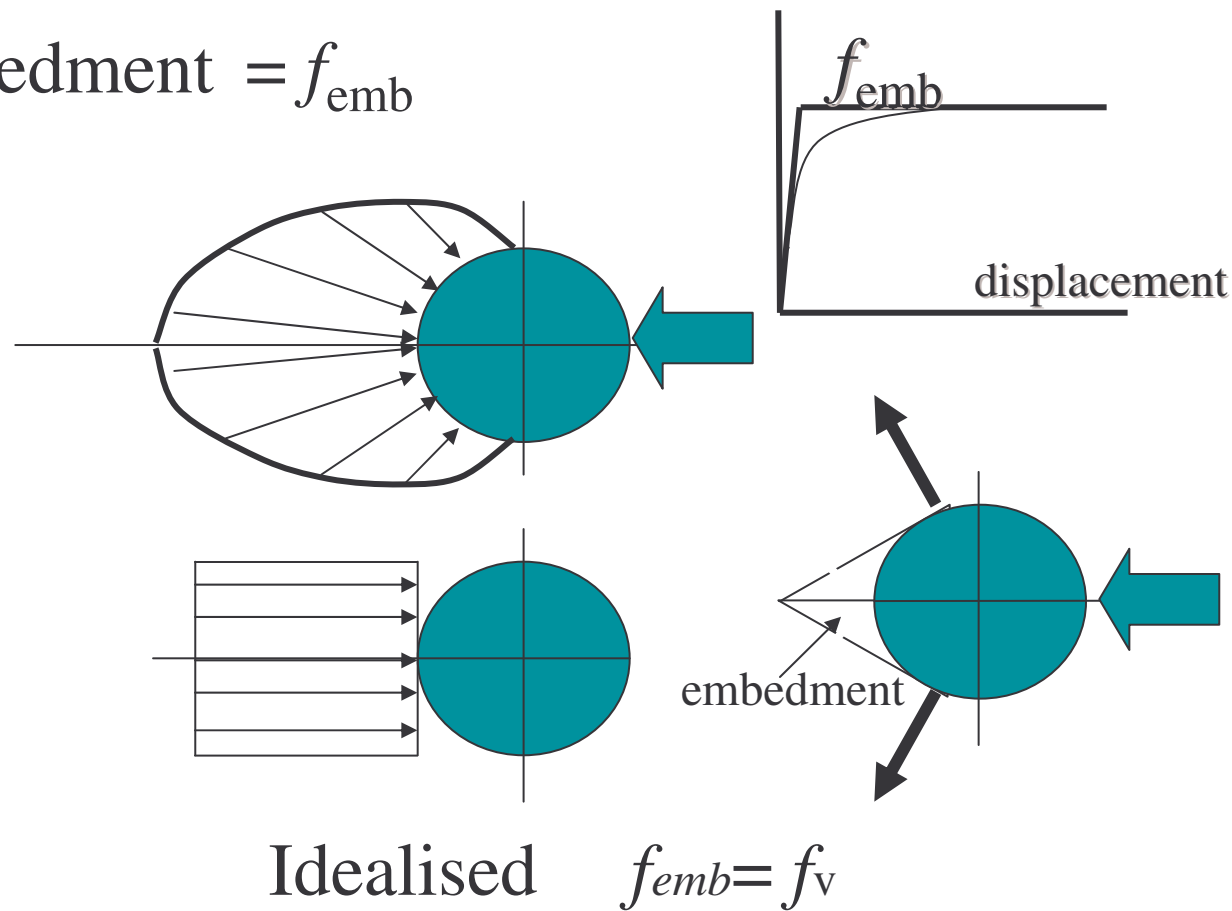


Embedment stresses

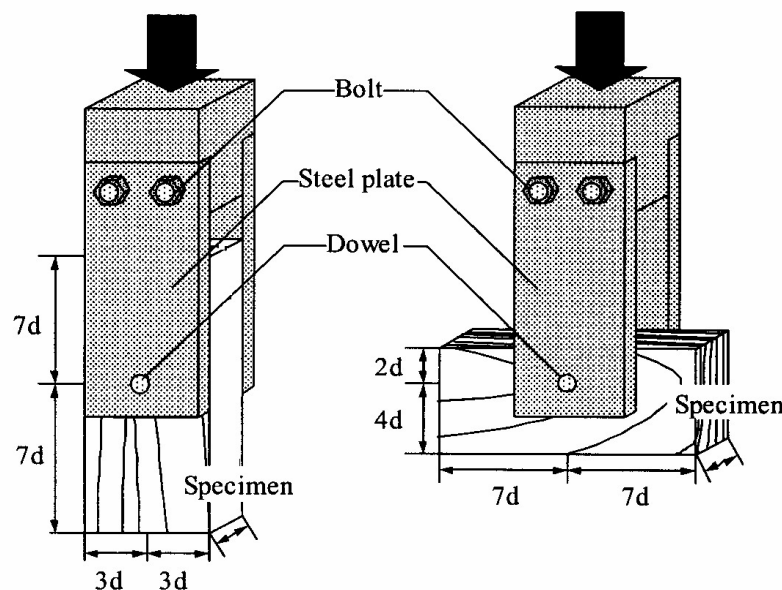


Starting point for strength model - Embedment strength

Embedment = f_{emb}



Determination of embedment strength –EN 383



Eurocode 5 Design clause embedment strength

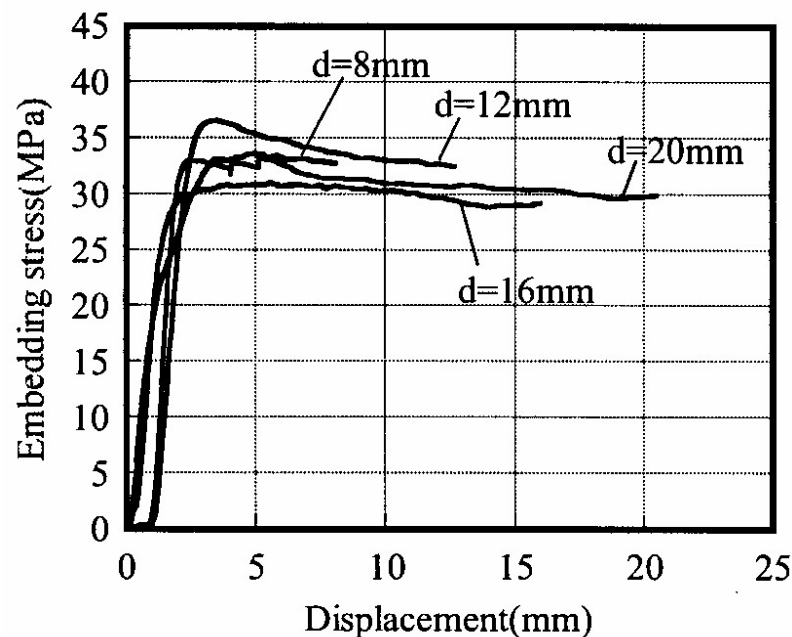
Nails (not pre-drilled) $f_{h,k} = 0,082 \rho_k d^{-0,3}$ N/mm²

Nails pre-drilled

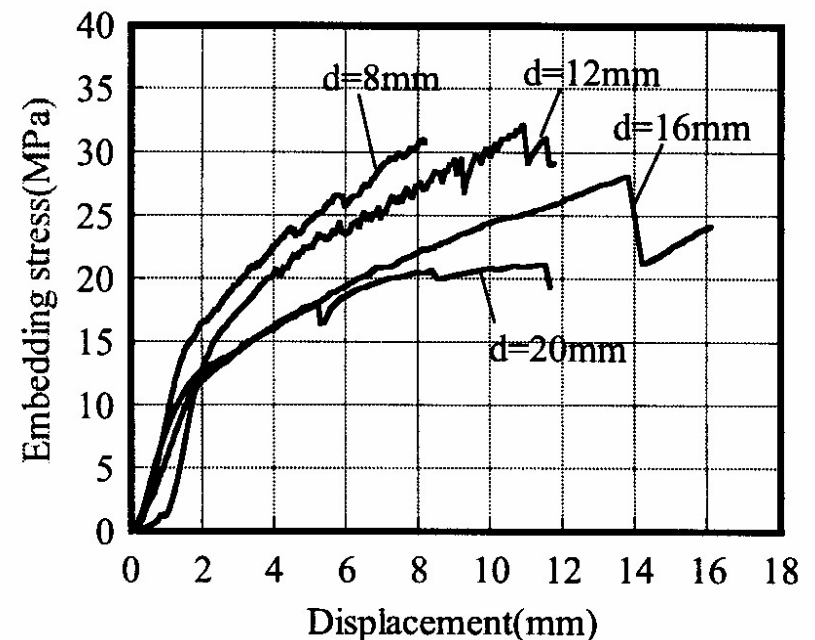
Bolts/dowels

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

Parallel



Perpendicular

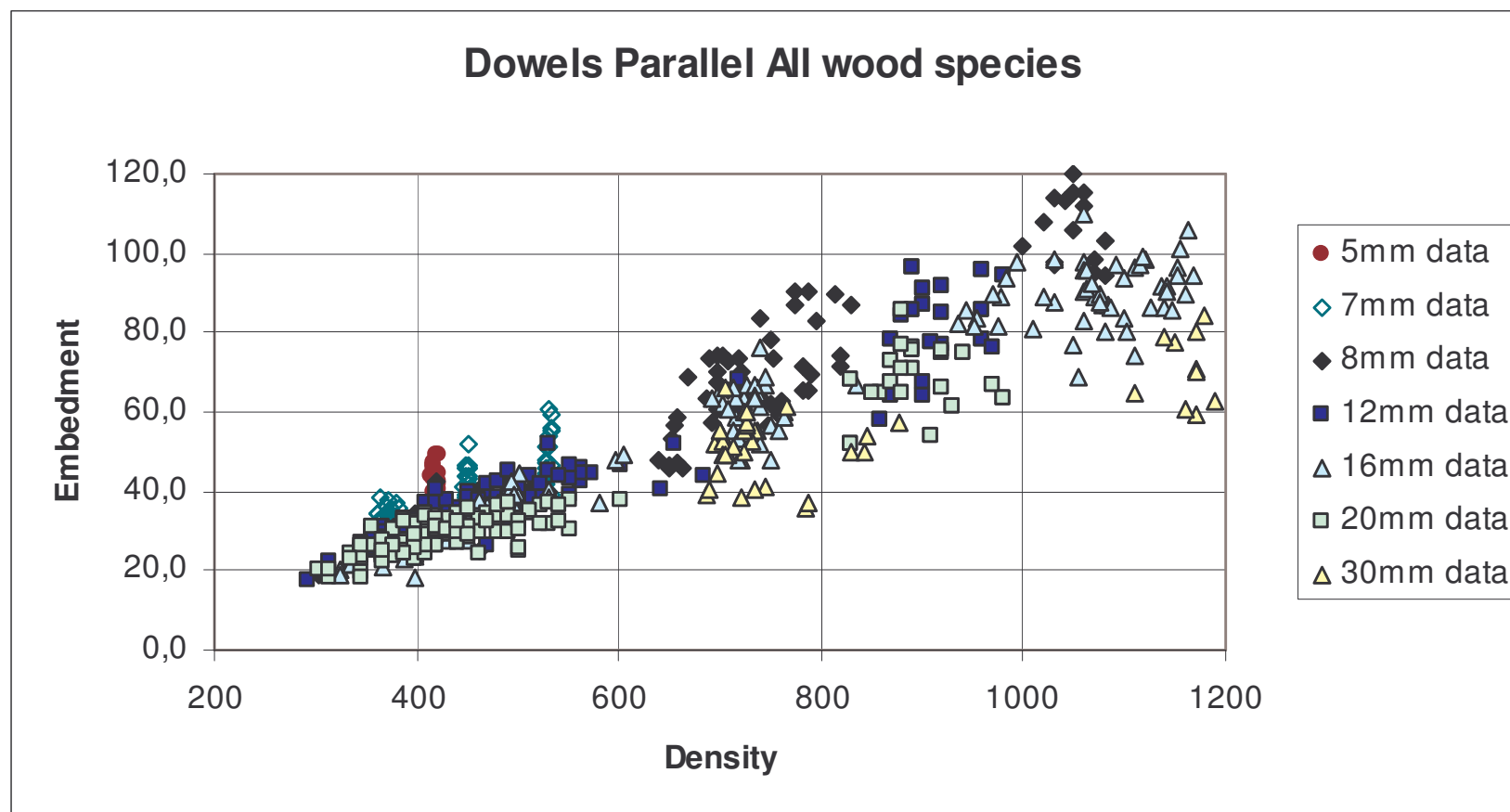


Taken from Sawata and Yasumura (2002).

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/ Firenze 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

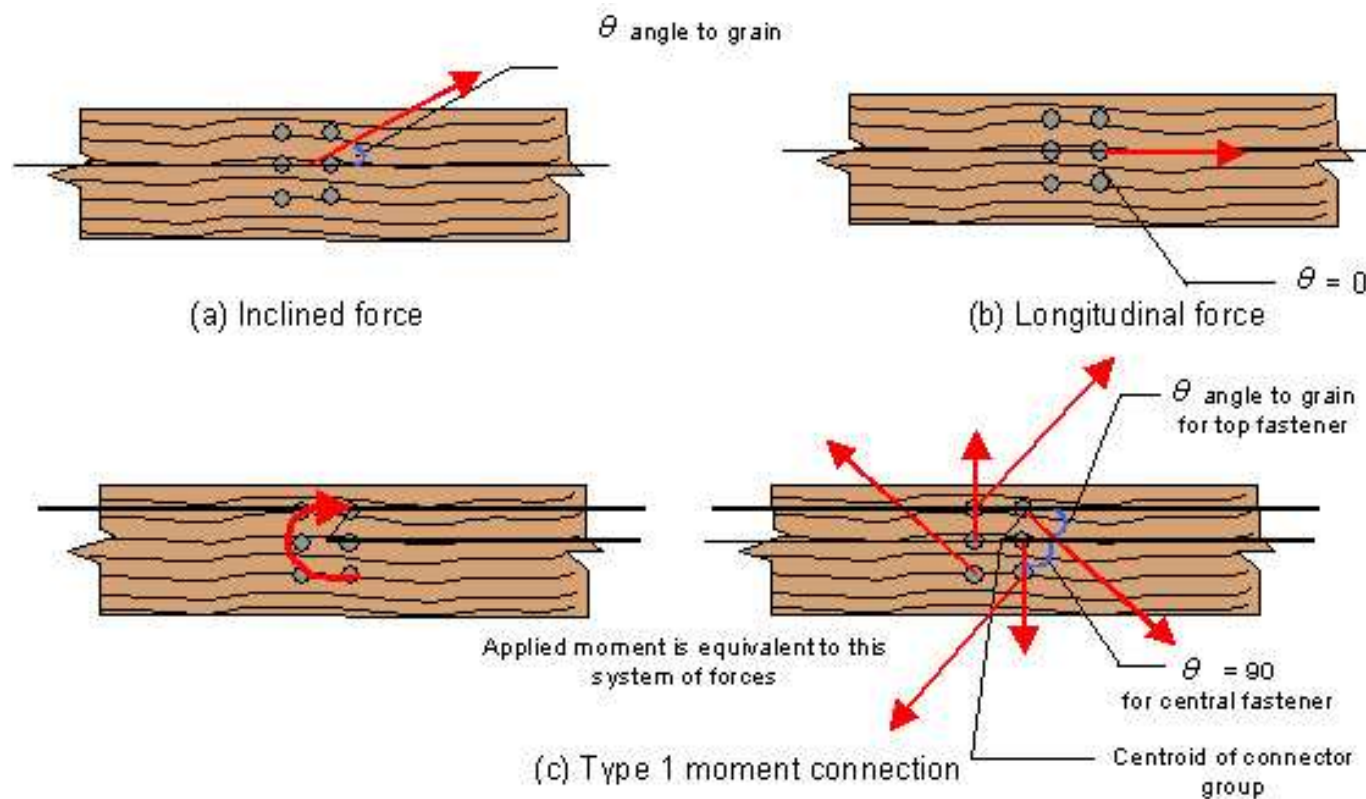
Coniferous

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

Decideous

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

Embedment - perpendicular to grain



Embedment – at angle to grain

Bolts/dowel:

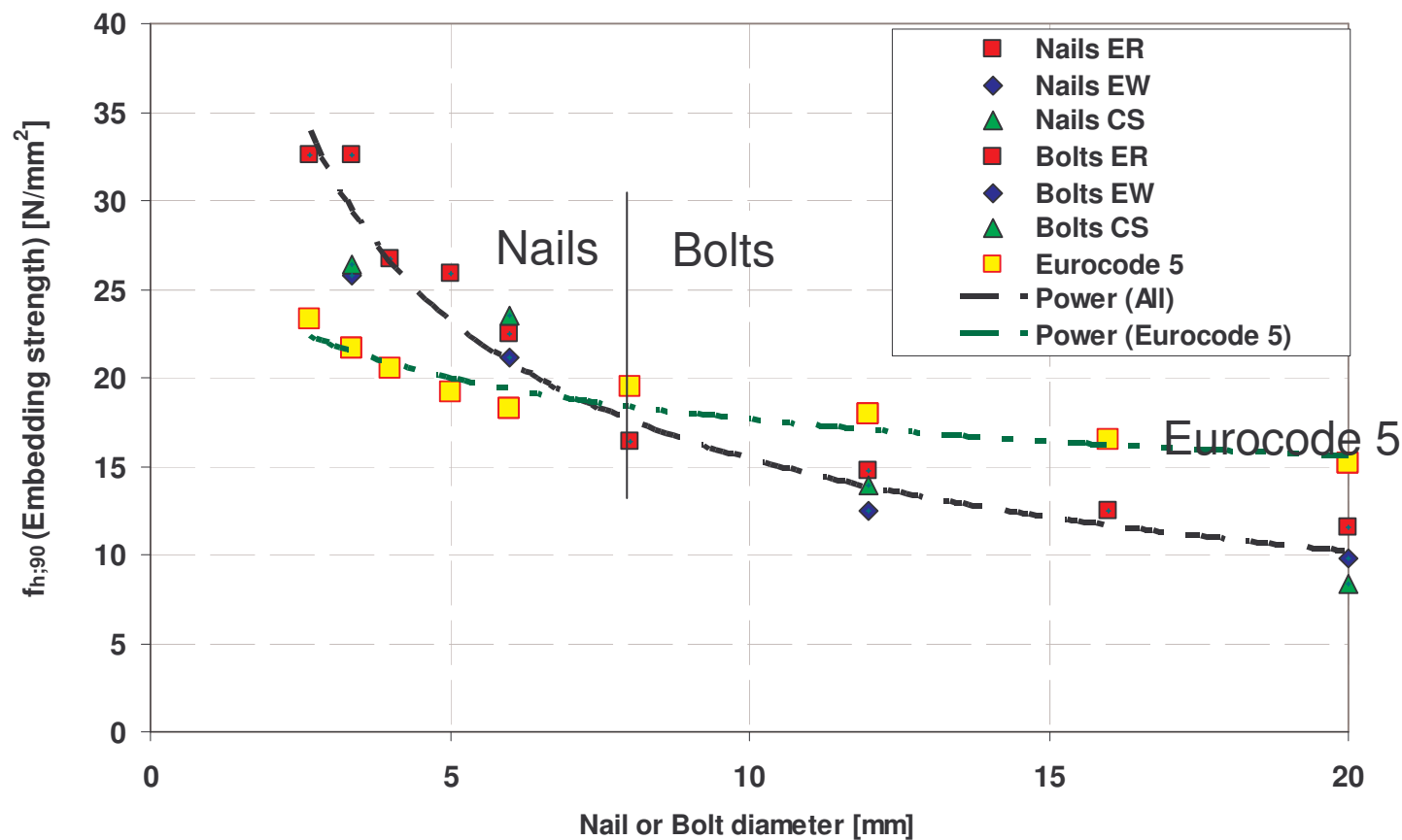
$$f_{h,0,k} = 0,082 (1 - 0,01 d) \rho_k$$

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

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

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

$$f_{h,k} = 0,11 \rho_k d^{-0,3}$$

Hardboard

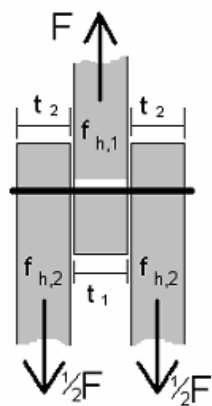
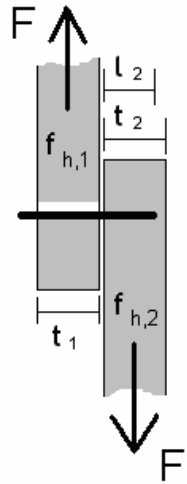
$$f_{h,k} = 30 d^{-0,3} t^{0,6}$$

Particleboard & OSB

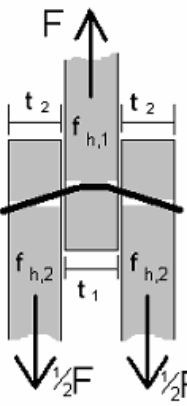
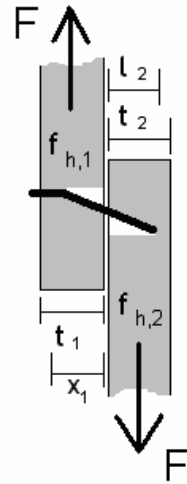
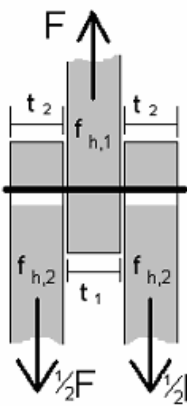
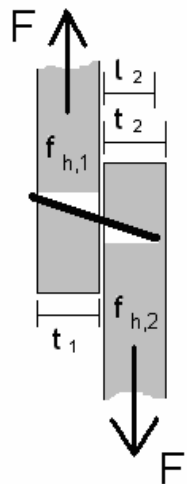
$$f_{h,k} = 65 d^{-0,7} t^{0,1}$$

Taken from DIN 1052

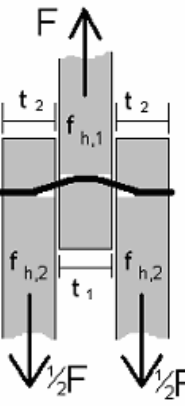
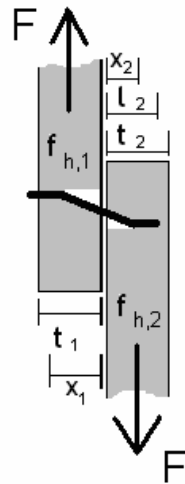
Mode I



Mode II



Mode III



Some failure modes of single shear fasteners

Some failure modes of double shear fasteners

Equations for every failure mode

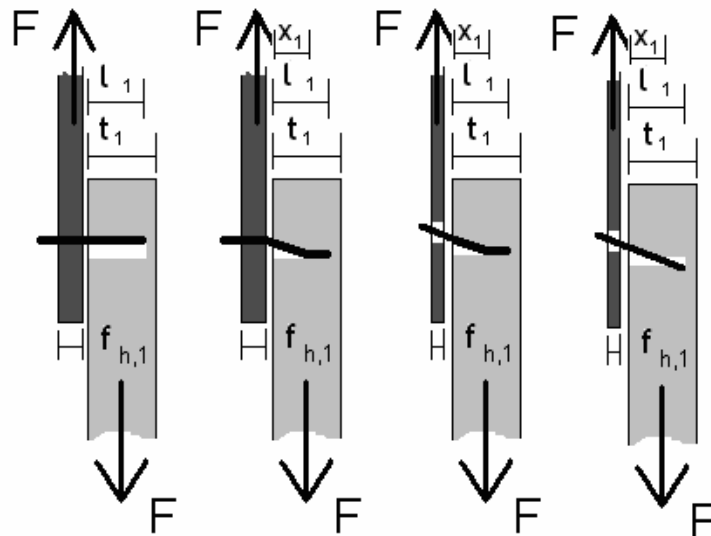
Fasteners in single shear

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

Equations for every failure mode

Fasteners in double shear

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



**Some failure modes of
single shear fasteners
steel to wood
connections**

thick steel plate $t > d$ = fastener diameter

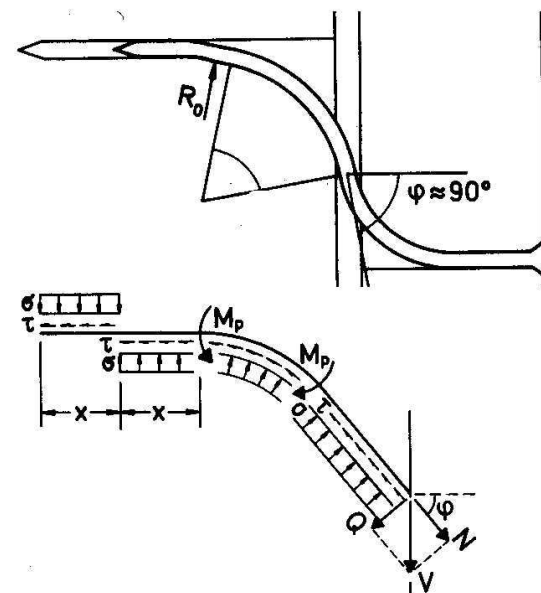
thin steel plate $t < 0,5d$

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: Ingenieurholzbau in Forschung und Praxis, J. Ehlebeck and G. Steck, editors, Bruderverlag Karlsruhe 1982

Test results still higher than Johansen equations

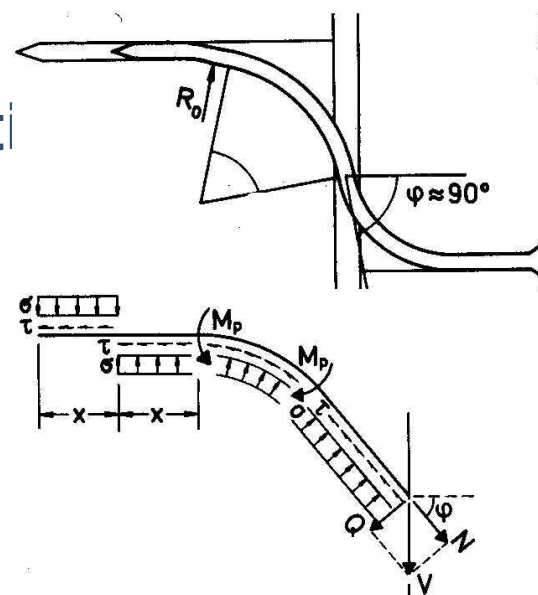
Cord effect:

$F_{ax}/4 = \text{withdrawal capacity}/4 = \text{est}$

% are estimates

Maximum

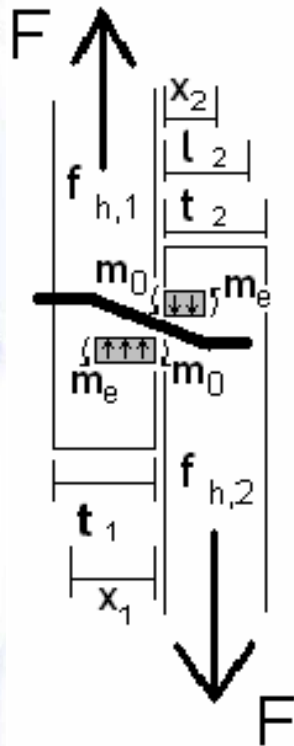
Nails	15%
Grooved nails	50%
Screws	100%
Bolts	25%
Dowels	0%



Fasteners in double shear

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

Test results still higher than Johansen equations



Mode III

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

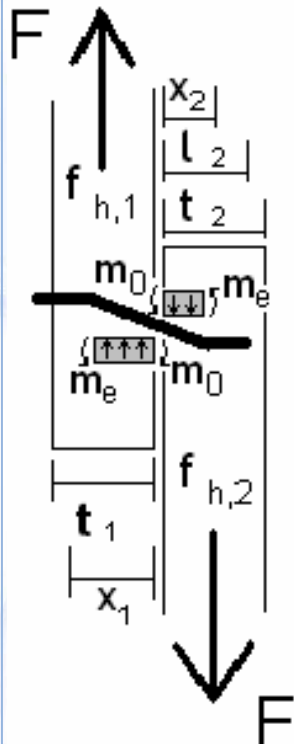
Design value $F_d = F_k \cdot \frac{k_{\text{mod}}}{y_m} = F_k \cdot \frac{0,9}{1,3} = 0,69 \cdot F_k$

M_s = yield bending moment steel fastener

Partial material factor of timber γ_m applied to M_s !!

Better seperate:

Mode III



Taking both γ_m - separately

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

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

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

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

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

For Mode II factor is 1,05

Fasteners in double shear

$$F_{v,Rk} = \min \left\{ \begin{array}{l} f_{h,1,k} t_1 d \quad (g) \\ 0,5 f_{h,2,k} t_2 d \quad (h) \\ 1,05 \frac{f_{h,1,k} t_1 d}{2 + \beta} \left[\sqrt{2\beta(1 + \beta) + \frac{4\beta(2 + \beta)M_{y,Rk}}{f_{h,1,k} d t_1^2}} - \beta \right] + \frac{F_{ax,Rk}}{4} \quad (j) \\ 1,15 \sqrt{\frac{2\beta}{1 + \beta}} \sqrt{2M_{y,Rk} f_{h,1,k} d} + \frac{F_{ax,Rk}}{4} \quad (k) \end{array} \right.$$

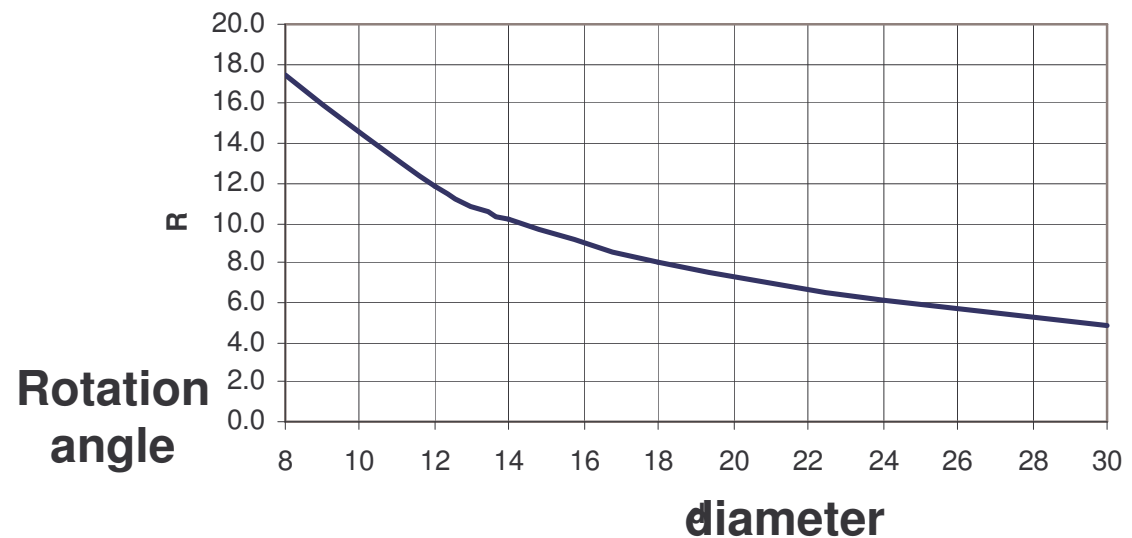
Eurocode 5 equations

Yield moment of dowel type fasteners

Large diameter bolts and dowels

Small rotation at failure → No full plastic yielding

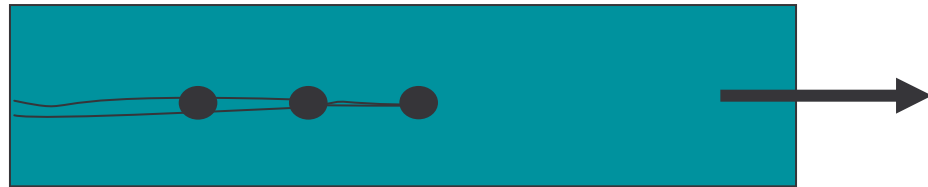
$$M_{y,Rk} = 0,3 f_{u,k} d^{2,6}$$



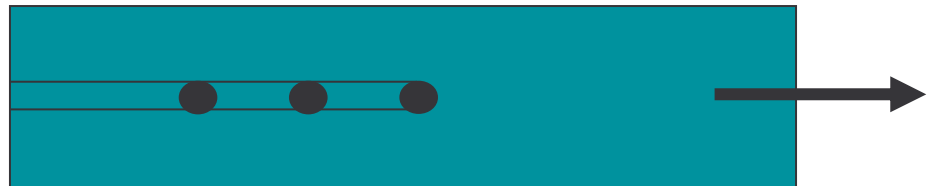
Background: Jorissen, A.J.M. Blass, H.J., the fastener
 yield strength in bending, In: Proceedings of CIB-W18
 paper 31-7-6, 1998

Failure of multiple of fasteners in a row

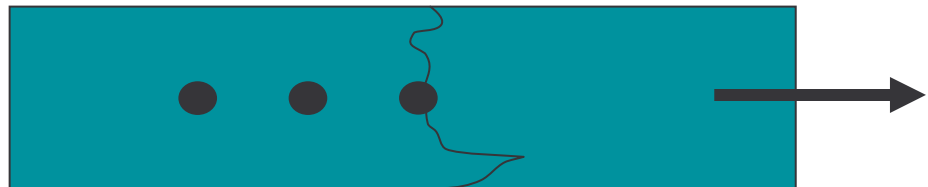
Splitting



Shear

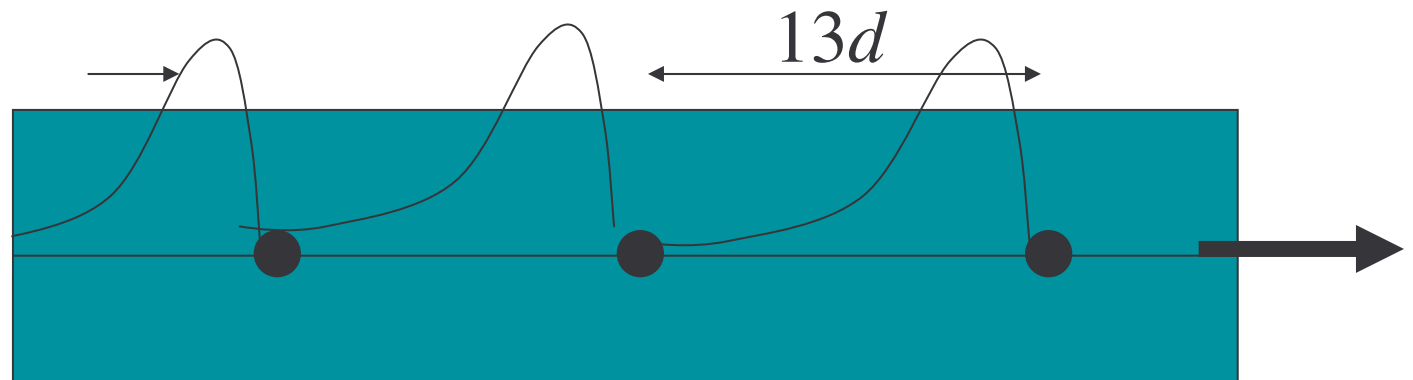


Tensile

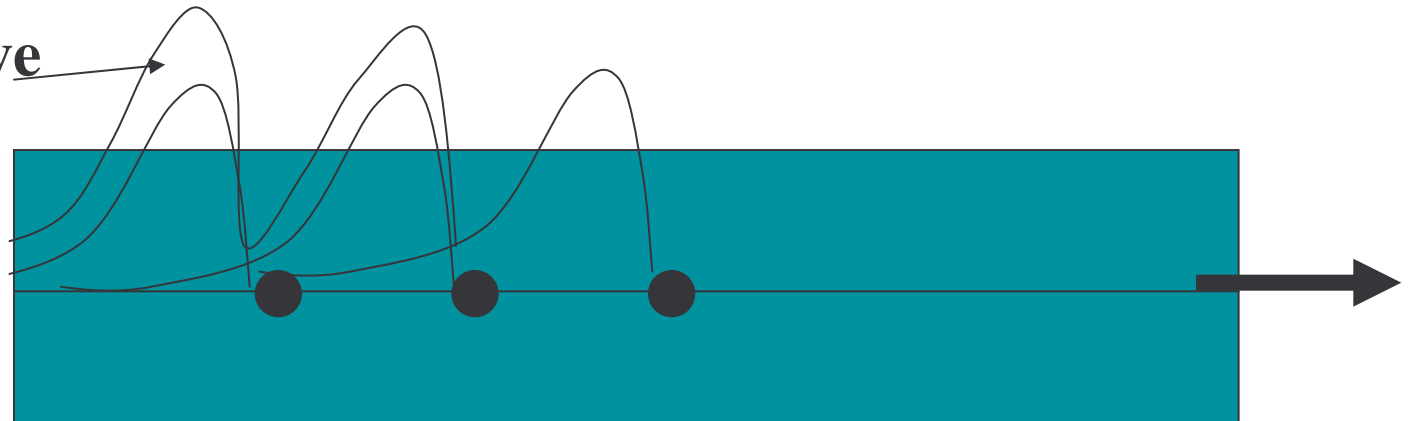


Failure of multiple of fasteners in a row Caused by group effect → Only for load component in grain direction

Stress \perp



Cumulative
stress



Failure of multiple of fasteners in one row

Caused by group effect → effective number

Nails:
Empirical (Gehri)

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

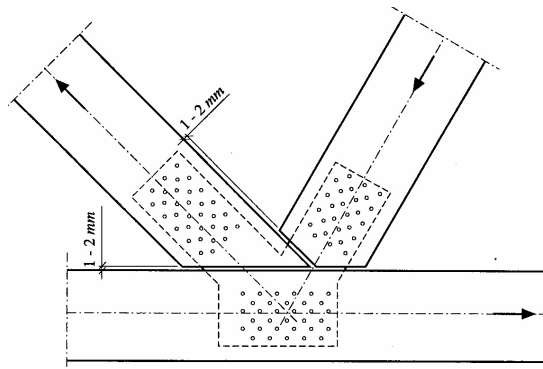
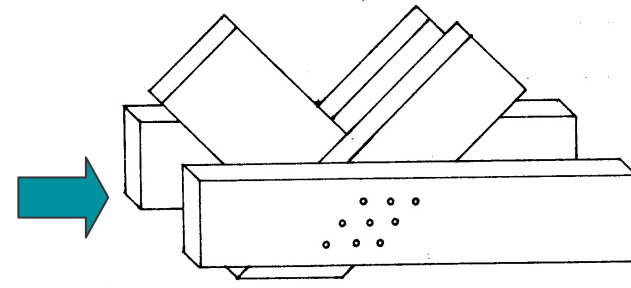
Bolts & dowels:
Fracture mechanics

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

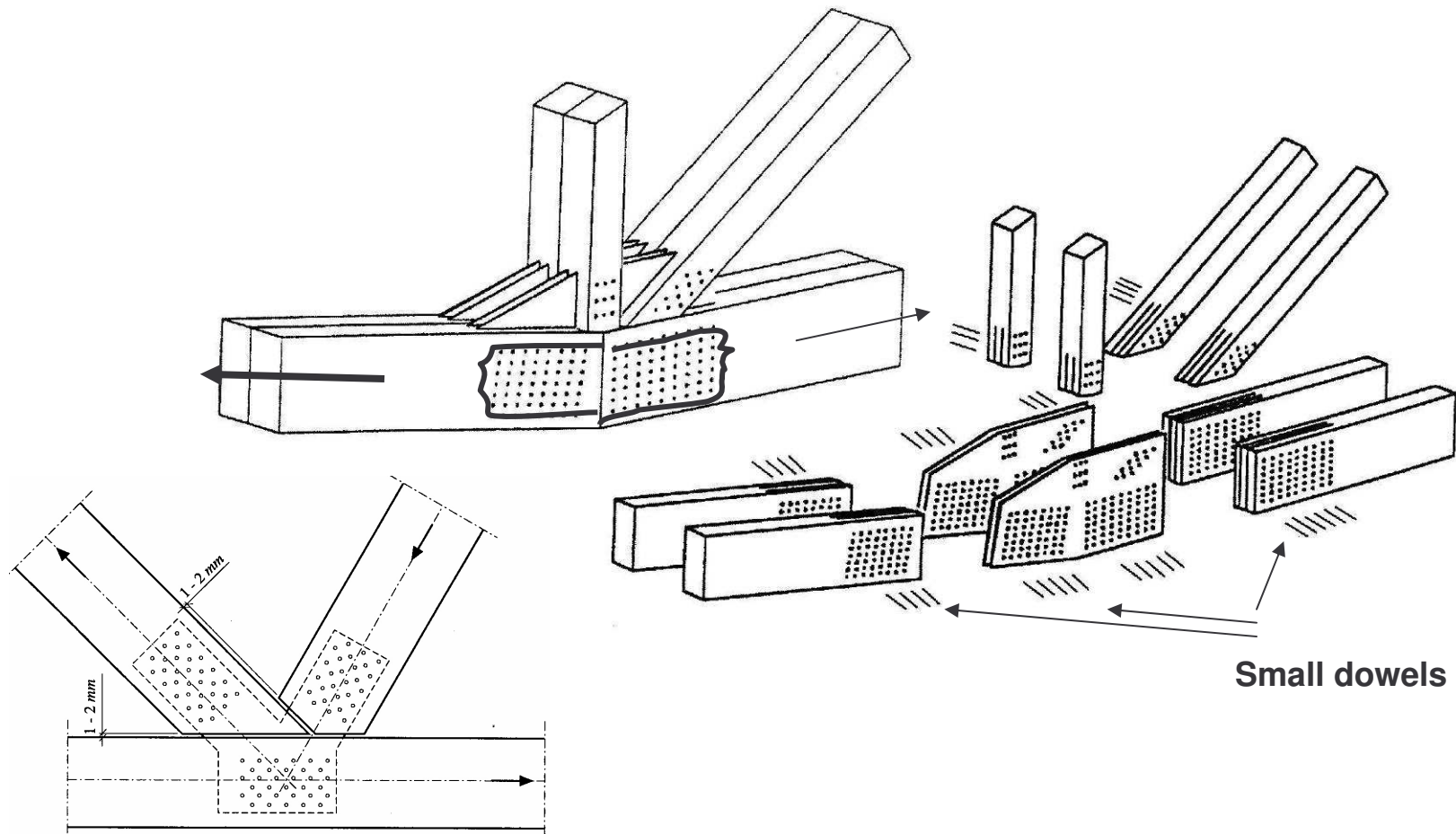
Spacing ^a	k_{ef}		
	Not predrilled	Predrilled	
$a_1 \geq 14d$	1,0	1,0	
$a_1 = 10d$	0,85	0,85	
$a_1 = 7d$	0,7	0,7	
$a_1 = 4d$	-	0,5	
^a For intermediate spacings, linear interpolation of k_{ef} is permitted			

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

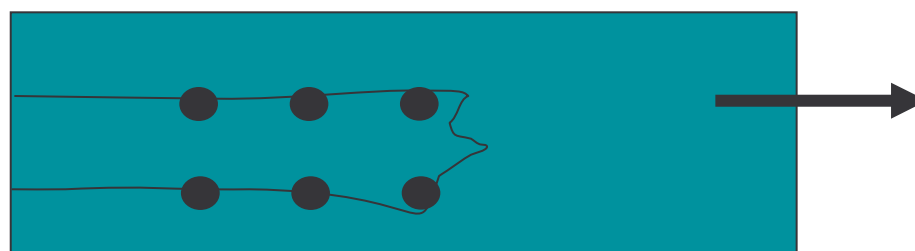


Steelplate – in – timber

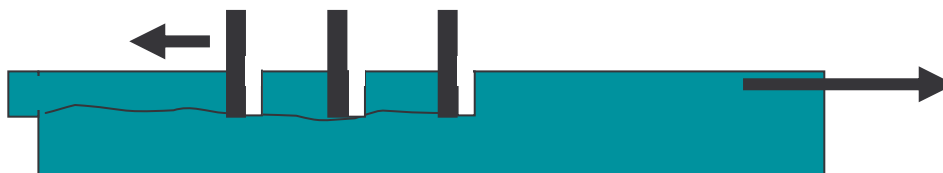


Failure at fastener perimeter (Prof.Racher, Fr.)

**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

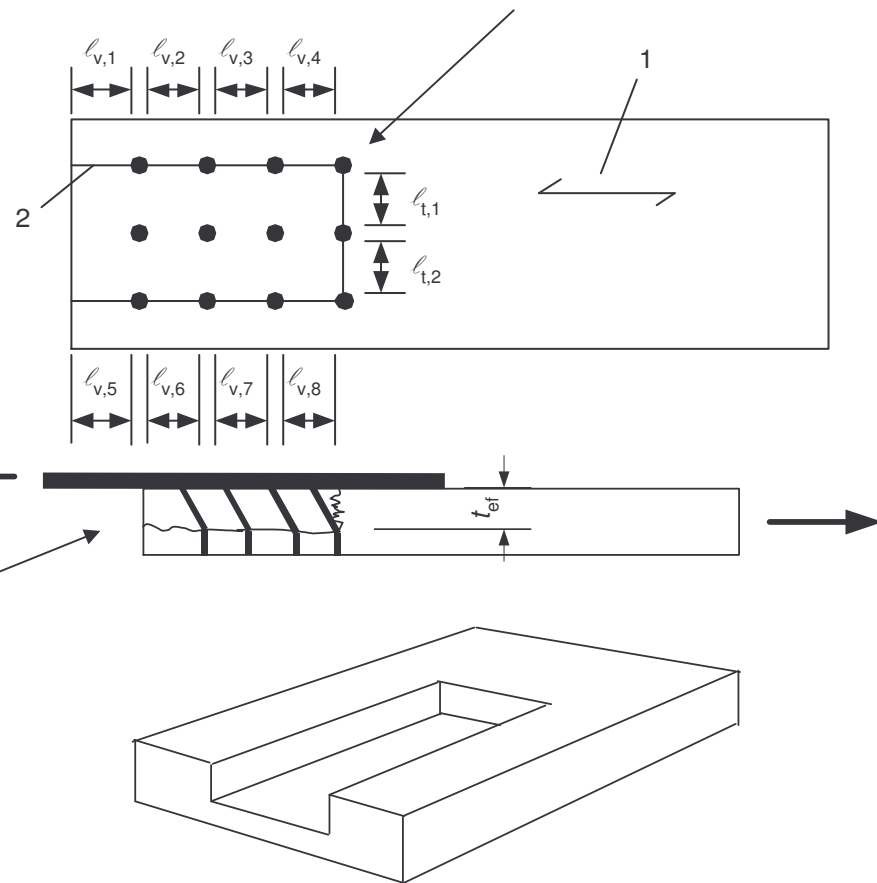
$$F_{bs,Rk} = \max \begin{cases} 1,5 A_{net,t} f_{t,o,k} & \text{Tensile failure} \\ 0,7 A_{net,v} f_{v,k} & \text{Shear fracture} \end{cases}$$

Correlation
parameters

Fasteners keep
straight

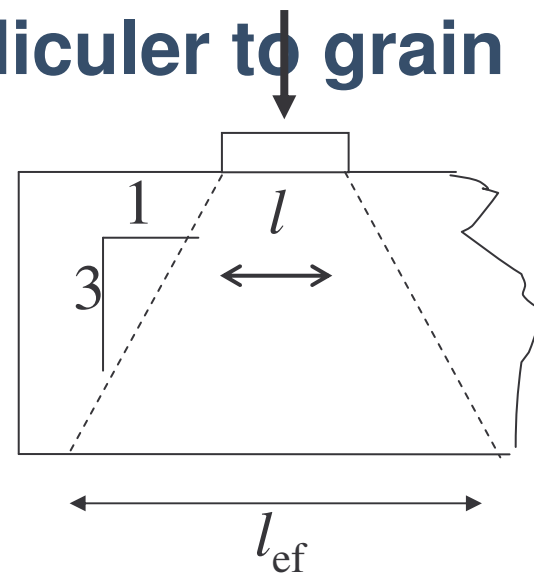
Not correct in
EC5

see previous
sheet



Amendment A1: Contains:

**New design rules for:
compressive strength perpendicular 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

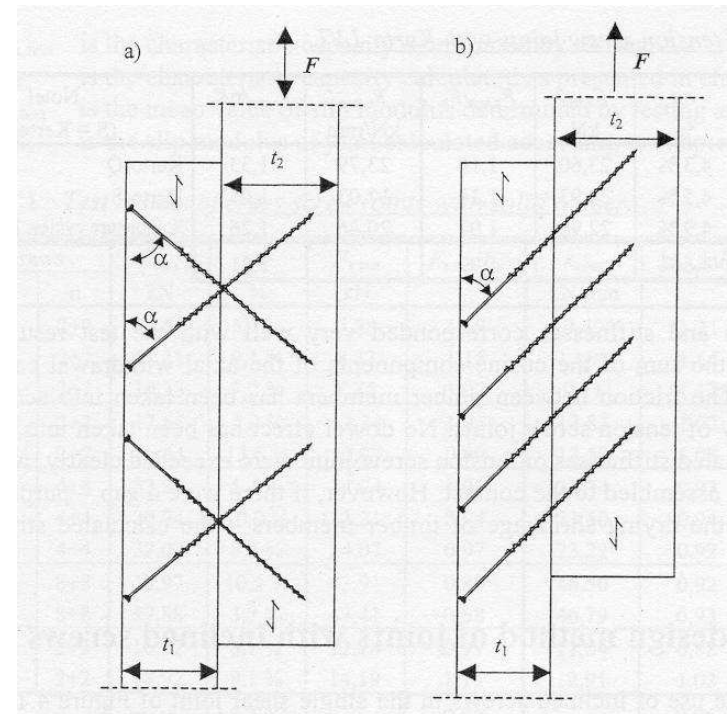
- >8mm requires predrilled holes



Amendment A1

Addition Axially loaded screws

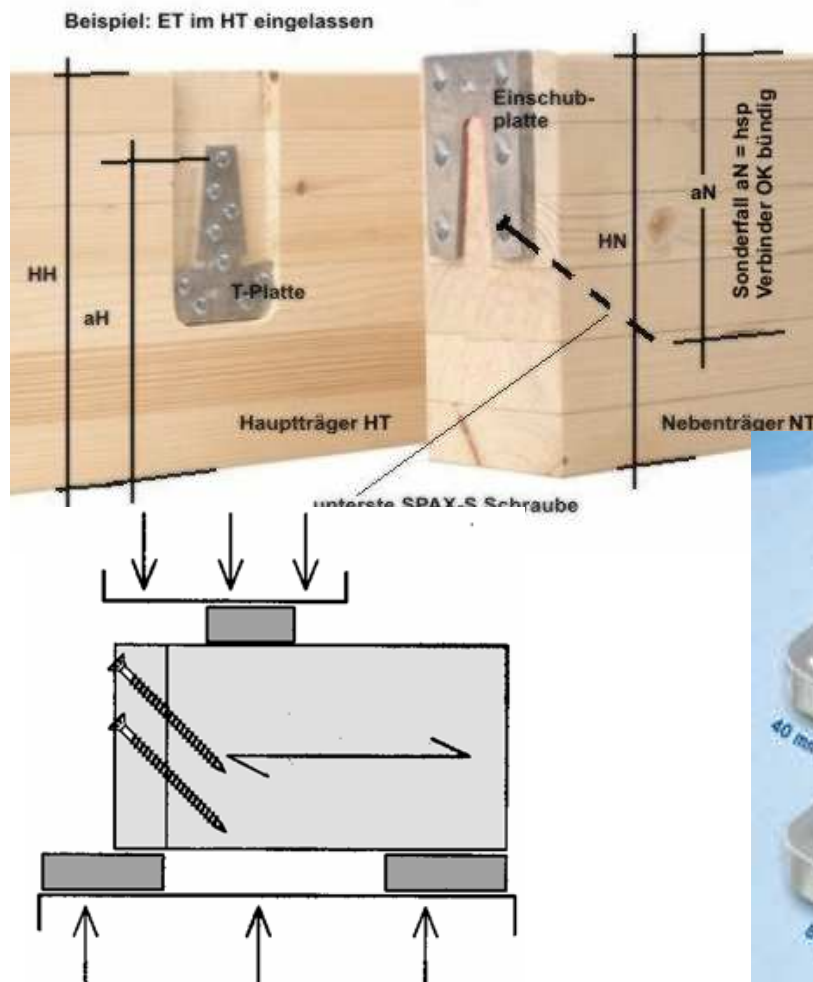
**Very effective
hardened
self tapping
high axial stiffness**



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):



Some examples

Spax



Leg or coach screw



Rapid



Heco



Tecfi



Some examples

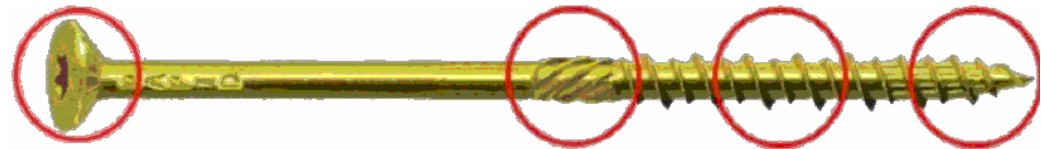
Spax-S



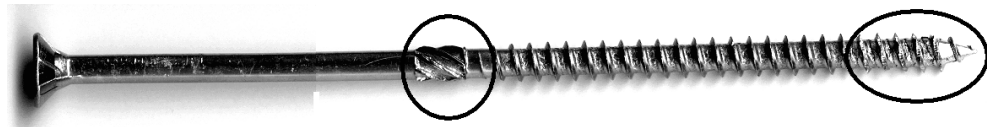
Heco Topix/Fix



Rapid Komplex



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)

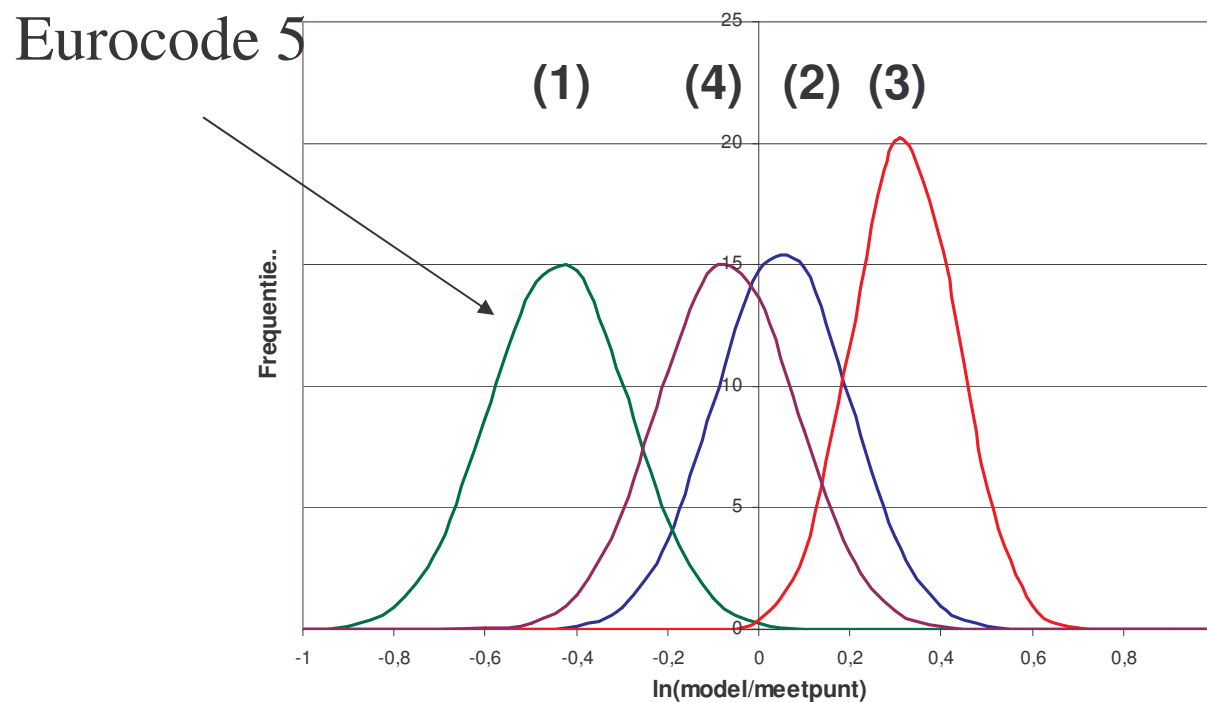
$$(1) \quad R_{ax,a,k} = (\pi \cdot d \cdot l_{ef})^{0,8} \cdot \frac{3,6 \times 10^{-3} \cdot \rho_k^{1,5}}{\sin^2 a + 1,5 \cdot \cos^2 a}$$

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

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

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

Model uncertainty – evaluation of test results



Current EC5 design rule unsafe

New proposal in Amendment A1:

Requirement Screws as defined in EN 14592

$$6 \text{ mm} \leq d \leq 12 \text{ mm}$$

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

All other screws:

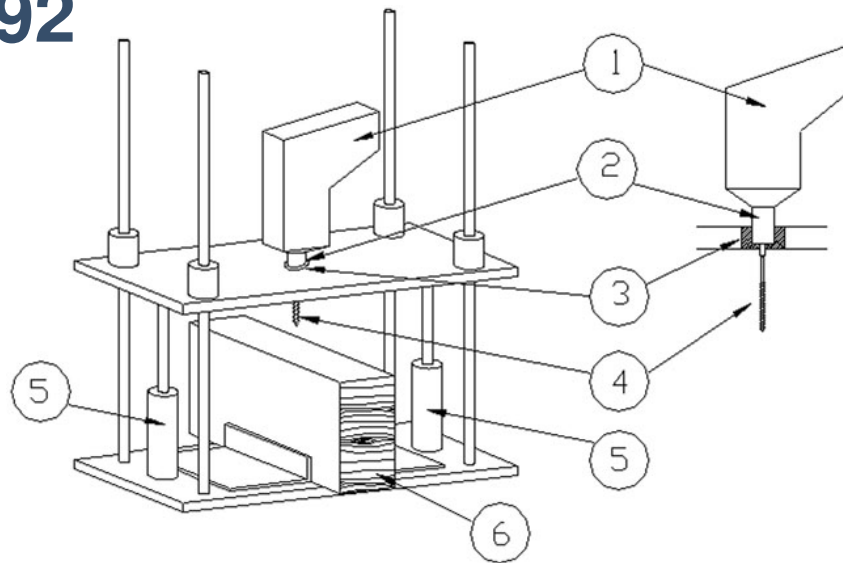
$$R_{ax,a,k} = n_{ef} \frac{f_{ax} \cdot d \cdot l_{ef}}{\sin^2 a + 1,2 \cdot \cos^2 a} \left(\frac{\rho_k}{\rho_a} \right)^{0,8}$$

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:

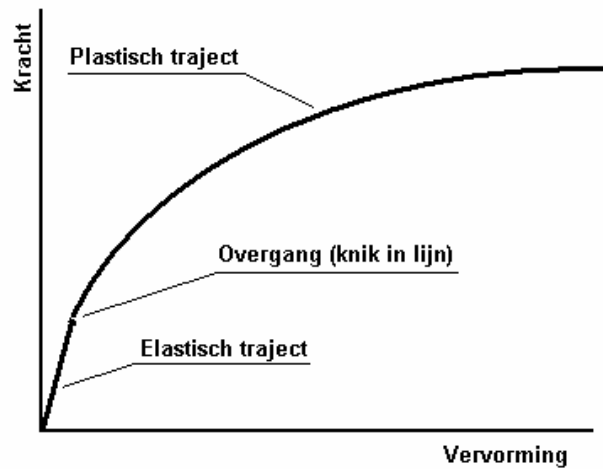
$$R_k = \pi \cdot \left(\left(\frac{1}{2} \cdot d_k \right)^2 - \left(\frac{1}{2} \cdot d_s \right)^2 \right) \cdot 3,0 \cdot f_{c,90,k}$$

Zulassung Germany 9.1-235:

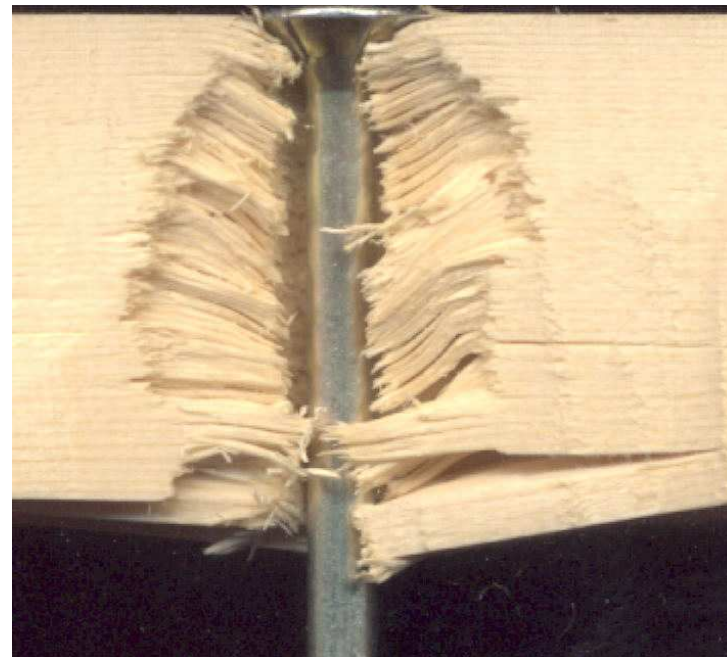
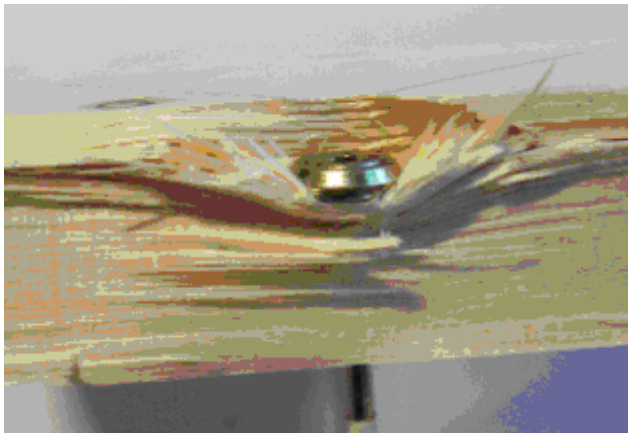
$$N_k = 16,0 \cdot d_k^2$$



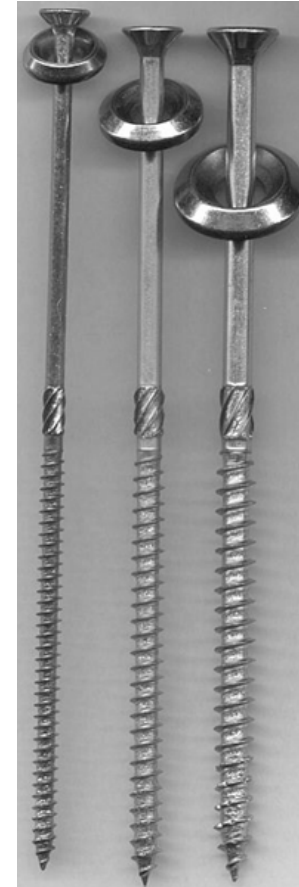
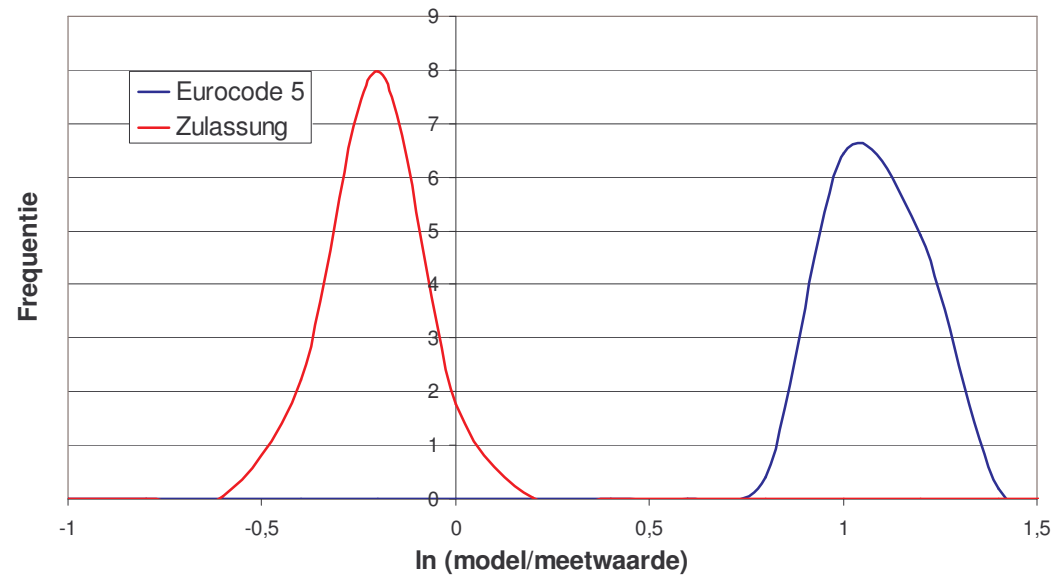
In the absents of information Clause 8.5.2. bolt washers



- short elastisch behaviour
- Large non-elastic traject

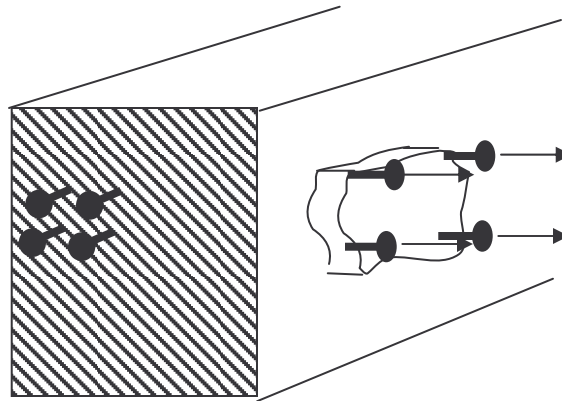


Model uncertainty design rule 9.1-235 and Eurocode 5 for screws with washers

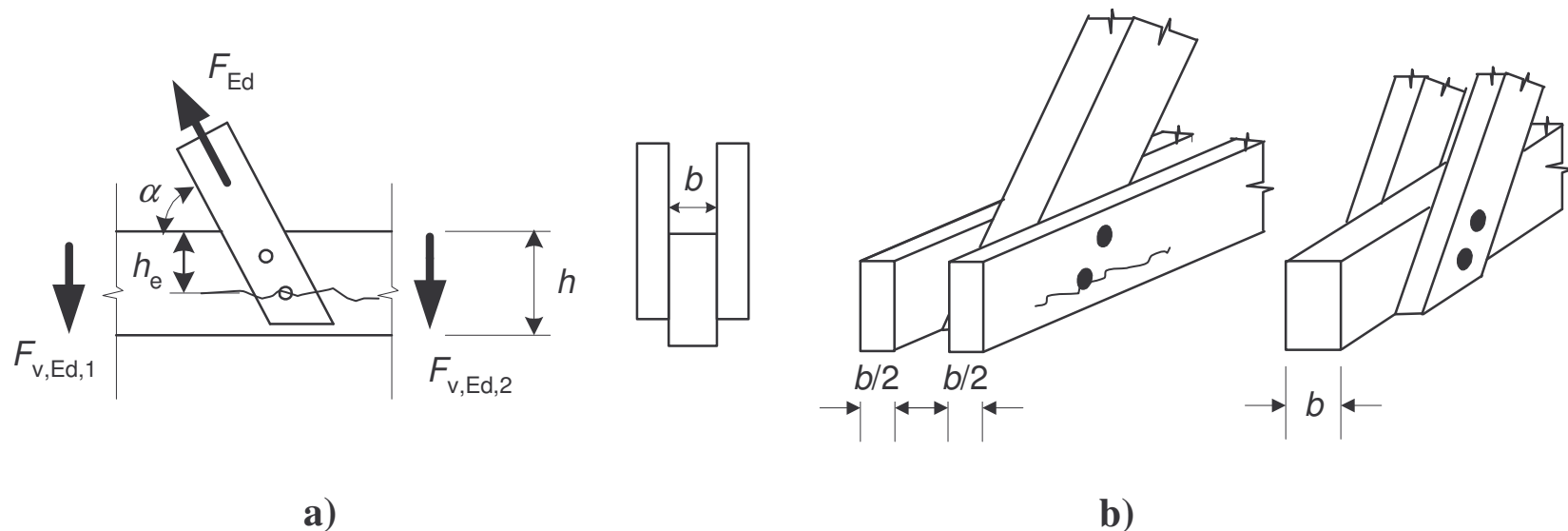


- **Group (tear out) effect:**
Due to a lack of background information
Based on test by Gehri (empirical):

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



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

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

Fracture mechanics background

14 is calibration parameter

w = (political factor)

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

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

Splitting by perpendicular to grain forces

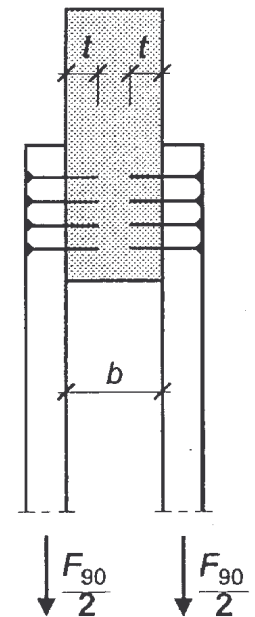
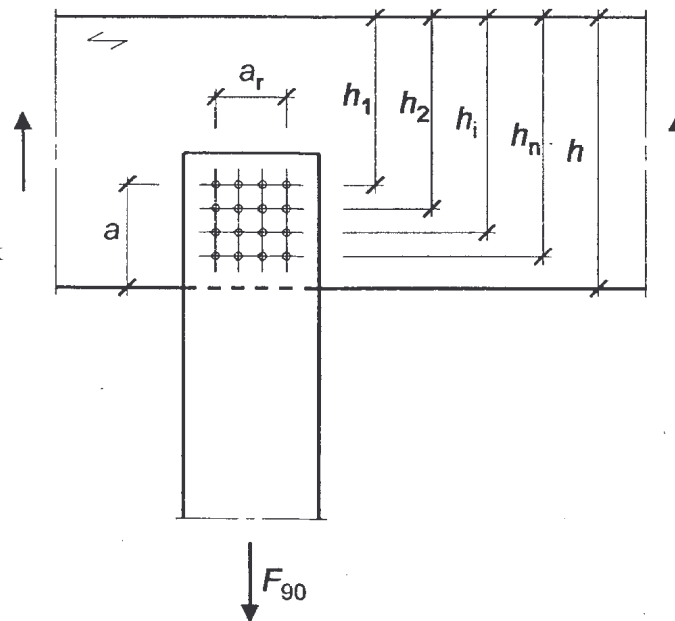
Some empirical models consider

Fastener spacing

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

$$k_s = \max \left\{ \begin{array}{l} 1 \\ 0.7 + \frac{1.4a}{h} \end{array} \right.$$

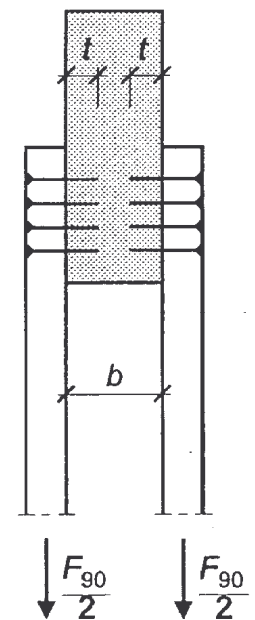
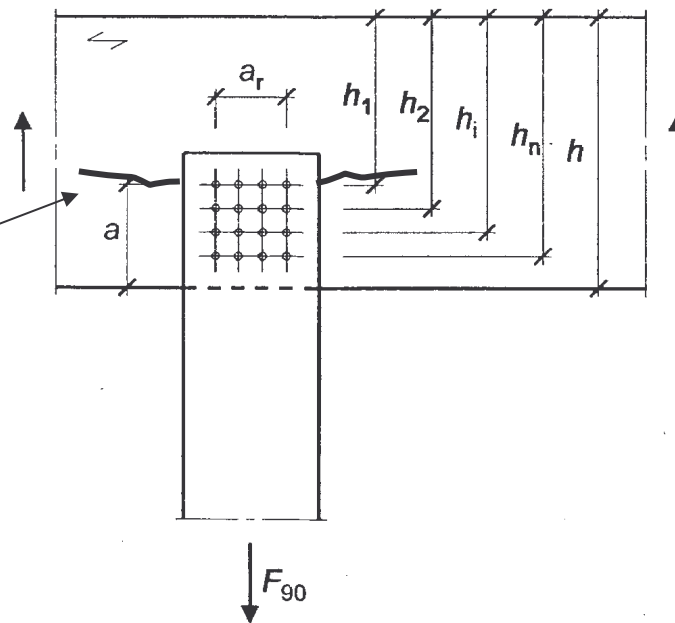
$$k_r = \frac{n}{\sum_{i=1}^n \left(\frac{h_1}{h_i} \right)^2}$$



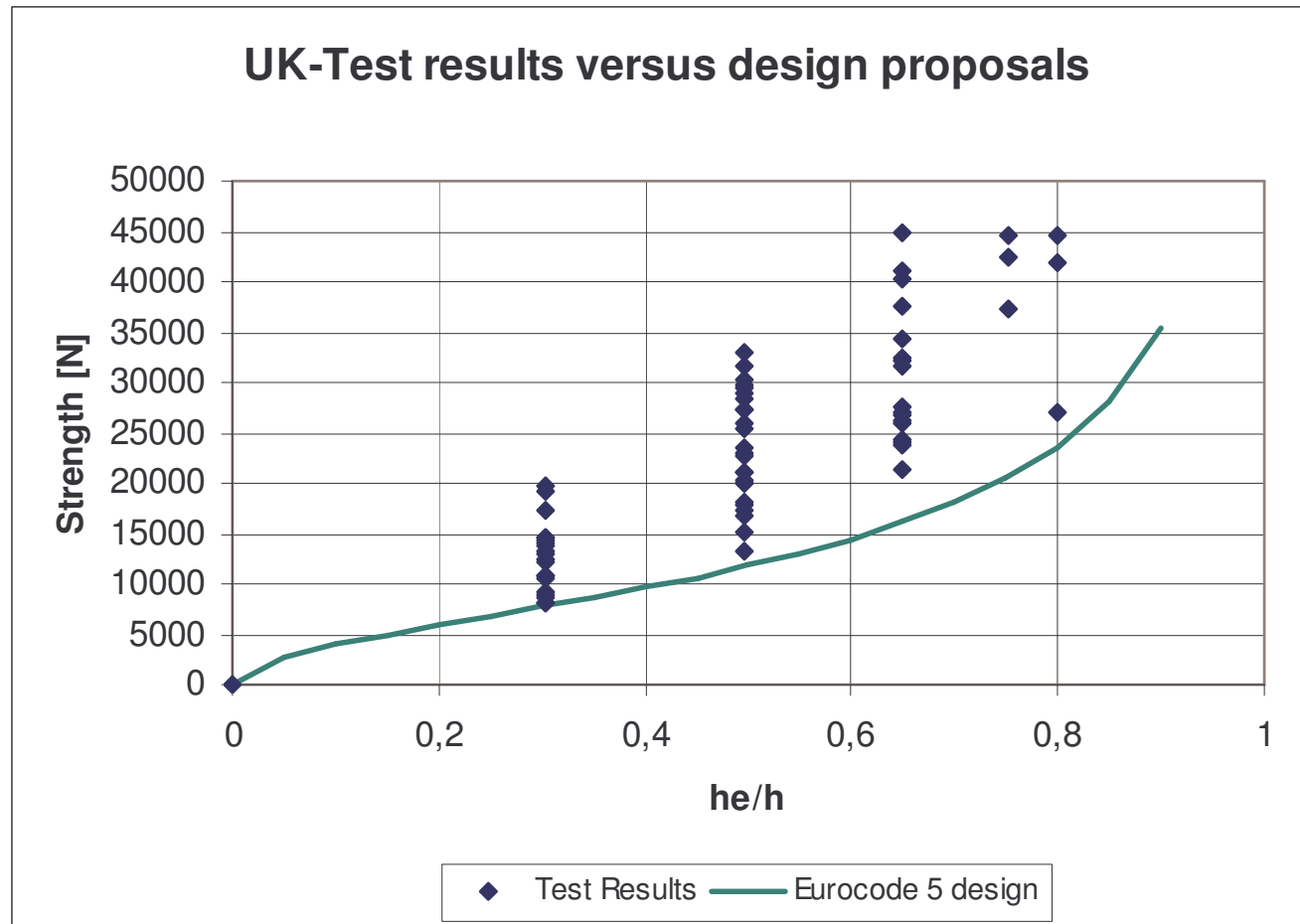
Splitting by perpendicular to grain forces

Fracture mechanical model

Consider energy balance after crack appearance

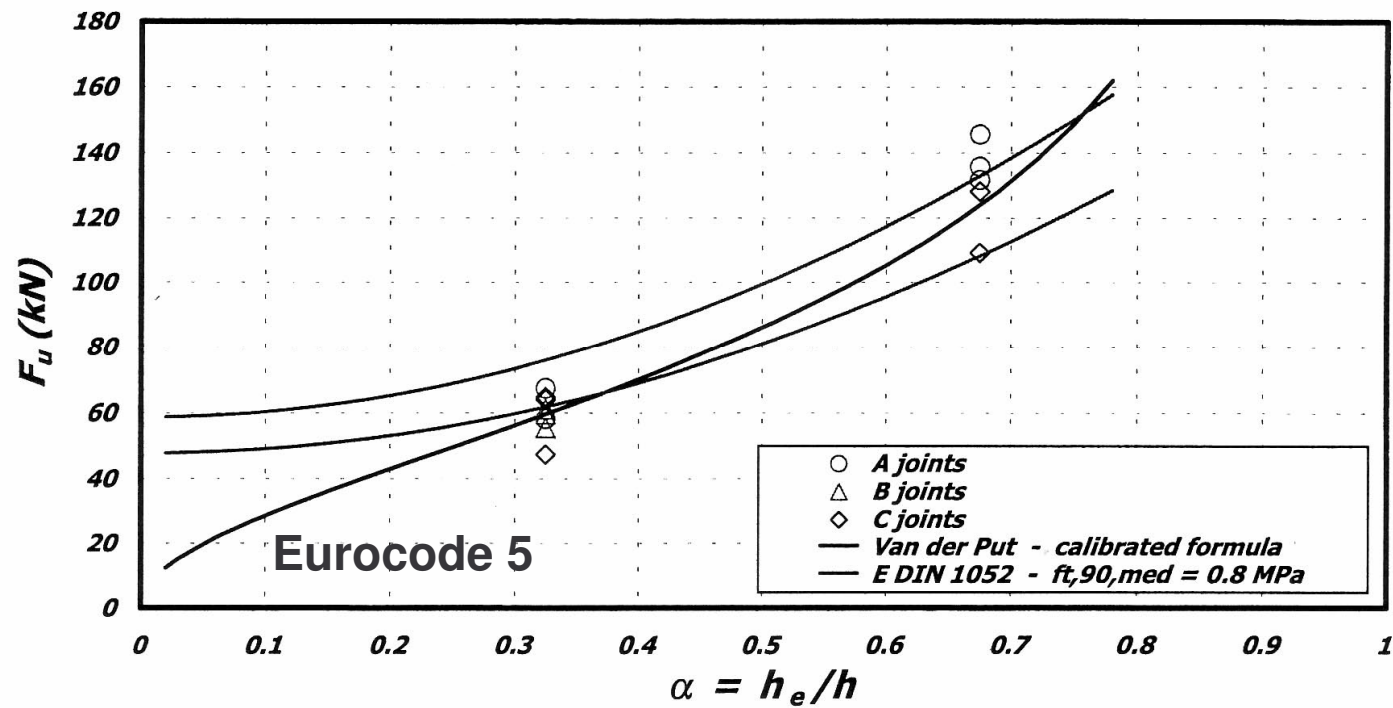


Splitting by perpendicular to grain forces



Punched metal plate fasteners

Comparison between models



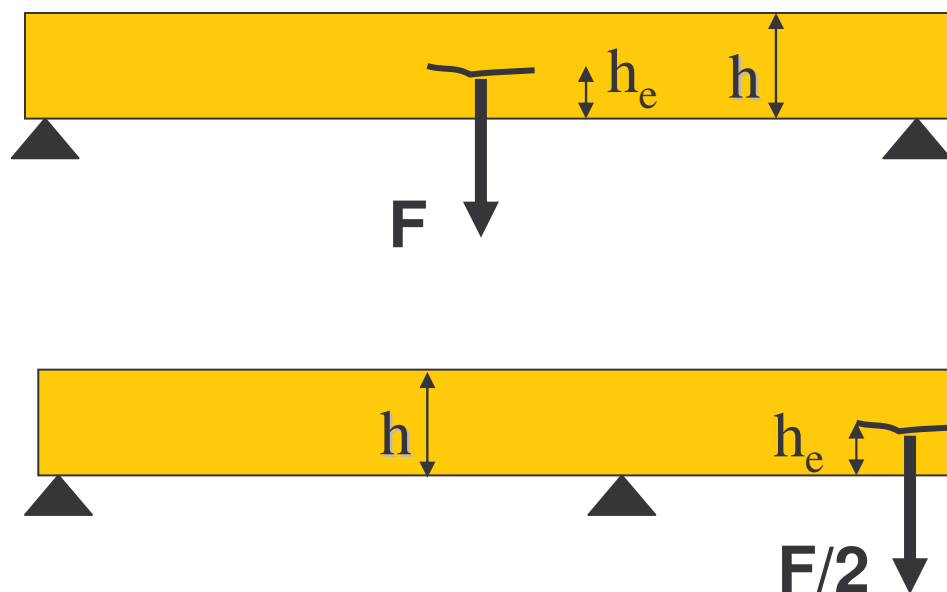
Splitting by perpendicular to grain forces

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

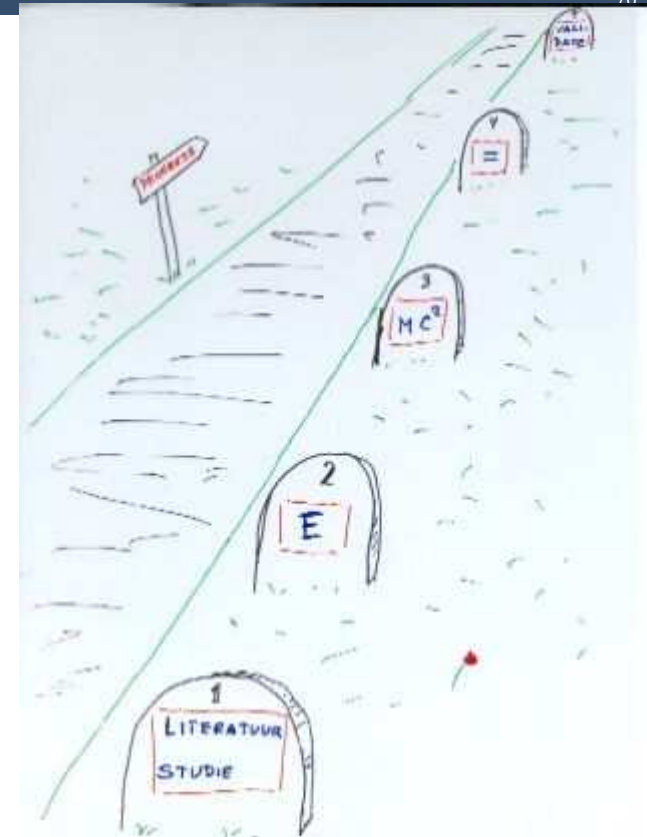
For loaded edges
 $>0,7 h \rightarrow$ no splitting

Simply supported
 $\rightarrow \max F$

Cantilever beam
 $\rightarrow \max F/2$



**Frequently heard:
Not found in Eurocode**



We don't know everything

**Research in progress
Future changes and additions are
expected**