# Ductility in timber connections

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|---|---|
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| • Quantifying ductility in timber structures | Kjell Arne Malo |
| • Ductility requirements for moment connections in statically indeterminate timber structures | Ad Leijten |
| • Consideration of plasticity within the design of timber structures due to connection ductility | Frank Brühl |
| • Elastic and ductile design of multi-storey crosslam massive wooden buildings | Massimo Fragiacomo |
| • Failure mechanisms of dowel type fastener connections perpendicular to grain | Ad Leijten |
| • Ductility in timber-concrete connections | Alfredo Dias |
| • Ductility aspects of reinforced and non-reinforced timber joints | Hans Joachim Blaβ |

# General notes on ductility in timber structures

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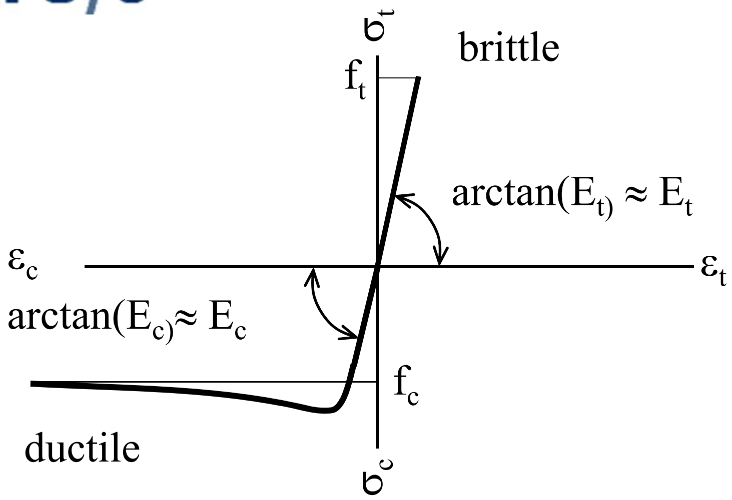
The Netherlands

- why do we need ductility
  - warning before failure (large displacements)
  - redistribution of loads
  - redistribution of stresses
  - energy dissipation for earthquake design
  - robustness

- why do we need ductility
- member ductility
    - hard to achieve (only in compression)



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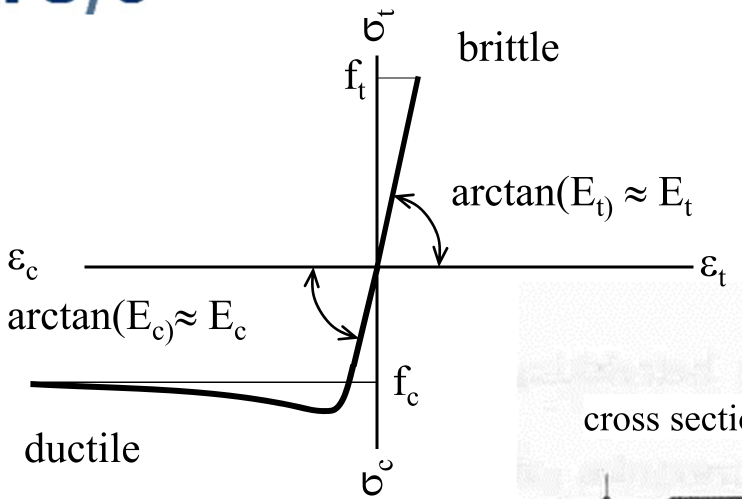
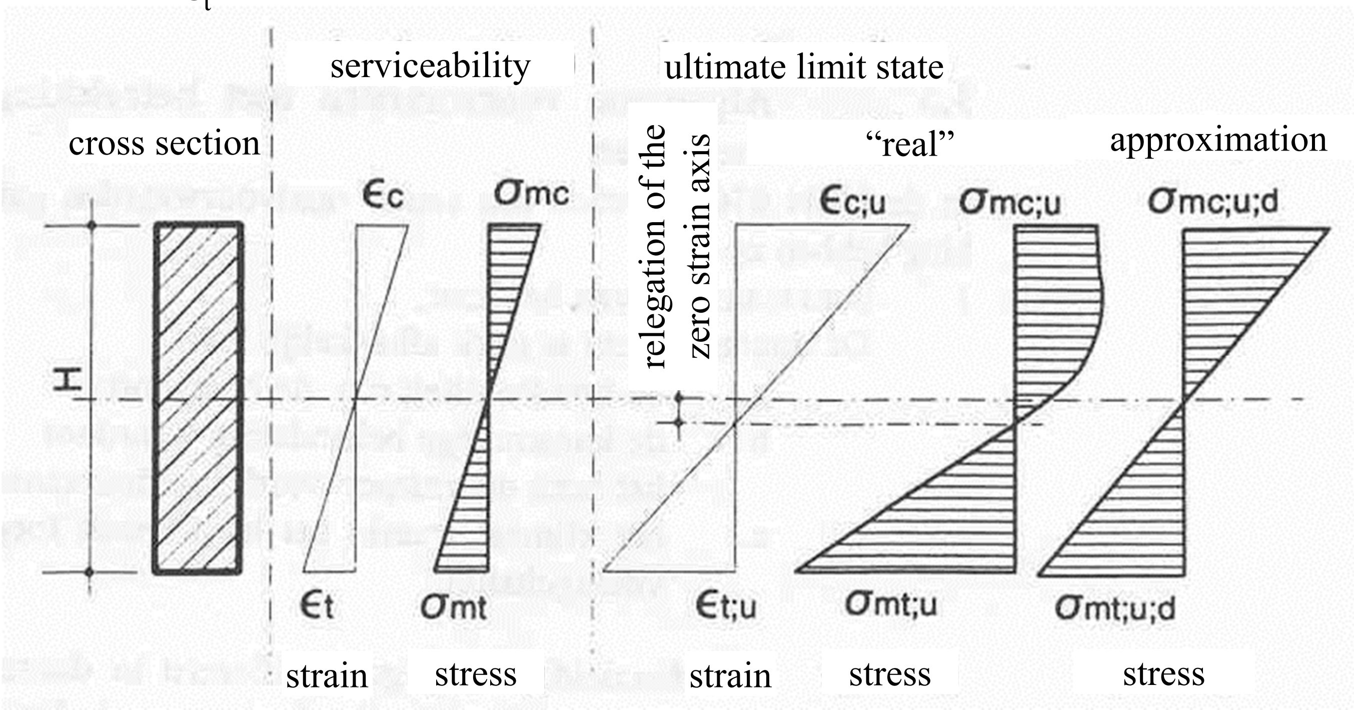
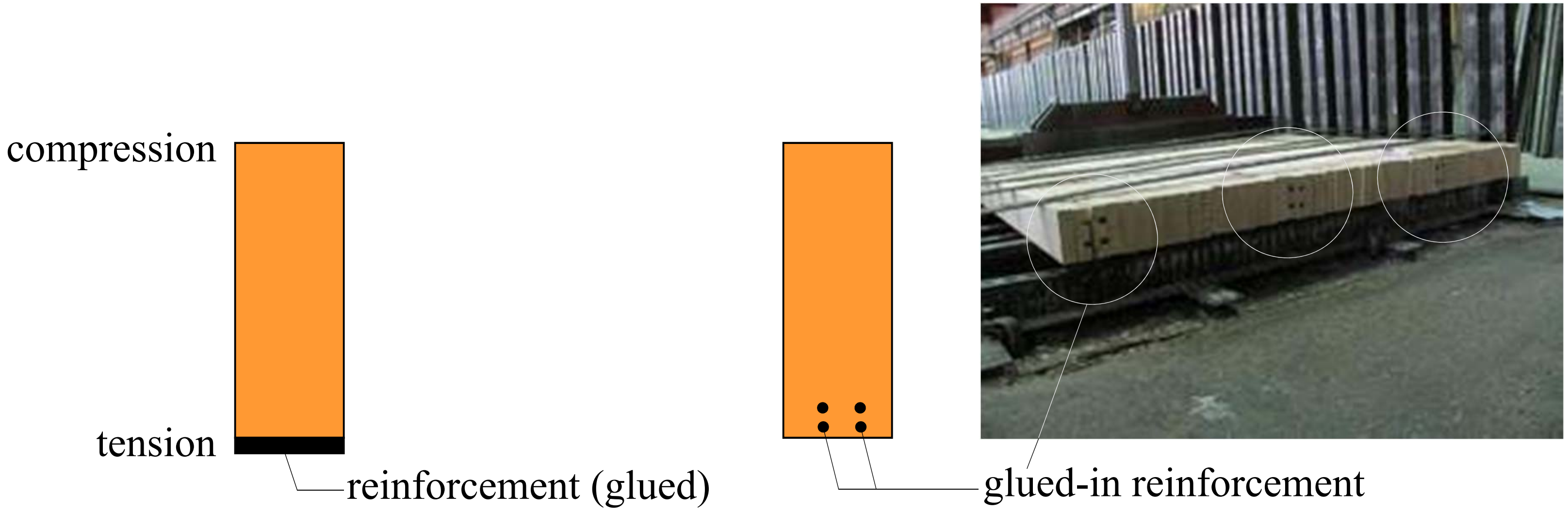
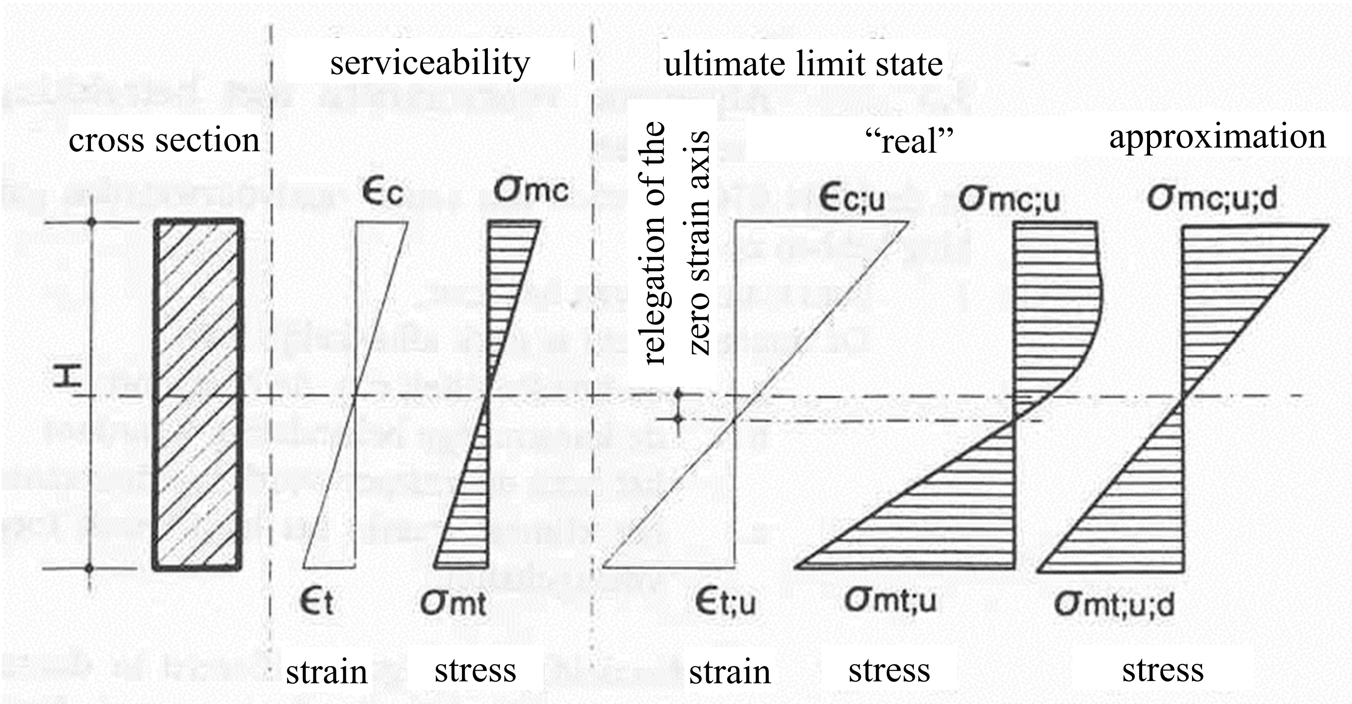


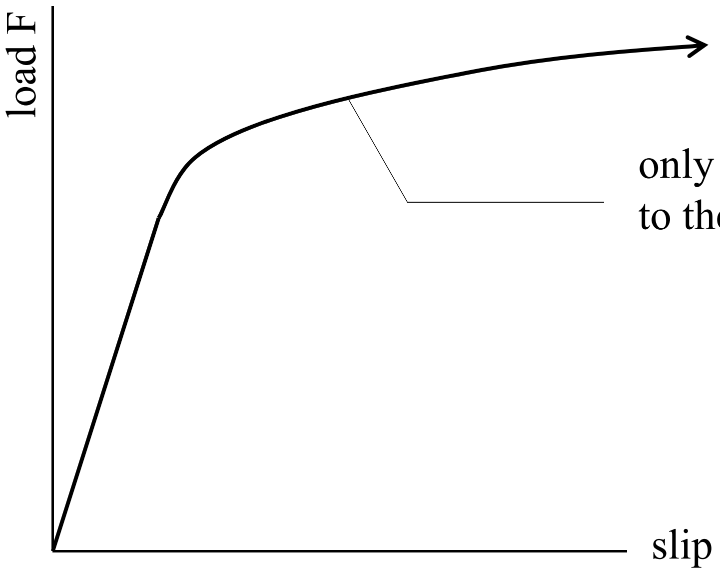




compression
tension
reinforcement (glued)
glued-in reinforcement


serviceability
ultimate limit state
cross section
relegation of the zero strain axis
"real"
approximation
H
εc
σmc
εt
σmt
εc;u
σmc;u
σmc;u;d
εt;u
σmt;u
σmt;u;d
strain
stress
strain
stress
stress

• why do we need ductility
• member ductility: only in compression
• connections
    • EYM: **yield** model → ductile

} connections governing




only obtained when no or limited tension perpendicular to the grain is developed:

- single dowel type fastener connections
- multiple nail or staple connections
- toothed plate connections
- bearing
- reinforced

- why do we need ductility
- member ductility: only in compression
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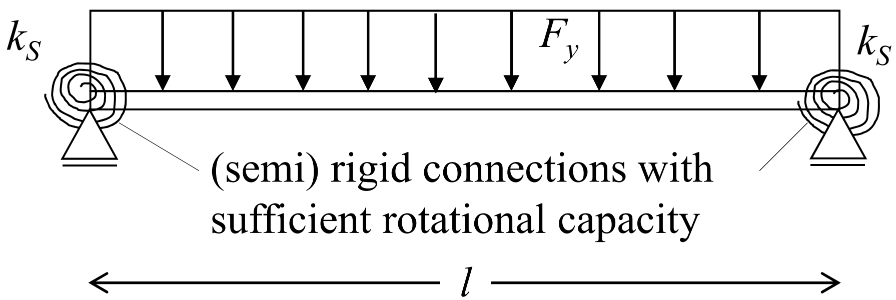
  - EYM: **yield** model → ductile

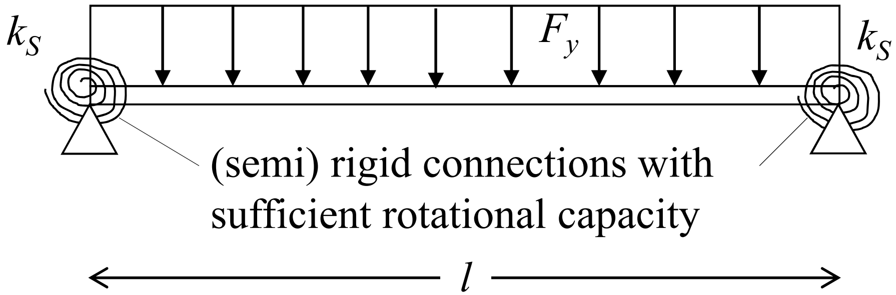
} connections governing ↓

Capacity Based Design




Capacity Based Design

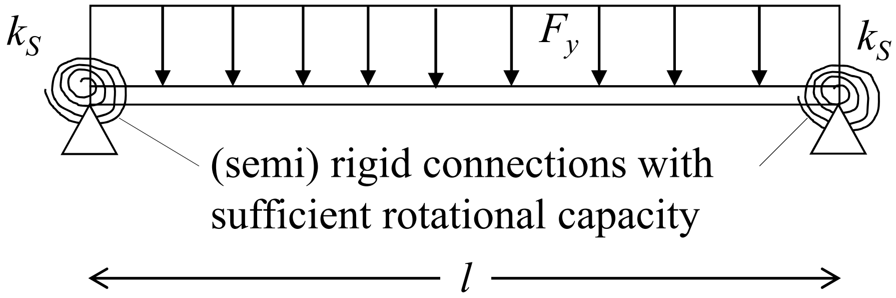
$$R_{beam} \geq R_{connection} \quad (R_b \geq R_c)$$




Capacity Based Design

$$R_{beam} \geq R_{connection} \quad (R_b \geq R_c)$$

$$R_{beam} \geq \gamma_{Rd}\, R_{connection}$$

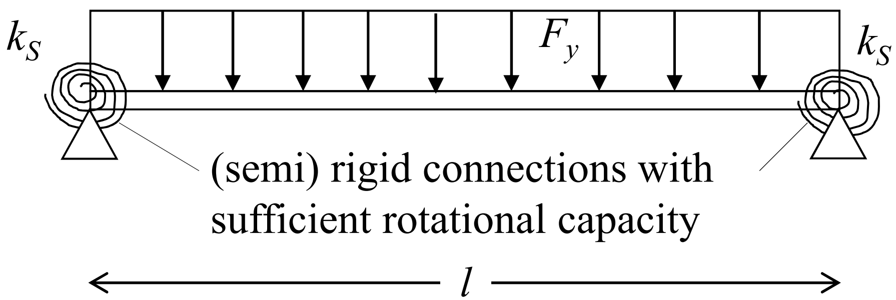



Analytical: $R_{b.k} \geq \gamma_{Rd}\, R_{c.k}$

**Capacity Based Design**

$$R_{beam} \geq R_{connection} \quad (R_b \geq R_c)$$

$$R_{beam} \geq \gamma_{Rd}\, R_{connection}$$




Analytical: $R_{b.k} \geq \gamma_{Rd}\ R_{c.k}$

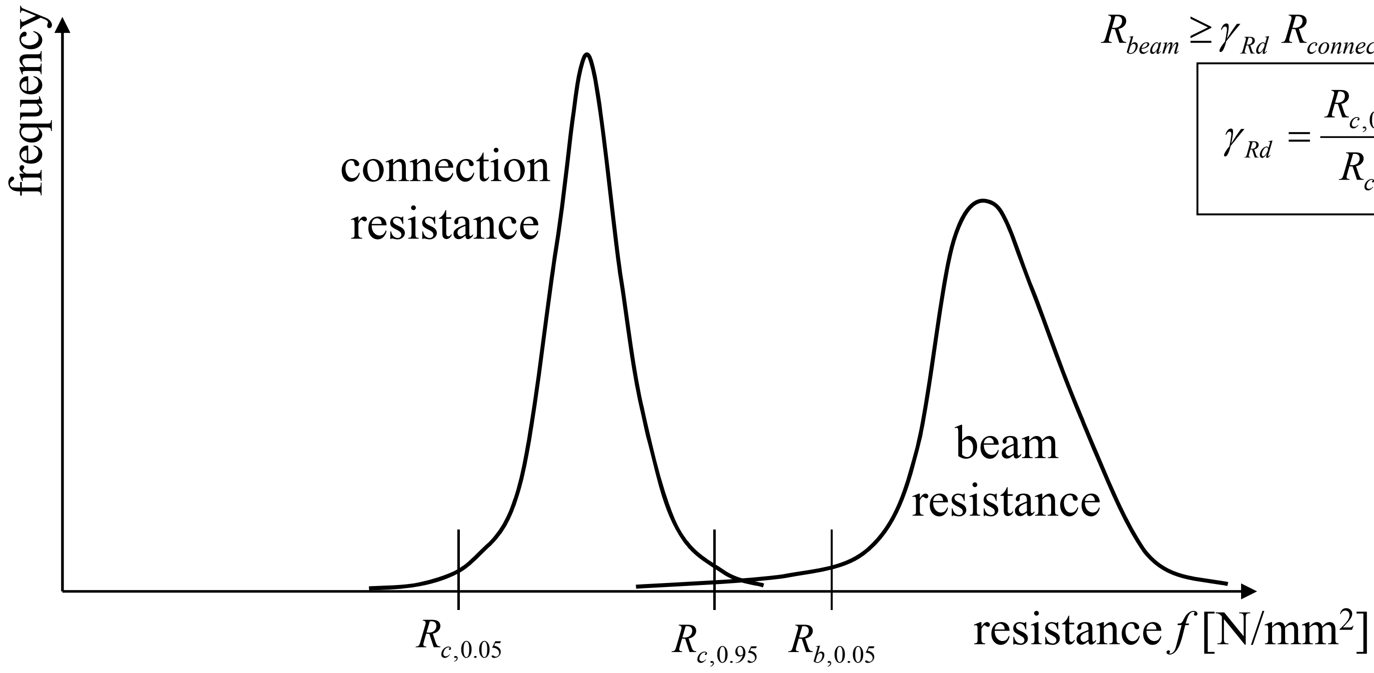
Experimental: $R_{b.k} \geq \quad R_{c,0.95}$

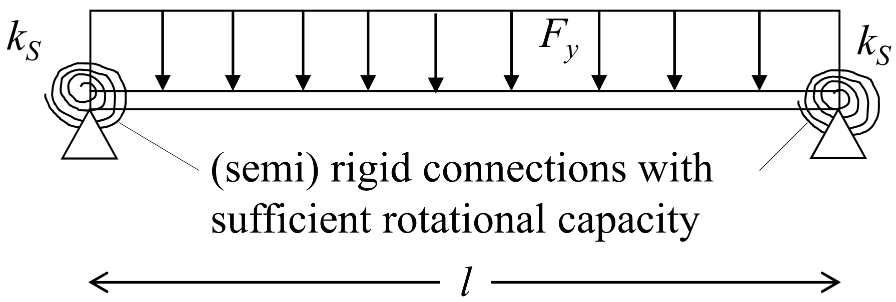
Capacity Based Design

$$R_{beam} \geq R_{connection} \quad (R_b \geq R_c)$$

$$R_{beam} \geq \gamma_{Rd}\ R_{connection}$$

$$\gamma_{Rd} = \frac{R_{c,0.95}}{R_{c,k}}$$






Analytical: $R_{b.k} \geq \gamma_{Rd}\, R_{c.k}$

Experimental: $R_{b.k} \geq R_{c,0.95}$

Capacity Based Design

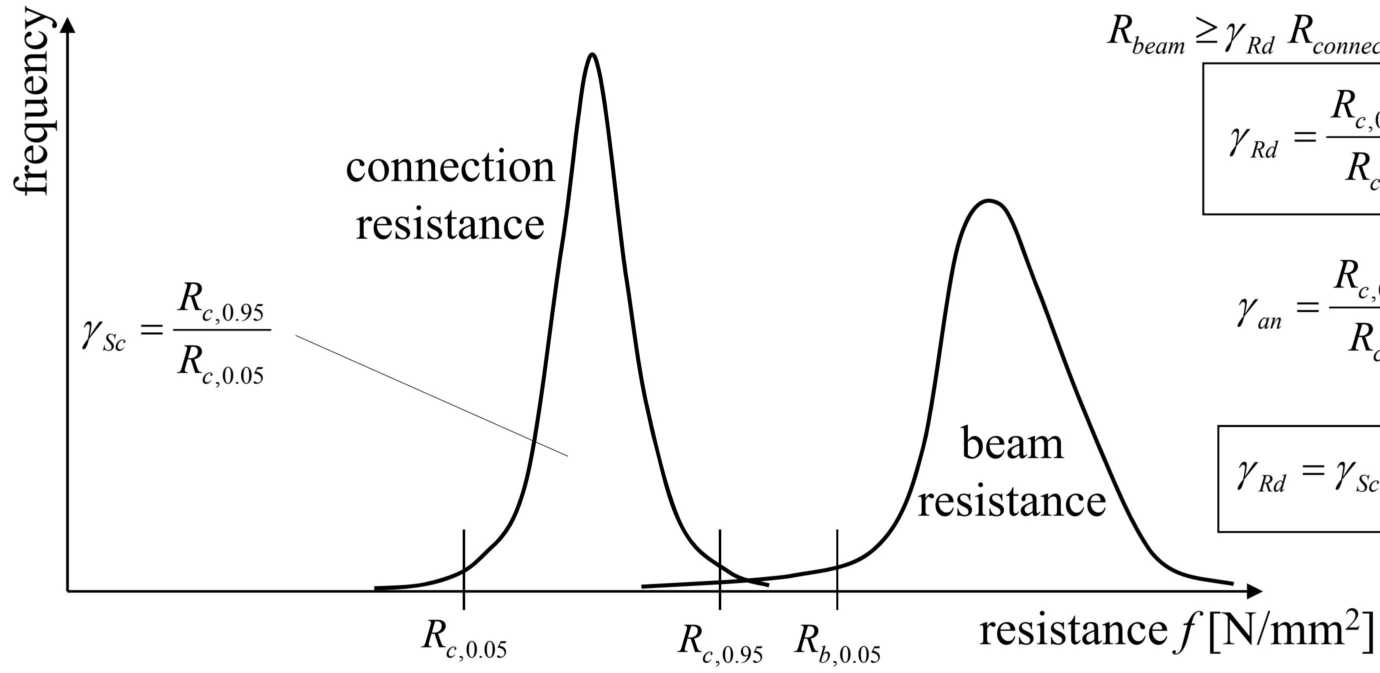
$R_{beam} \geq R_{connection} \quad (R_b \geq R_c)$

$R_{beam} \geq \gamma_{Rd}\, R_{connection}$

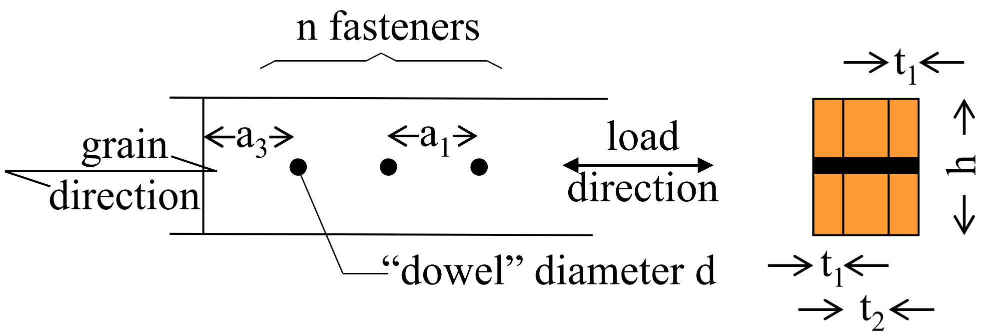
$$\gamma_{Rd} = \frac{R_{c,0.95}}{R_{c,k}}$$

$$\gamma_{an} = \frac{R_{c,0.05}}{R_{c,k}}$$

$$\gamma_{Rd} = \gamma_{Sc}\, \gamma_{an}$$



## Load slip analyses (static ductility)




d = 10,65 – 11,75 mm
$d \leq t_1 \leq 4d$
$2d \leq t_2 \leq 6d$
h = 6d
$a_3 = 7d$
(3d) $5d \leq a_1 \leq 11d$

$10 \leq n \leq 20$
$N \approx 1000$

$R_{c,k}$ according to EYM
$R_{c,0.05}$ and $R_{c,0.95}$ based on tests

# Load slip analyses (static ductility)

| $t_1$ [mm] | $t_2$ [mm] | $d$ [mm] | $n$ | $a_1$ [mm] | $F_{c,k}$ [N] | $F_{c,0.05}$ [N] | $F_{c,0.95}$ [N] | $\gamma_{an}$ | $\gamma_{sc}$ | $\gamma_{Rd}$ | $N$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 12 | 24 | 11,75 | 1 | | 7142 | 6393 | 8536 | 0.90 | 1.34 | 1.20 | 25 |
| | | | 3 | 60 | 15198 | 12428 | 24102 | 0.82 | 1.94 | 1.59 | 10 |
| | | | | 84 | 16532 | 13998 | 25674 | 0.85 | 1.83 | 1.55 | 10 |
| | | | | 132 | 18510 | 18448 | 21754 | 1.00 | 1.18 | 1.18 | 10 |
| | | | 5 | 60 | 24069 | 19363 | 33346 | 0.80 | 1.72 | 1.39 | 20 |
| | | | | 84 | 26181 | 27038 | 36394 | 1.03 | 1.35 | 1.39 | 20 |
| | | | | 132 | 29313 | 29794 | 40430 | 1.02 | 1.36 | 1.38 | 20 |
| | | | 9 | 60 | 40851 | 41487 | 69400 | 1.02 | 1.67 | 1.70 | 20 |
| | | | | 84 | 44436 | 36106 | 73207 | 0.81 | 2.03 | 1.65 | 20 |
| 24 | 48 | 10,65 | 1 | | 8624 | 10779 | 13032 | 1.25 | 1.21 | 1.51 | 25 |
| | | 11,25 | 3 | 60 | 20221 | 30574 | 36386 | 1.51 | 1.19 | 1.80 | 10 |
| | | | | 84 | 21995 | 30574 | 36386 | 1.39 | 1.19 | 1.65 | 10 |
| | | | | 132 | 24626 | 31568 | 35028 | 1.28 | 1.11 | 1.42 | 10 |
| | | 11,75 | 5 | 60 | 33939 | 41455 | 57286 | 1.22 | 1.38 | 1.69 | 20 |
| | | | | 84 | 36917 | 51415 | 60337 | 1.39 | 1.17 | 1.63 | 20 |
| | | | | 132 | 41333 | 52189 | 60793 | 1.26 | 1.16 | 1.47 | 20 |
| | | | 9 | 60 | 57602 | 82933 | 106391 | 1.44 | 1.28 | 1.85 | 20 |
| | | | | 84 | 62657 | 93689 | 107971 | 1.50 | 1.15 | 1.72 | 20 |
| | | | | 132 | 70153 | 93668 | 113854 | 1.34 | 1.22 | 1.62 | 10 |
| 36 | 48 | 10,65 | 1 | | 9846 | 11351 | 11645 | 1.15 | 1.03 | 1.18 | 10 |
| | | | 5 | 84 | 36988 | 47880 | 57465 | 1.29 | 1.20 | 1.55 | 20 |
| 59 | 72 | 11,75 | 1 | | 14754 | 15403 | 22184 | 1.04 | 1.44 | 1.50 | 20 |
| | | 10,65 | 3 | 60 | 27808 | 34668 | 47994 | 1.25 | 1.38 | 1.73 | 10 |
| | | | | 84 | 30249 | 38690 | 51298 | 1.28 | 1.33 | 1.70 | 10 |
| | | | | 132 | 33867 | 44261 | 51391 | 1.31 | 1.16 | 1.52 | 10 |
| | | 11,75 | 5 | 60 | 49718 | 55022 | 74471 | 1.11 | 1.35 | 1.50 | 20 |
| | | | | 84 | 54081 | 60543 | 87346 | 1.12 | 1.44 | 1.62 | 20 |
| | | | 9 | 60 | 84384 | 102186 | 132747 | 1.21 | 1.30 | 1.57 | 20 |
| | | | | 84 | 91789 | 113628 | 148372 | 1.24 | 1.31 | 1.62 | 20 |
| | | | | 132 | 91031 | 149074 | 187003 | 1.64 | 1.25 | 2.05 | 10 |

# Load slip analyses (static ductility)

$1{,}2 \leq \gamma_{Rd} \leq 2{,}0$

| $t_1$ [mm] | $t_2$ [mm] | $d$ [mm] | $n$ | $a_1$ [mm] | $F_{c,k}$ [N] | $F_{c,0.05}$ [N] | $F_{c,0.95}$ [N] | $\gamma_{an}$ | $\gamma_{sc}$ | $\gamma_{Rd}$ | $N$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 12 | 24 | 11,75 | 1 | | 7142 | 6393 | 8536 | 0.90 | 1.34 | 1.20 | 25 |
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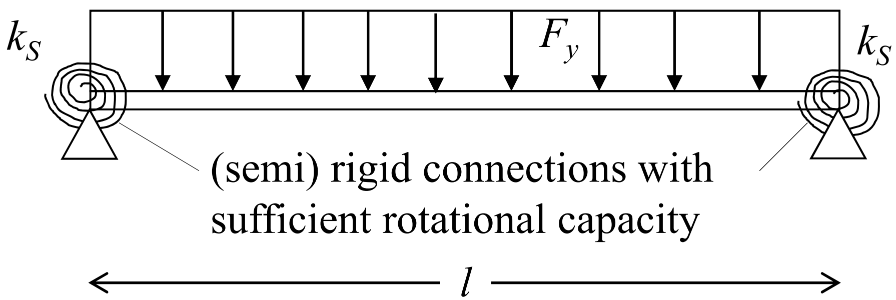
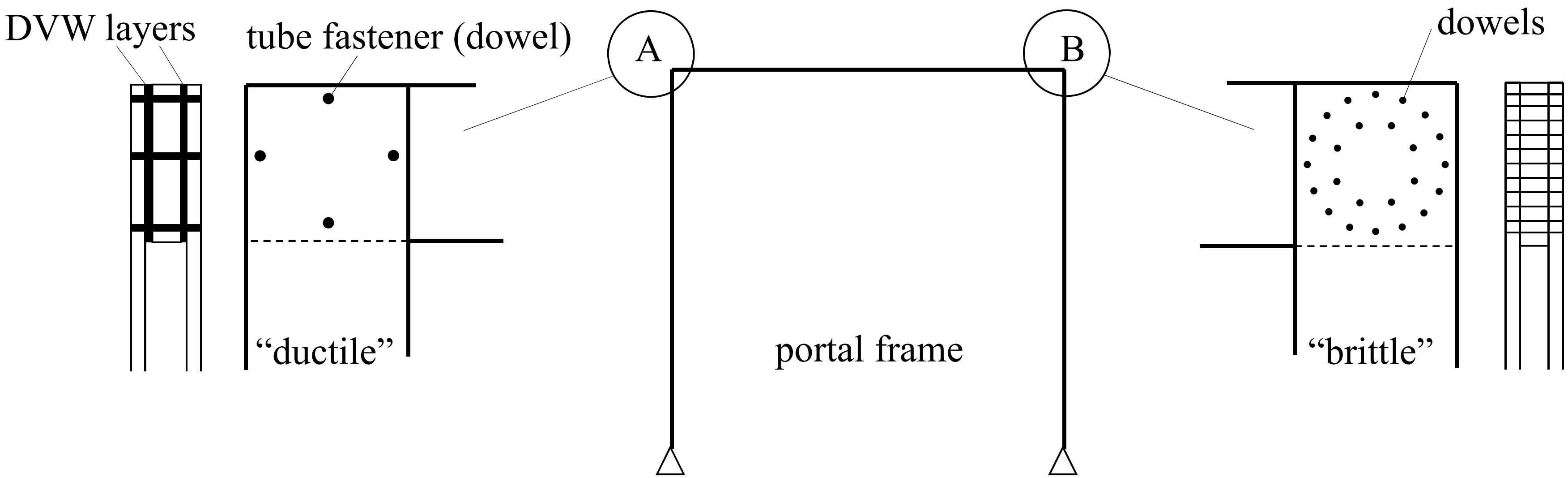


$k_S$
$F_y$
$k_S$
(semi) rigid connections with sufficient rotational capacity
$l$

DVW layers
tube fastener (dowel)
A
B
dowels
"ductile"
portal frame
"brittle"

- why do we need ductility
- member ductility: only in compression
- connections
  - EYM: **yield** model → ductile

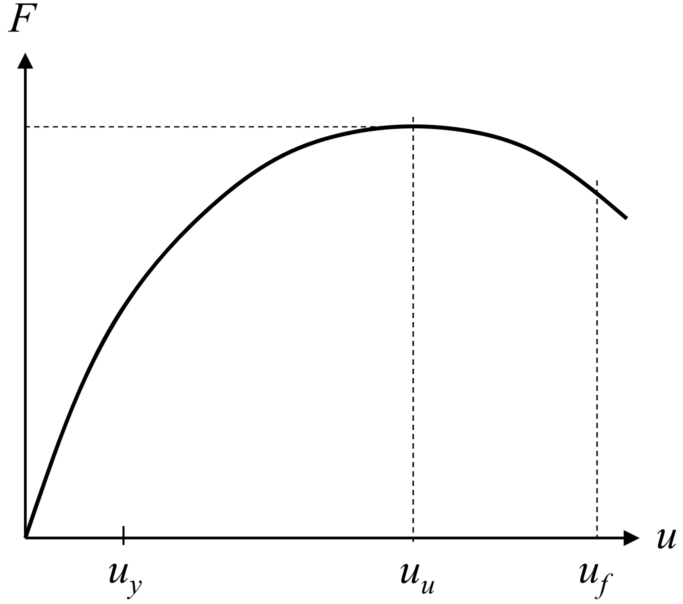
} connections governing

↓

Capacity Based Design

- static ductility
  - definitions
  - load slip analyses —— $\gamma_{Rd}$ —— (Capacity Based Design)

## Load slip analyses (static ductility)




$$D_f = \frac{u_f}{u_y} \quad (1) \qquad D_u = \frac{u_u}{u_y} \quad (2)$$

$$C_u = \frac{u_u - u_y}{u_u} \quad (3) \qquad C_f = \frac{u_f - u_y}{u_f} \quad (4)$$

$$D_{f/u} = \frac{u_f}{u_u} \quad (5)$$

$$D_{s/u} = \frac{K_0}{F_1} u_u \quad (6) \qquad D_{s/f} = \frac{K_0}{F_1} u_f \quad (7)$$

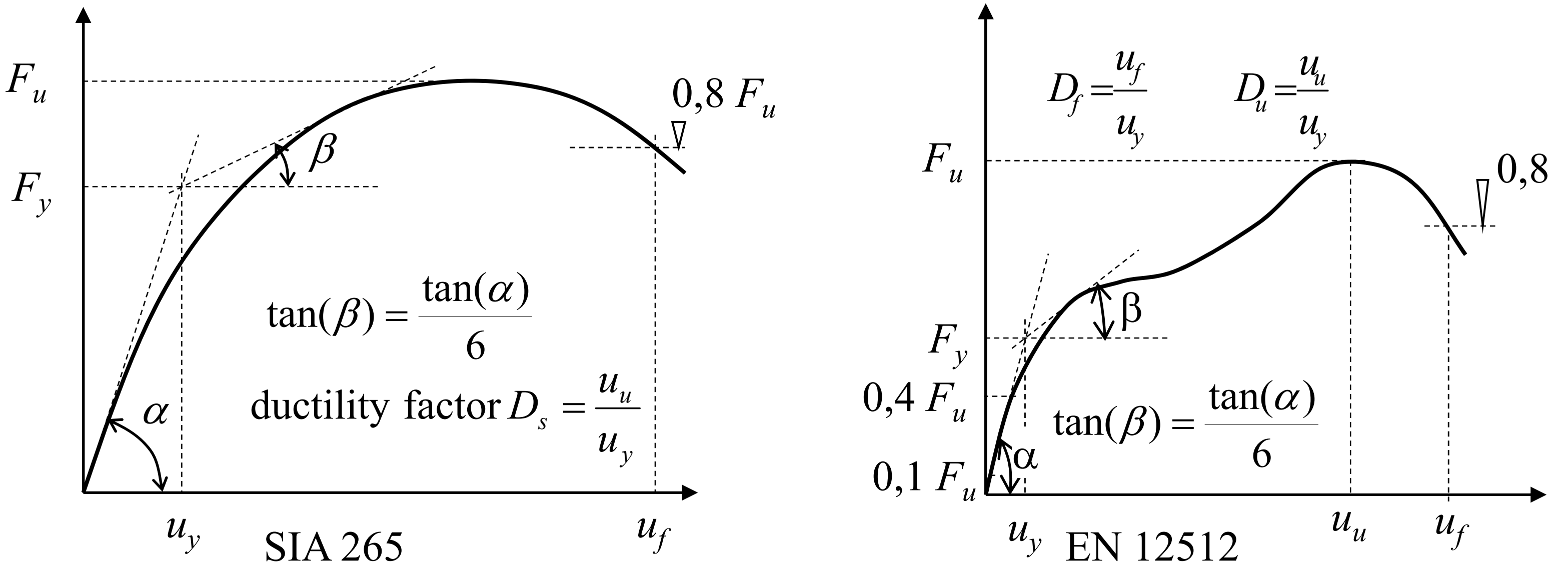
$$F_1 = \max F(0 \le u \le 5\,\mathrm{mm})$$

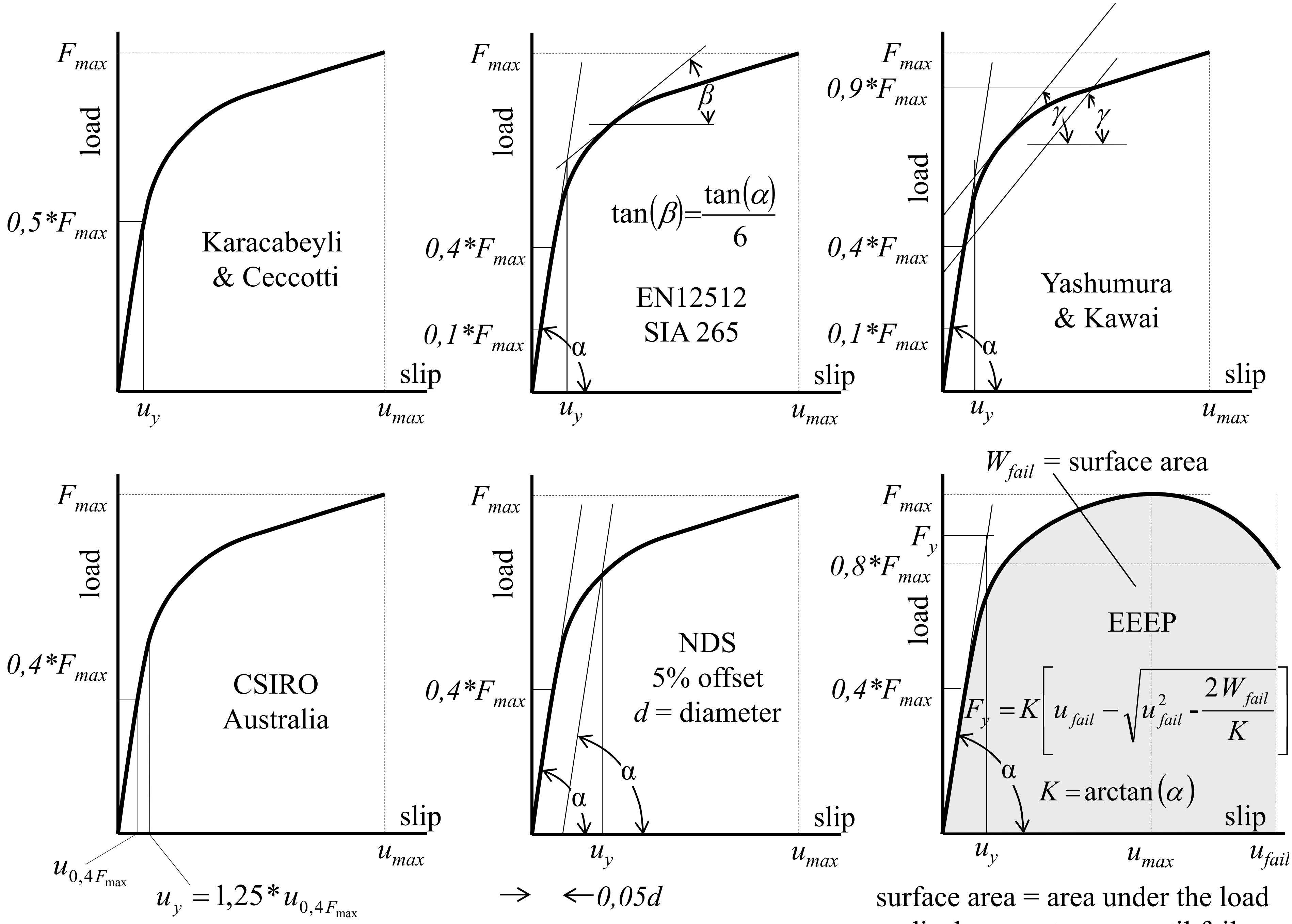
$$D_{uy} = u_u - u_y \quad (8) \qquad D_{fy} = u_f - u_y \quad (9)$$

$$D_{fu} = u_f - u_u \quad (10)$$

$$E_u = \int_{u=0}^{u=u_u} f(F,u)\,du \quad (11) \qquad E_f = \int_{u=0}^{u=u_f} f(F,u)\,du \quad (12)$$

Load slip analyses (static ductility)






surface area = area under the load displacement curve until failure

- why do we need ductility
- member ductility: only in compression
- connections
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} connections governing ↓

**Capacity Based Design**

- static ductility
  - definitions
  - load slip analyses —— $\gamma_{Rd}$ —— (Capacity Based Design)
- dynamic ductility
  - bridge design
  - earthquake design

- why do we need ductility
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} connections governing ↓

Capacity Based Design

- static ductility
  - definitions
  - load slip analyses —— $\gamma_{Rd}$ ——

- dynamic ductility
  - bridge design → reverse loading → pinching / fatigue ↓
  - earthquake design

elastic analyses with $F_d = F_{d,\max} + \frac{1}{3} F_{d,\min}$

overstrength only needed for ductility when loaded excessive

- why do we need ductility
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} connections governing ↓

Capacity Based Design

- static ductility
  - definitions
  - load slip analyses —— $\gamma_{Rd}$ —— (Capacity Based Design)

- dynamic ductility
  - bridge design → reverse loading → pinching / fatigue
  - earthquake design

elastic analyses with $F_d = F_{d,\max} + \frac{1}{3} F_{d,\min}$

overstrength only needed for ductility when loaded excessive

vibrations (serviceability limit state)

- why do we need ductility
- member ductility: only in compression
- connections
  - EYM: **yield** model → ductile

(member ductility / connections → connections governing → Capacity Based Design)

- static ductility
  - definitions
  - load slip analyses — $\gamma_{Rd}$ — Capacity Based Design
- dynamic ductility
  - bridge design
  - earthquake design → behaviour factor ($q$)

$$\text{design seismic action} = \frac{\text{real seismic action}}{q}$$

- why do we need ductility
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connections governing

↓

Capacity Based Design

- static ductility
  - definitions
  - load slip analyses —— $\gamma_{Rd}$

- dynamic ductility
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↓

ductility
energy dissipation → hysteresis analyses

- why do we need ductility
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} connections governing ↓

**Capacity Based Design**

- static ductility
    - definitions
    - load slip analyses — $\gamma_{Rd}$ — (Capacity Based Design)
- dynamic ductility
    - bridge design
    - earthquake design → behaviour factor ($q$)

$$\text{design seismic action} = \frac{\text{real seismic action}}{q}$$

↓

(static) ductility

energy dissipation → hysteresis analyses

overstrength → load-slip analyses

dynamic ductility

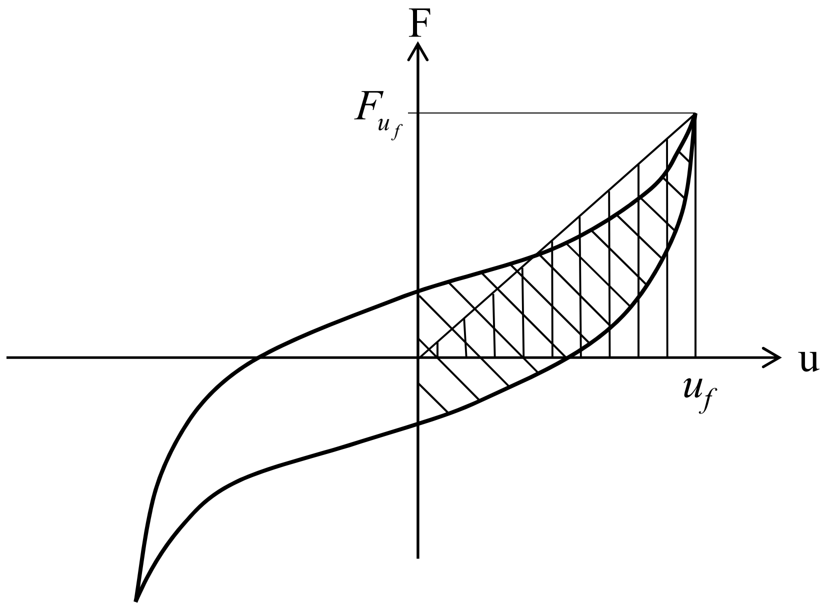
- bridge design
- earthquake design ⟹ hysteresis analyses

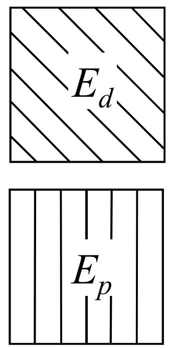
$$\upsilon_{eq} = \frac{E_d}{4\pi E_p}$$

$E_d$ = energy dissipated in a half hysteresis cycle

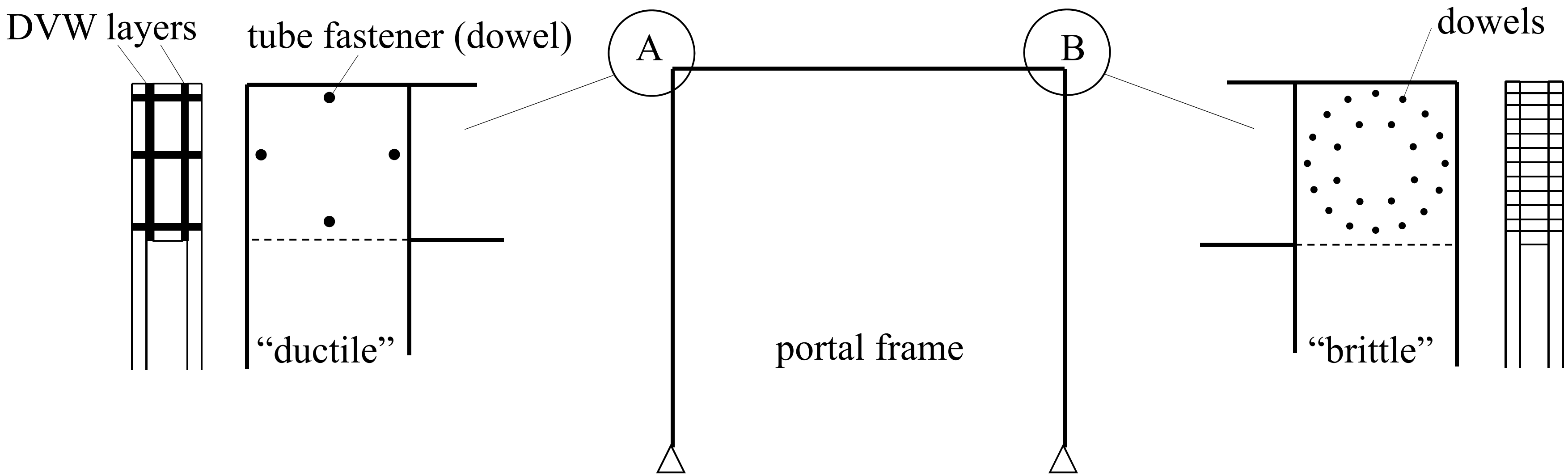
$E_p = \frac{1}{2} F_{u_f} u_f$ = potential energy to failure

$E_{py} = \frac{1}{2} F_y u_y$ = elastic potential energy

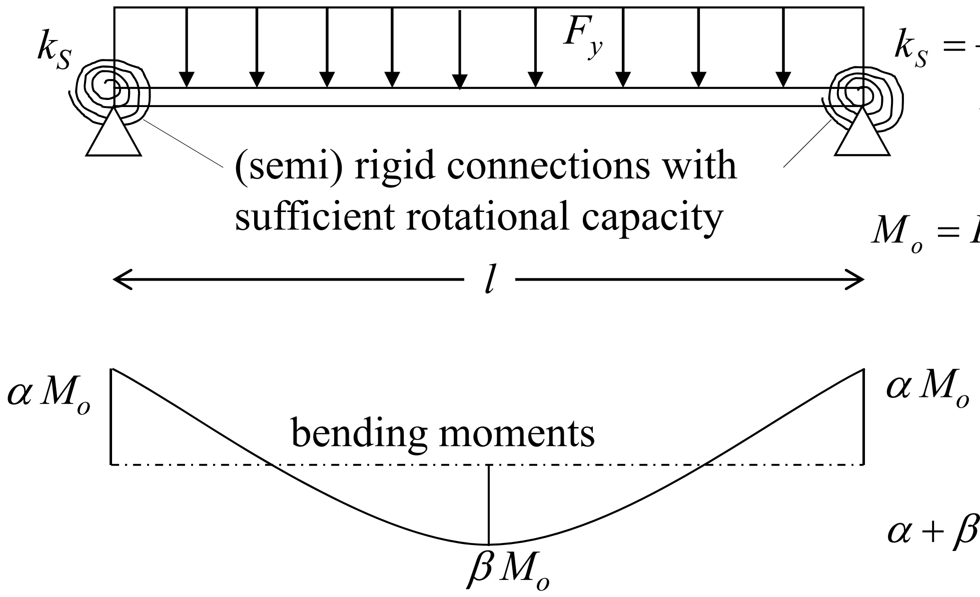


plastic verses elastic analysis for a statically indeterminate timber structure



Elastic:

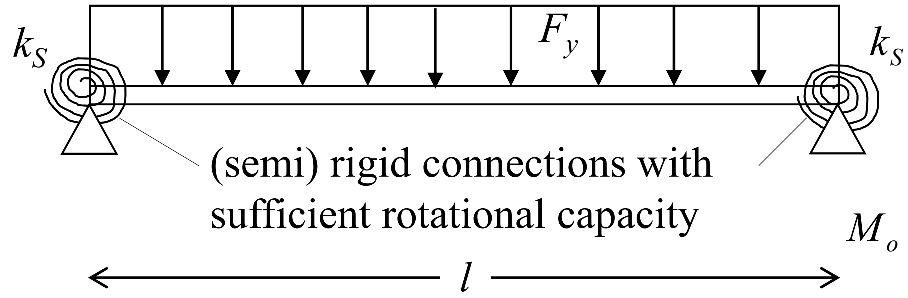



$$k_S = \frac{24\,EI}{\frac{F_y\,l^3}{\alpha\,M_o} - 12\,l}$$

$$M_o = F_y\,l^2$$

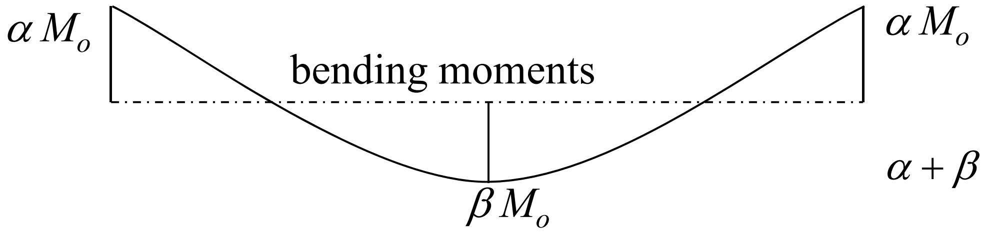
$$\alpha + \beta = \frac{1}{8}$$

Plastic : $\alpha M_0 = M_{Rc}$




$$k_S = \frac{24\,EI}{\dfrac{F_y\, l^3}{\alpha\, M_o} - 12\, l}$$

$$M_o = F_y\, l^2$$




$$\alpha + \beta = \frac{1}{8}$$

ideally $\alpha = \beta = \dfrac{1}{16}$

## Conclusions

- If the connection in a statically indeterminate structure shows sufficient rotational deformation capacity (ductility control), a non linear elastic- perfectly plastic analyses can be used for load carrying capacity analyses

Conclusions

- If the connection in a statically indeterminate structure shows sufficient rotational deformation capacity (ductility control), a non linear elastic- perfectly plastic analyses can be used for load carrying capacity analyses
- For achieving ductility a Capacity Based Design method, as defined in the paper, has to be applied
- Overstrength factors for different types of connections have to be developed to apply a Capacity Based Design method
- For the connections evaluated for this paper overstrength factor $1{,}2 < \gamma_{Rd} < 2{,}0$ was found. $\gamma_{Rd} = 1{,}6$ is suggested to use in practice.
- The behaviour factor q in seismic design is based on static ductility. However, dynamic ductility based on energy dissipation ability is a more appropriate bases.

*Thank you for your attention*

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| • Failure mechanisms of dowel type fastener connections perpendicular to grain | Ad Leijten |
| • Ductility in timber-concrete connections | Alfredo Dias |
| • Ductility aspects of reinforced and non-reinforced timber joints | Hans Joachim Blaβ |