Reliability analysis of ductility in steel structures

Max Gündel

RWTH AACHEN
STAHLBAU UNIVERSITY

Global plastic design of Steel Structures

Earthquake, …

Blast, …

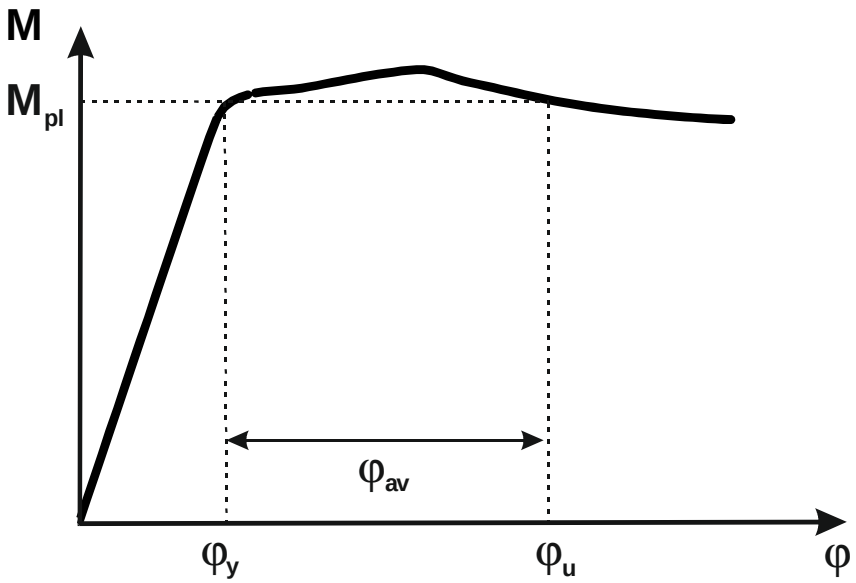
Impact …

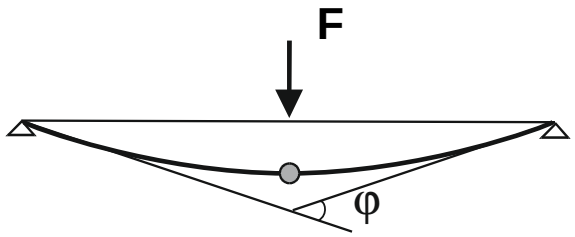
… and any unexpected exceptional loads.

Basic design requirements:

- control where the plastic hinge occurs (capacity design)
- sufficient ductility in the plastic hinge (rotation capacity)

Rotation capacity



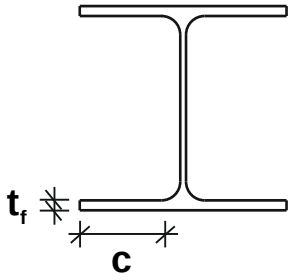


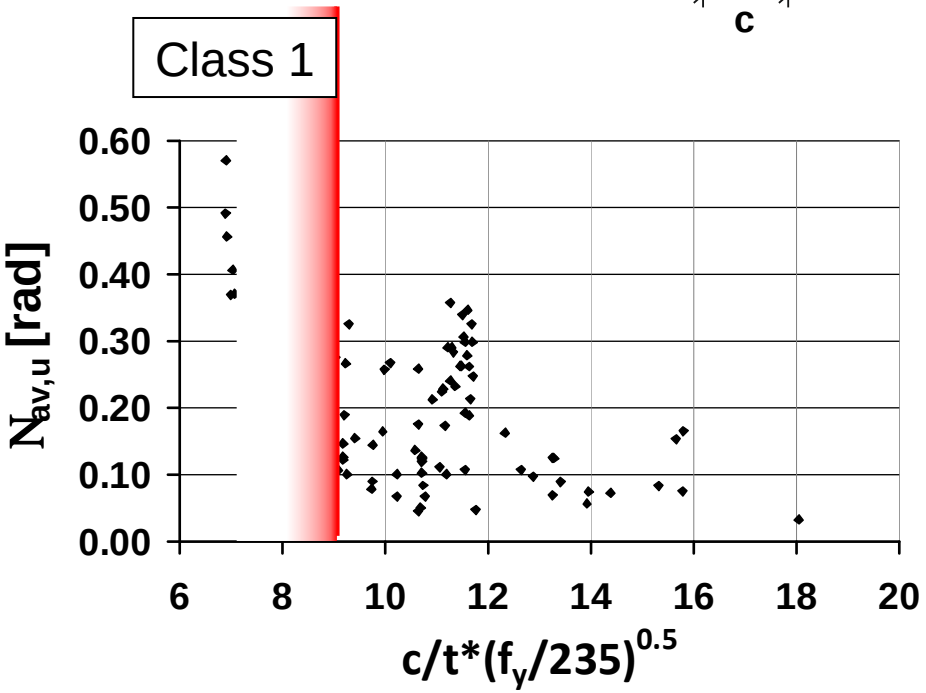
In Eurocodes the rotation capacity is related to cross section classes:

- **Eurocode 3: cross section Class 1 is required for global plastic analysis**
- **Eurocode 8: cross section Class 1 is required for ductility class high (DCH)**

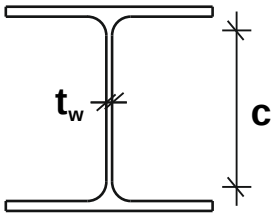
Rotation capacity vs. cross section class

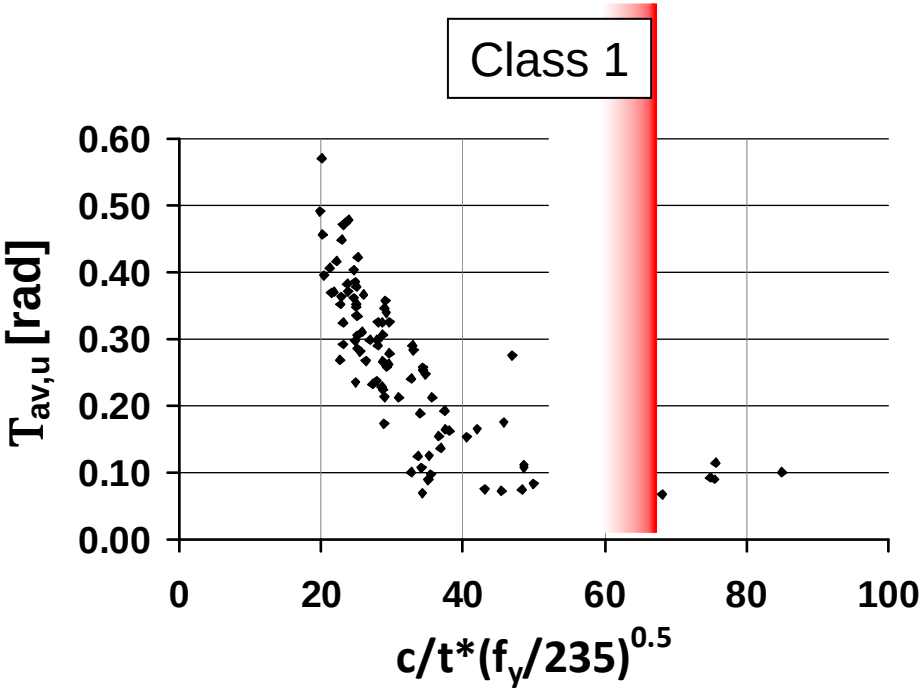
Flange slenderness





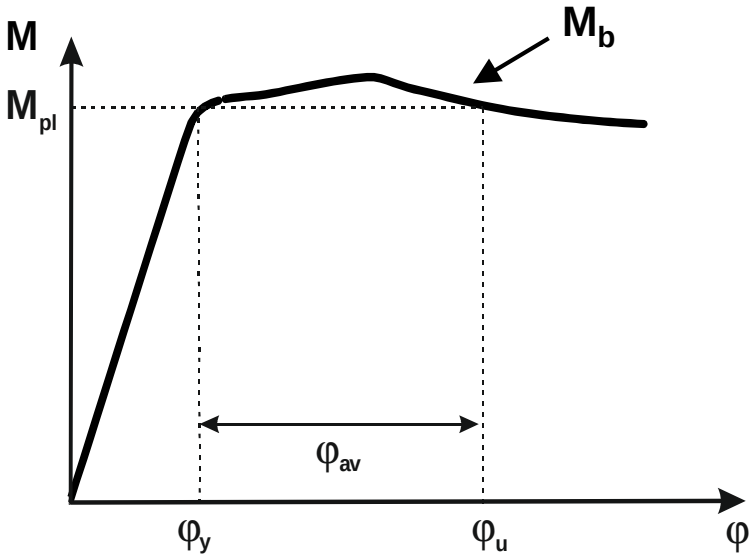
Web slenderness

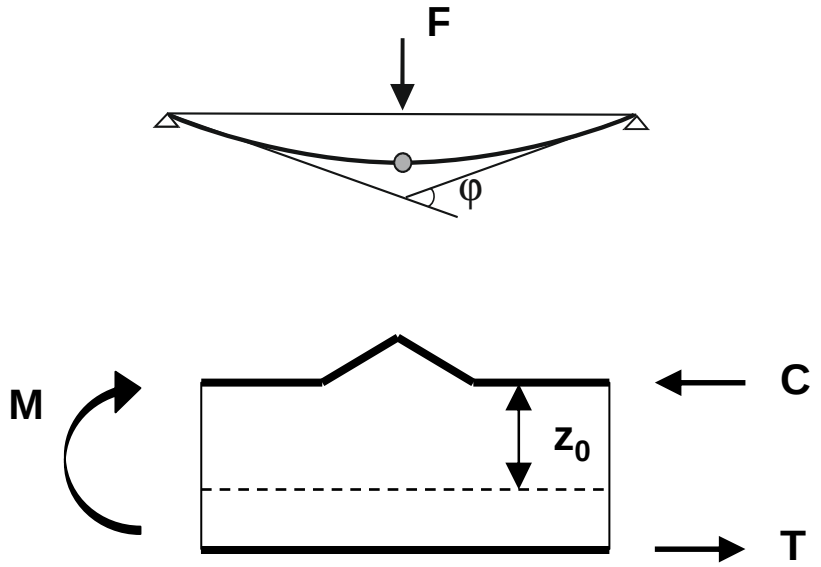




- poor correlation between cross section class and rotation capacity
- cross section classes do not provide rotation capacity directly

Available rotation capacity





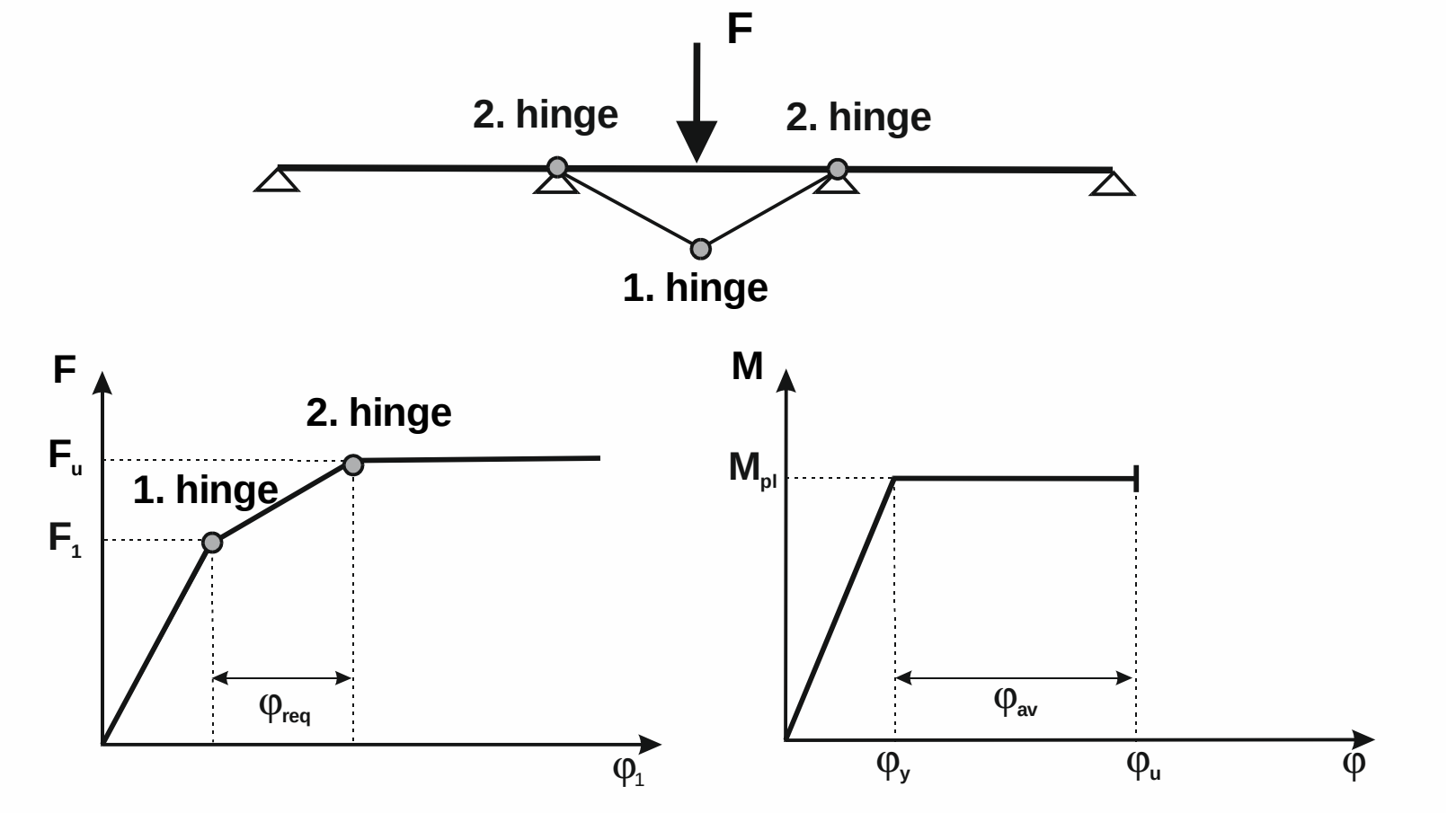
Several analytical models available to determine directly the rotation capacity (e.g. (Kuhlmann, 1987), (Kato, 1989), (Feldmann, 1995), (Gioncu, 2001), …)

Feldmann:

$$M_b = C \cdot z_0 + T \cdot (h - z_0) + \frac{f_y \cdot t_w \cdot z_0^2}{2} + \frac{f_y \cdot t_w \cdot (h - z_0)^2}{2}$$

$$C = \underbrace{(f_y + \Delta\sigma) \cdot t_f \cdot b \cdot \left(1 - \frac{h \cdot \varphi_{pl}}{4h}\right)}_{\text{capacity of buckled flange}} + \underbrace{\frac{f \cdot E \cdot b \cdot t_w^3}{5h^2}}_{\text{stiffness of web}}$$

Rotation capacity assessment – option 1



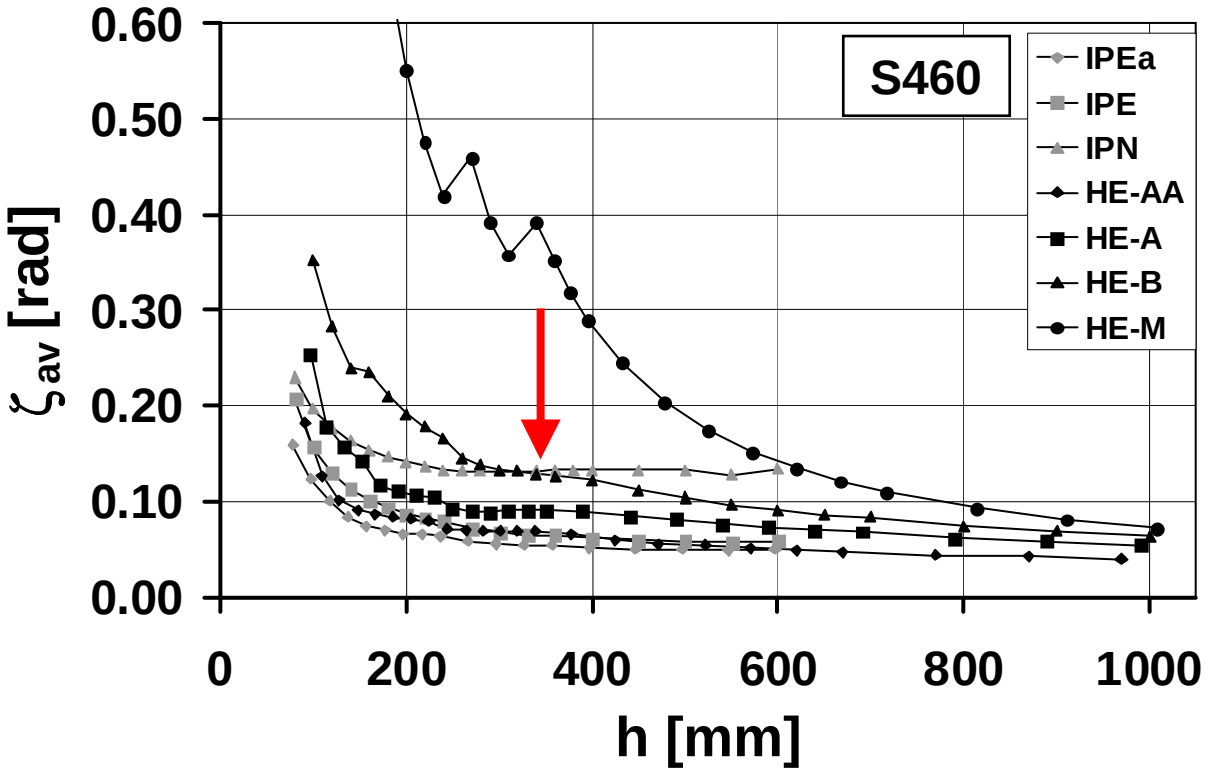
1. **Plastic capacity of the structure must be higher than the load:**
   $F_u > F$
2. **Available rotation capacity must be higher than required rotation capacity:**
   $\varphi_{av} > \varphi_{req}$

RWTH AACHEN STAHLBAU UNIVERSITY

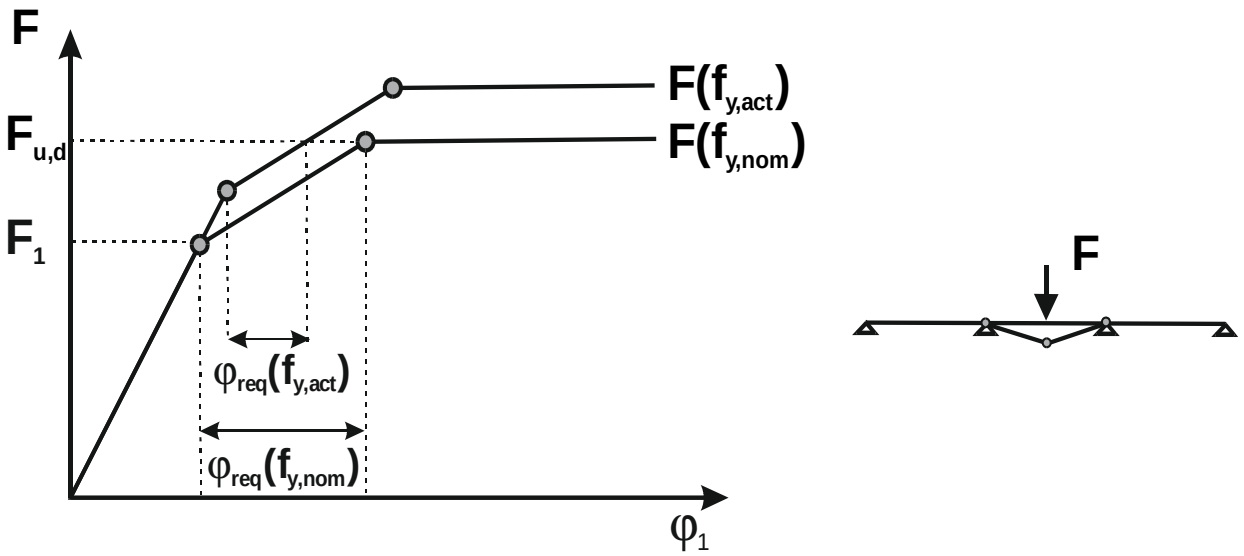
Available rotation capacity

$$\varphi_{av} = \frac{4 \cdot k_{fy}}{\left(f_{y,f} + \Delta\sigma\right) \cdot b \cdot h} \left(\frac{4 \cdot E \cdot b \cdot t_w^{\,3}}{5 \cdot h^2} + \sqrt{\left(f_{y,w} \cdot h \cdot t_w\right)^2 + 4 \cdot f_{y,w} \cdot b \cdot t_f \cdot t_w \cdot h \cdot \Delta\sigma} - f_{y,w} \cdot h \cdot t_w \right)$$

→ $$\varphi_{av} \sim \frac{1}{f_y} \cdot \left(\frac{t_w}{h}\right)^3$$



Required rotation capacity

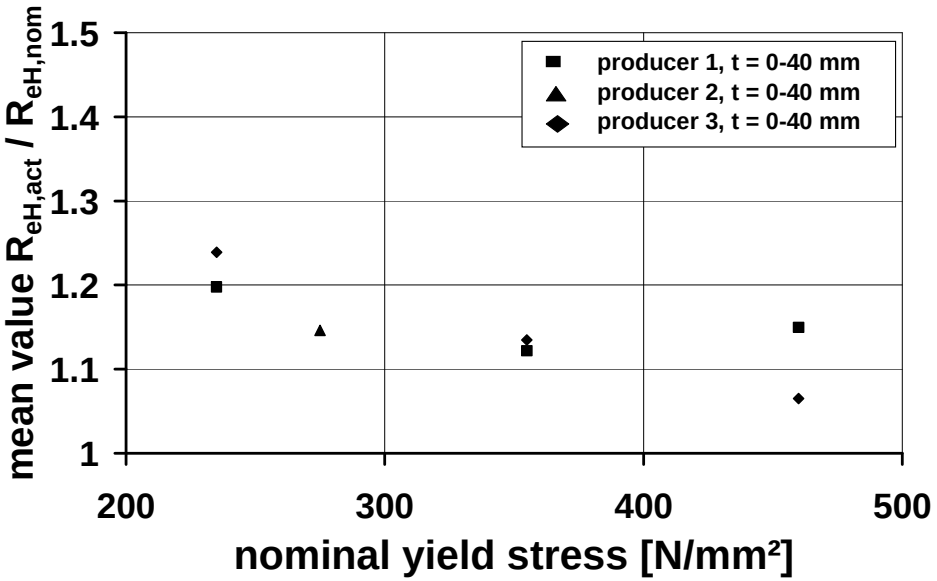


→ <u>available</u> rotation capacity decreases with increasing material overstrength

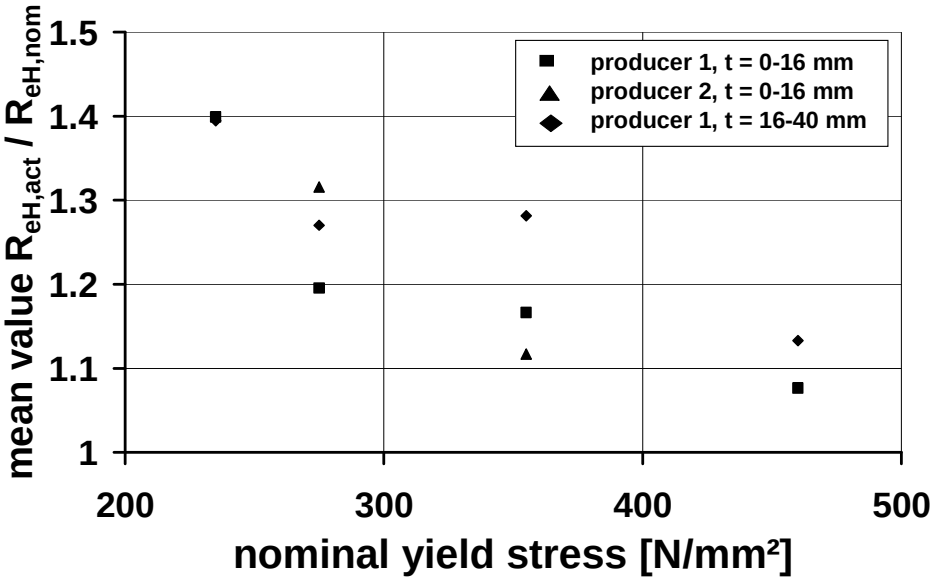
→ <u>required</u> rotation capacity decreases with increasing material overstrength

Reliability analysis – random variables

“as rolled”



“thermomechanical”



- 1 600 data sets from 1984 to 1995 of production process “as rolled”
- 13 000 data sets from 2007 to 2008 of “thermomechanical” steel

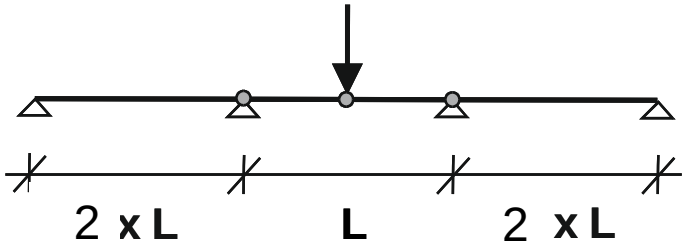
Reliability analysis – random variables

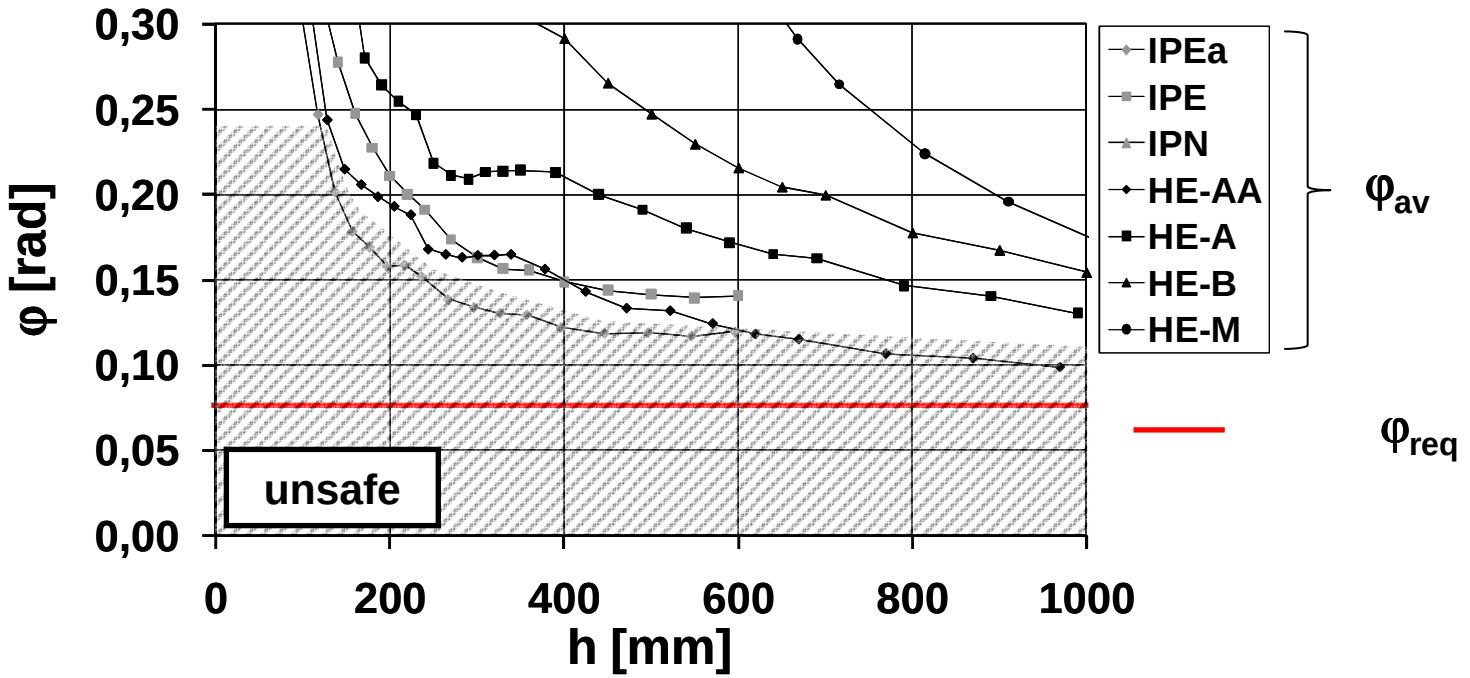
- material properties (E, f_y, f_{yw}/f_{yf})
- cross section properties (h, b, t_w, t_f)
- model uncertainty (θ_u)
- load deterministic (F)

variable	mean value	stand. dev.	unit	distribution
E	21 000	630	[kN/cm²]	lognormal
f_y (AR)	8.0 + 0.92 $f_{y,nom}$	3.2	[kN/cm²]	lognormal
f_y (TM)	12.5 + 0.83 $f_{y,nom}$	3.0	[kN/cm²]	lognormal
f_{yw}/f_{yf}	1.08	0.07	[-]	lognormal
Δh	0	0.18	[cm]	normal
Δb	0	0.14	[cm]	normal
Δt_w	0	0.04	[cm]	normal
Δt_f	-0.04	0.05	[cm]	normal
θ_u	1.24	0.33	[-]	normal

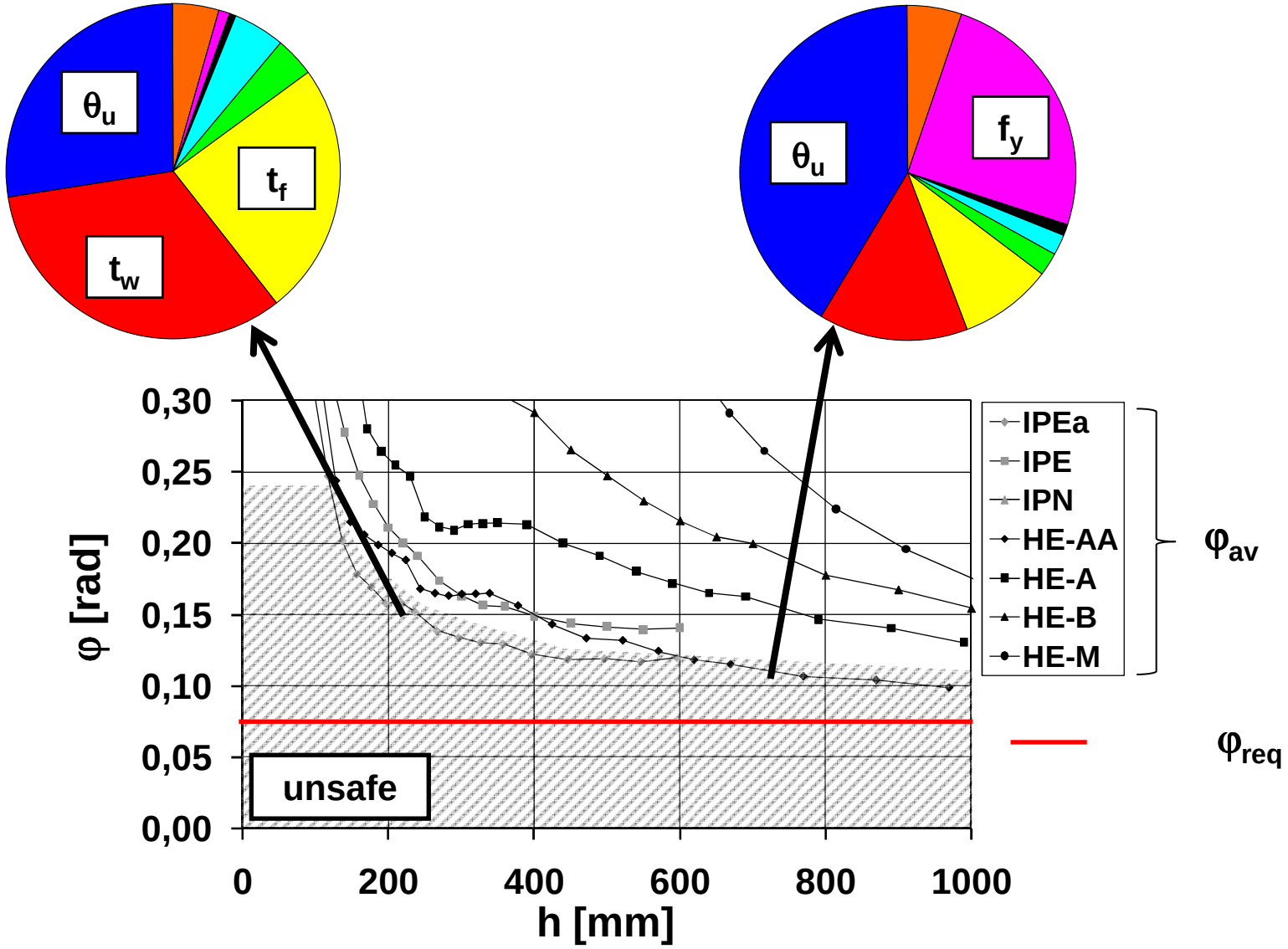
Reliability analysis - results

- Steel grade S235 AR
- 3-span girder
- limit state functions: $F_u > F$ and $\varphi_{av} > \varphi_{req}$
- target reliability index: $\beta \cdot \alpha_R > 3.04$



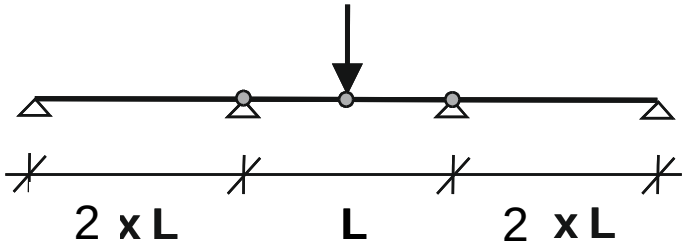


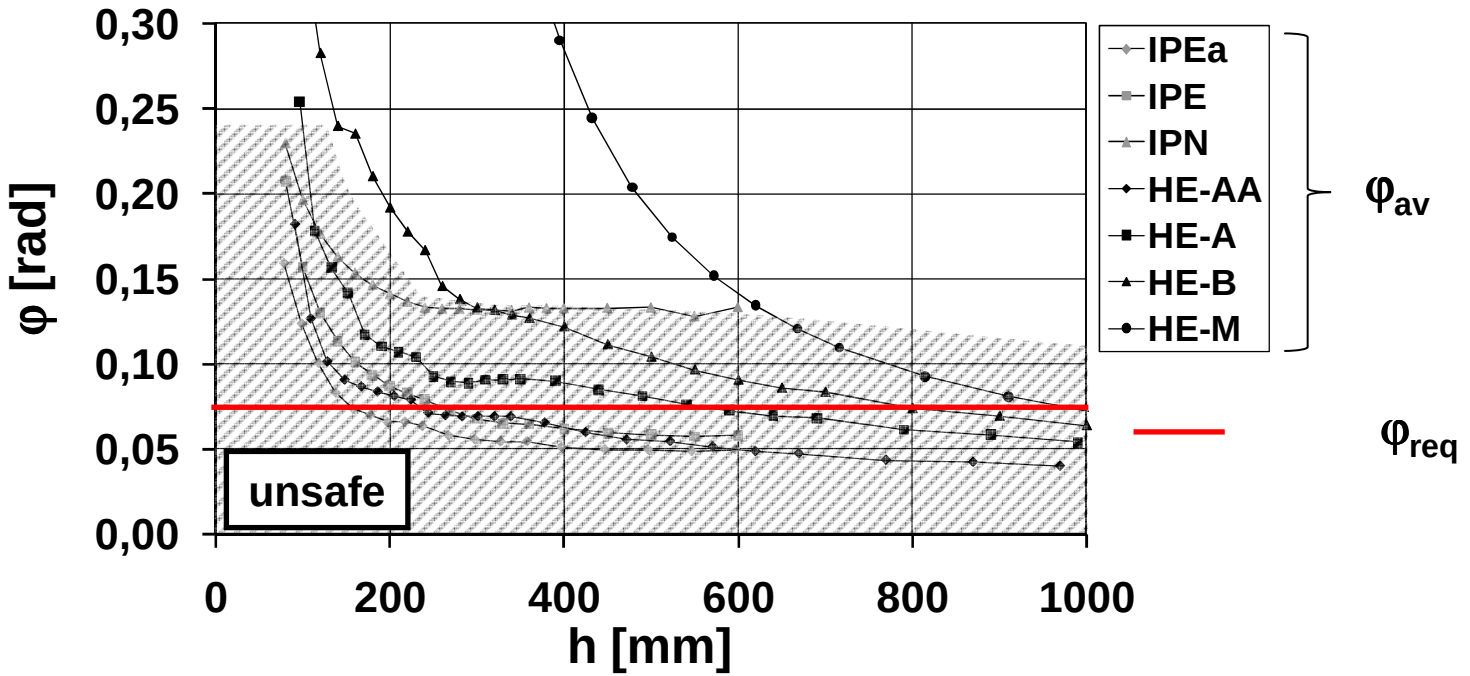
Reliability analysis - results



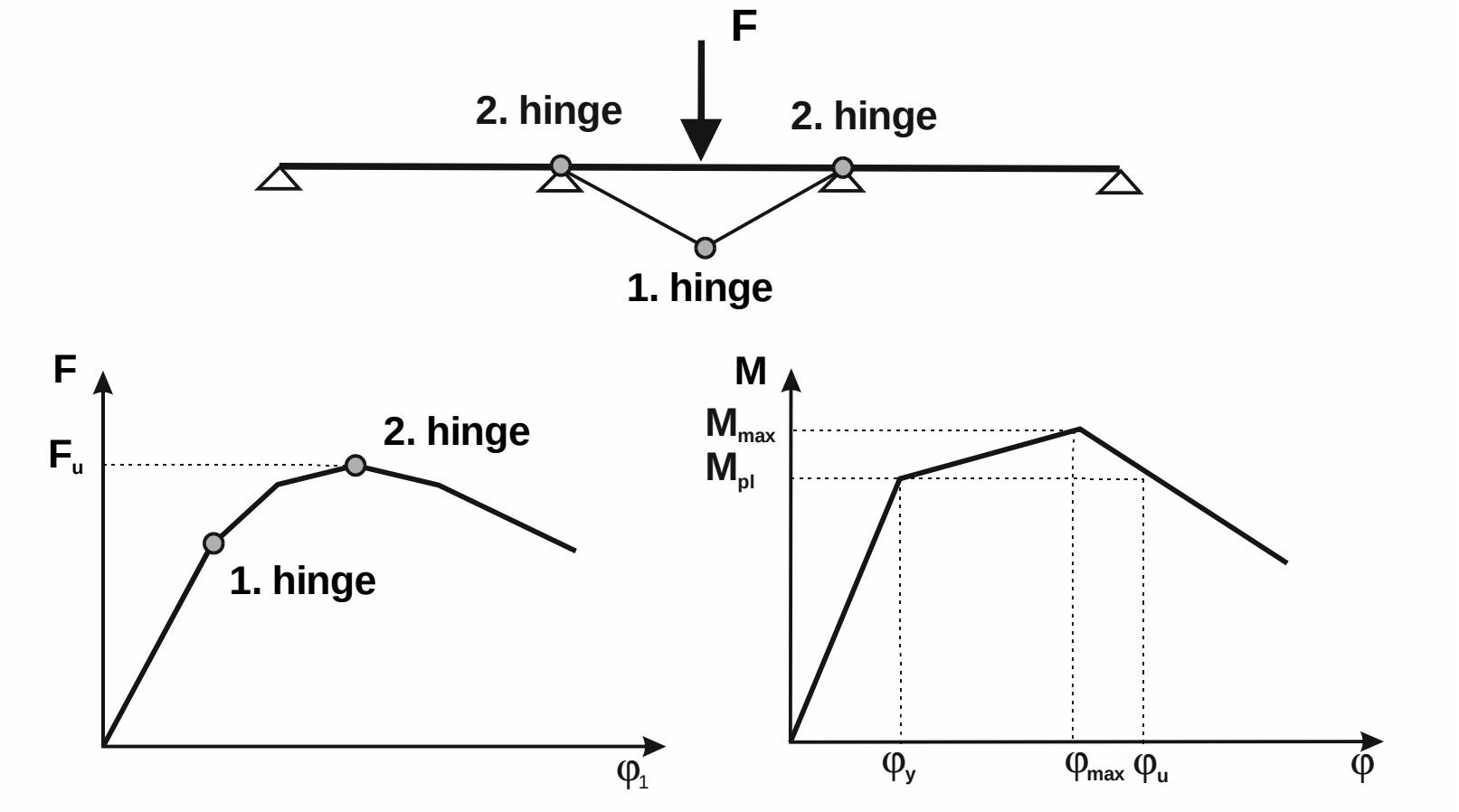
Reliability analysis - results

- Steel grade S460 TM
- 3-span girder
- limit state functions: $F_u > F$ and $\varphi_{av} > \varphi_{req}$
- target reliability index: $\beta \cdot \alpha_R > 3.04$



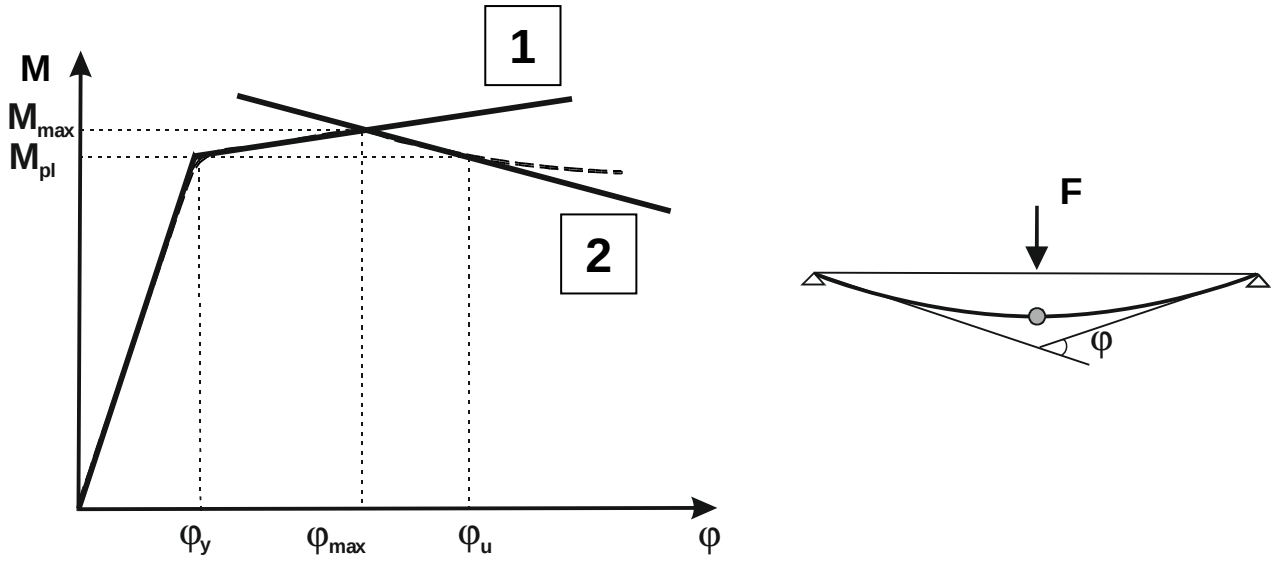


Rotation capacity assessment - option 2



1. **Plastic capacity of the structure must be higher than the load:**
   $F_u > F$

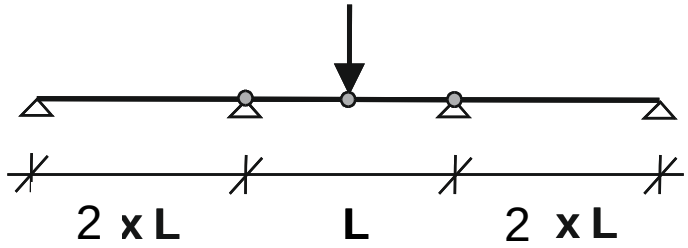
Moment-rotation curve

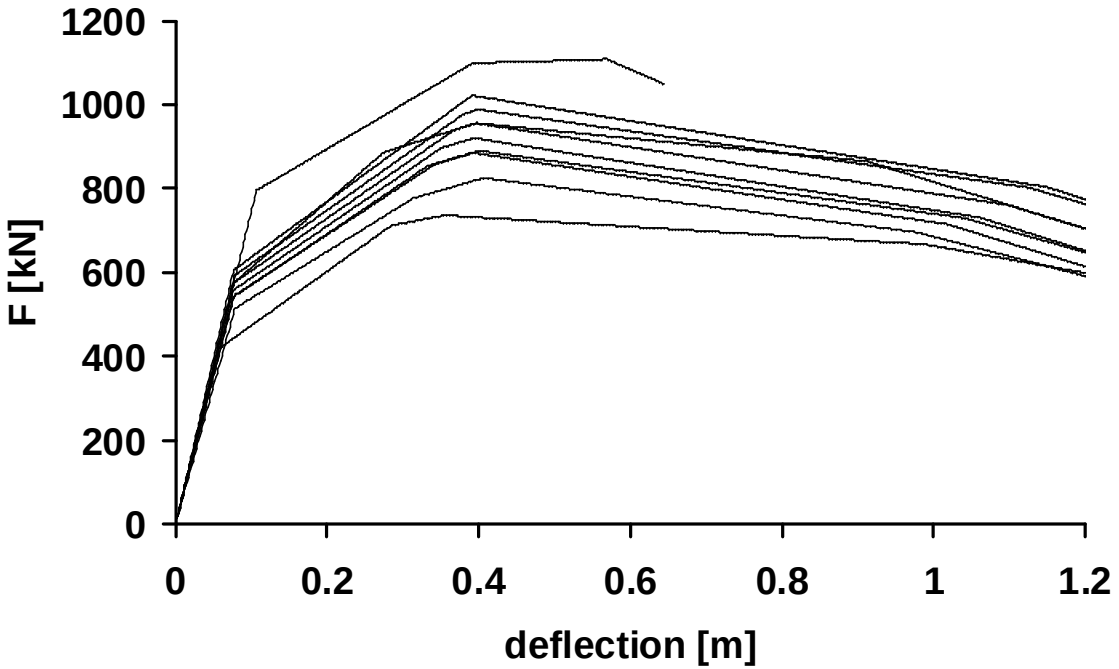


- **hardening branch according to Lay** 1
- **descending branch according to Feldmann** 2

Reliability analysis - results

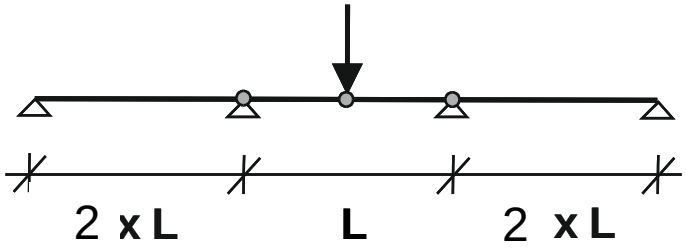
- 3-span girder
- limit state functions: $F_u > F$
- target reliability index: $\beta \cdot \alpha_R > 3.04$



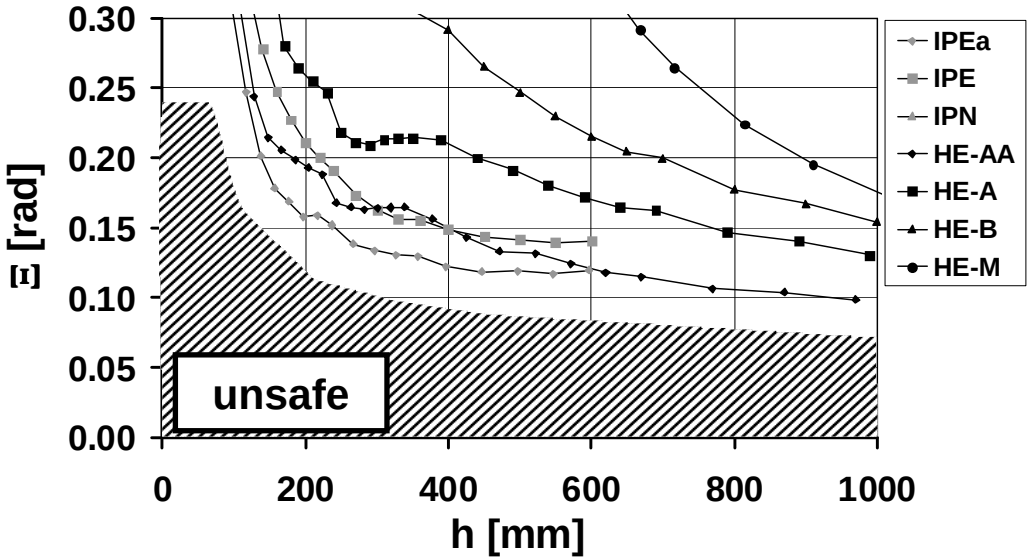


Reliability analysis - results

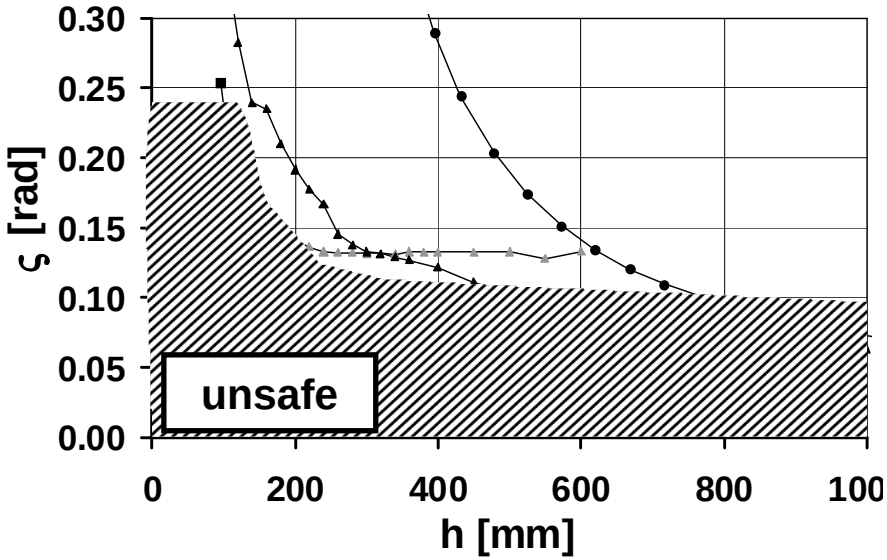
- 3-span girder
- limit state functions: $F_u > F$
- target reliability index: $\beta \cdot \alpha_R > 3.04$



S235 AR



S460 TM



Conclusions

- material overstrength reduce the required and the available rotation capacity; the reduction of required rotation capacity is higher than the reduction of the available rotation capacity
- rotation capacity of typical rolled sections in S235 seems to be sufficient for most of the structural configurations
- some rolled section in S460 seems to have insufficient rotations capacity even if they are classified as section class 1
- most important random variables are the model uncertainty, flange and web thickness (only small sections) and yield stress (only large sections).
- the results based on the bi-linear and tri-linear model are similar; the positive effect due to strain hardening is small