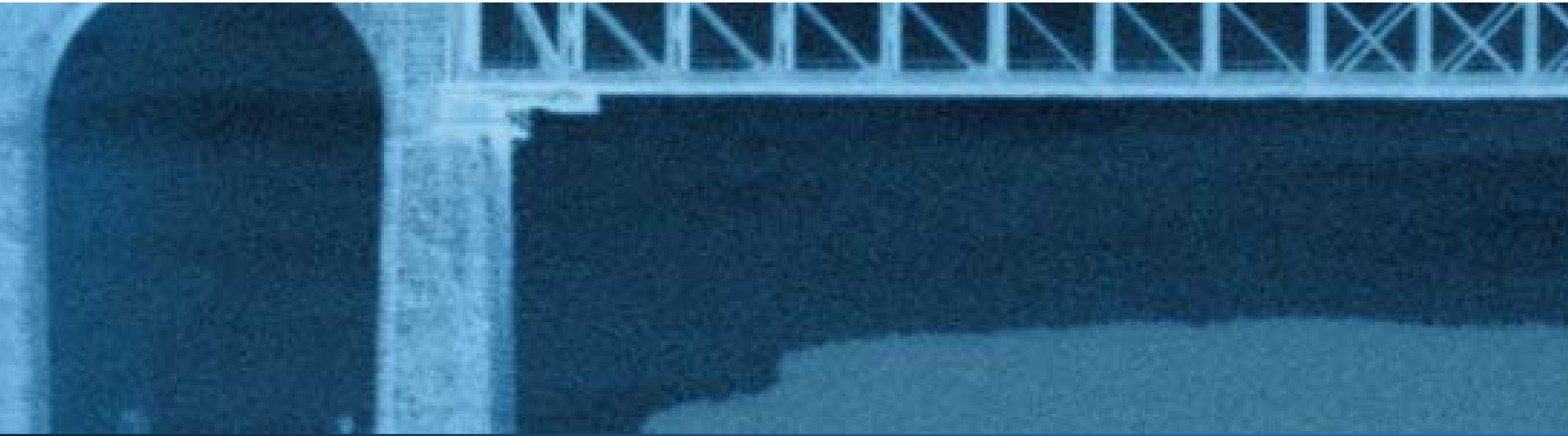
ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Design for Robustness

Prof. Thomas Vogel



Content

- Introduction
- Simple examples
- Elements of robustness
- Evaluation of some design provisions in codes
- What happens with real structures?

Definition for Robustness

- Ability of a structure and its members to keep the amount of deterioration or failure within reasonable limits in relation to the cause.

[SIA 260]

- The ability of a structure to withstand events like fire, explosions, impact or the consequences of human error, without being damaged to an extent disproportionate to the original cause.

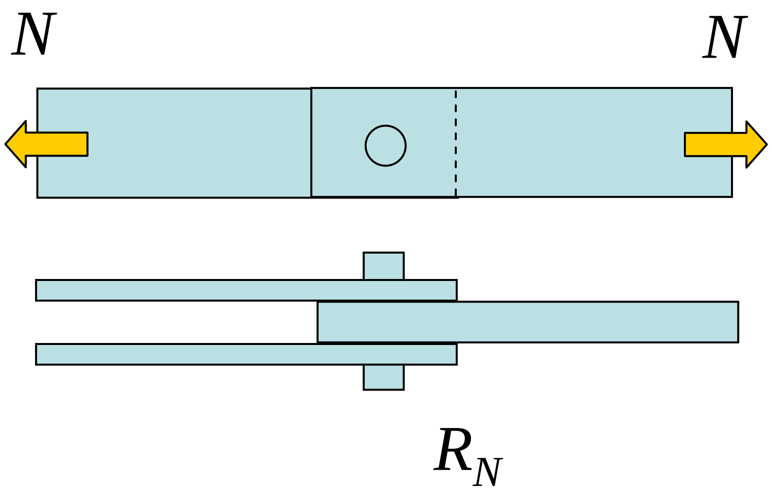
[EN 1991-1-7]

Which design is more robust?

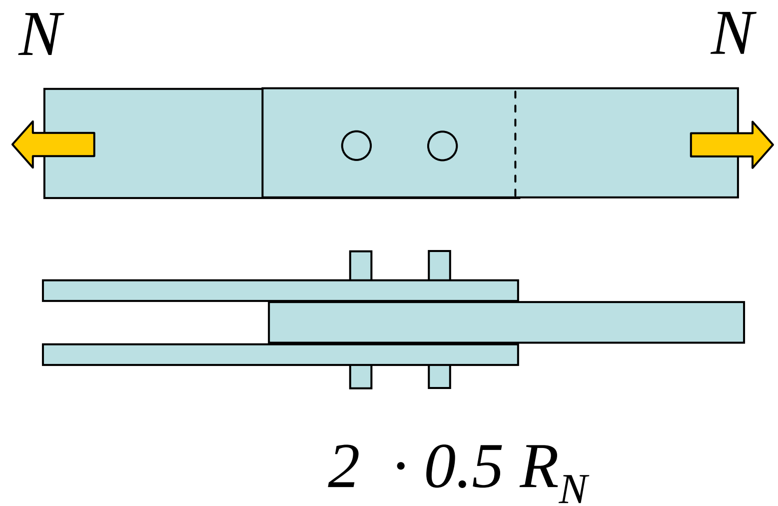
- Multiple choice
- 4 Examples
- Distribute sheets

Bolted connection in tension (1)

A: 1 bolt



B: 2 bolts

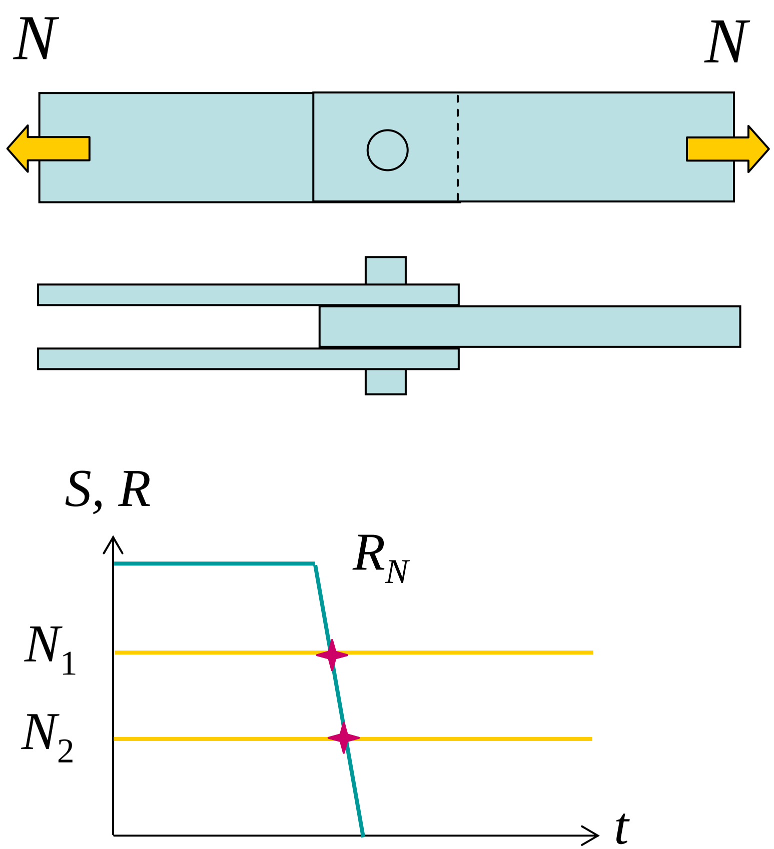


Which design is more robust?

☐ ☐

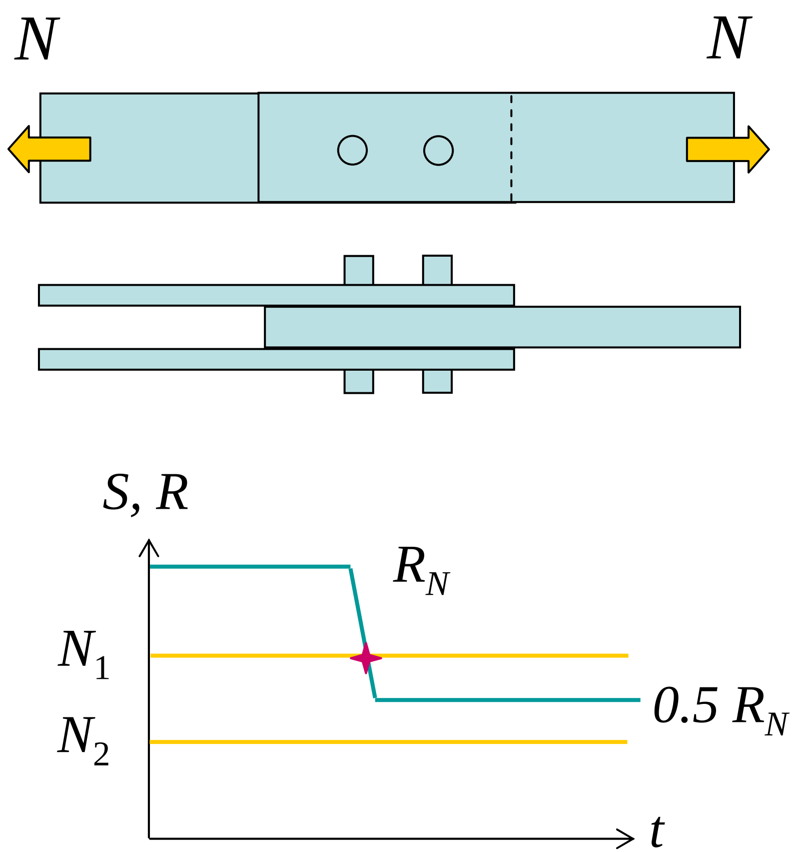
Bolted connection in tension (1)

A: 1 bolt



B: 2 bolts

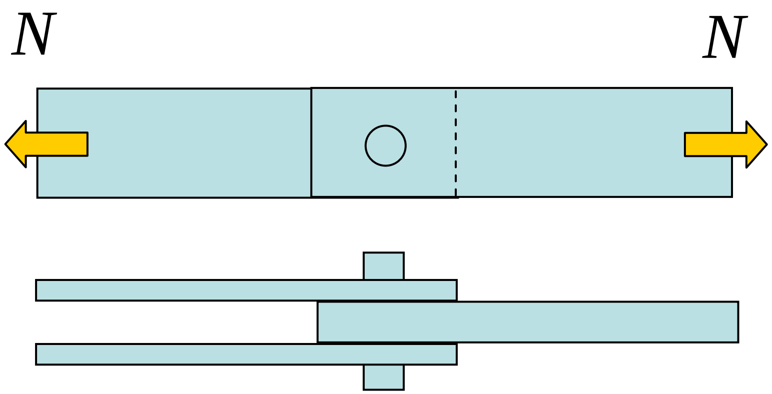
more robust, if
$N < 0.5\ R_N$



Bolted connection in tension (1)

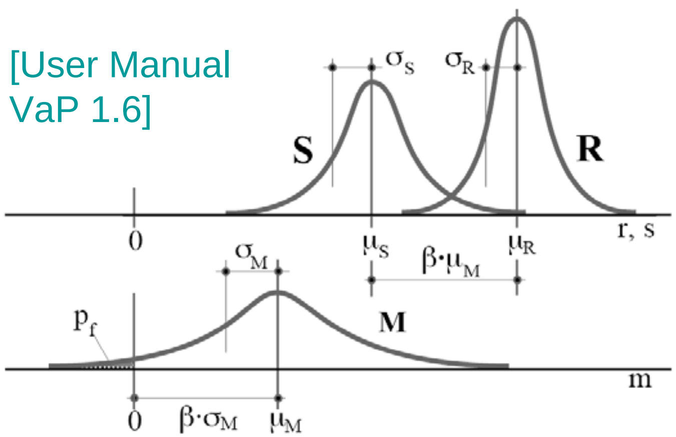
safer, if variation coefficient σ/μ of bolts constant

A: 1 bolt

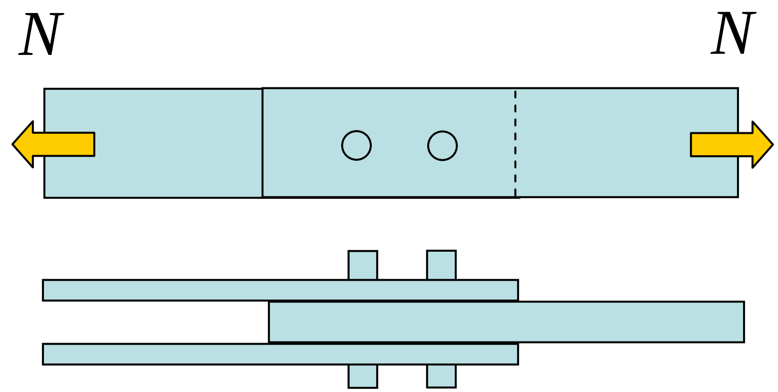


$$R = R\left(\mu_R^A, \sigma_R^A\right)$$

[User Manual VaP 1.6]



B: 2 bolts



$$R = R\left(\mu_R^B, \sigma_R^B\right) = \left(\mu_R^A, \sqrt{0.5}\sigma_R^A\right)$$

$$\mu_R^B = 2\cdot\mu_{R,B} = 2\cdot 0.5\mu_R^A = \mu_R^A$$

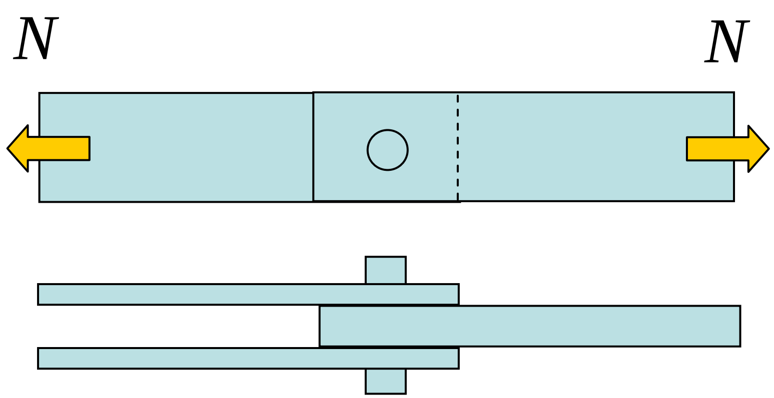
$$\sigma_R^B = \sqrt{\sigma_{R,B}{}^2 + \sigma_{R,B}{}^2} =$$

$$\sqrt{\left(\frac{\sigma_R^A}{2}\right)^2 + \left(\frac{\sigma_R^A}{2}\right)^2} = \sqrt{0.5}\sigma_R^A$$

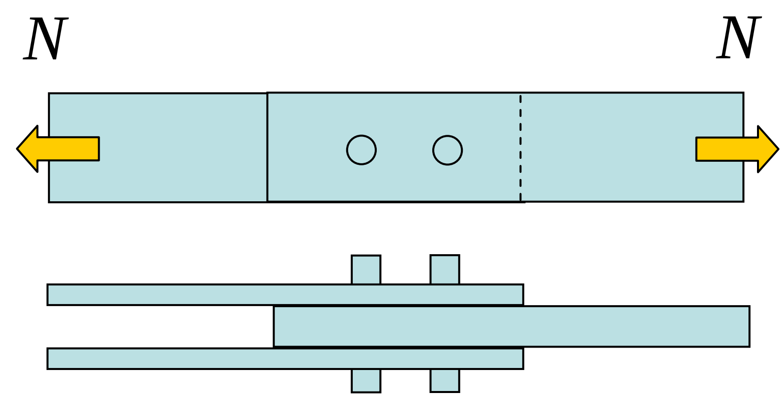
Bolted connection in tension (1)

ductility reduced by imperfect fit

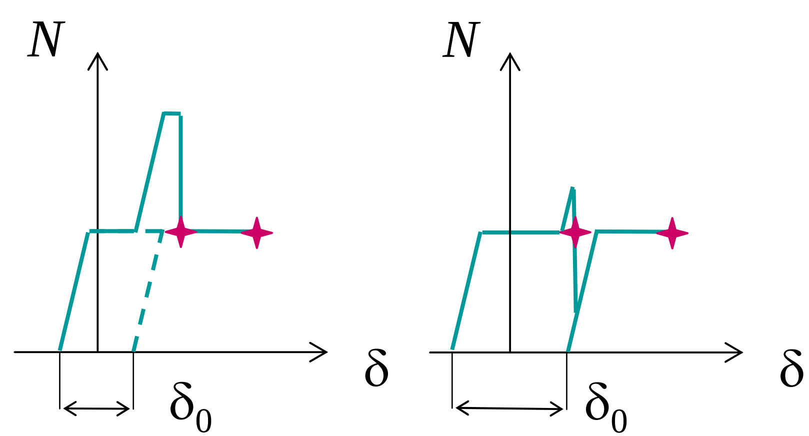
A: 1 bolt



B: 2 bolts

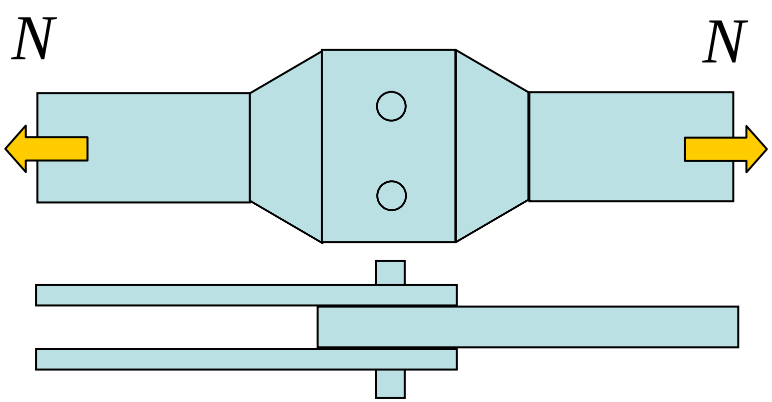


imperfect fit δ_0



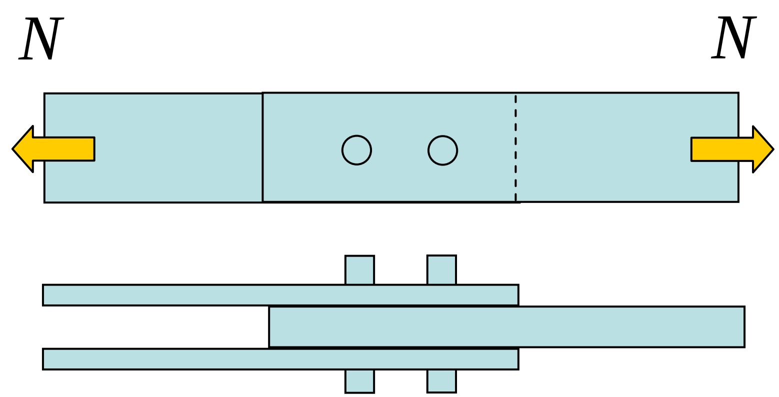
Bolted connection in tension (2)

A: 2 bolts aside each other



$2 \cdot 0.5\, R_N$

B: 2 bolts in a row

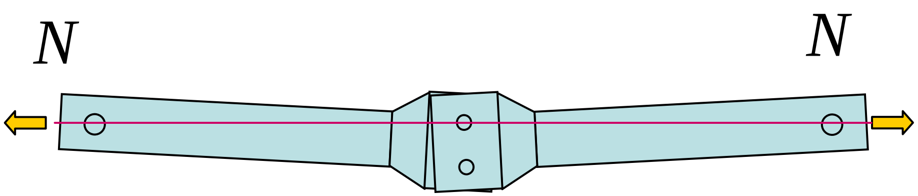


$2 \cdot 0.5\, R_N$

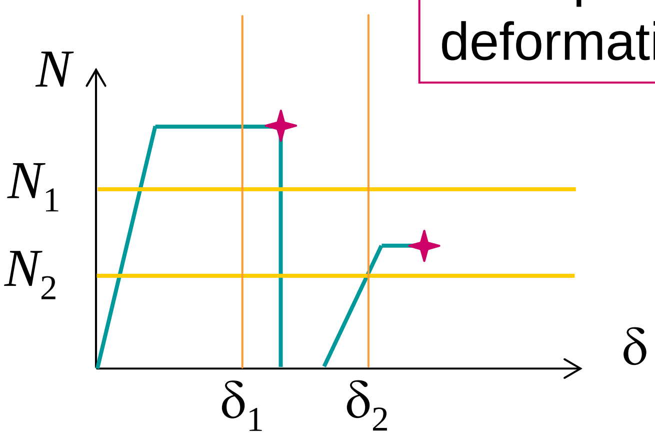
Which design is more robust?

Bolted connection in tension (2)

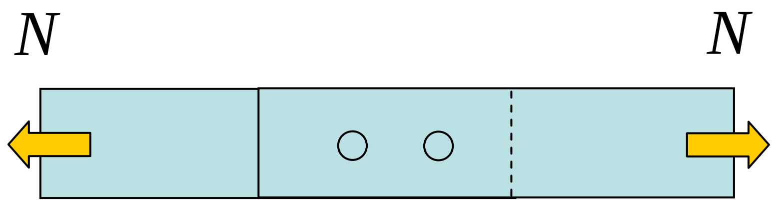
A: 2 bolts aside each other



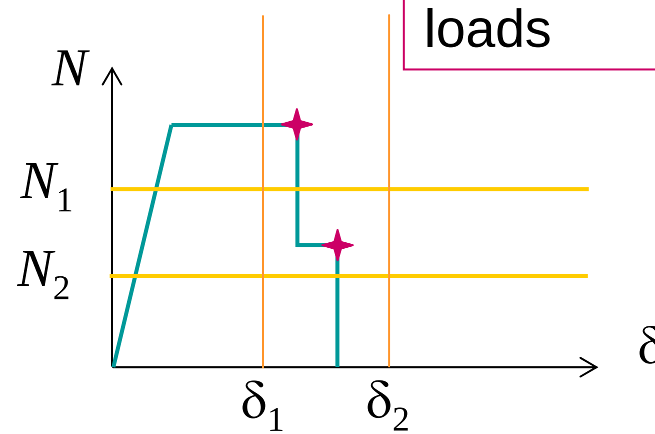
more robust for imposed deformations



B: 2 bolts in a row

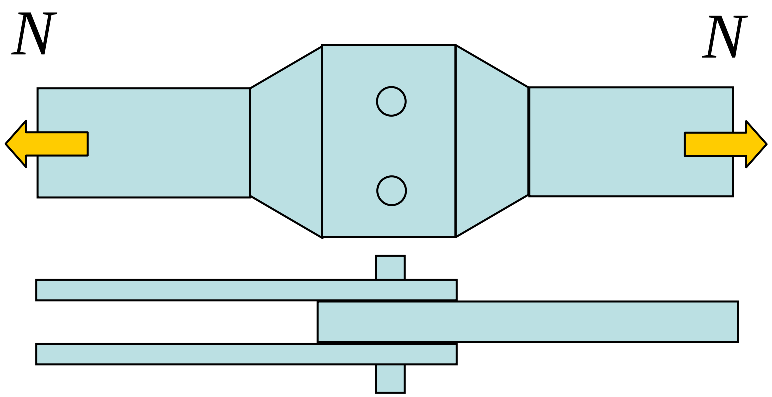


more robust for imposed loads



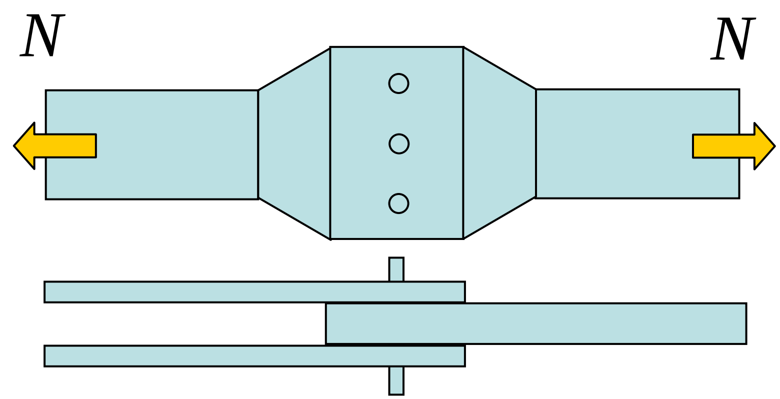
Bolted connection in tension (3)

A: 2 bolts aside each other



$$2 \cdot 0.5\, R_N$$

B: 3 bolts aside each other



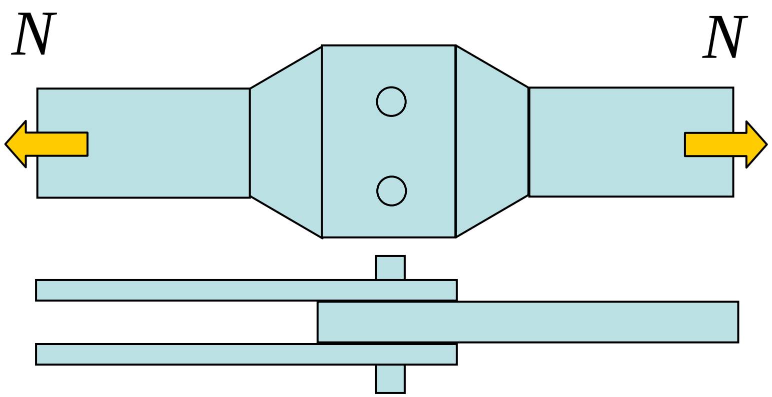
$$3 \cdot 0.333\, R_N$$

Which design is more robust?

☐ ☐

Bolted connection in tension (3)

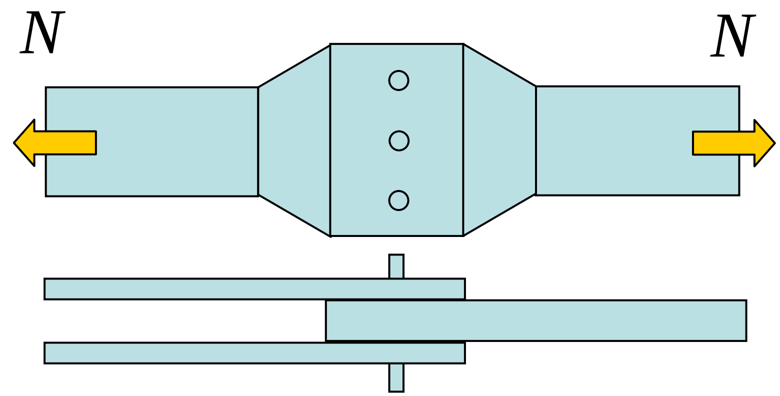
A: 2 bolts aside each other



$$2 \cdot 0.5\, R_N$$

statically determinate

B: 3 bolts aside each other

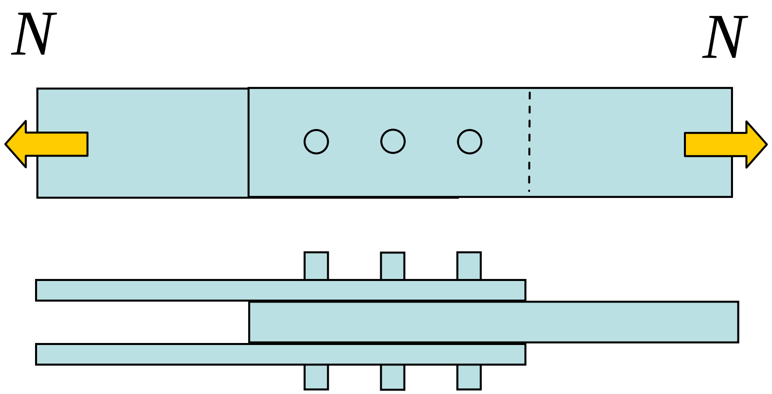


$$3 \cdot 0.333\, R_N$$

statically indeterminate, distribution of forces depending on fit and shear stiffness of gusset plate

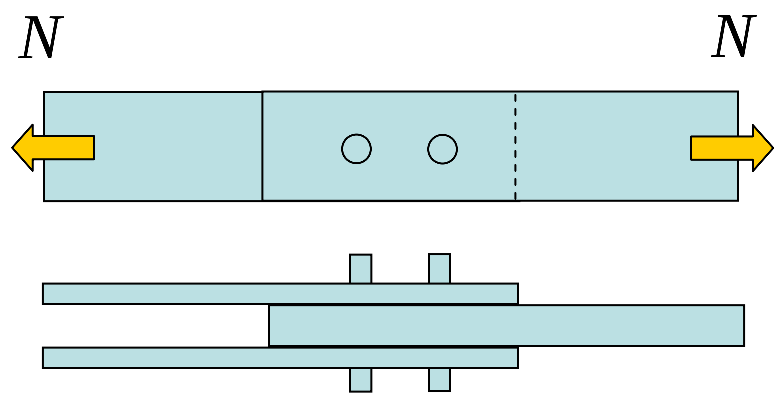
Bolted connection in tension (4)

A: 3 bolts



$3 \cdot 0.33\ R_N$

B: 2 bolts

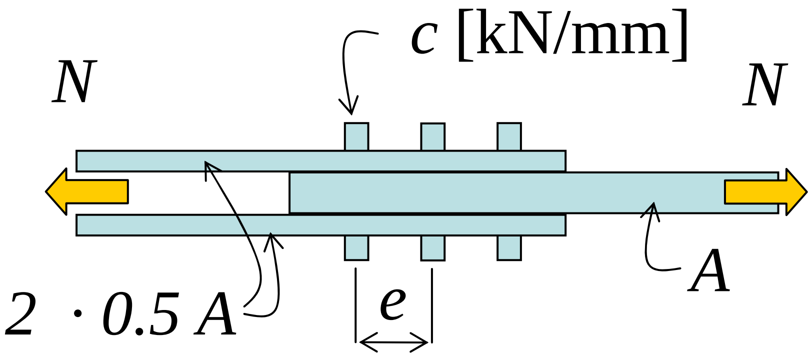


$2 \cdot 0.5\ R_N$

Which design is more robust?

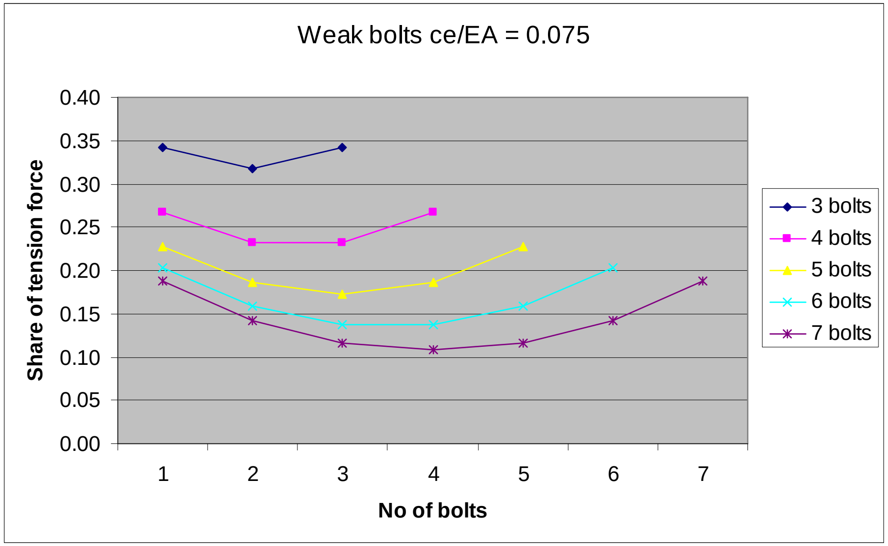
Bolted connection in tension (4)

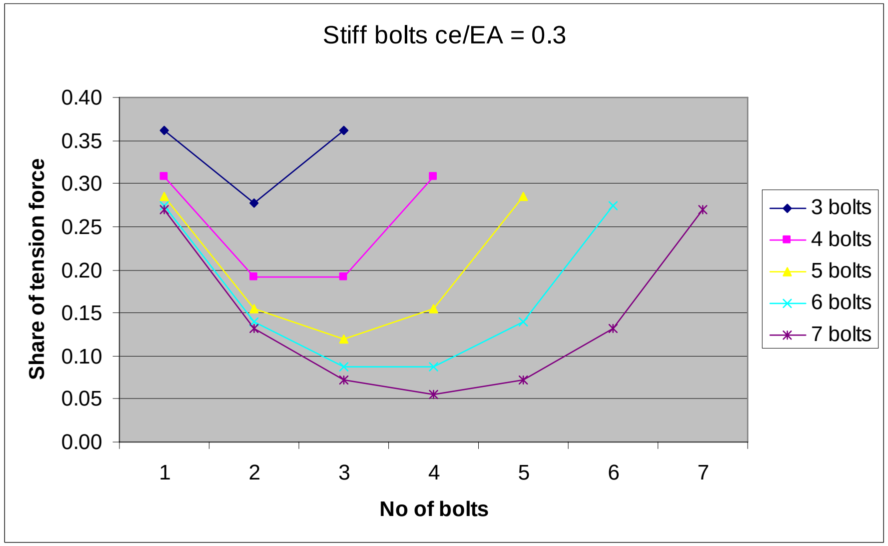
A: 3 bolts



B: 2 bolts

Decisive parameter $\dfrac{ce}{EA}$





Elements of robustness (1)

$$R = \sum_{i=1}^{N_H} p(H_i) \sum_{j=1}^{N_D} \sum_{k=1}^{N_S} p(D_j \mid H_i)\, p(S_k \mid D_j)\, C(S_k)$$

- N_H number of hazards H_i
- N_D number of direct (local) damages D_j
- N_S number of types of follow up behaviour S_k
- $p(H_i)$ probability of occurrence of hazard H_i
- $p(D_j|H_i)$ probability of the occurrence of direct damage D_j due to hazard H_i
- $p(S_k|D_j)$ probability of the occurrence of structural behaviour S_k due to direct damage D_j
- $C(S_k)$ (monetarized) consequences of structural behaviour S_k

Elements of robustness (2)

$$R = \sum_{i=1}^{N_H} p(H_i) \sum_{j=1}^{N_D} \sum_{k=1}^{N_S} p(D_j \mid H_i)\, p(S_k \mid D_j)\, C(S_k)$$

- Reduce the probability of occurrence of an accidental event and its magnitude.
- Reduce the probability of local damage due to an accidental event
- Reduce the probability of progressive collapse in the case of local damage
- Reduce the consequences of the collapse
- Reduce the number of different accidental events N_H
- Reduce the number of possible induced damages N_S

Elements of robustness (4)

	Event control	Direct approaches		Indirect approaches	Reduction of conse-quences
		Specific load resistance method	Alternate path method		
Monitoring	x				x
Provide strength		x		x	
Provide ductility		x		x	
Second line of defence			x		
Provide continuity			x		
Capacity design					x
Sacrificial and protective devices			x		x
Compartimentisation					x

Code provisions improving robustness

- Provisions for ductility
  - ...
  - Capacity design for shelters
- Uneven distribution of internal forces
  - Reduction of shear resistance for long bolted connections
- Second line of defence
  - Prevention of collapse due to punching shear
- Provisions for the failure of a single element
  - Externally bonded reinforcement
  - Impact on bridge piers
  - Cable stayed bridges

Capacity design for shelters (1)

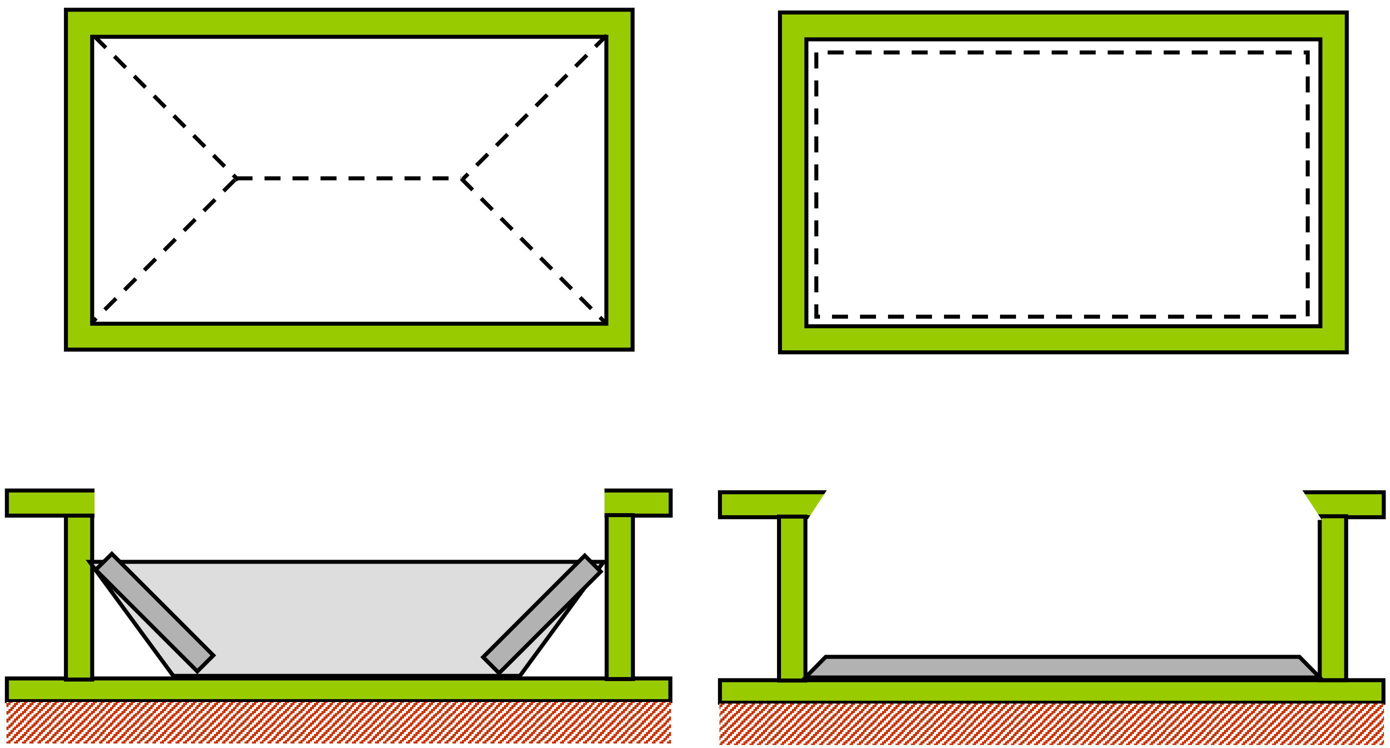
[TWK 1994]

Failure modes:

Bending failure **Shear failure**

Plan view:

Section:



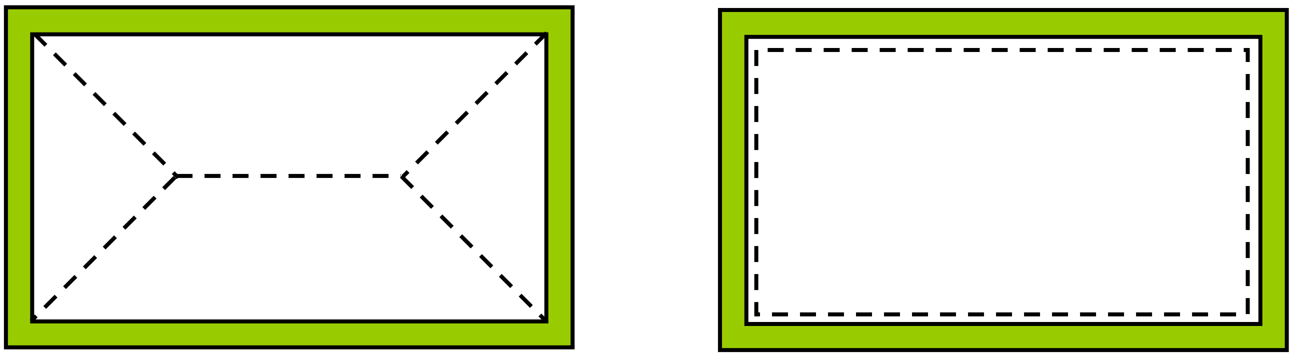
Capacity design for shelters (2)

[TWK 1994]

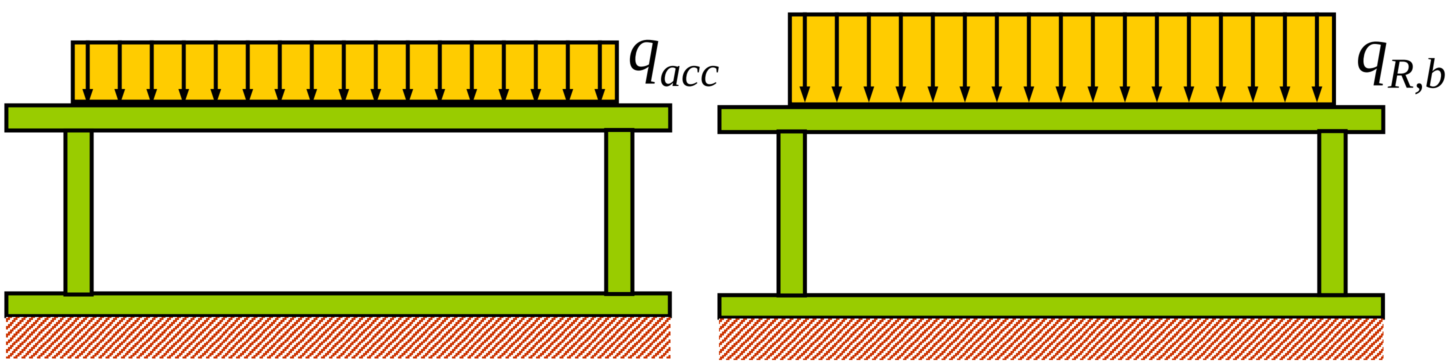
Failure modes:

Bending failure | **Shear failure**

Plan view:



Section:

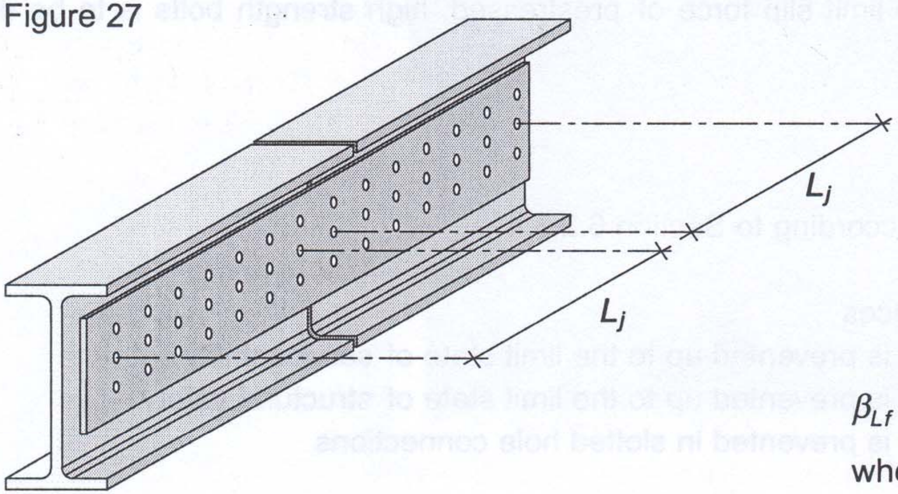


$$q_{acc} \Rightarrow m_d < m_{Rd} \quad \Rightarrow \quad q_{R,b} \Rightarrow v_R \geq v(q_{R,b})$$

Reduction of shear resistance for long bolted connections

6.2.2.2 If the transmission of forces is distributed over a distance greater than 15 d, the ultimate shear resistance, $F_{v,Rd}$, shall be reduced by factor β_{Lf}.

Figure 27



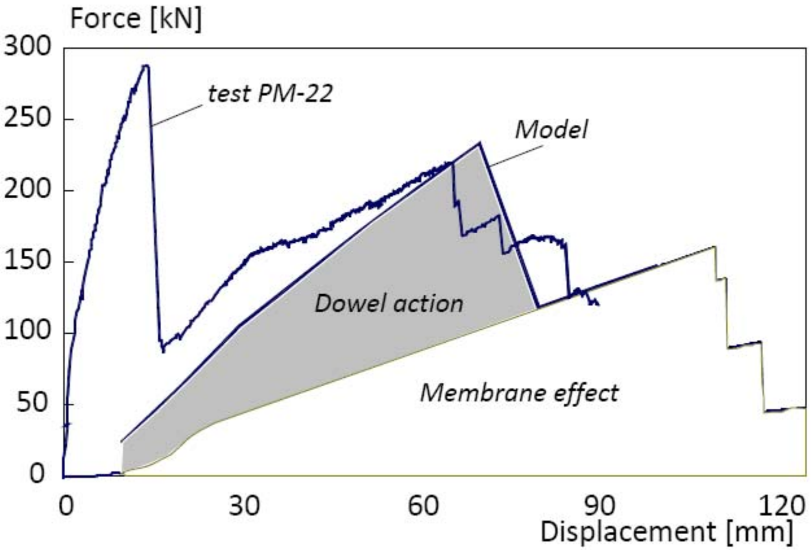
$$\beta_{Lf} = 1-(L_j-15\,d)/(200\,d); \quad 0{,}75 \le \beta_{Lf} \le 1{,}0$$

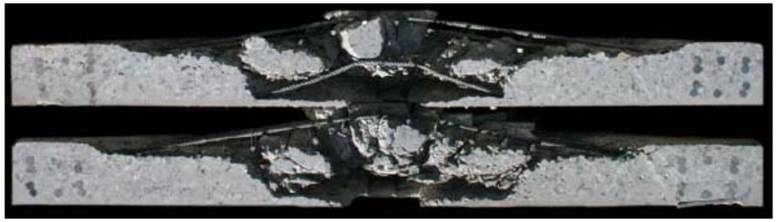
where L_j : length of force transmission

This reduction is not necessary if a uniform force transmission can be guaranteed over the entire length of the connection.

 [Steel structures, SIA 263]

Prevention of collapse due to punching shear





PM-22

[Concrete structures, SIA 262]

In order to prevent the slab from totally collapsing after a possible punching, some reinforcement shall be provided on the flexural compression side. The reinforcement shall be extended over the supported area and dimensioned as follows:

$$A_s \geq 1{,}5\ \frac{V_d}{f_{sd}}$$

Prof. Dr Aurelio Muttoni + Dr Miguel Fernández Ruiz, EPFL, SIA 262/7, 23.1.2008

Externally bonded reinforcement

[SIA 166]

- ... Two types of hazard scenarios can be distinguished:
  - hazard scenarios which result from the intended use;
  - failure of the externally bonded reinforcement as an accidental design situation.
- For the hazard scenario *Failure of plate bonding* the design value [...] is calculated as follows:

$$E_d = E\left(G_k, P_k, A_d, \psi_{2i} Q_{ki}, X_d, a_d\right)$$

Design criteria for impact loads

[Guideline Swiss Railways, 1983]

Distance from obstacle to rail axis	Required provision
< 3.00 m	"normally" not allowed
> 3.00 m	$QA_{\parallel}$ = 2'000 kN $QA_{\perp}$ = 1'000 kN
< 5.00 m	Protection of pier by guiding device or dimensioning of bridge with missing pier

Cable stayed bridges

- Failure / replacement of a stay (together with full or part of the traffic load) is an ordinary design situation

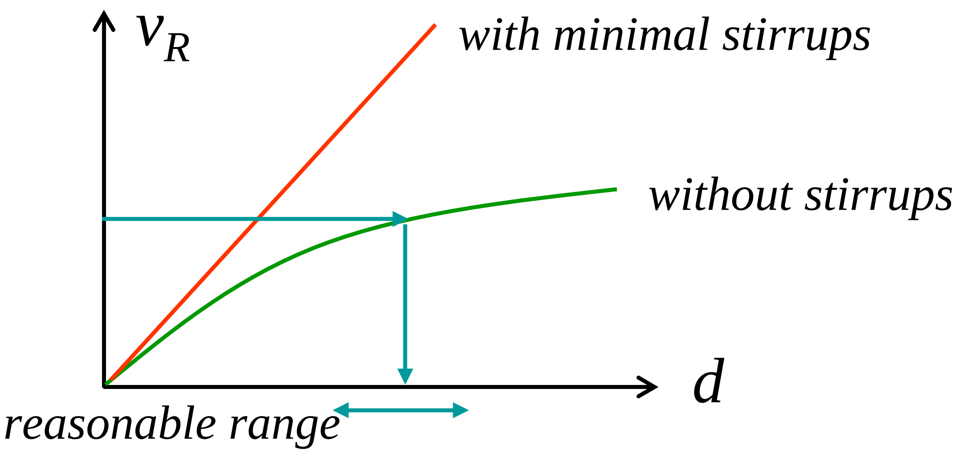
Chesapeak-Delaware-Canal Bridge, USA

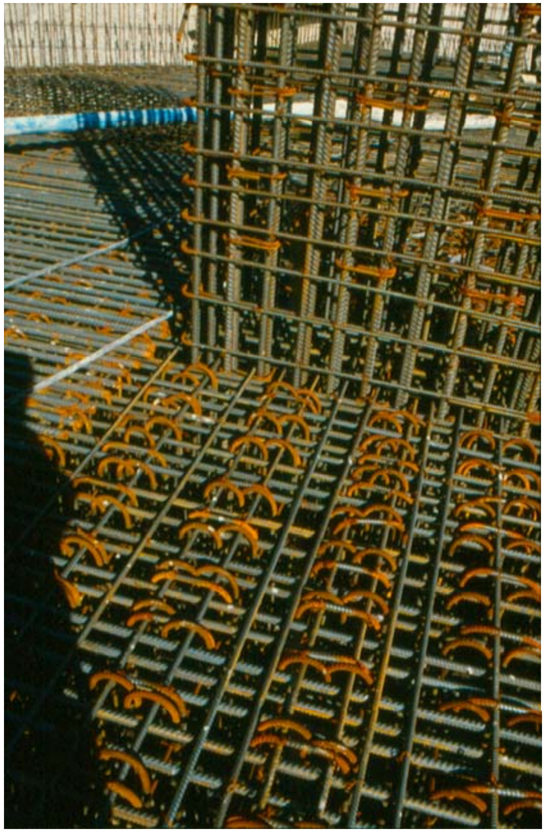
Code provisions preventing robustness

- Shear capacity of solid slab bridges
- Punching shear capacity of flat slabs
- Design criteria for impact loads
- Ambitious requirements for post-tensioning

Shear capacity of solid slab bridges

- Beam or slab?
- Beam $\Rightarrow$ stirrups required
- Slab $\Rightarrow$ shear resistance without stirrups design criterion:





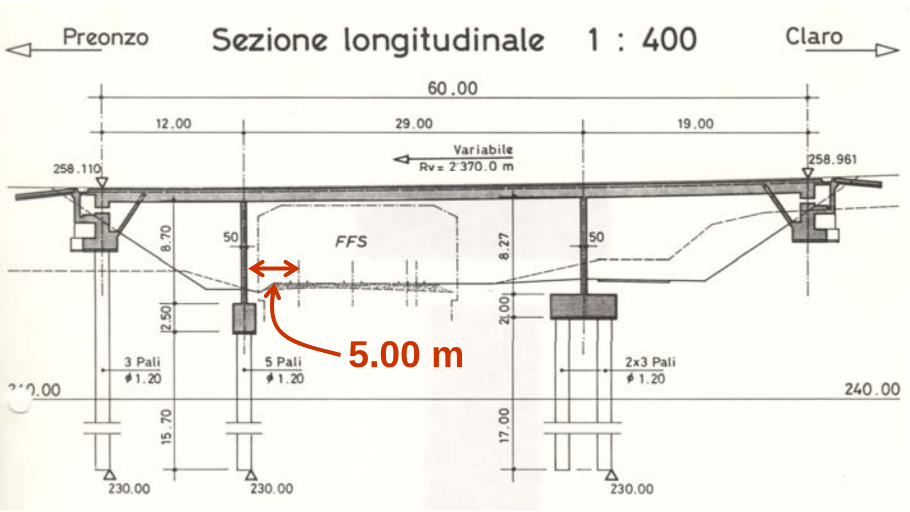
Punching shear capacity of flat slabs

Prof. Dr Aurelio Muttoni + Dr Miguel Fernández Ruiz, EPFL, SIA 262/7, 23.1.2008 2

Gretzenbach, 2004

- Usual code provisions:
  - Increase of punching shear capacity with increased bending reinforcement (but reduction of ductility)
  - Punching reinforcement allows for a further increase (but is expensive)
- The designers optimize the slab depth, aiming at
  - no punching reinforcement
  - necessary bending reinforcement

Design criteria for impact loads



Distance from obstacle to rail axis	Required provision
< 3.00 m	"normally" not allowed
> 3.00 m	$QA_{\parallel}$ = 2'000 kN $QA_{\perp}$ = 1'000 kN
< 5.00 m	Protection of pier by guiding device or dimensioning of bridge with missing pier

Ambitious requirements for post-tensioning

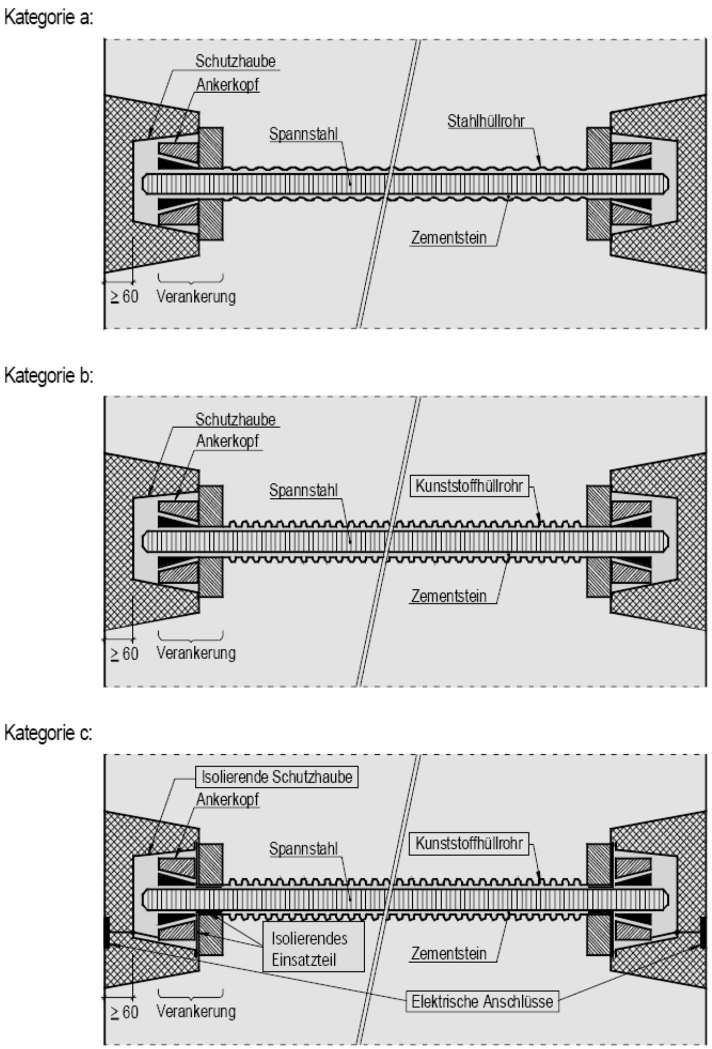


Abb. 2.1: Schematische Darstellung der Spanngliedkategorien a, b und c.

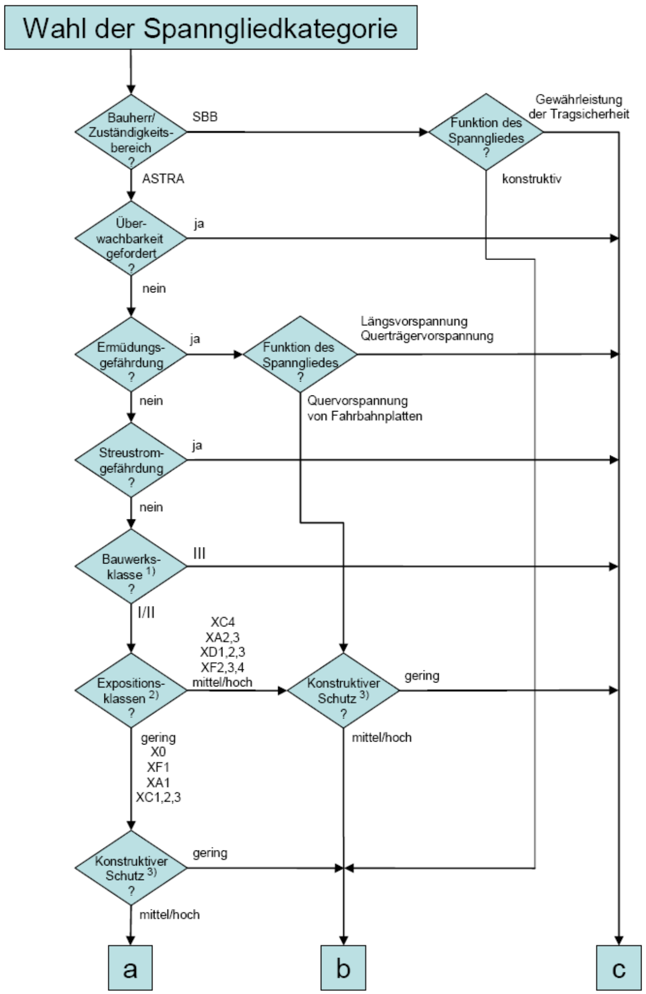


Abb. 3.1: Flussdiagramm zur Wahl der Spanngliedkategorie.

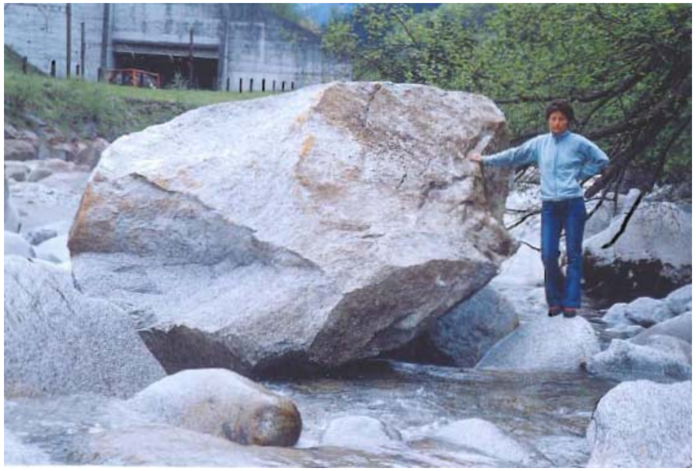
[Guideline ASTRA/SBB 2007]

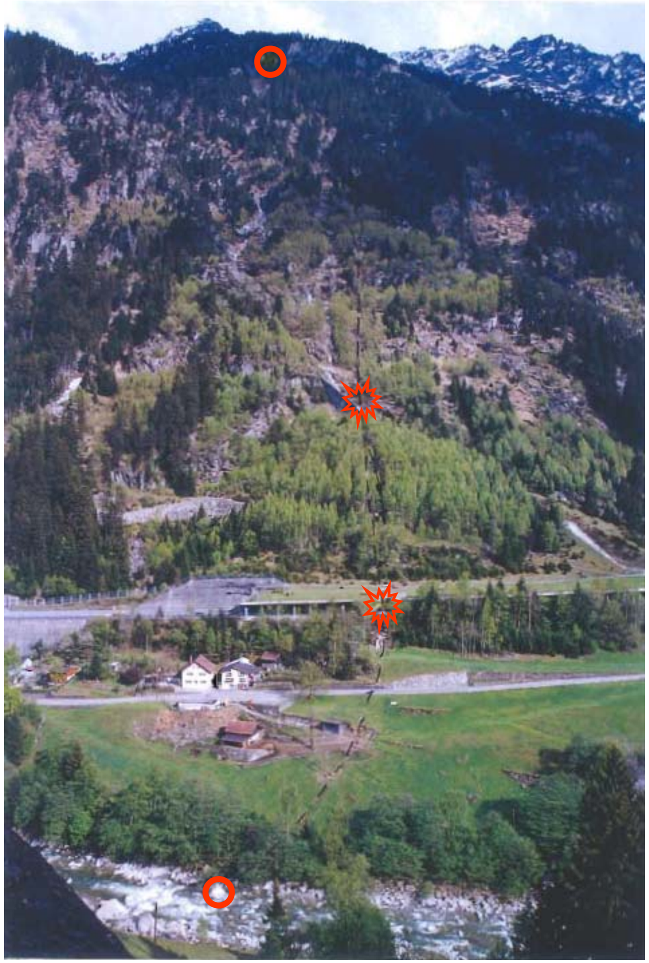
What happens with real structures?

- What has already happened?
- What can we consider?
- What could happen in future?

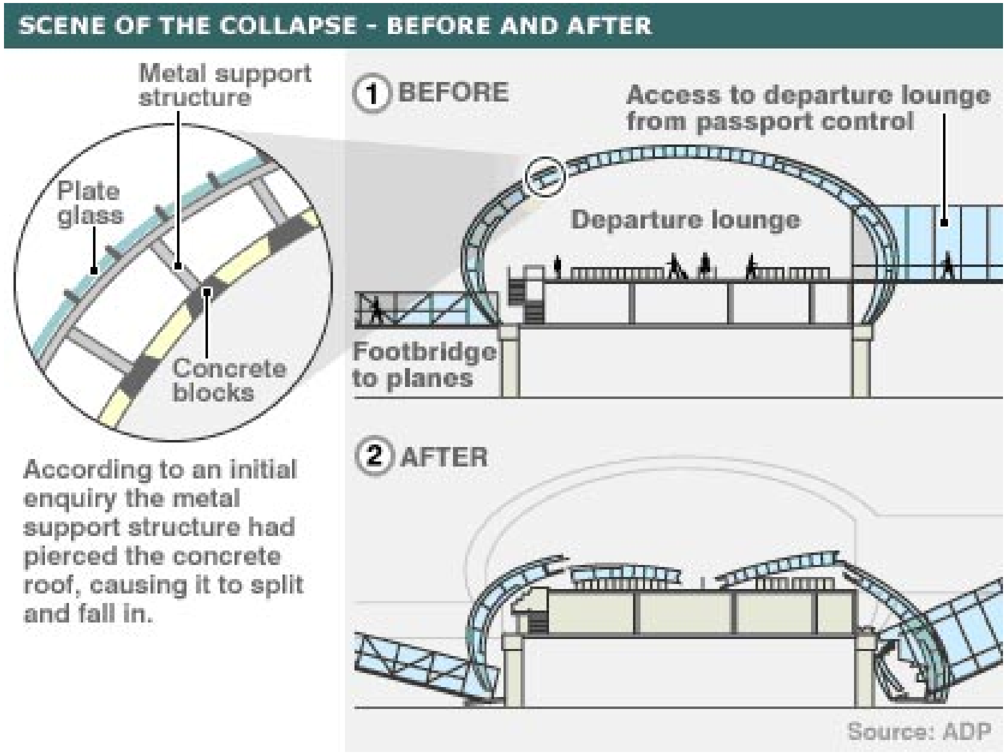
Rock fall gallery subject to train impact 05.01.07

Avalanche gallery subject to rock fall 29.04.2003



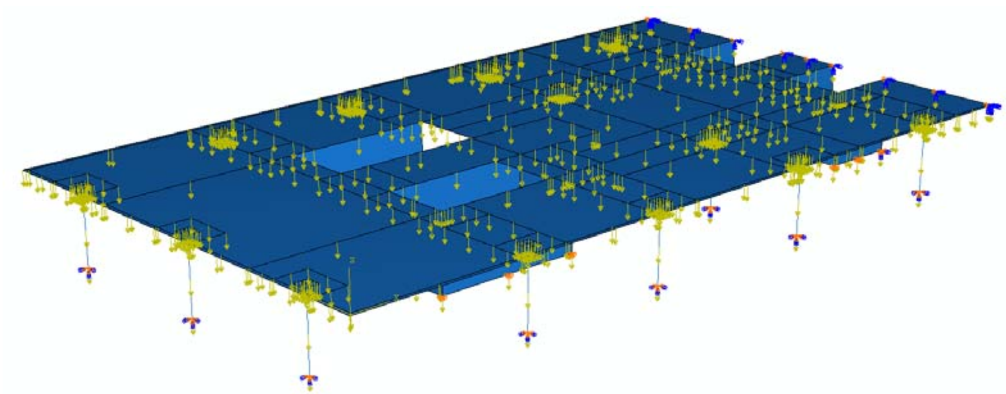


Charles de Gaulle Airport Roissy/Paris 23.5.04



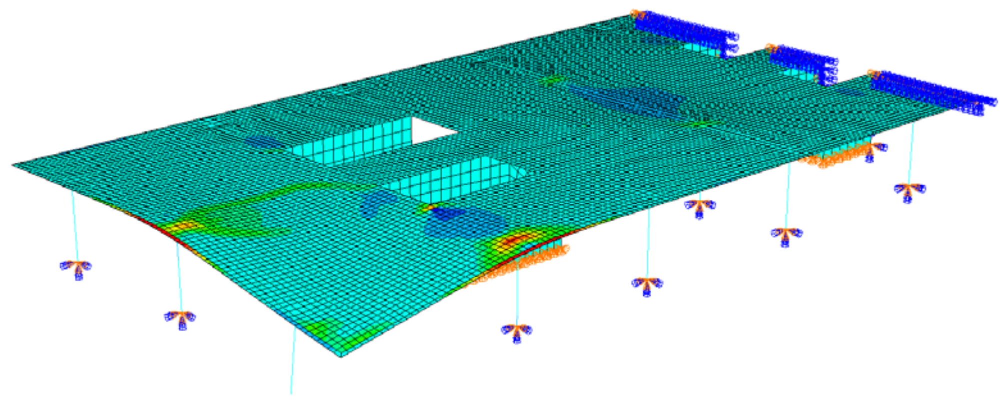
Robustness of Reinforced Concrete Flat Slab Structures

(PhD thesis of Ingo Müllers)

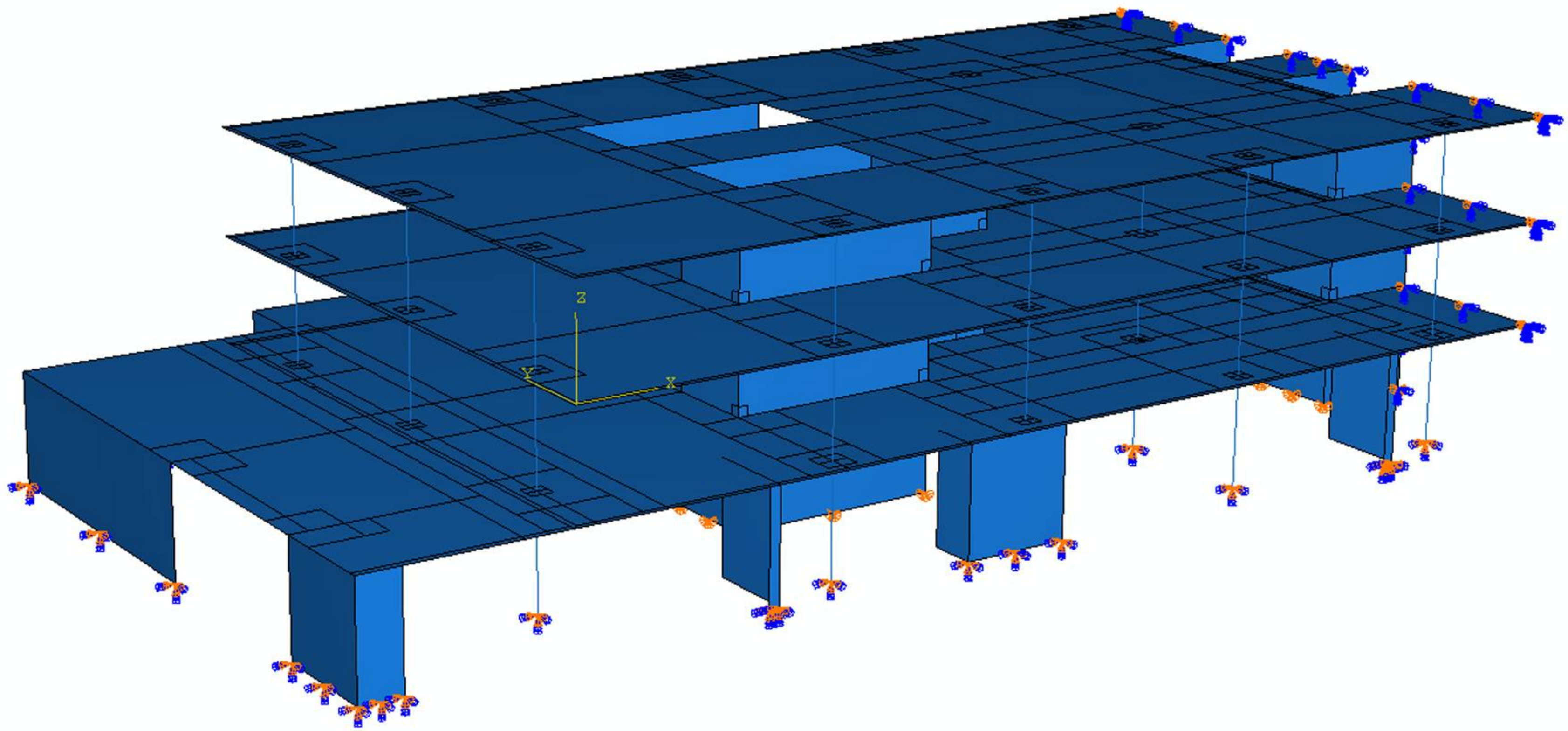


Structural analysis

- FE-method
- Actions forces due to inertia and gravity
- Sudden failure of a column

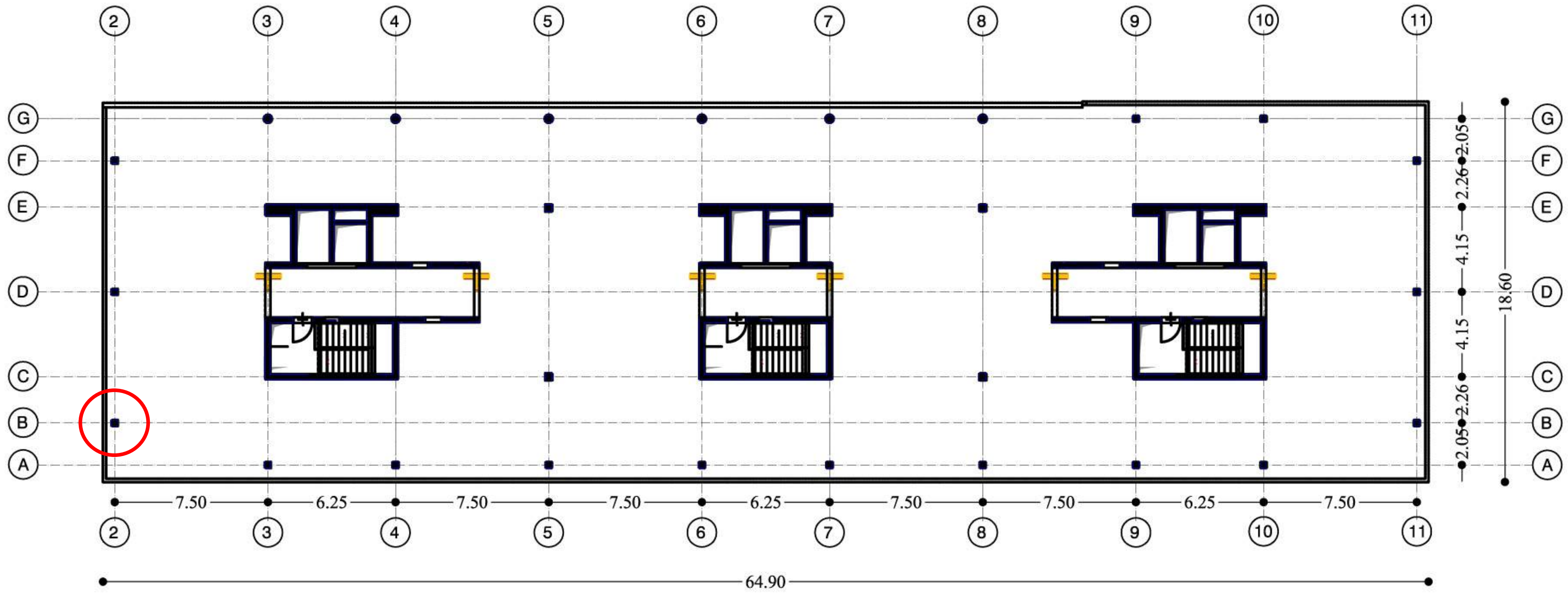


Size of the FE model



Model for ground floor, 1st and 2nd upper floor

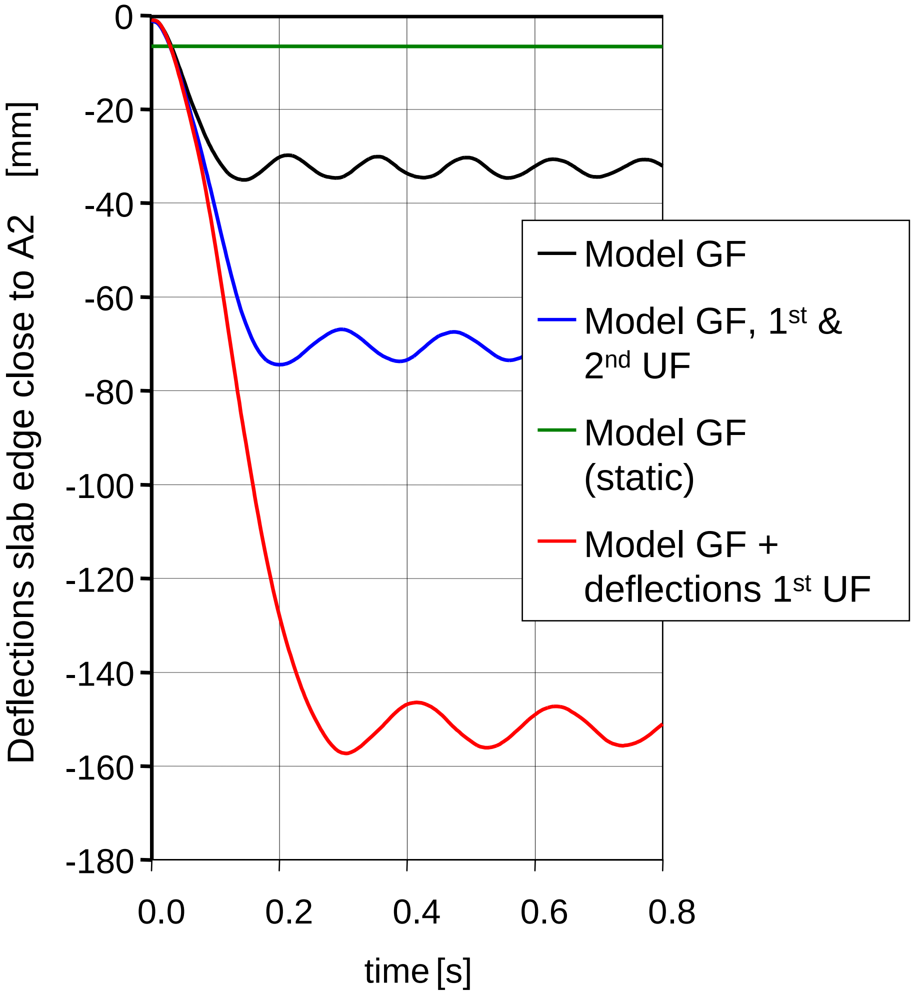
Modelled structure

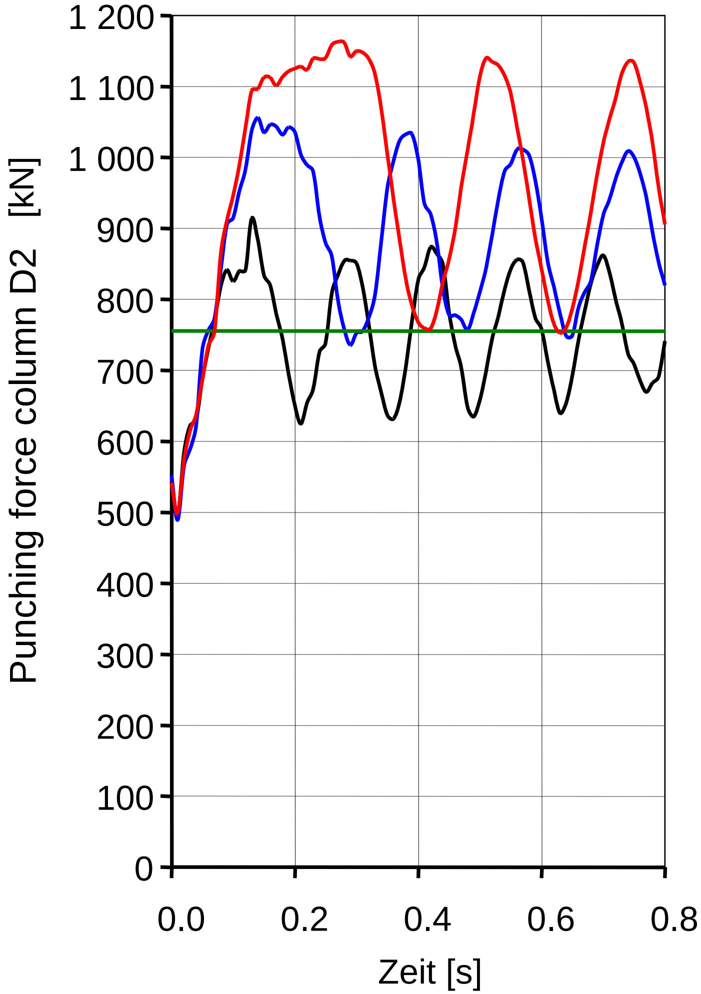


Plan view 1st upper floor

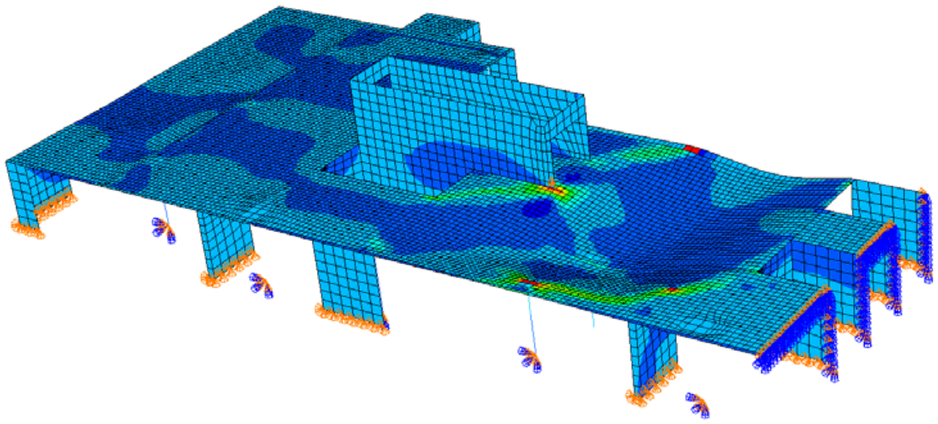
Action effects – Slab over ground floor

after failure of corner column B2





Failure modes



- Breaking or buckling of bending reinforcement
- Punching above columns, wall corners and wall ends
- Shear failure in slabs or edge beams
- Buckling of adjacent columns

[www.structurae.de]

Robustness of large roofs? (1)

Robustness of large roofs? (2)

- Spatial structures (shells, …)
  - generally robust structures, unless
  - buckling in compression
  - progressive failure of textile membranes in tension
- Uniaxial structures (beams, arches, cantilevers, …)
  - local failure possible
  - what means local?
- Critical structural elements
  - tension & compression rings
  - supportive structures

[www.structurae.de]

Tension & compression rings (1)

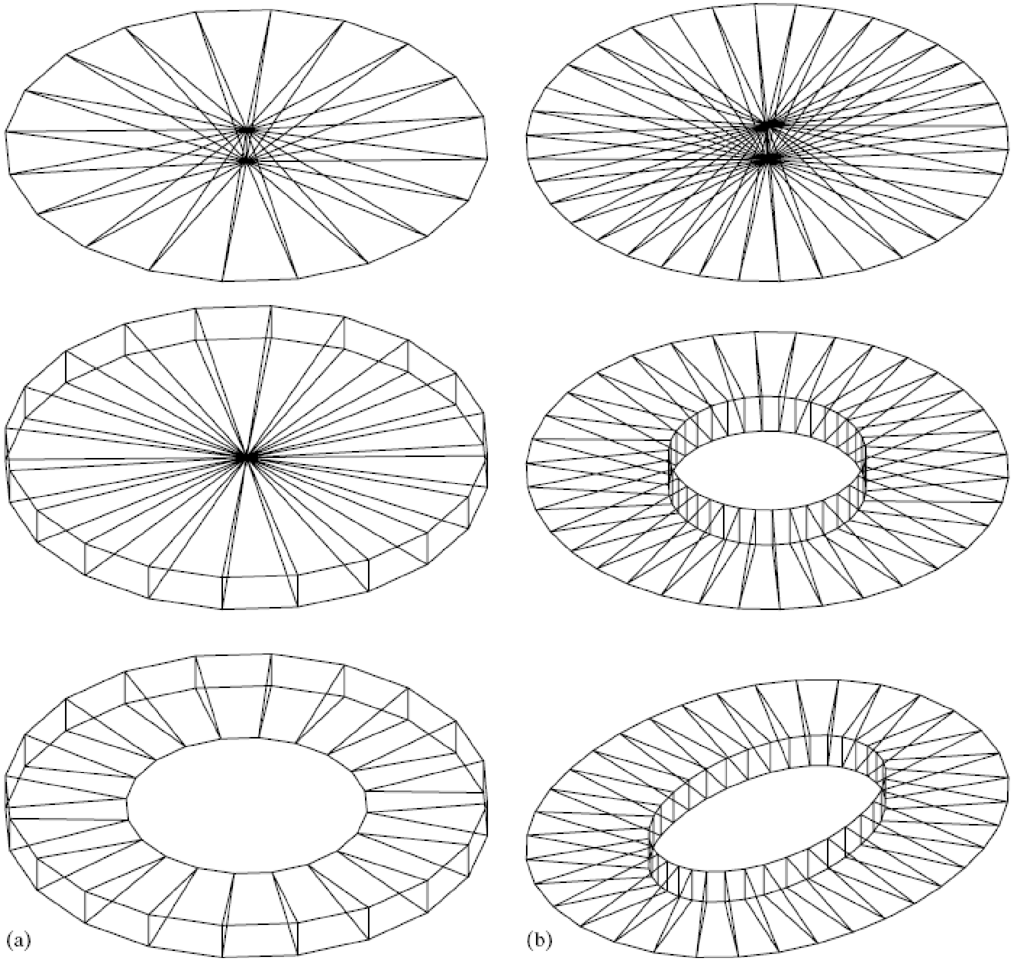
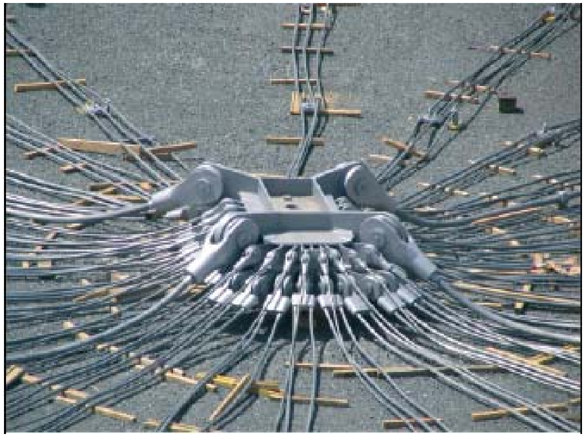


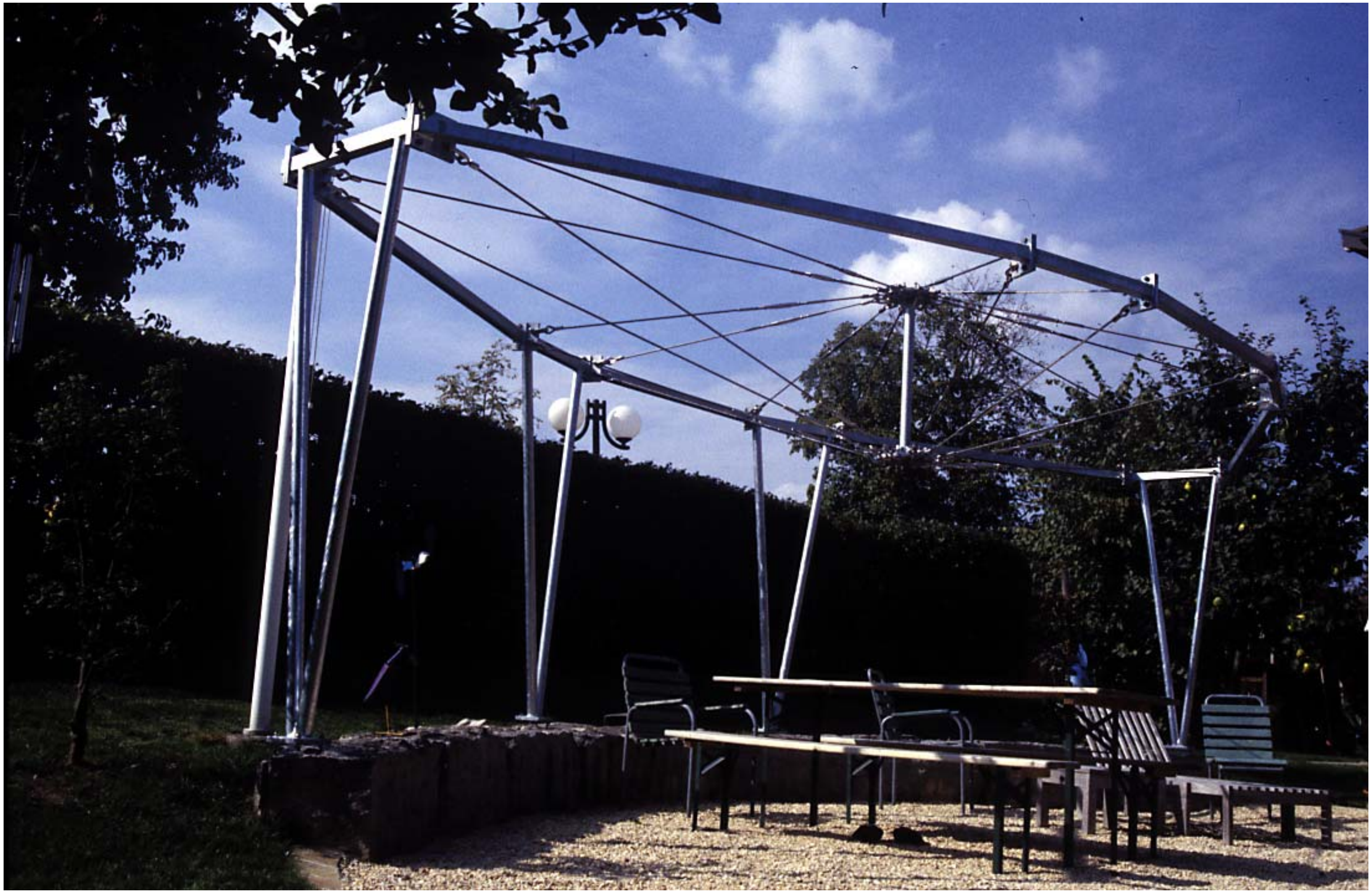
Fig. 2: Viable spoked wheel arrangements (Photocredit: sbp)



New Commerzbank Arena
Frankfurt, Germany

[K. Göppert, SEI 4/2007]

Tension & compression rings (2)



Supportive structures

Fig. 1: Aerial view of the stadium

[D. A. Nethercot / T. Ruffell, SEI 4/2007]

Thank you for your attention!