Use of FEM in floor design

Björn Engström

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Guidelines for FEA of HC floors

Contributions by:

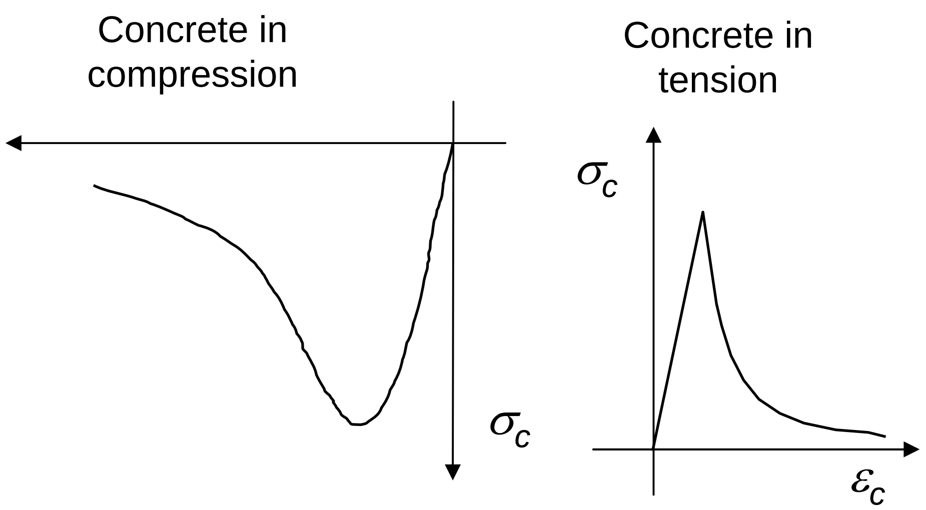
Karin Lundgren, Helén Broo, Mario Plos

Concrete Structures

Chalmers University of Technology

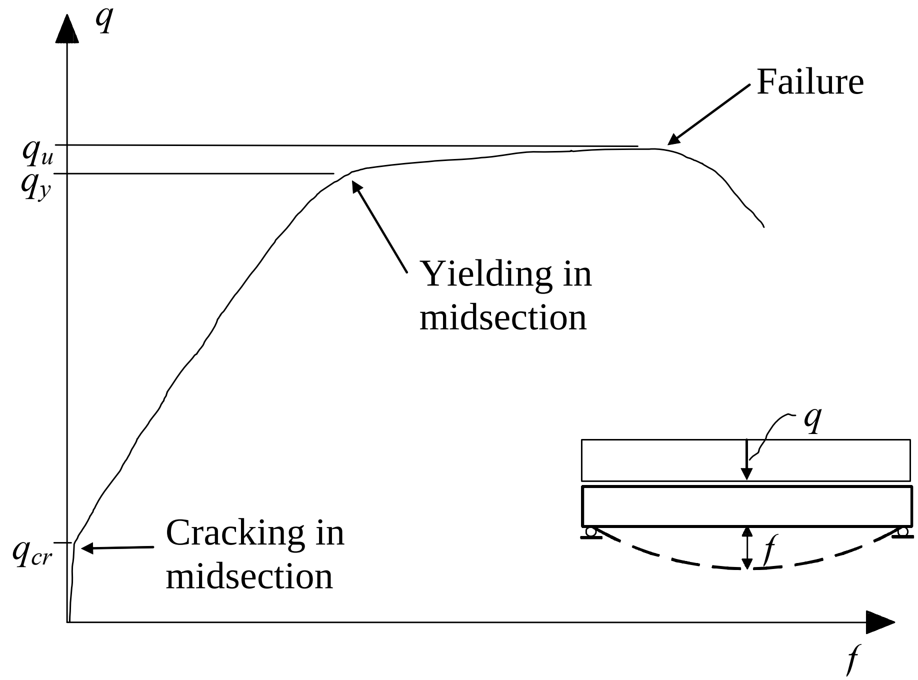
Concrete material – non-linear response

- Crack formation, fracture mechanics
- Plastic deformation in compression, crushing, tri-axial effects



Concrete structures – non-linear response

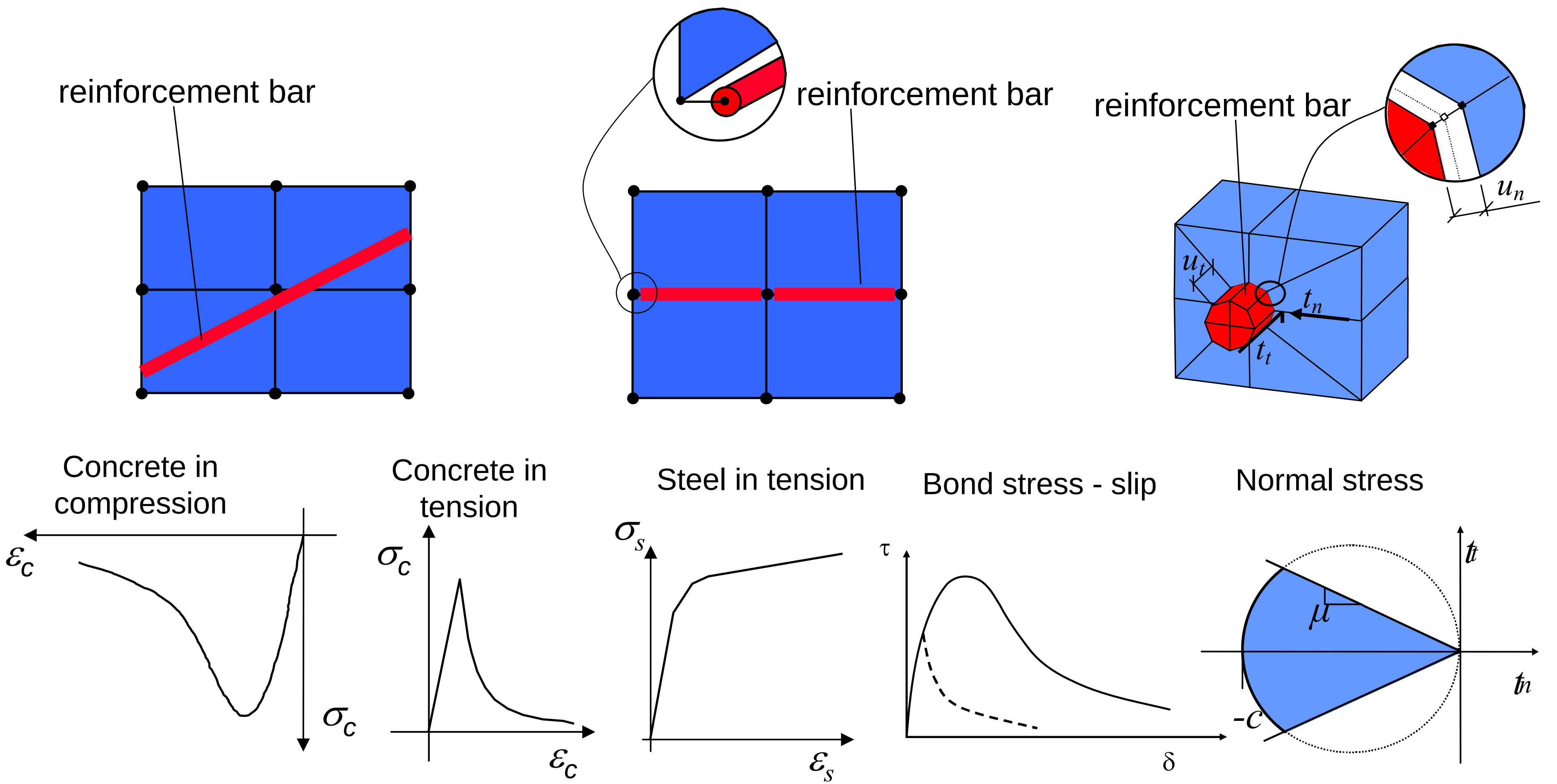
– Change of stiffness due to cracking, force redistribution
– Yielding of reinforcing steel – plastic force redistribution



What is 'accurate calculation according to FEM'?

- What can the model simulate?
- Linear analysis or nonlinear analysis?
  - Can the non-linear response be simulated at all?
  - In most cases linear analysis is used
- Non-linear analysis on different levels?
  - What different phenomena can be simulated?
  - Many possibilities to choose level of detailing, generalisation

Interaction between steel and concrete



Conclusion

- There is no unique ‘Finite element method’
- It is not possible to refer to ’accurate calculation according to FEM’

Traditional engineering approach

- Determine sectional forces
  - Global model – typically a model for linear elastic response
- Design the sections
  - Local sectional or regional model for the response in the ultimate state (based on non-linear material response)

Improved engineering approach

- Determine sectional forces
  - Global model – typically a model for linear response
- Design the sections
  - Local sectional or regional model for the response in the ultimate state (based on non-linear material response)
- Verify the performance
  - Non-linear response in the service and ultimate states

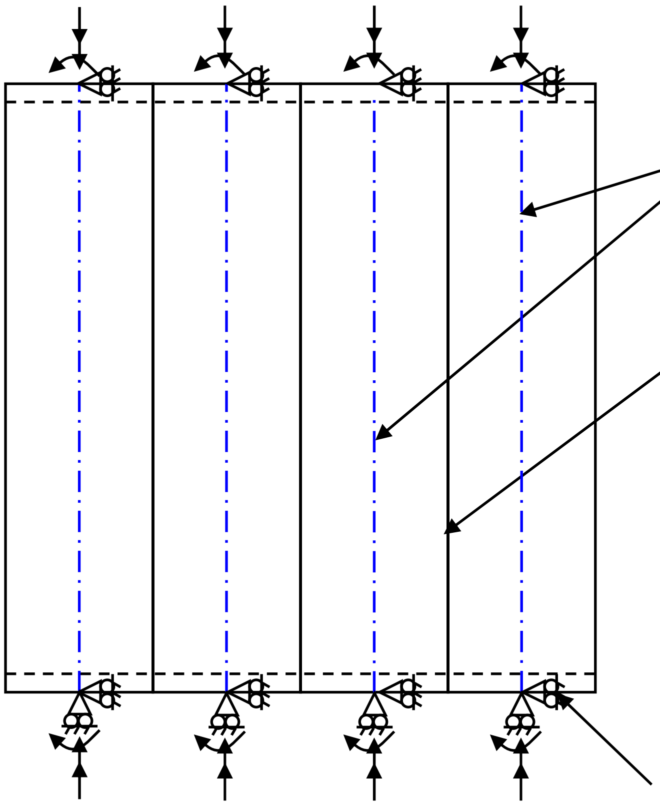
Modelling of complete floors

- Simplified global model
  - to determine bending moments, shear forces and torsional moments in single elements of a hollow core floor

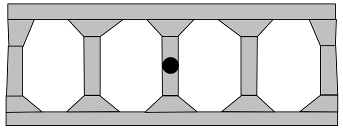
Hollow core units

- One beam element represents one hollow core unit
  - Bending in the vertical plane with rotation around the horizontal axis
  - Bending in the horizontal plane with rotation around the vertical axis
  - Torsion around the longitudinal axis
  - Correct values are needed for the bending stiffness in both directions and the torsional stiffness

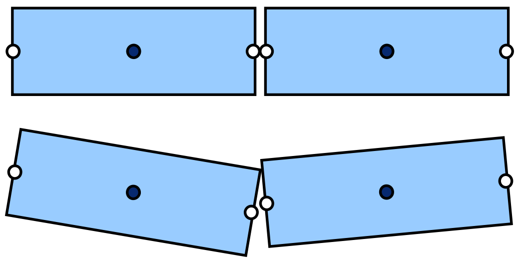
Effect of longitudinal joints

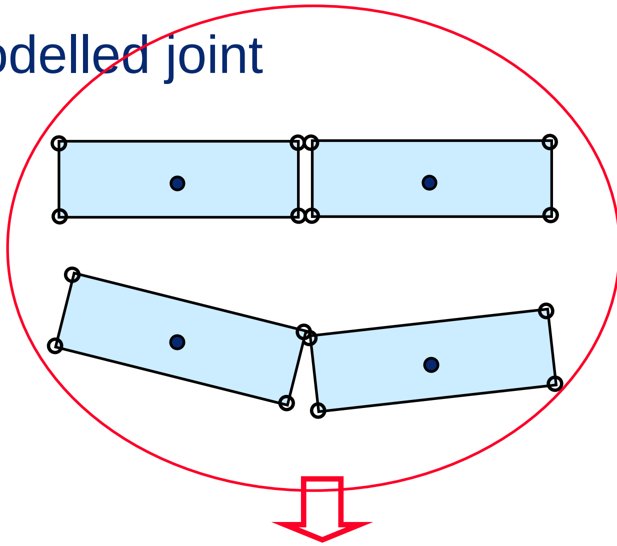


Beam element modelled a hollow core unit



‘Interface’ element modelled joint





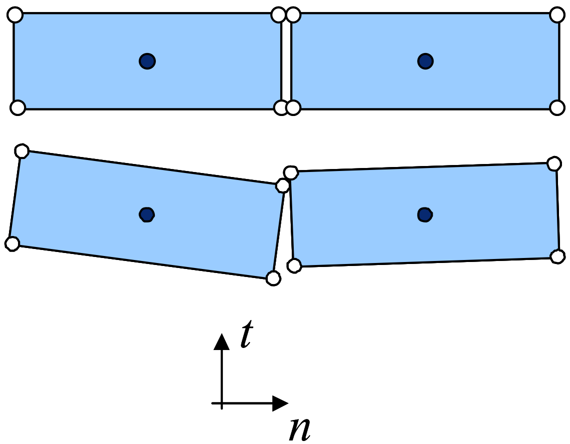
Tie beam modelled by tyings

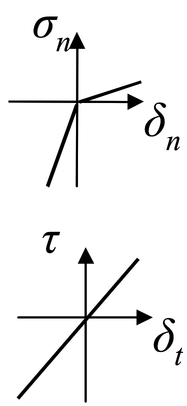
Verified model

Reduced torsional moment

Longitudinal joints

- Connection elements between the corners (slave nodes in the model)
- The slave nodes follow the deflection and the rotation of the beam section. The sections remain plane with stiff rotation

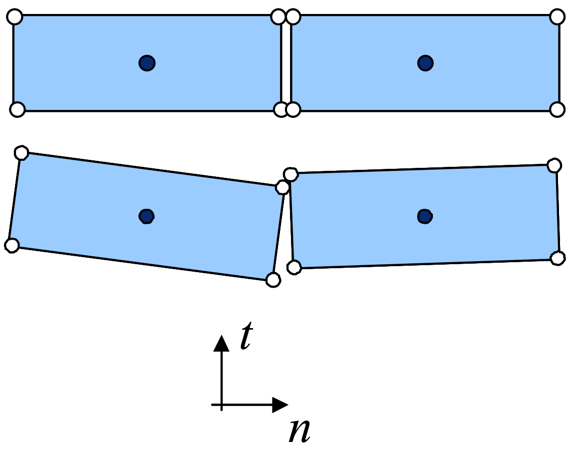


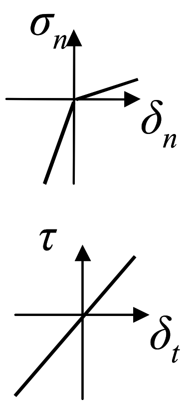


- ● Main nodes, defining the beam elements
- ○ Slave nodes, positioned in the corners of the hollow core units

Response of the joint

- Normal compressive forces are allowed, very small stiffness in tension represents cracking
- Shear stiffness in longitudinal and vertical direction





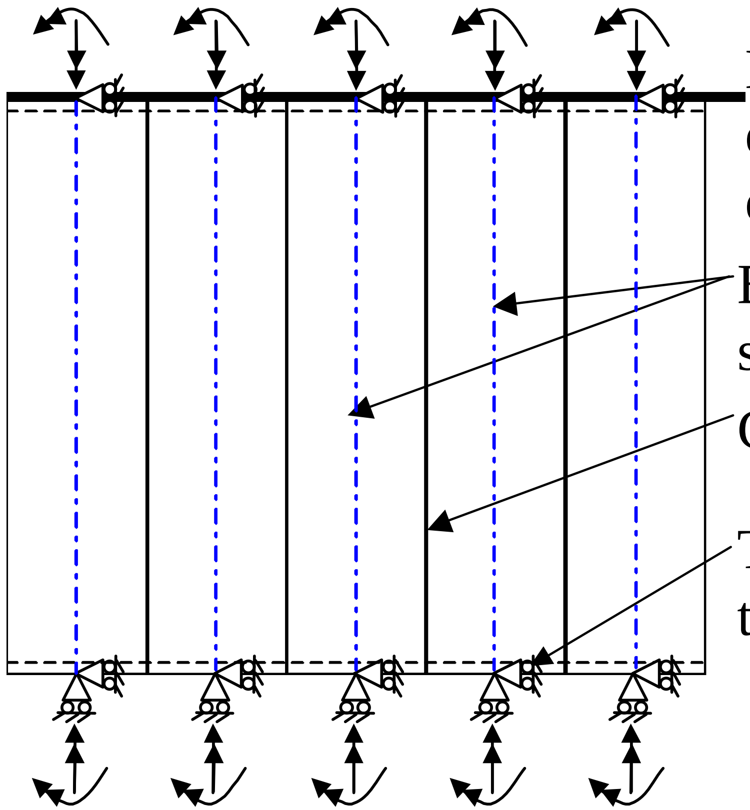
● Main nodes, defining the beam elements

○ Slave nodes, positioned in the corners of the hollow core units

Number of nodes along the hollow core element

- Large enough to describe the variation of the contact forces acting along the longitudinal joint
- It is recommended to evaluate the effect of mesh refinement. At least two analyses, one with at least the double amount of nodes

Example: model of the floor Boundary conditions



Deformations tied to each other in the direction along the slabs; i.e. longitudinal deformations must be equal

Beam elements to model single hollow core units

Connecting elements to model joints

Tie beams modelled by supporting the elements in this direction

Effect of prestressing and dead weight

- These effects are active already before the joints are grouted, and will not influence the contact forces
- These effects can be included directly in the analysis of added to the results afterwards
- After activation of the connection elements, the additional load can be applied

Needed input data

- Geometry of the floor
- Material properties
- Geometry of the HC cross-section
- Properties of the contact elements, simulating the response of the joint

Material models

- Linear or non-linear material response can be assumed
- To determine sectional forces it is normally sufficient to use linear material response

Non-linear material models

- If concrete is non-linear, the reduced stiffness due to cracking is accounted for (important to consider if elements are not prestressed)
- If yielding of strands is included, bending failure can be described.
- Torsion and shear failure cannot be described using beam elements

Sectional geometry

Alternative approaches depending on the commercial code used:

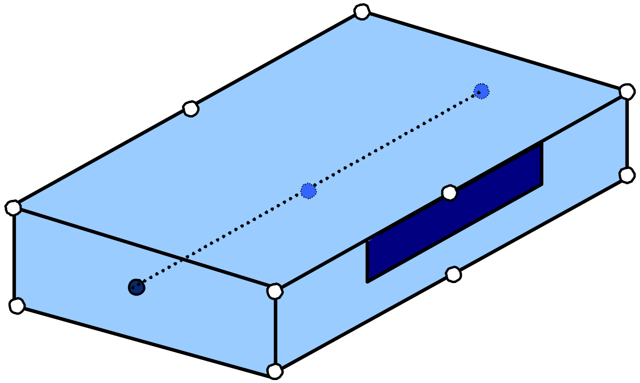
- Arbitrary geometry of the cross-section of beam elements
- Approximate the cross-section, but use correct values for the bending stiffness in two directions and the torsional stiffness

Joint characteristics – recommended data

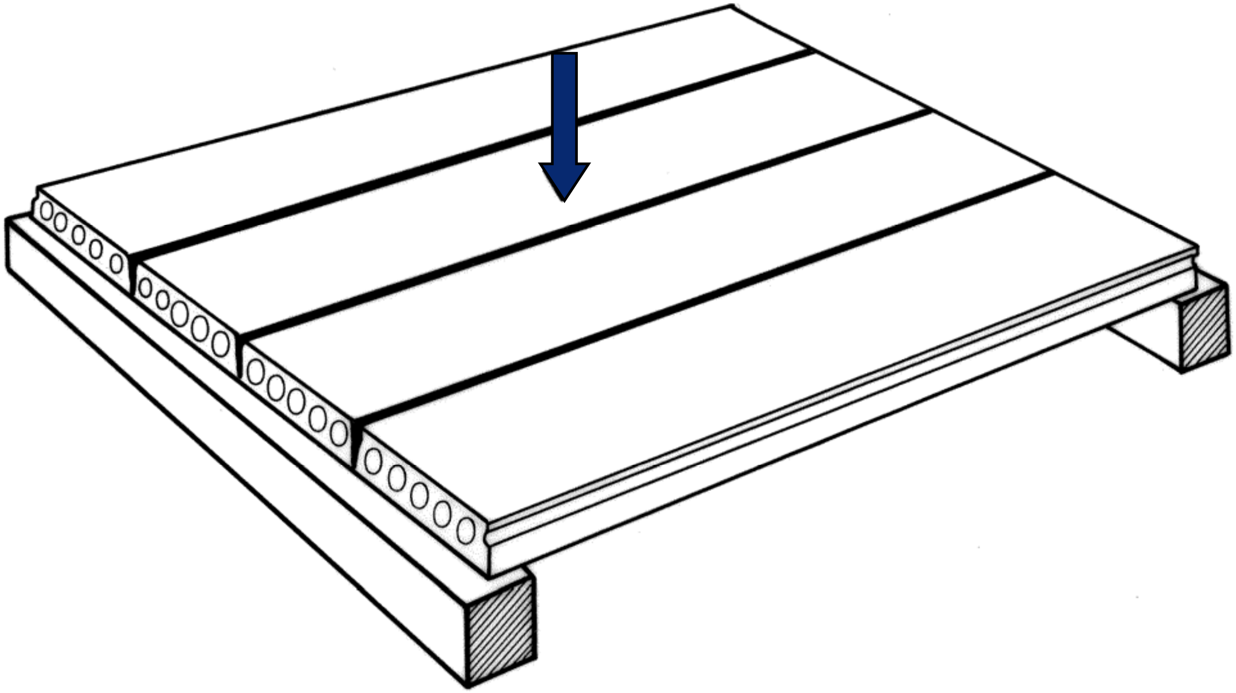
- Shear stiffness $1 \cdot 10^{9}\ \text{N/m}^{3}$
- Stiffness for compression (normal direction) $3 \cdot 10^{10}\ \text{N/m}^{3}$
- Stiffness for tension (normal direction) $1 \cdot 10^{4}\ \text{N/m}^{3}$

Unit for stiffness

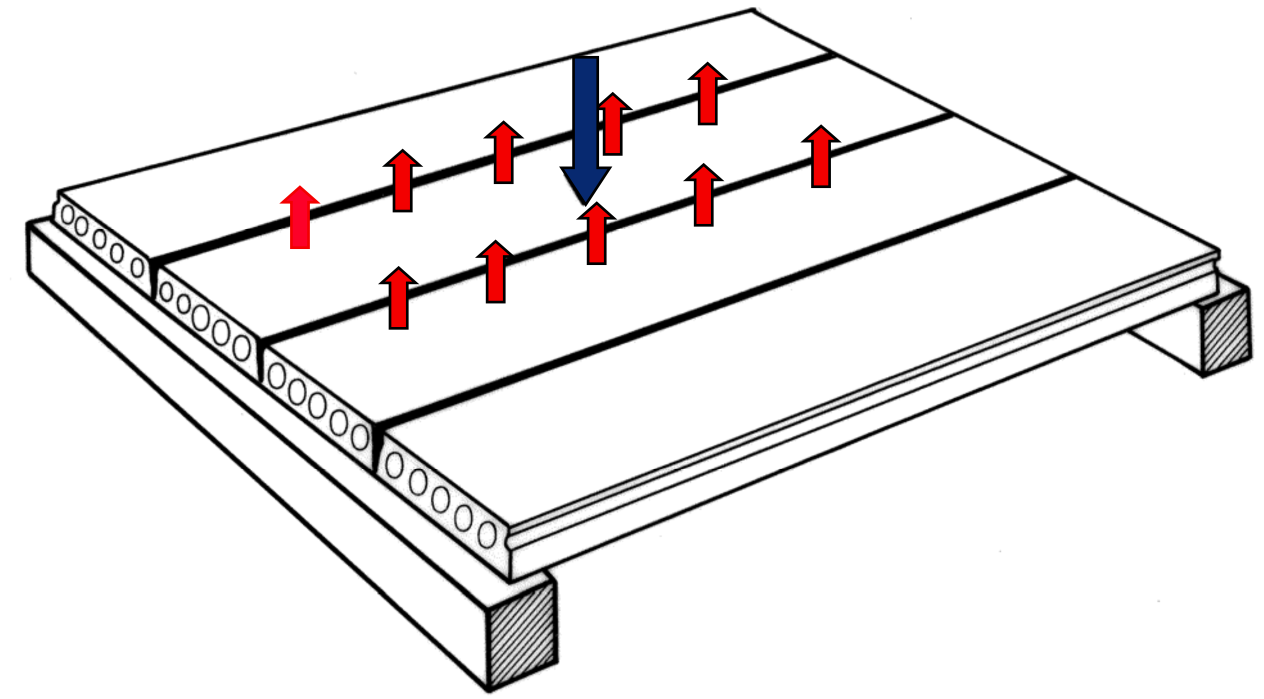
- The stiffness values above describe the relation between stress and deformation, unit N/m^3
- Spring elements gives the relation between force and deformation. The area one connection element represents needs to be accounted for



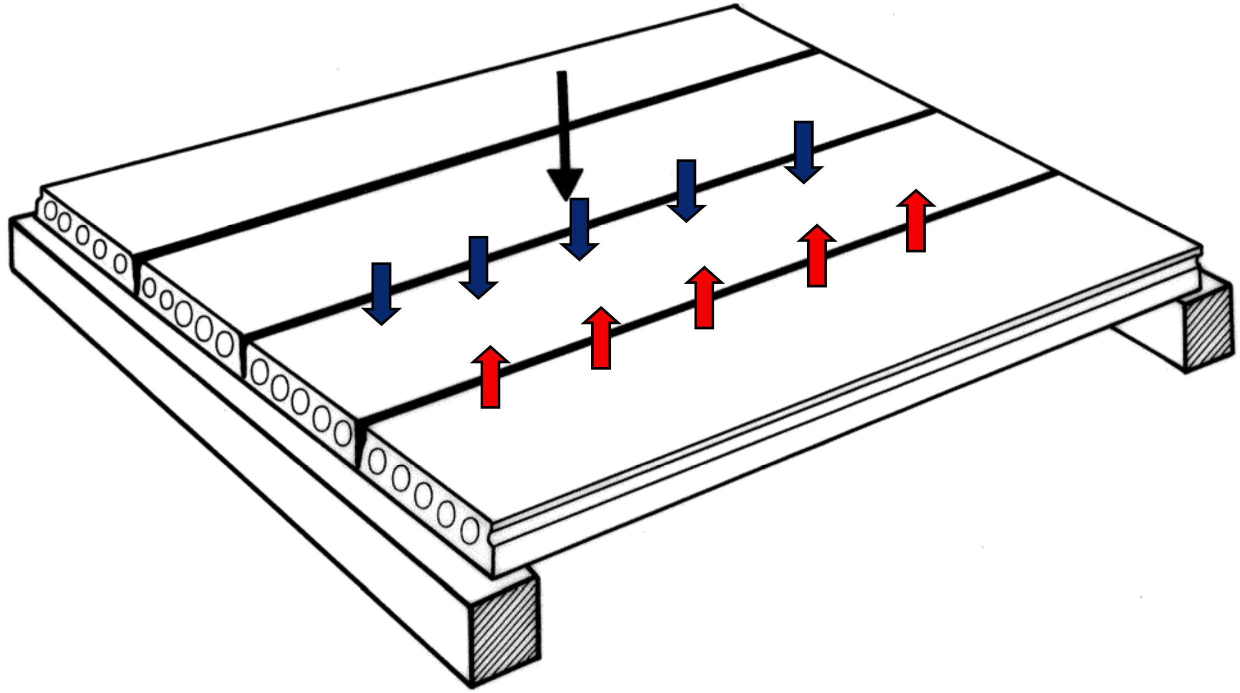
Transverse load distribution?



Transverse distribution of load effects

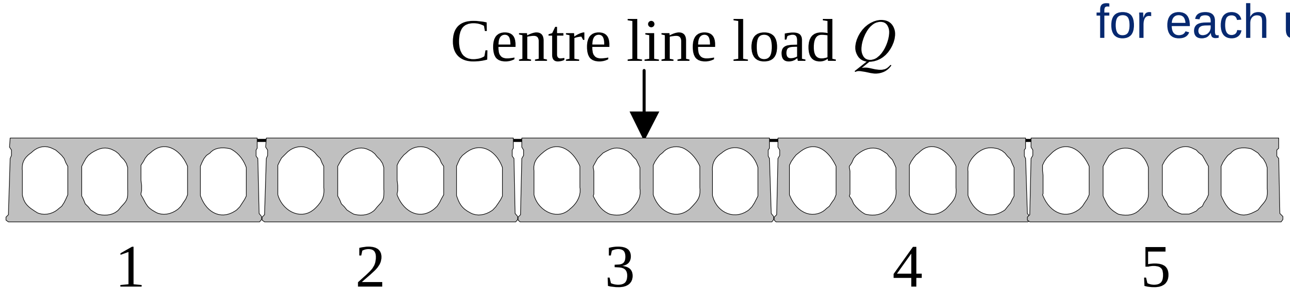


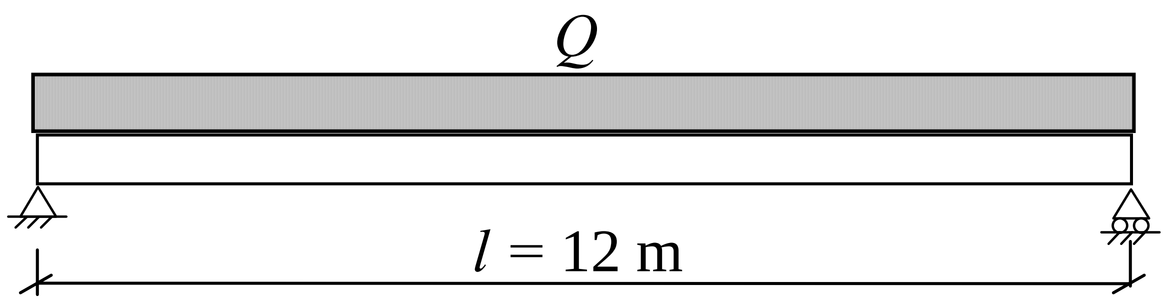
Transverse distribution of load effects

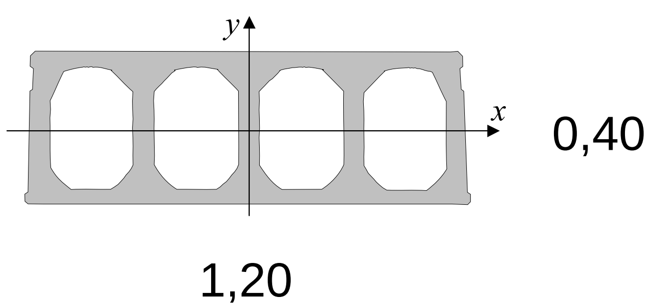


Example 1

30 beam elements for each unit







$Q = 70$ kN/m

No dead weight
no prestressing

$I_x = 4{,}44 \cdot 10^{-3}\ \mathrm{m}^4$

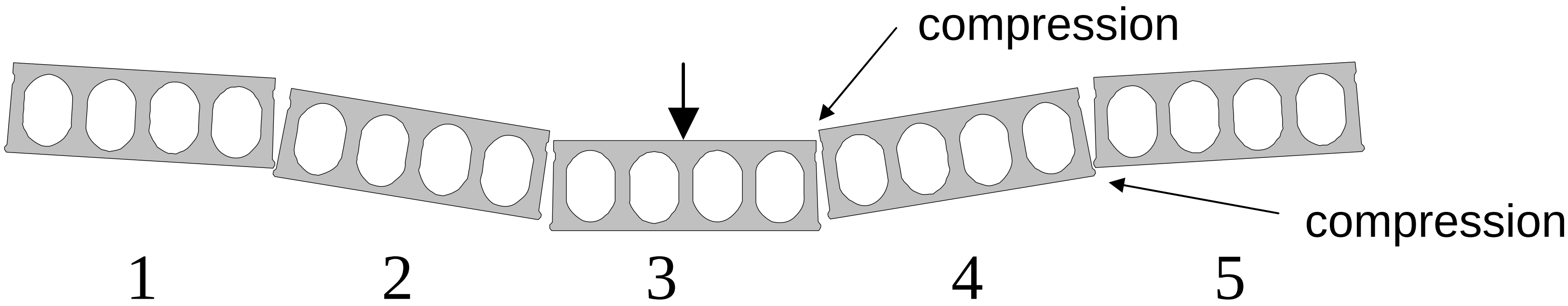
$I_y = 28{,}0 \cdot 10^{-3}\ \mathrm{m}^4$

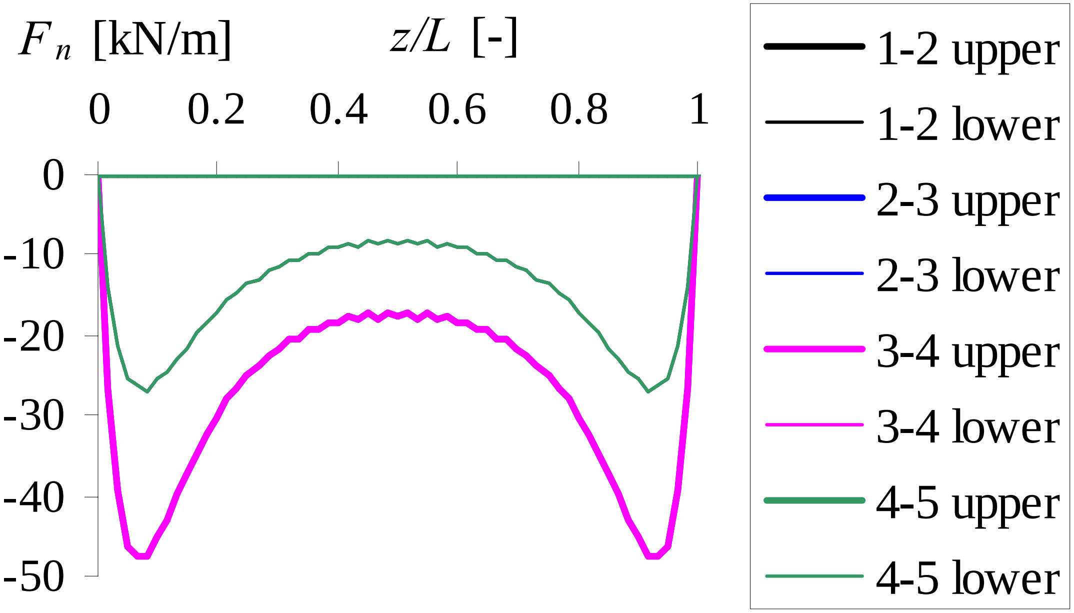
$I_t = 8{,}02 \cdot 10^{-3}\ \mathrm{m}^4$

$E_c = 30\ \mathrm{GPa}$

$\nu = 0{,}15$

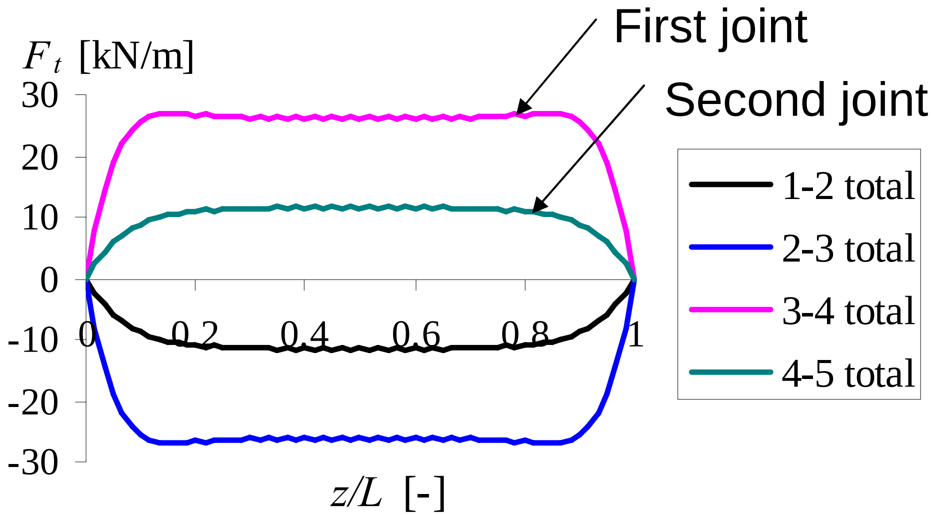
Normal force in the joints



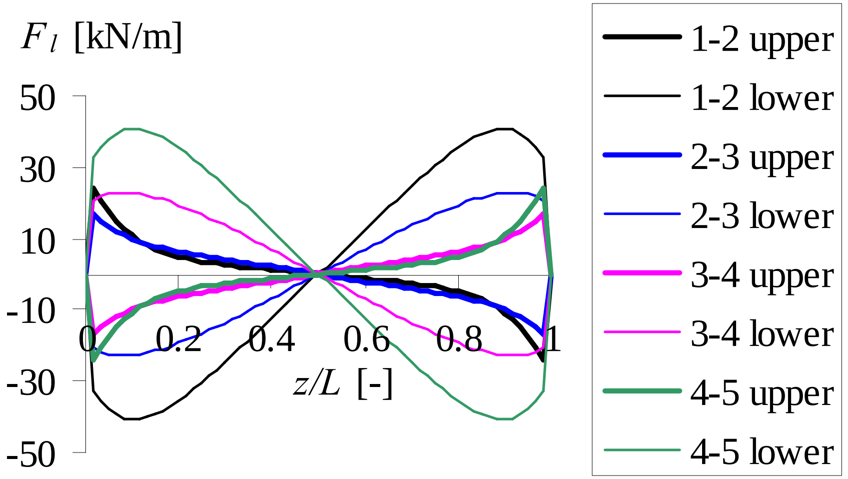


Shear force in the joints

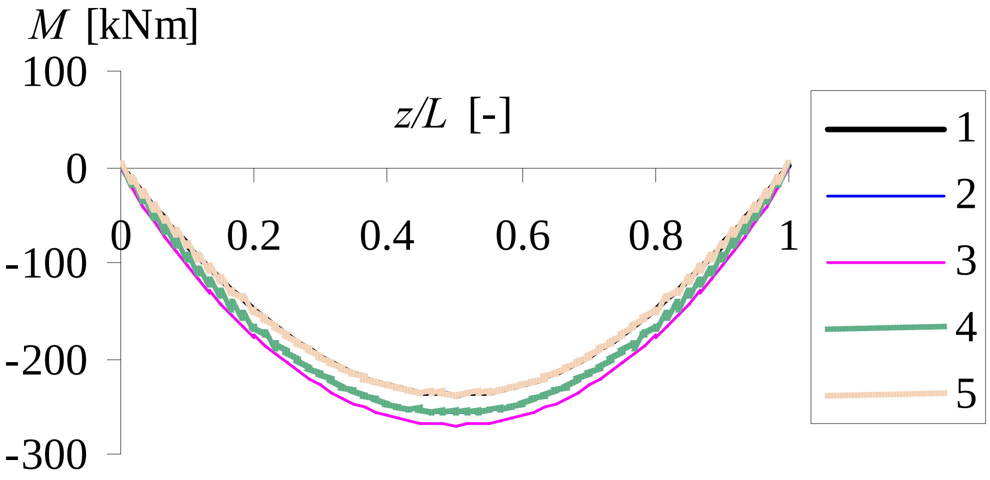
Vertical

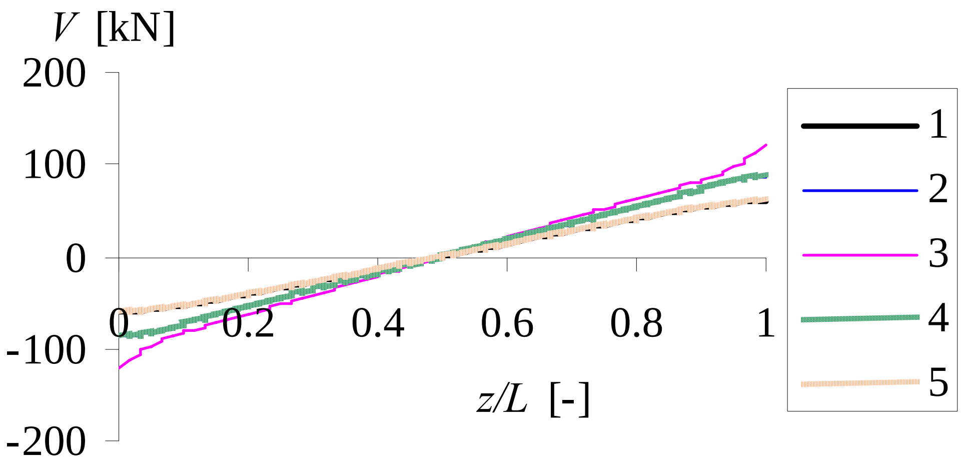


Longitudinal



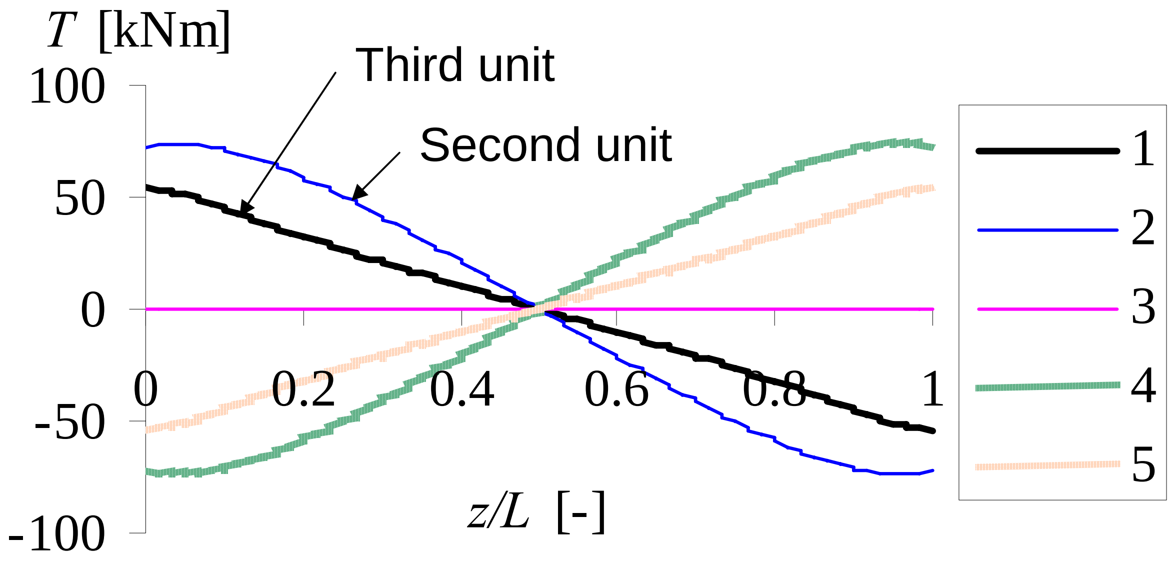
Bending moment and shear force



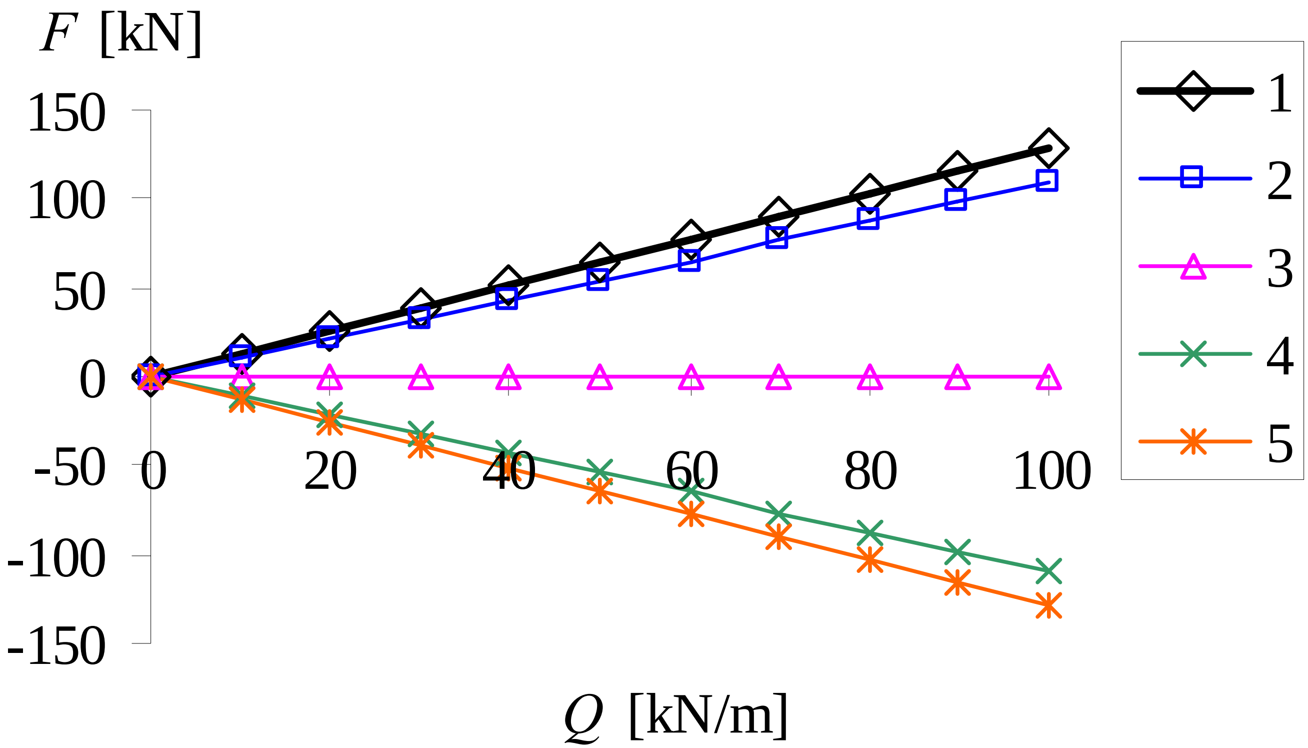


The effect of dead weight and prestressing must be added

Torsional moment

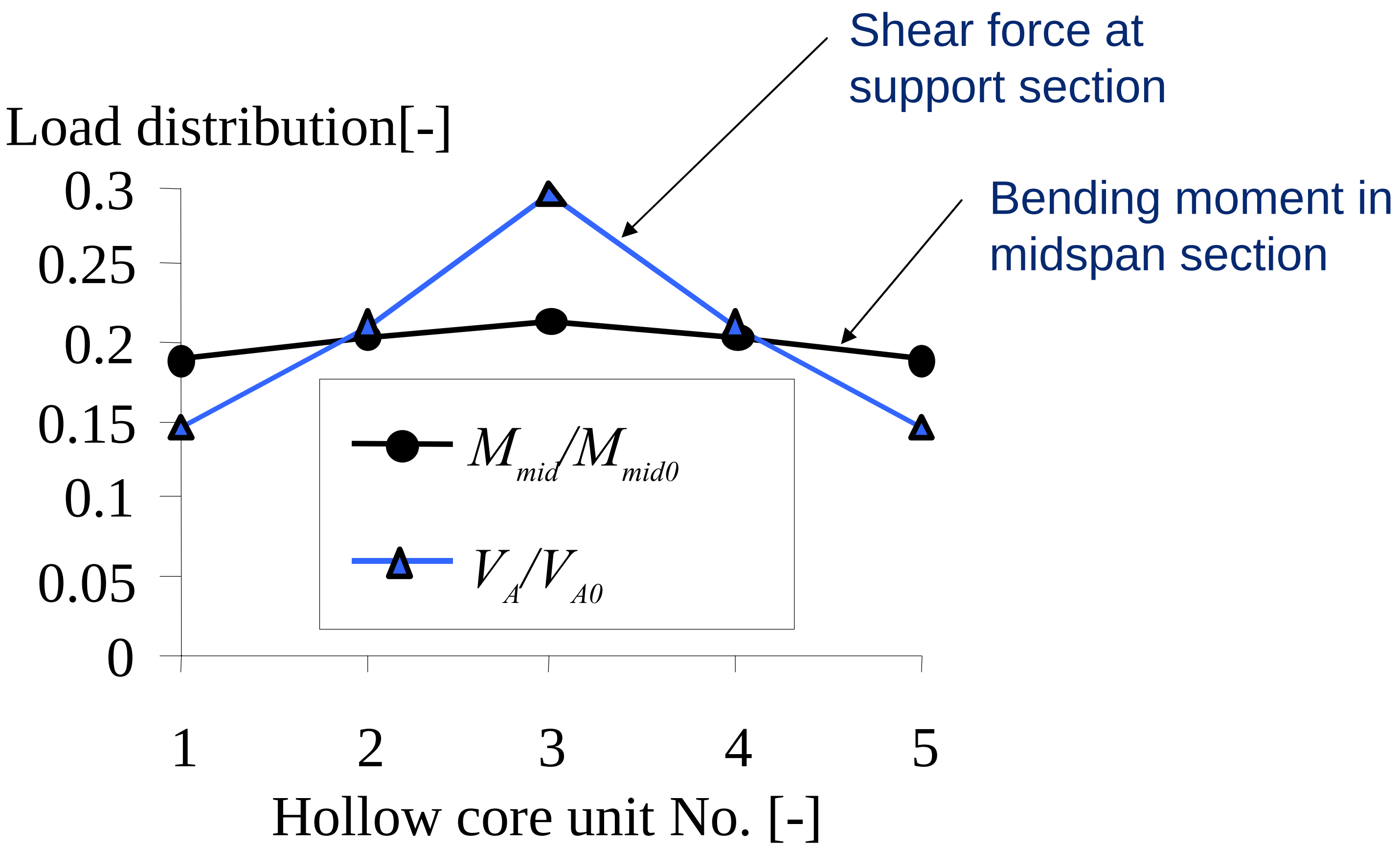


Force between tie beam and hollow core units

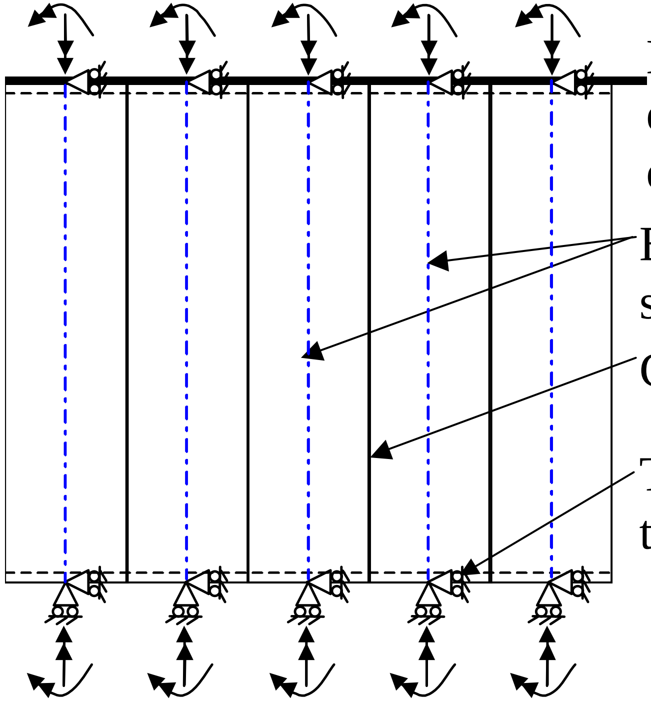


If these forces exceed the capacity of the tie beams, a capacity limit should be included in the model

Transverse distribution of load effects



Example 2: three-sided support



Deformations tied to each other in the direction along the slabs; i.e. longitudinal deformations must be equal

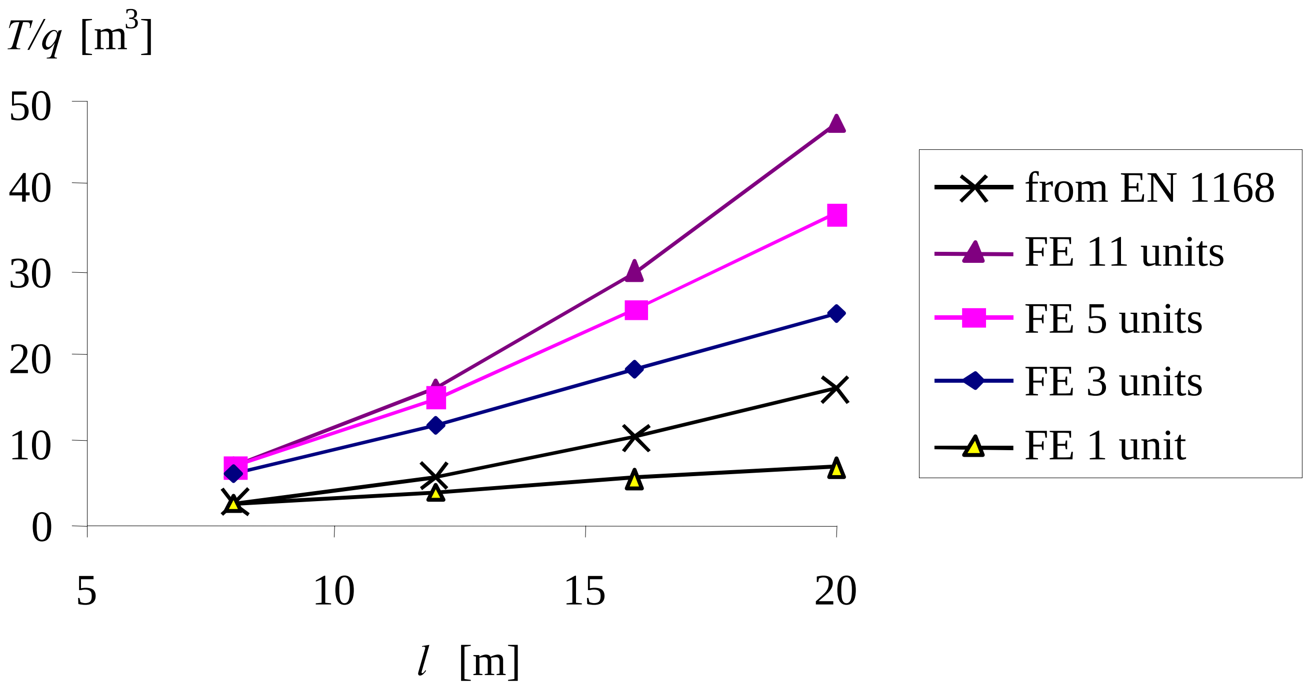
Beam elements to model single hollow core units

Connecting elements to model joints

Tie beams modelled by supporting the elements in this direction

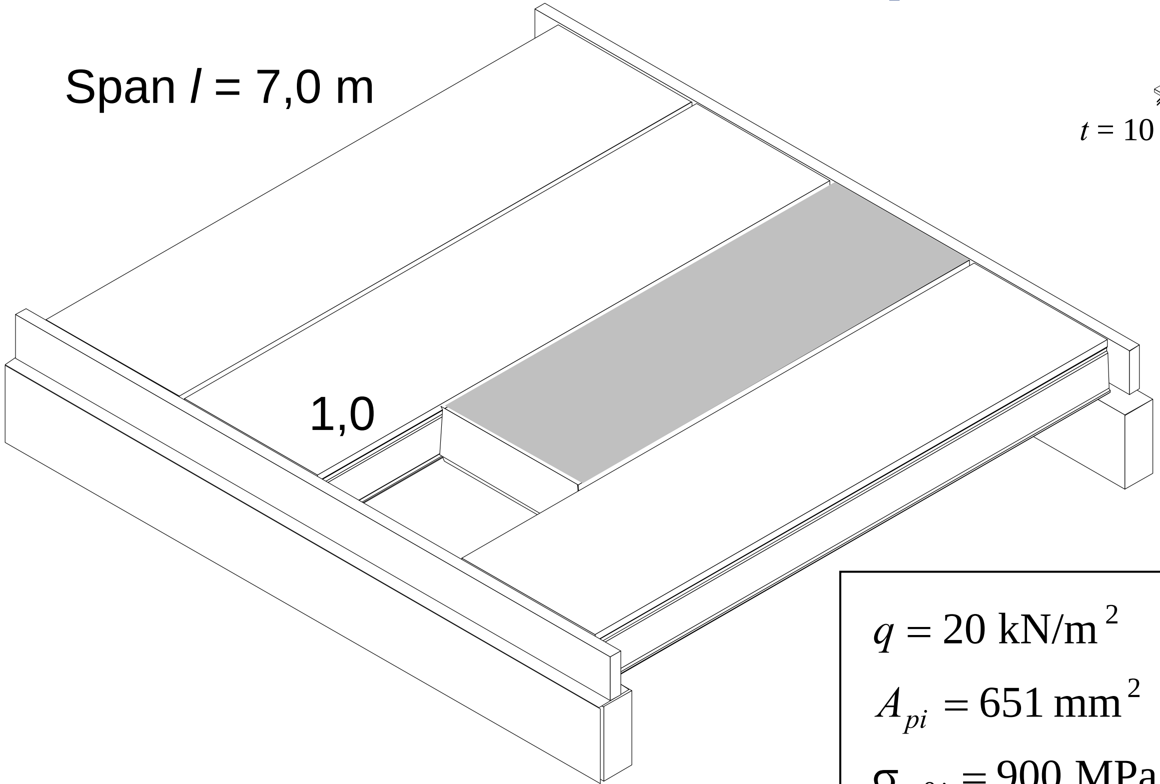
Uniformly distributed load *q*
Otherwise, the same input data as in the previous example

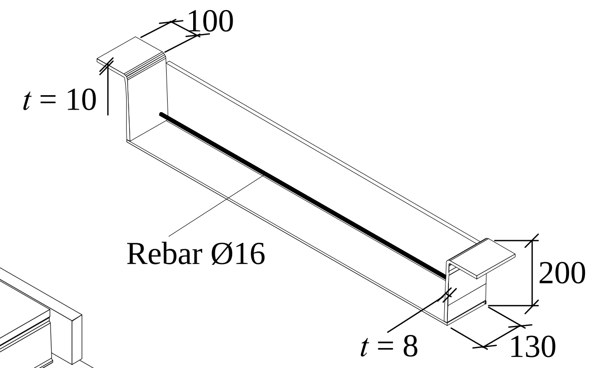
Maximum torsional moment

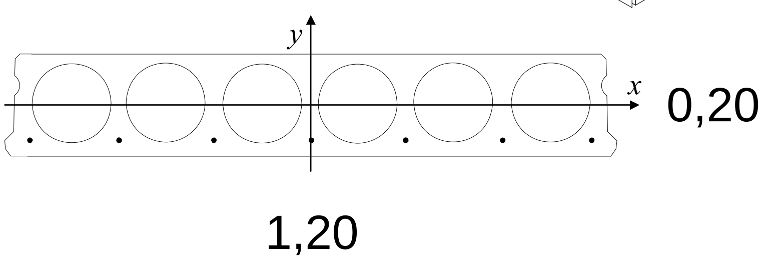


- The maximum torsional moment always appears at corner of the supported edge
- The torsional moment increases with
  - increasing span
  - increasing number of HC units

Example 3







$q = 20\ \text{kN/m}^2$

$A_{pi} = 651\ \text{mm}^2$

$\sigma_{p0i} = 900\ \text{MPa}$

Effect of dead weight and prestressing included

$I_x = 0{,}61 \cdot 10^{-3}\ \text{m}^4$

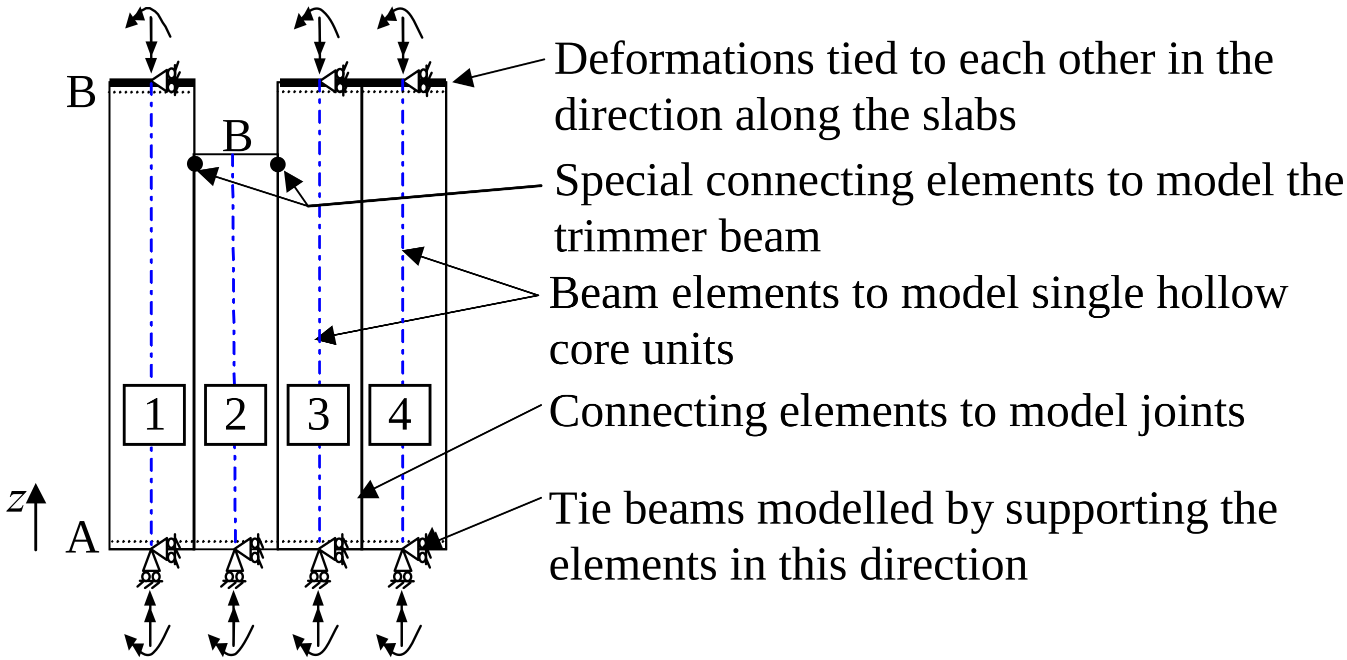
$I_y = 15{,}9 \cdot 10^{-3}\ \text{m}^4$

$I_t = 1{,}59 \cdot 10^{-3}\ \text{m}^4$

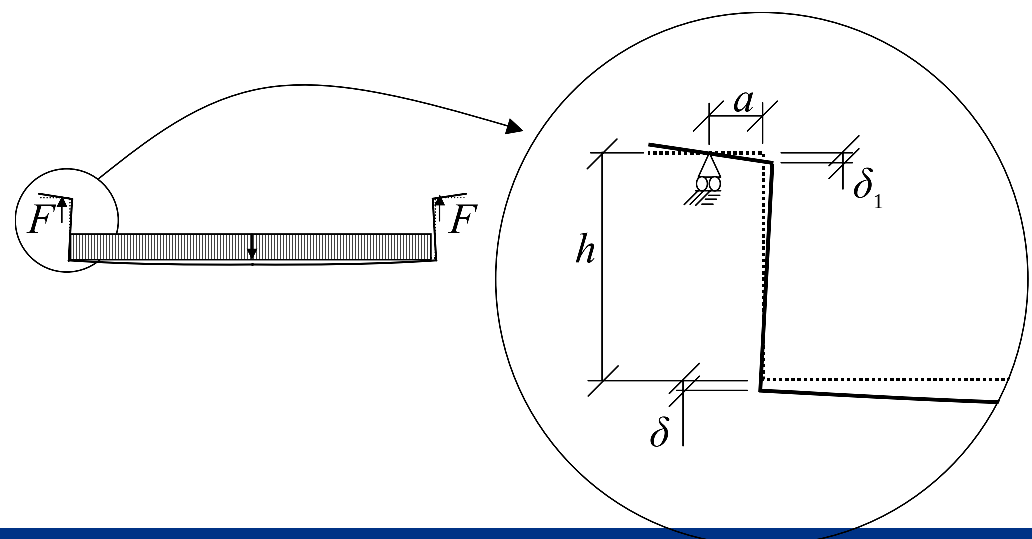
$E_c = 36\ \text{GPa}$

$\nu = 0{,}15$

Model



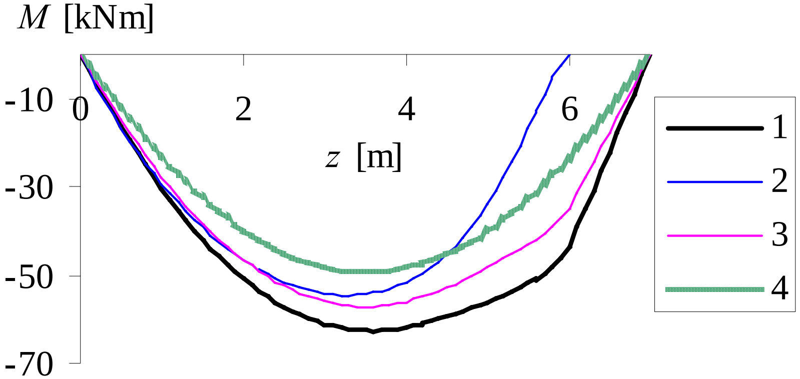
The effect of the trimmer beam was considered by vertical spring elements at joints representing the stiffness in the vertical direction



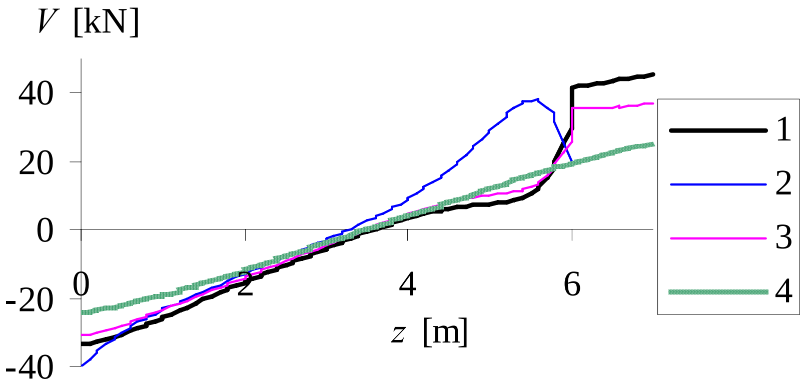
Analysis

- Step 1
  - Dead weight and prestressing were applied
  - The connecting elements simulating the joint were not activated
  - The connecting elements simulating the trimmer beam were active
- Step 2
  - The load q was applied. All the connecting elements between the HC units were active

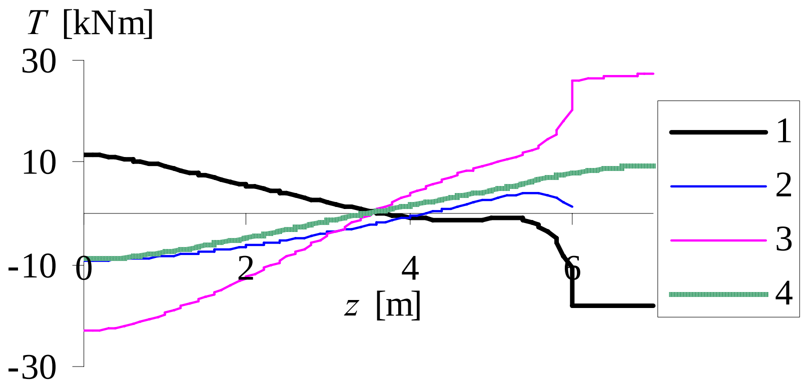
Total sectional forces



(a)



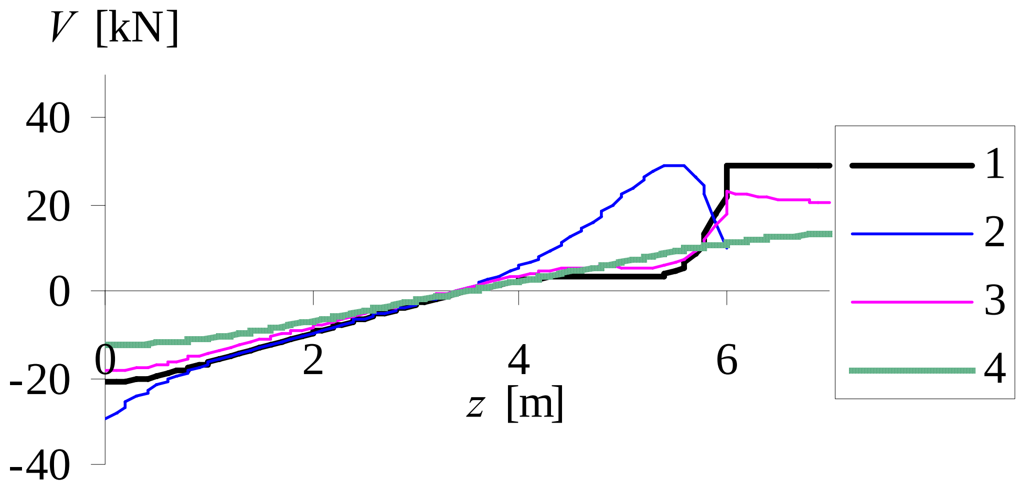
(c)



(e)

Effect of trimmer beam

Shear force due to applied load only

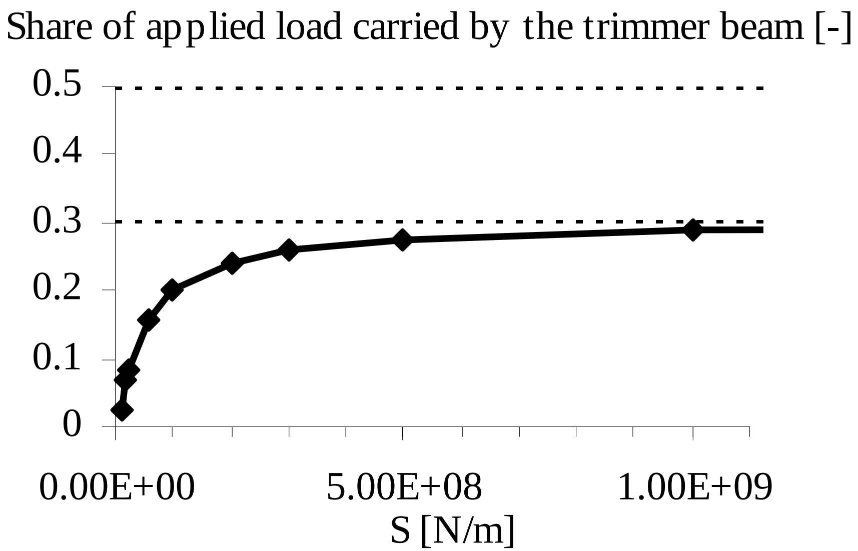


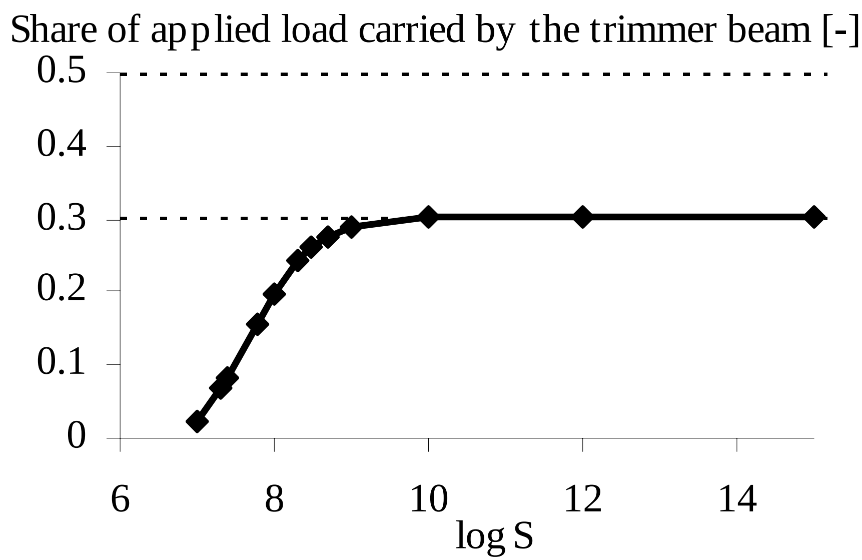
(d)

The trimmer beam carried all of the dead weight and 6,8% of the applied load.

If no load was transferred by shear in the joints, the trimmer beam would carry 50% of the applied load

Influence of stiffness of trimmer beam

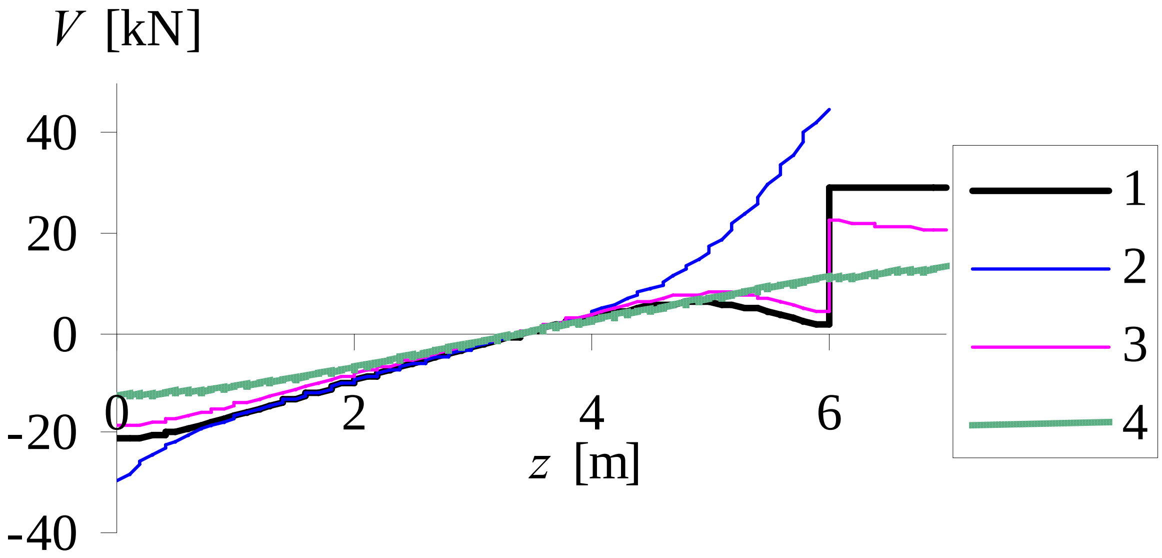




In the example the stiffness of the trimmer beam was estimated to $2 \cdot 10^7$ N/m.
The stiffness of the grouted joint was estimated to $1 \cdot 10^9$ N/m^3.

Even with a very stiff trimmer beam, the trimmer beam will never take more than 30 % of the applied load.

Distribution of shear force with a very stiff trimmer beam



Some of the applied load is always transferred by the grouted joints

Conclusions – design approach

- To determine sectional forces
  - Global model typically a model for linear response
  - FEA is possible and easy to use now
- Design the section
  - Local sectional or regional model for the response in the ultimate state (based on non-linear material response). Simplified approach or FEA
  - Non-linear FEA can be used to determine V-T interaction curves (once for each section)
  - Can be used now, but not every day.
  - M-V-T interaction curves are desired

Conclusions design approach

- Verify the performance
  - Non-linear response in the services and ultimate states
  - Non-linear FEA is needed
  - A detailed model of the whole floor is too demanding
  - Combinations of detailed and simplified models are possible to use. Indication of future possibilities. More development is needed.

FEA as a tool

- We use (too) simple approaches
  - Single units
  - One effect at the time
- Interaction of sectional forces, M-V-T
- Influence of boundaries: supports, joints, detailing
- The unit is part of the complete floor: favourable and unfavourable restraint effects
- We need FEA as a tool in research. All information we can get is needed in order to reach better understanding (Example: the complex connection zone)