Fundamentals of Structural Design
Part of Steel Structures

Civil Engineering for Bachelors
133FSTD

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Syllabus of lectures

1. Introduction, history of steel structures, the applications and some representative structures, production of steel
2. Steel products, material properties and testing, steel grades
3. Manufacturing of steel structures, welding, mechanical fasteners
4. Safety of structures, limit state design, codes and specifications for the design
5. Tension, compression, buckling
6. Classification of cross sections, bending, shear, serviceability limit states
7. Buckling of webs, lateral-torsional stability, torsion, combination of internal forces
8. Fatigue
9. Design of bolted and welded connections
10. Steel-concrete composite structures
11. Fire and corrosion resistance, protection of steel structures, life cycle assessment

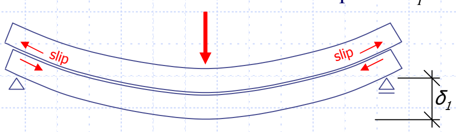
Scope of the lecture

- Basic principles of the composite structures
- Shear connectors
- Composite beams
- Composite columns
- Steel-concrete slabs

Principle of behaviour of composite beams

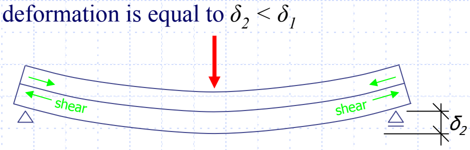
Steel beam and concrete slab are not connected

- They share the load (each take a part from the total)
- The deformation of both is the same – equal to δ_1



Steel concrete composite beam

- The beam and the concrete slab are connected by shear connectors eliminating the slip on steel-concrete interface
- The composite beam takes the whole load
- The deformation is equal to $\delta_2 < \delta_1$



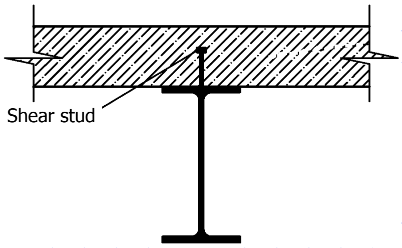
Steel concrete composite structures

Advantages

- Convenient stresses
  (concrete in compression / steel in tension)
- Saving expensive material (steel) - low cost of the structure
- Increase of stiffness
- Better fire resistance (compared to steel structures) – no need for additional fire protection – low cost of the structure

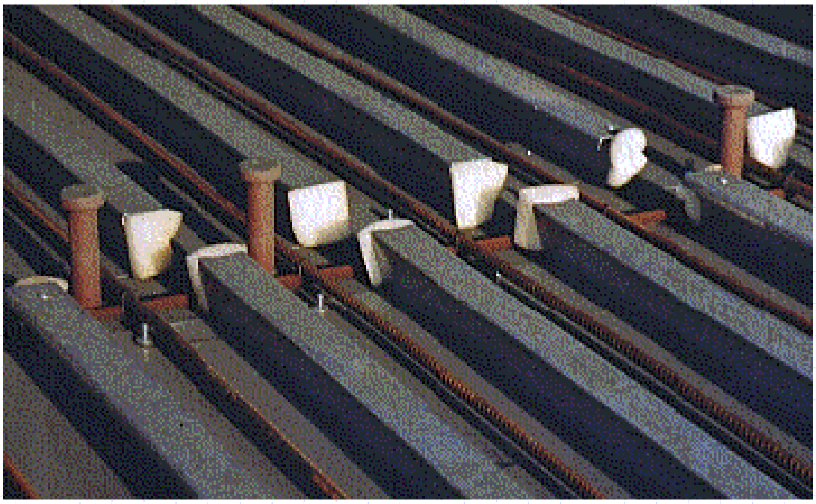
Steel concrete composite elements

- Beams
- Columns
- Composite slabs



Steel concrete beam section
with welded stud
providing shear connection

Beam with welded shear studs



Standards for design of composite structures

European standard EN 1994-1-1

Design strength

- concrete ……… $f_{cd} = 0{,}85\, f_{ck} / \gamma_c$

  $\gamma_c = 1{,}5$

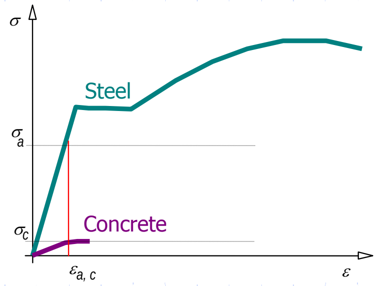
- steel ……….…. $f_{yd} = f_y / \gamma_{M0}$

  $\gamma_{M0} = 1{,}0$

- reinforcement … $f_{sd} = f_{sk} / \gamma_s$

  $\gamma_s = 1{,}15$

- shear connectors $\gamma_V = 1{,}25$



Stress-strain diagram of steel and concrete
Note: for equal strain $\varepsilon_{a,c}$, steel gets much higher stress than concrete because of different modules of elasticity

7

Scope of the lecture

Basic principles of the composite structures

➡ Shear connectors

Composite beams

Composite columns

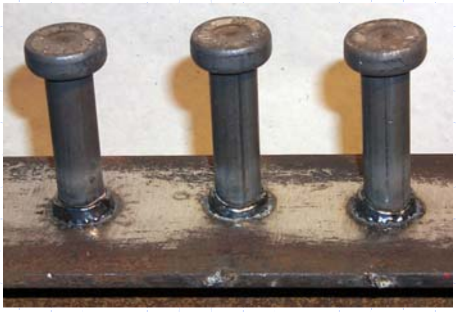
Steel-concrete slabs

8

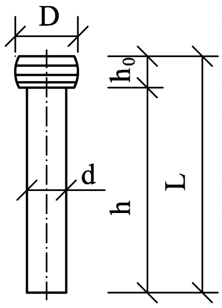
Welded studs

- Common, cheap, simple to install
- Convenient $F - \delta$ relationship
  (high resistance and ductility)

☹Need of strong electric source for welding



Studs welded to the steel beam



Shear stud

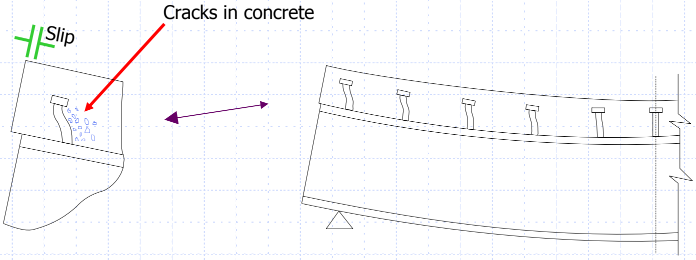
Welding of shear studs

Semi-automatic welding of the shear studs

Advantages of studs

Deformation of ductile studs

- High deformation capacity of studs allows for plastic distribution of shear forces among the studs
- As the studs at the ends of the beam are overloaded, they deform and cracks in the concrete appear, which leads to small slip of the concrete slab, this causes the other studs are loaded by increasing forces



Resistance of studs

Characteristic resistance of the stud

- Steel failure

$$P_{Rk} = 0{,}8\, f_u \, \frac{\pi d^2}{4}$$

- Concrete failure

$$P_{Rk} = 0{,}29\, \alpha\, d^2 \sqrt{f_{ck}\, E_{cm}}$$

f_u ultimate strength of material of studs, max. 500 MPa

Reduction due to stud height

- Short stud

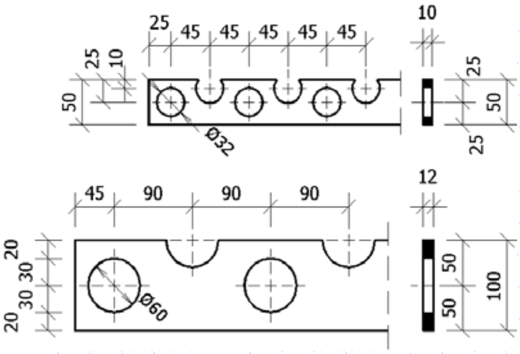
$$3 \le \frac{h}{d} \le 4 \qquad \alpha = 0{,}2\left(\frac{h}{d} + 1\right)$$

- Long stud

$$4 < \frac{h}{d} \qquad \alpha = 1{,}0$$

Perforated strips

- Various types exist worldwide
- The resistance can be increased by reinforcement placed into the holes
- Non-ductile shear connection
- Two types are used in Czech Republic:
  - height 50 mm, thickness 10 mm, holes d = 32 mm
  - height 100 mm, thickness 12 mm, holes d = 60 mm



Thin walled connectors

- Manufactured by Hilti
- Zinc-coated steel sheet, thickness 2 mm
- Easy to apply, no need for electricity for welding
- Connected to steel beams by two shot nails
- Height from 80 up to 140 mm


Range of Hilti HVB connectors

Expensive ⇒ refurbishment


Hilti HVB shear connectors

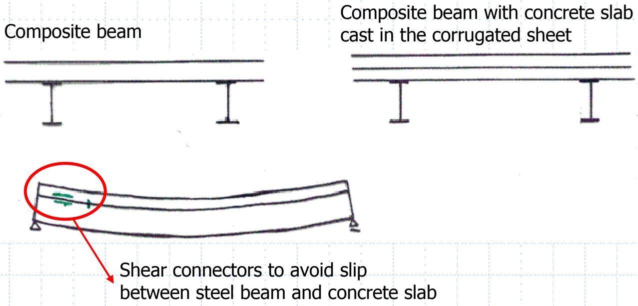
Thin walled connectors

Application of Hilti shear connectors

Scope of the lecture

- Basic principles of the composite structures
- Shear connectors
- ➡ Composite beams
- Composite columns
- Steel-concrete slabs

Composite beams



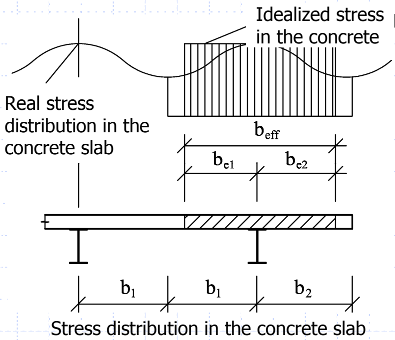
Effective cross section

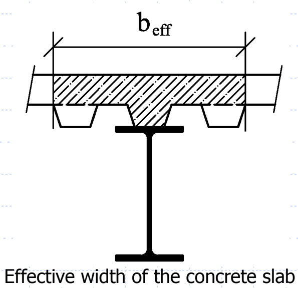
The stress in the concrete slab is not uniform because of effect of shear lag

Idealized stress distribution (i.e. uniform stress on the effective width b_{eff}) is considered in the concrete slab

Considering imply supported beams, the effective width b_{eff} is equal to

$$b_{eff} = \frac{L}{4}$$





Classification of cross sections

Beam flange connected to the concrete slab by shear connectors is assumed to be fully stabilized - no local buckling of the flange can occur – Class 1 for any *c/t* ratio

The other parts are classified in similar way as normal steel beams

19

Resistance of the beam

Two cases should be distinguished:

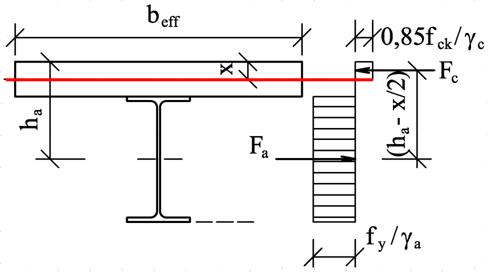
- Full shear connection
  (the shear connection is not critical part of the beam)
  - This is the preferable way of design
- Partial shear connection
  (shear connection limits the resistance of the beam)
  - It is used in cases when the number of the connectors required for full shear connection does not fit on the beam and smaller number of the connectors must be used
  - Stiffness of the beam decrease - deformation increase

Check of cross section – plastic stress distribution at ULS (full shear connection)

- Positive plastic bending moment capacity is evaluated with one of the following options
  - Neutral axis in the slab
  - Neutral axis in the beam
- Negative plastic moment capacity needs to be evaluated at supports of continuous beams, etc.

20

Plastic bending moment capacity



Full shear connection

Assumption: neutral axis is in the concrete slab

Force equilibrium equation to get the depth of concrete zone in compression

$$F_c = F_a$$

$$b_{eff}\ x\ 0{,}85\ \frac{f_{ck}}{\gamma_c} = A_a\ \frac{f_y}{\gamma_a} \quad \Rightarrow \quad x = \ldots$$

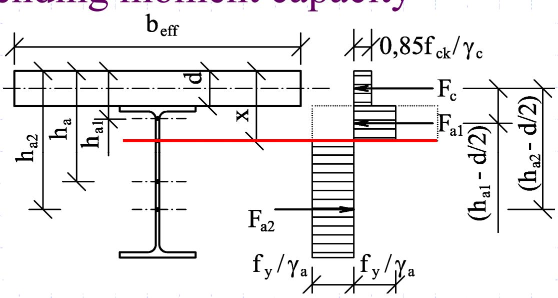
but x must be smaller than depth of the slab

Moment equilibrium equation to get the bending moment capacity

$$M_{pl,Rd} = F_a\ r = F_c\ r$$

21

Plastic bending moment capacity



Full shear connection

Assumption: neutral axis is in the steel section

Force equilibrium equation to get the depth of concrete zone in compression

$$F_c + F_{a1} = F_{a2} \quad \Rightarrow \quad x = \ldots$$

(limits for x exist)

Moment equilibrium equation to get the bending moment capacity

$$M_{pl,Rd} = F_c \left(h_{a2} - \frac{d}{2} \right) + F_{a1} \left(h_{a1} - \frac{d}{2} \right)$$

22

Criteria to be checked

Ultimate Limit States

- Moment resistance of critical cross section
- Resistance in shear
- Resistance in longitudinal shear (resistance of shear connectors)

Serviceability Limit States

- Elastic behaviour
- Deflections

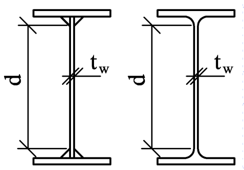
Resistance in shear

See shear resistance of steel beams

The concrete slab has no effect on the shear resistance

$$V_{pl,Rd} = \frac{A_v\, f_y}{\sqrt{3}\,\gamma_{M0}}$$

A_v shear area = area of the beam web



Shear area of I sections

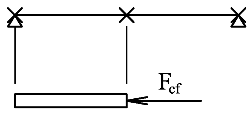
Shear connection

Shear connectors transfer longitudinal shear V_ℓ

Ductile shear connectors: the connectors can be uniformly distributed

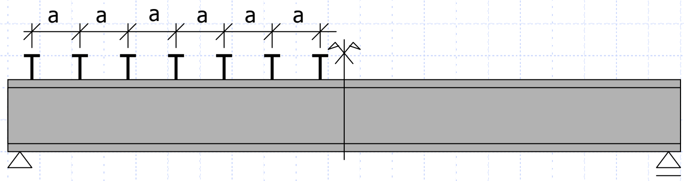
- Shear force to be transferred by connectors

$$F_{cf} = A_c \, 0{,}85 \frac{f_{ck}}{\gamma_c}$$



- Number of connectors on half-span:

$$n_f = \frac{F_{cf}}{P_{Rd}}$$

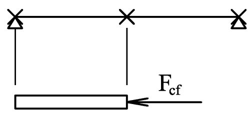


Shear connection

Shear connectors transfer longitudinal shear V_ℓ

Non-ductile connectors: the connectors follow shear force distribution

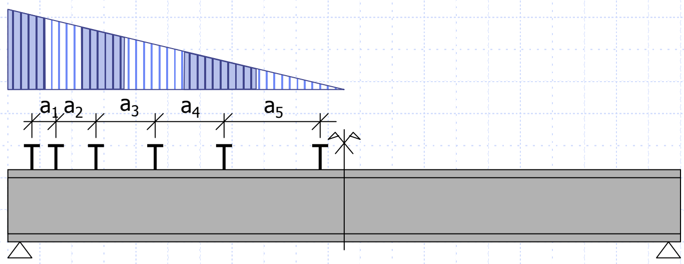
$$V_\ell = \frac{V_{Ed} \, S_c}{I_i}$$



V_{Ed} shear force on the beam,

S_i static moment of effective cross section of slab to the centre of gravity of the beam,

I_i moment of inertia of the beam



Serviceability limit states

Service load is assumed for the calculations ($\gamma_G = \gamma_Q = 1{,}0$; $\gamma_M = 1{,}0$)

Beam is in elastic stage – this should be checked by calculating the maximum stress in the steel and concrete and comparing it to the yield limit of steel and to the concrete strength

Deflections

Cracking of concrete (limit of crack width)

Limit crack width $w_k = 0{,}3$ mm

This is controlled by the slab reinforcement

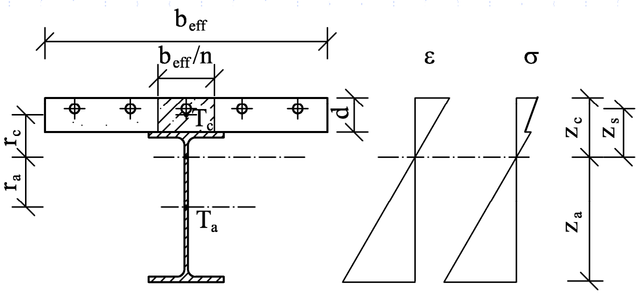
The assembling procedure has significant effect on both the stress and the deflection of the beam

27

Elastic behaviour

Assumption of Navier's hypothesis (planar cross-section after deformation)

- Components and maximum stress
  - Concrete ($0{,}85 f_{ck} / \gamma_c$)
  - Steel (f_y / γ_{M0})
  - Reinforcement (f_{sk} / γ_s)



28

Properties of idealized cross section

Concrete slab is transformed to the equivalent steel part
The ratio at which the dimensions are modified is

$$n = \frac{E_a}{0{,}5\, E_{cm}}$$

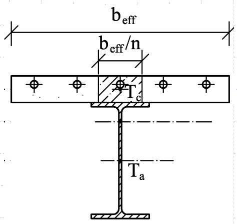
E_a is modulus of elasticity of steel
E_{cm} is modulus of elasticity of concrete, the factor 0,5 is used to take into account the creep in a simplified way

- Area of cross section A_i

$$A_i = A_a + \frac{A_c}{n} + A_s$$

- Centre of gravity
- Moment of inertia I_i

$$I_{y,i} = ...$$



Idealized section of composite beam

Assembling procedure

Has influence on deformation and elastic stress distribution (but not on $M_{pl,Rd}$)
Two procedures can be used

- Without scaffolding

  Two stages need to be considered:
  - the assembly stage, when steel beam is loaded by weight of fresh concrete (and some temporary load presented at the assembling) - no composite action
  - the final stage, when the concrete is hard and ready to carry the load - the composite beam has to carry all the load

  In elastic calculation, the stress from the assembly stage (from the weight of the fresh concrete) and from the remaining load (other dead load applied after the concrete gets hard and from variable load) add

- On scaffolding

  The weight of the fresh concrete is supported by temporary structure - scaffolding, therefore no stresses and deformation occur, all the load is resisted by the composite beam

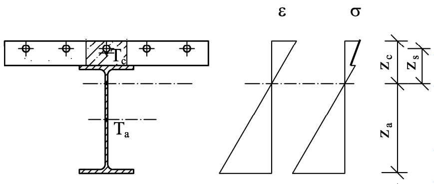
Assembling with scaffolding
Stresses, deflections

Stress at upper edge of the concrete slab

$$\sigma_c = \frac{1}{n}\frac{M_{Ek}\, z_c}{I_{y,i}} \qquad \sigma_c \le f_{c,k}$$

Stress at lower edge of steel section

$$\sigma_a = \frac{M_{Ek}\, z_a}{I_{y,i}} \qquad \sigma_a \le f_y$$



Deformation (for simply supported beam with uniformly distributed load)

$$\delta = \frac{5}{384}\frac{v_k\, l^4}{E_a\, I_{y,i}}$$

Note: easy method for the design
saves the steel - the beams are smaller as only the composite beam is loaded
cheap? - consider the price of rent and erection of the scaffolding
effective for large spans, i.e. spans exceeding 7 m

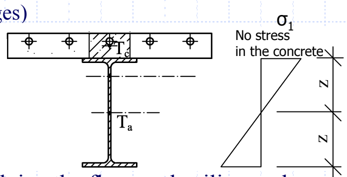
Assembling without scaffolding
Stresses

Assebling stage

The load at assembly should be considered, i.e. self weight of the beam, weight of the fresh concrete and people working with the concrete

Stress in the steel section (top and bottom edges)

$$\sigma_{a1} = \frac{M_{Ek.1}\, z}{I_y} \qquad \sigma_{a1} \le f_y$$



Final stage

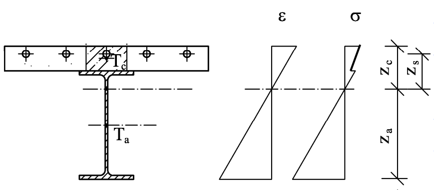
The remaining load should be considered, i.e. the floor and ceiling and any variable load

Stress in the steel section (bottom edge)

$$\sigma_{a2} = \frac{M_{Ek.2}\, z_a}{I_{y,i}}$$

Stress in the concrete (top surface of the slab)

$$\sigma_c = \frac{1}{n}\frac{M_{Ek.2}\, z_c}{I_{y,i}}$$



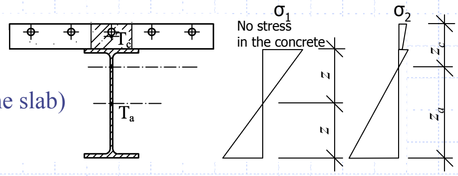
Assembling with scaffolding
Stresses

Total stress

The total stress is obtained as the sum of the previous

Stress in the steel section (bottom edge)

$$\sigma_a = \sigma_{a1} + \sigma_{a2}$$



Stress in the concrete (top surface of the slab)

$$\sigma_c = 0 + \sigma_{c2}$$

Note: more complicated method for the design (two situations need to be considered)
the beams are bigger - usually the assembling stage limits the size of the steel beam
effective for small spans, i.e. spans up to 7 m

33

Assembling with scaffolding
Deformation

Deformation (for simply supported beam with uniformly distributed load)

At assembly stage

The load at assembly should be considered, i.e. self weight of the beam, weight of the fresh concrete and people working with the concrete

The moment of inertia of the steel section only (I_y) is used

$$\delta_1 = \frac{5}{384} \frac{v_{k1}\, l^4}{E_a\, I_y}$$

At final stage

The remaining load should be considered, i.e. the floor and ceiling and any variable load

The moment inertia of the composite beam ($I_{y,i}$) is used

$$\delta_2 = \frac{5}{384} \frac{v_{k2}\, l^4}{E_a\, I_{y,i}}$$

Total deformation

The total stress is obtained as the sum of the previous

$$\delta = \delta_1 + \delta_2$$

34

Scope of the lecture

Basic principles of the composite structures

Shear connectors

Composite beams

➡ Composite columns

Steel-concrete slabs

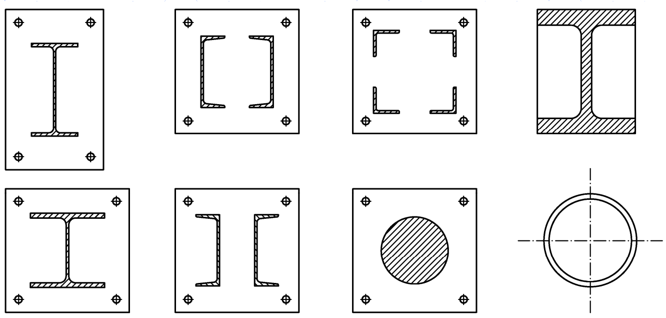
35

Columns

Fully encased columns

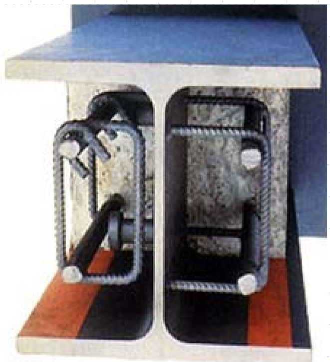
Partially encased columns

Concrete filled hollow sections (circular, rectangular)



36

Columns



37

Simplified method of resistance evaluation of columns

Criteria

- Columns with double-symmetric steel sections
- Constant section along length
- $0{,}2 < \delta < 0{,}9$, where $\delta = \frac{(A_a\, f_y / \gamma_a)}{N_{pl,Rd}}$
- $0{,}2 < h_c/b_c < 5{,}0$
- Relative slenderness of column $\bar{\lambda} \leq 2{,}0$
- Area of the reinforcement should be max. 6 % of concrete area

38

Centric compression

Full plastification of all parts

$$N_{pl.Rd} = A_a \left(\frac{f_y}{\gamma_a}\right) + A_c \left(\frac{0{,}85\, f_{ck}}{\gamma_c}\right) + A_s \left(\frac{f_{sk}}{\gamma_s}\right)$$

Concrete filled hollow sections

... use f_{ck} instead of $0{,}85\, f_{ck}$

Increase of concrete strength confined by the steel section

Buckling resistance

$$N_{Ed} \leq \chi\, N_{pl.Rd}$$

χ ... reduction factor (buckling factor) as for steel members

Use buckling curves a, b, c

$$\bar{\lambda} = \sqrt{\frac{N_{pl.Rd}}{N_{cr}}}$$

Critical load of composite element

$$N_{cr} = \frac{\pi^2 (EI)_e}{\ell^2}$$

Bending stiffness

$$(EI)_e = E_a\, I_a + 0{,}6\, E_{cm}\, I_c + E_s\, I_s$$

ℓ buckling length

$E_a = E_s$ modulus of elasticity of steel

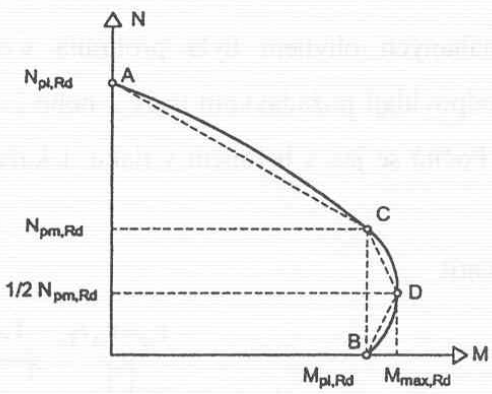
E_{cm} modulus of elasticity of concrete

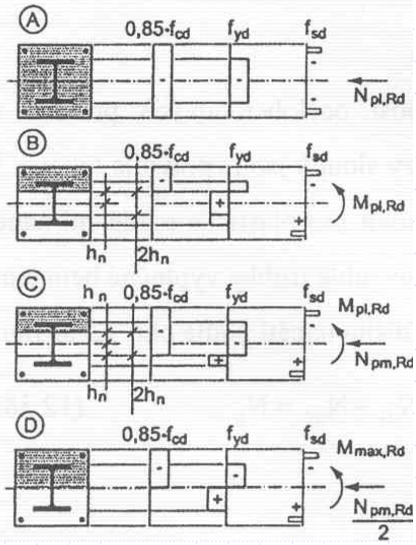
I_a, I_c, I_s moments of inertia of steel part, concrete part and reinforcement to the centroidal axis

41

Compression and bending

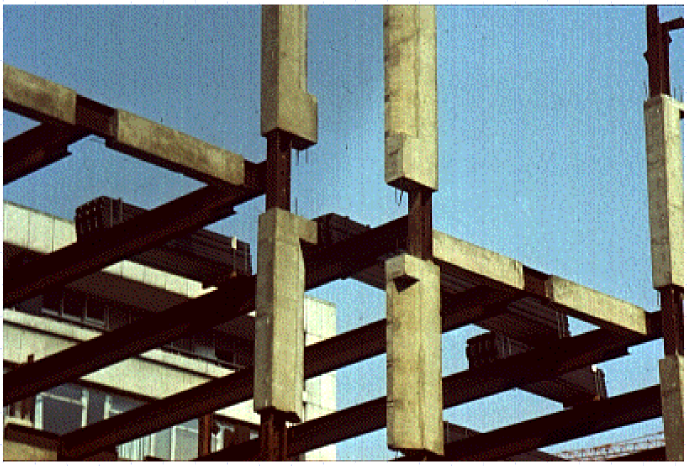
Interaction curve for combined $M_{Ed} + N_{Ed}$





Joints of composite structures

Joints are encased in concrete afterwards (to maintain the same fire resistance of the joints as of the other parts)



43

Scope of the lecture

- Basic principles of the composite structures
- Shear connectors
- Composite beams
- Composite columns
- ➡ Steel-concrete slabs

44

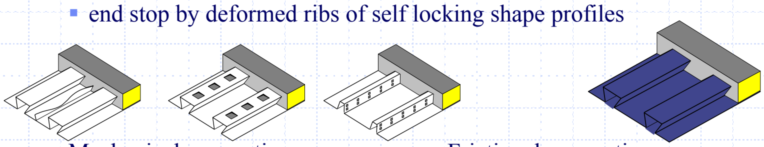
Concrete slab cast on corrugated steel sheets

- Corrugated sheet filled by concrete
  1. Fresh concrete = assembling stage: load to sheet
  2. After hardening of concrete: sheet = reinforcement (plus standard reinforcement when necessary)
- For static loading

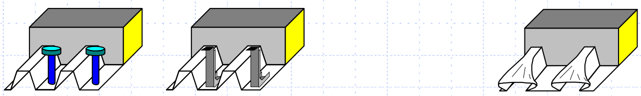
Concrete slabs cast on corrugated steel sheets

Shear connection

- mechanical connection assured by nops or profiling in sheet
- frictional connection of profiles with self locking shape profiles
- end stop by welded studs
- end stop by deformed ribs of self locking shape profiles



Mechanical connection   Frictional connection



Shear connection   End connection

Slip between steel and concrete

Thank you for your attention