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

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 $\delta_1$

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

Beam with welded shear studs
Standards for design of composite structures

European standard EN 1994-1-1

Design strength

- concrete ......... $f_{cd} = 0.85 \cdot f_{ck} / \gamma_c$
  $\gamma_c = 1.5$

- steel .............. $f_{yd} = f_{y} / \gamma_{M0}$
  $\gamma_{M0} = 1.0$

- reinforcement ... $f_{rd} = f_{rk} / \gamma_s$
  $\gamma_s = 1.15$

- shear connectors $\gamma_f = 1.25$

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

Scope of the lecture

Basic principles of the composite structures

- Shear connectors
- Composite beams
- Composite columns
- Steel-concrete slabs
Welded studs

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

Need of strong electric source for welding

Welding of 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
  \[ P_{u} = 0.8 f_u \frac{\pi d^2}{4} \]

- Concrete failure
  \[ P_{u} = 0.29 \alpha d^2 \sqrt{f_{cm}} E_{cm} \]

\( f_u \) ultimate strength of material of studs, max. 500 MPa

Reduction due to stud height

- Short stud
  \[ 3 \leq \frac{h}{d} \leq 4 \quad \alpha = 0.2 \left( \frac{h}{d} + 1 \right) \]

- Long stud
  \[ 4 < \frac{h}{d} \quad \alpha = 1.0 \]
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 \( d = 32 \text{ mm} \)
- height 100 mm, thickness 12 mm, holes \( d = 60 \text{ mm} \)

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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

Expensive \( \Rightarrow \) refurbishment
Thin walled connectors

Application of Hilti shear connectors

Scope of the lecture

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

Shear connectors to avoid slip between steel beam and concrete slab

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.

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.
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
\[ F_c = F_a \]
\[ h_{eff} \times 0.85 \frac{f_{ck}}{f_y} = A_s \frac{f_y}{f_y} \Rightarrow x = \ldots \text{ but } x \text{ must be smaller than depth of the slab} \]

Moment equilibrium equation to get the bending moment capacity
\[ M_{pl,full} = F_c r = F_a r \]

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
\[ F_c + F_{cl} = F_{sl} \Rightarrow x = \ldots \text{ (limits for } x \text{ exist)} \]

Moment equilibrium equation to get the bending moment capacity
\[ M_{pl,full} = F_c \left( h_{sl} - \frac{d}{2} \right) + F_{sl} \left( h_{sl} - \frac{d}{2} \right) \]
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

\[ V_{\mu,ld} = \frac{A_v f_s}{\sqrt{3} \gamma_{M0}} \]

\( A_v \) shear area = area of the beam web
Shear connection

Shear connectors transfer longitudinal shear $V_f$.

Ductile shear connectors: the connectors can be uniformly distributed

- Shear force to be transferred by connectors
  \[ F_{df} = A_c \times 0.85 \frac{f_{ck}}{f_c} \]

- Number of connectors on half-span:
  \[ n_f = \frac{F_{df}}{P_{dud}} \]

Non-ductile connectors: the connectors follow shear force distribution

\[ V_f = V_{eff} \frac{S_i}{I_i} \]

$V_{eff}$ 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 $w_k = 0.3\, \text{mm}$
- This is controlled by the slab reinforcement

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

Elastic behaviour

Assumption of Navier’s hypothesis (planar cross-section after deformation)
- Components and maximum stress
  - Concrete ($0.85 f_{ck} / \gamma_c$)
  - Steel ($f_y / \gamma_M$)
  - Reinforcement ($f_{sk} / \gamma_s$)
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 \( A_i \)
  \[ A_i = A_s + \frac{A_c}{n} + A_s \]

- Centre of gravity

- Moment of inertia \( I_{iy} \)
  \[ I_{iy} = \ldots \]

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
\[ \sigma_{c,1} = \frac{M_{Ek} z_c}{I_{y,d}} \quad \sigma_{c,1} \leq f_{c,k} \]

Stress at lower edge of steel section
\[ \sigma_{a} = \frac{M_{Ek} z_a}{I_{y,d}} \quad \sigma_{a} \leq f_y \]

Deformation (for simply supported beam with uniformly distributed load)
\[ \delta = \frac{5}{384} \frac{v_k I_z^3}{E_a I_{y,d}} \]

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

Assembling 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)
\[ \sigma_{a,1} = \frac{M_{Ek,1} z}{I_{y,d}} \quad \sigma_{a,1} \leq f_y \]

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)
\[ \sigma_{a,2} = \frac{M_{Ek,2} z_a}{I_{y,d}} \]
Stress in the concrete (top surface of the slab)
\[ \sigma_{c,2} = \frac{1}{n} \frac{M_{Ek,2} z_c}{I_{y,d}} \]
Assembling with scaffolding

Stresses

Total stress
The total stress is obtained as the sum of the previous
Stress in the steel section (bottom edge)
\[ \sigma_{z1} = \sigma_{z1} + \sigma_{z2} \]
Stress in the concrete (top surface of the slab)
\[ \sigma_{z2} = 0 + \sigma_{z2} \]

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

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
\[ \delta_1 = \frac{5}{384} \frac{E_y I_y}{E} l^4 \]
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
\[ \delta_2 = \frac{5}{384} \frac{E_i I_{y,i}}{E} l^4 \]
Total deformation
The total stress is obtained as the sum of the previous
\[ \delta = \delta_1 + \delta_2 \]
Scope of the lecture

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

Columns

- Fully encased columns
- Partially encased columns
- Concrete filled hollow sections (circular, rectangular)
Columns

Simplified method of resistance evaluation of columns

Criteria
- Columns with double-symmetric steel sections
- Constant section along length
- \(0.2 < \delta < 0.9\), where \(\delta = \frac{A_a f_y / f_a}{N_pl,rd}\)
- \(0.2 < h_c/b_c < 5.0\)

- Relative slenderness of column \(\lambda \leq 2.0\)
- Area of the reinforcement should be max. 6% of concrete area
Centric compression

Full plastification of all parts

\[ N_{pl,Rd} = A_a \left( \frac{f_y}{\gamma_a} \right) + A_e \left( \frac{0.85 f_{ck}}{\gamma_e} \right) + A_s \left( \frac{f_{ck}}{\gamma_s} \right) \]

Concrete filled hollow sections

... use \( f_{ck} \) instead of 0.85 \( f_{ck} \)

Increase of concrete strength confined by the steel section

Buckling resistance

\[ N_{Ed} \leq \lambda N_{pl,Rd} \]

\( \lambda \) ... reduction factor (buckling factor) as for steel members

Use buckling curves a, b, c

\[ \lambda = \sqrt{\frac{N_{pl,Rd}}{N_{cr}}} \]
Critical load of composite element

\[ N_{cr} = \frac{\pi^2 (EI)_{cr}}{\ell^2} \]

Bending stiffness

\[ (EI)_{cr} = E_a I_a + 0.6 E_{cm} I_c + E_s I_s \]

\( \ell \) buckling length

\( E_a \) 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

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)

Scope of the lecture

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