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

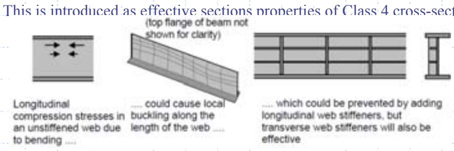
- Stability of webs
  - Web stiffeners
  - Shear loads
  - Local concentrated loads
- Torsion
- Combined actions

Stability (buckling) of webs

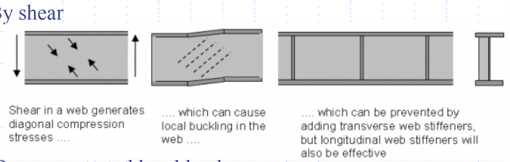
Webs are loaded

- By compression

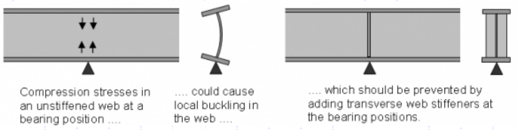
  This is introduced as effective sections properties of Class 4 cross-sections, but not explained in details in FSTD



- By shear

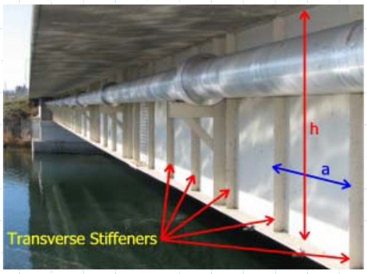


- By concentrated local load

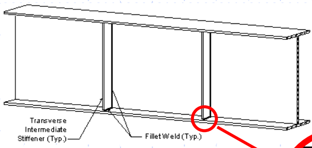


Beam web stiffeners

Beam web stiffeners



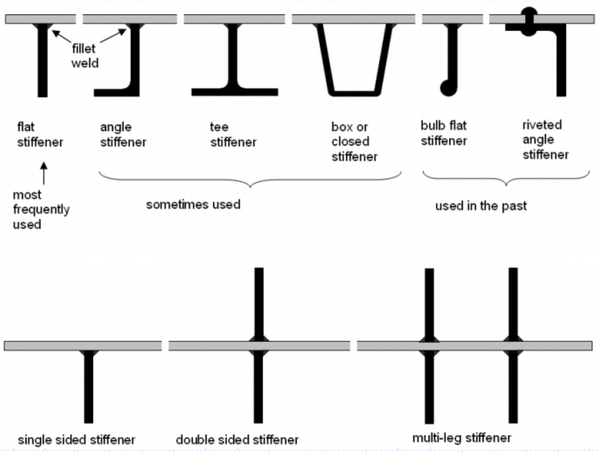
Beam web stiffeners



I section beam with stiffeners welded by fillet welds

Stiffeners of composite box girder for steel-concrete composite bridge

Beam web stiffeners



Typical shapes of beam web stiffeners

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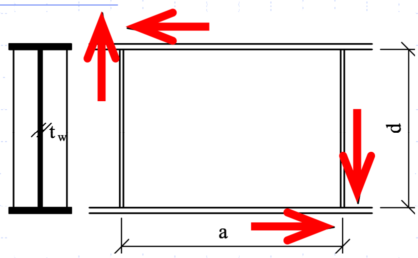
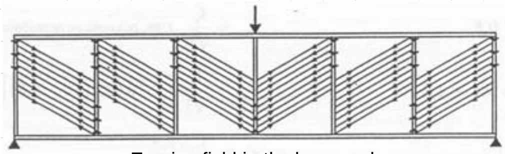
Shear buckling of beam web



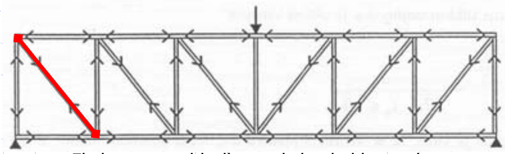
Shear buckling of beam web

Principle of tension field

Fictive truss is used as model for the beam just before the collapse when the shear is resisted by tensile fields (now replaced by diagonals of the truss) and the stiffeners of the beam web are loaded in compression (now replaced by vertical elements of the truss)



Tension field in the beam web



Fictive truss with diagonals loaded in tension

Web loaded by shear

Buckling of the web is in principle similar to buckling of elements in compression

Two cases need to be considered:

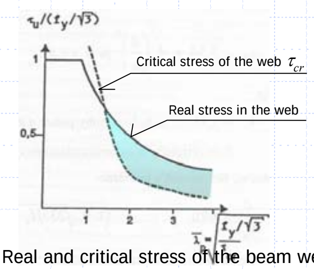
- Perfect plate – critical stress τ_{cr} can be obtained
- Real plate – imperfections play important role and should be considered

However, behaviour of web after buckling occurs is significantly different

The effect of these parameters needs to be considered

- \- Imperfections lead to web buckling and reduce the shear resistance
- \+ Post-critical reserve caused by tensile fields which reduce the effect of imperfections (actually reduce the amplitude of bow-shaped deformation of the web)

The tensile fields reduce the effect of buckling and increase the resistance of the web, therefore higher resistance can be observed than resistance based on critical stress τ_{cr}



Real and critical stress of the beam web

Shear buckling of webs – when to check

It is necessary to consider web buckling in shear and therefore to reduce the shear resistance in the following cases:

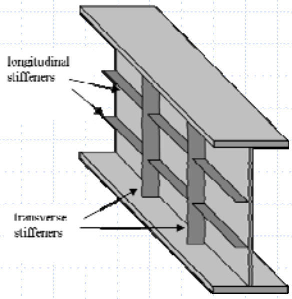
- web without stiffeners

$$\frac{d}{t_w} > 69\,\varepsilon$$

- web with transverse stiffeners only

$$\frac{d}{t_w} > 30\,\varepsilon\,\sqrt{k_\tau}$$

- for more complicated stiffeners pattern, the method is given in Eurocode



Beam web stiffened by longitudinal and transverse stiffeners

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Shear resistance of slender web

The shear resistance with respect to web buckling is given by

$$V_{ba,Rd} = \frac{d\,t_w\,\tau_{ba}}{\gamma_{M1}}$$

where τ_{ba} is function of the web slenderness λ_w

$$\bar{\lambda}_w = \sqrt{\frac{f_y/\sqrt{3}}{\tau_{cr}}} = \frac{d\,t_w\,\tau_{ba}}{37{,}4\,t_w\,\varepsilon\,\sqrt{k_\tau}}$$

The strength τ_{ba} is equal to

$$\tau_{ba} = \frac{f_y}{\sqrt{3}} \quad \text{............................when} \quad \bar{\lambda}_w \le 0{,}8$$

$$\tau_{ba} = \frac{f_y}{\sqrt{3}}\left(1 - 0{,}425\left(\bar{\lambda}_w - 0{,}8\right)\right) \quad \text{...when} \quad 0{,}8 < \bar{\lambda}_w \le 1{,}2$$

$$\tau_{ba} = \frac{f_y}{\sqrt{3}}\,\frac{0{,}9}{\bar{\lambda}_w} \quad \text{.......................when} \quad 1{,}2 < \bar{\lambda}_w$$

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Scope of the lecture

- Stability of webs
  - Web stiffeners
  - Shear loads
  - Local concentrated loads
- Torsion
- Combined actions

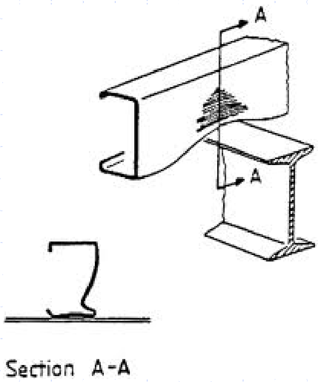
Local concentrated loads (transverse forces)

Normally, web stiffener is designed at locations where local concentrated load is presented (column, connected beam, etc.)

In some situations, the load can not transferred into the stiffener (wheel of bridge crane)

The column delivers a concentrated load to the beam and a bearing stiffener is used on the web

Local concentrated loads (transverse forces)



Web crushing at a support point
of thin-walled cold formed C section,
no stiffeners can be used here

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Local concentrated loads

Resistance check to concentrated loads include:

- Buckling of the web below the concentrated load
- Combination of stresses in web at the vicinity of load

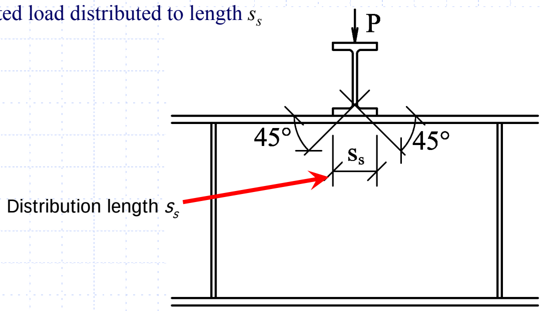
$$\sqrt{\sigma_x^2 + \sigma_z^2 - \sigma_x\,\sigma_z + 3\,\tau^2} \le \frac{f_y}{\gamma_{M1}}$$

where σ_x, σ_z are axial stresses at perpendicular directions (sign included)

σ_x is the stress from bending moment

σ_z is the stress from concentrated load distributed to length s_s

τ is the shear stress



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Scope of the lecture

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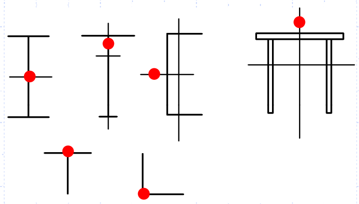
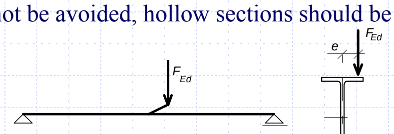
Torsion

- Only torsion is quite rare but combination of torsion and bending is more frequent
- Torsion occurs when the load plane does not pass through the shear centre



Shear center of typical steel sections

- It is always better to avoid torsion when possible
- When torsion can not be avoided, hollow sections should be preferably used

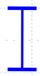


Bending and torsion of I-sections beam

Torsion – cross-sections

- Open cross-sections

  They have low torsional stiffness, therefore are not suitable for high torsion moments

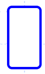
  Significant stresses (both shear and axial) are created which must be considered for the resistance check

  St.Venant + warping torsion occurs, resulting in shear $\tau_t + \tau_w$ and axial stress σ_w appear ($M_x = T_t + T_w$)

  Exception: when all parts intersect at single point (L, T sections), only St. Venant torsion and only τ_t occurs ($M_x = T_t$)

- Hollow cross-sections

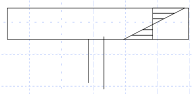
  

  They have high torsional stiffness and are suitable to transfer torsion

  St.Venant occurs, only shear stress τ_t appears

Open cross-sections, St. Venant torsion

Shear stress



$$\tau_{t,i} = \frac{T_t}{I_t} t$$

where

T_t torsion moment

I_t torsion constant

t thickness of the element

The torsion constant is

$$I_t = \frac{1}{3}\left(\alpha \sum b_i \, t_i^3\right)$$

b_i width

t_i thickness of that part of the element

α cross-section shape coefficient ($\alpha \cong 1$)

Open cross-sections, warping torsion

Axial stress

$$\sigma_w = \frac{B}{I_w} w$$

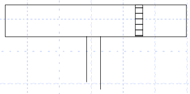
where

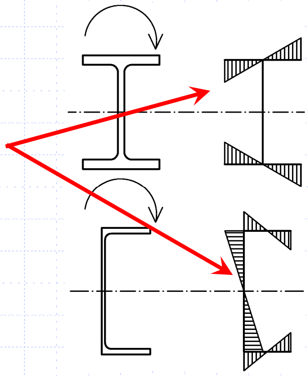
I_w warping moment of inertia [m^6]

B bimoment [kNm^2]

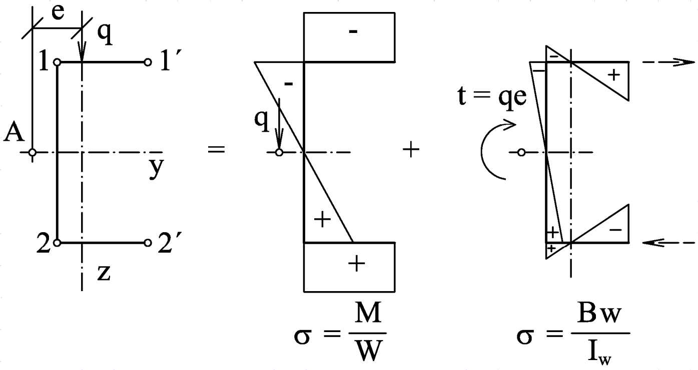
w warping coordinate [m^2]

Axial stress patterns for I and channel sections



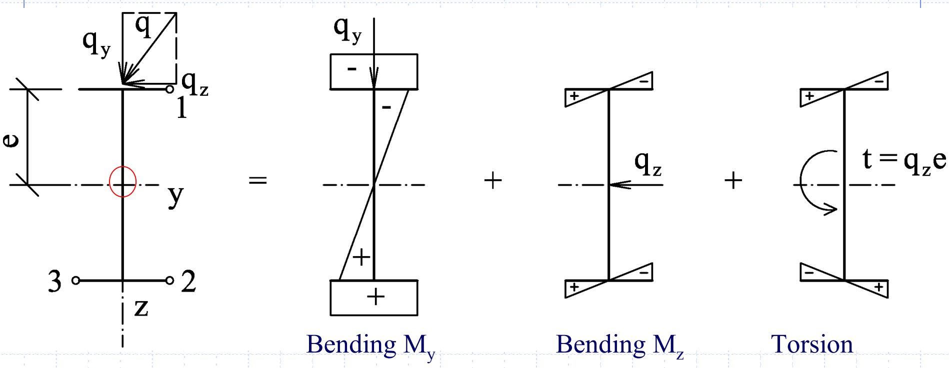


Bending and torsion of U cross-section



Bending Torsion

Bi-axial bending and torsion of I cross-section



Hollow cross-sections

Only shear stress occurs

$$\tau_{t,i} = \frac{Q_1}{t_i} = \frac{T_t}{\Omega\, t_i}$$

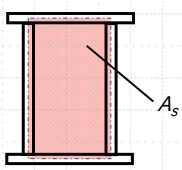
where

T_t torsion moment

t_i thickness of the element

A_s area enclosed by the cross-section

$$\Omega = 2\, A_s$$



Scope of the lecture

Stability of webs

Shear loads

Local concentrated loads

Torsion

➡ Combined actions

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Combined actions

- Bi-axial bending
- Bending + tension
- Bending + compression

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Bi-axial bending - review

$$\left(\frac{M_{y,Ed}}{M_{c,y,Rd}}\right)^{\alpha} + \left(\frac{M_{z,Ed}}{M_{c,z,Rd}}\right)^{\beta} \le 1$$

$M_{y,Ed}$, $M_{z,Ed}$ bending moments acting about y and z axes

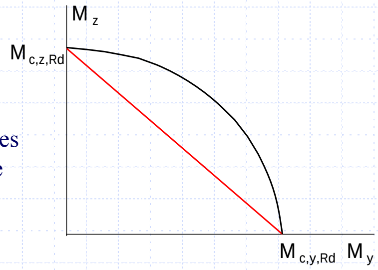
$M_{c,y,Rd}$, $M_{c,z,Rd}$ bending moment resistances

It is possible to take into account

$\alpha = \beta = 1$

(conservative approach)

Accurate method for various cross section shapes (i.e. the values of α and β) is given in Eurocode



Interaction diagram for bi-axial bending

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Bending + tension

Example: Tension chord of truss with inter-nodal load

- Class 1,2 sections – plastic behaviour can be considered

$$\frac{M_{Ed}}{M_{pl,Rd}} + \left(\frac{N_{t,Ed}}{N_{pl,Rd}}\right)^2 \le 1$$

- Class 3 sections – elastic behaviour is be considered, the stresses from bending and axial force are combined

$$\sigma = \frac{N_{t,Ed}}{A} + \frac{M_{Ed}}{W_{el,y}} \le \frac{f_y}{\gamma_{M0}}$$

$$\frac{N_{t,Ed}}{A\frac{f_y}{\gamma_{M0}}} + \frac{M_{Ed}}{W_{el,y}\frac{f_y}{\gamma_{M0}}} \le 1$$

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Bending + tension

Bi-axial bending + tension

$$\frac{N_{t,Ed}}{N_{pl,Rd}} + \frac{M_{y,Ed}}{M_{pl,y,Rd}} + \frac{M_{z,Ed}}{M_{pl,z,Rd}} \leq 1$$

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Bending + compression

Typical cases:

- columns with lateral load
- columns with eccentric load
- frames
- compression chord of truss with inter-nodal load

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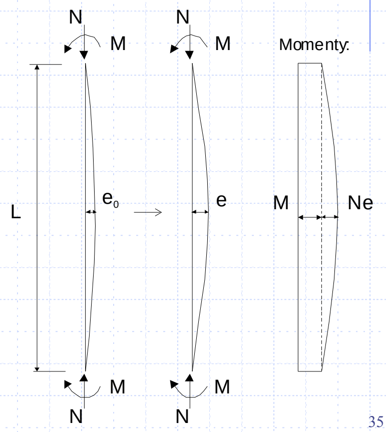
Bending + compression

Bending + compression

Bending + compression

- Second-order effect should be included
- Derivation – as for buckling resistance of elements loaded in compression
  - initial curvature
  - primary moments M_{Ed}
  - secondary moments $N_{Ed} \cdot e$



Bending + compression

For element pinned at both ends, the maximum bending moment on the element (including the second order effect) is equal to:

$$max\ M = M_{Ed} + N_{Ed}\ e = M_{Ed} \left(\frac{1}{1 - \frac{N_{Ed}}{N_{cr}}} \right)$$

when $N_{Ed} \Rightarrow N_{cr}$, the moment $max\ M \Rightarrow \infty$

Maximum stress in the element is

$$\sigma_{max} = \frac{N_{Ed}}{A} + \frac{max\ M}{W} \leq f_y$$

or

$$\frac{N_{Ed}}{A\ f_y} + \frac{M_{Ed}}{\left(1 - \frac{N_{Ed}}{N_{cr}}\right) W\ f_y} \leq 1$$

factor k_{yy} introducing the second order effect

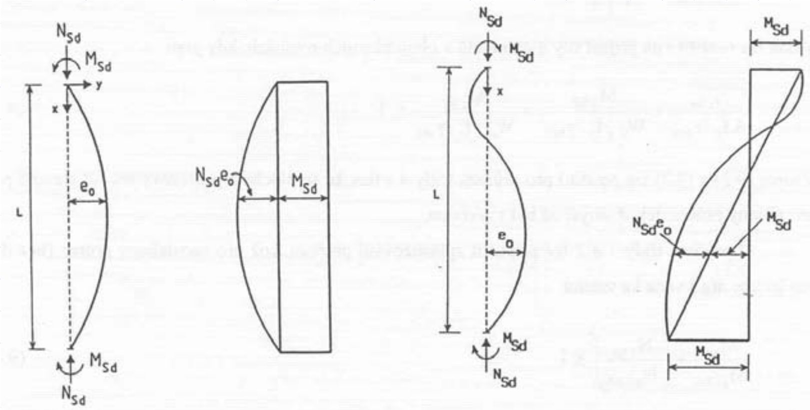
Effect of moment pattern

Effects of N+M add

$k_{yy} > 1$

Effects of N+M eliminate

$k_{yy} < 1$



Check according to EN 1993-1-1

2 conditions are considered:

1. In plane buckling

$$\frac{N_{Ed}}{\frac{\chi_y N_{Rk}}{\gamma_{M1}}} + k_{yy} \frac{M_{y,Ed} + \Delta M_{y,Ed}}{\frac{\chi_{LT} M_{y,Rk}}{\gamma_{M1}}} \leq 1$$

2. Out of plane buckling

$$\frac{N_{Ed}}{\frac{\chi_z N_{Rk}}{\gamma_{M1}}} + k_{zy} \frac{M_{y,Ed} + \Delta M_{y,Ed}}{\frac{\chi_{LT} M_{y,Rk}}{\gamma_{M1}}} \leq 1$$

Both formulas have to be fulfilled

W (and $M_{y,Rk}$) should be taken according to class of the cross-section

Factors k_{ij} – second order effect

There is influence of some parameters on the k_{ij} factors

- Effect of applied axial force $N_{Ed}\ e$
- Effect of applied moment pattern M_{Ed} along $L_{cr,y}$ (as seen recently)

when N_{Ed} is small or $\chi \rightarrow 1$
then $k_{yy} = 1{,}0$, $k_{zy} = 1{,}0$
(no second order effect is presented)

Thank you for your attention