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

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Connections

Welding ↔ in workshop
Bolting ↔ on site

On-site welding is also acceptable but should be avoided when possible as it brings some difficulties

- maintaining the proper environment for welding to achieve good quality,
- need for completing/repair of corrosion protection,
- need for qualified workers,
- etc.

Design of connections:

- to comply to resistance of connected elements
  (connections are not the weak part of the structure)
- to resist calculated internal forces
  (connections might be the weak part of the structure)

Scope of the lecture

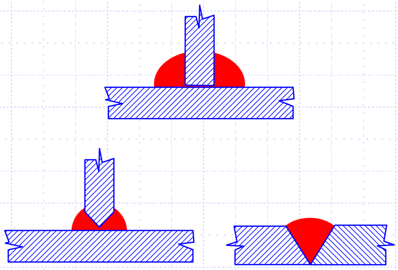
➡ Welded connections
Bolted connections
Distribution of forces among fasteners
Connections in the structures
Hybrid connections

Welded connections

Welds = rigid connections (no slip)

There are two basic types of the welds

- Fillet welds
- Butt welds



Fillet weld (top)
and butt welds (bottom)

Other types exist, but these are used in other industrial applications

- Groove welds
- Spot welds
- …many other, not typical for building industry

Fillet welds

Dimensions

a effective throat thickness of the fillet weld

L length

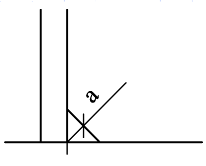
Stress components (need to be evaluated by the engineer)

$\sigma_\perp$ axial stress perpendicular to the throat

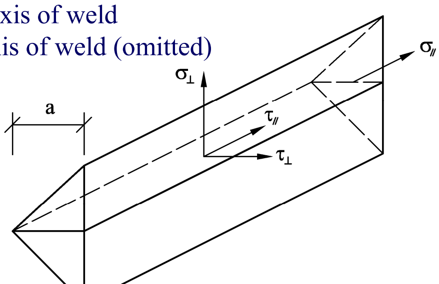
$\tau_\perp$ shear stress perpendicular to the axis of weld

$\tau_\parallel$ shear stress parallel to the axis of weld

$\sigma_\parallel$ axial stress parallel to the axis of weld (omitted)



Definition of throat thickness



Stress components in a fillet weld

Plasticity criteria of the weld (see Structural mechanics)

Huber –Misses- Henckey plasticity criteria (HMH)

it exists in these modifications:

- Tri-axial stress - σ_x, σ_y, σ_z, τ_{xy}, τ_{xz}, τ_{yz} (usually not needed)
- Plane stress (often needed, it is used for check of fillet welds)

$$\sigma_x^2 + \sigma_z^2 - \sigma_x^2\, \sigma_z^2 + 3\tau^2 \le (f_y / \gamma_{M2})^2$$

- Uni-axial stress (known from the material tests)

$$\sigma \le f_y / \gamma_M$$

$$\tau \le f_y / (\gamma_M \sqrt{3})$$

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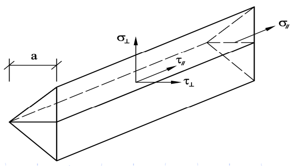
Resistance check of fillet weld

Plasticity criteria for fillet welds

$$\sqrt{\sigma_\perp^2 + 3\left(\tau_\perp^2 + \tau_{II}^2\right)} \le \frac{f_u}{\beta_w\, \gamma_{M2}}$$

$$\sigma_\perp \le \frac{f_u}{\gamma_{M2}}$$



Stress components

$\sigma_\perp$ axial stress perpendicular to the throat

$\tau_\perp$ shear stress perpendicular to the axis of weld

$\tau_\parallel$ shear stress parallel to the axis of weld

$\sigma_\parallel$ axial stress parallel to the axis of weld (omitted)

$$\gamma_{M2} = 1{,}25$$

β_w is correlation factor depending on steel grade
it is based on experiments

Steel	S235	S275	S355	S420	S460
β_w	0,80	0,85	0,90	1,00	1,00

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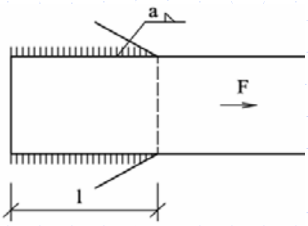
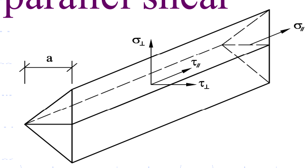
Example 1: Two fillet welds in parallel shear





Stress components
$\sigma_\perp$ axial stress perpendicular to the throat
$\tau_\perp$ shear stress perpendicular to the axis of weld
$\tau_\parallel$ shear stress parallel to the axis of weld
$\sigma_\parallel$ axial stress parallel to the axis of weld (omitted)

The side welds:

$$\tau_\perp = \sigma_\perp = 0$$

$$\tau_{//} = \frac{F}{2\,a\,L}$$

Because of zero values of $\sigma_\perp$ and $\tau_\perp$, the plasticity criteria is simplified to

$$\tau_{//} \le \frac{f_u}{\sqrt{3}\,\beta_w\,\gamma_{M2}}$$

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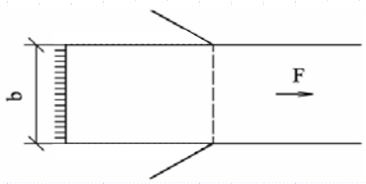
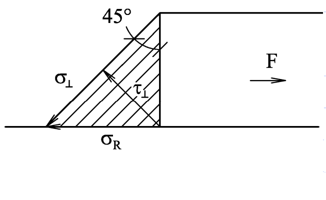
Example 2: Fillet weld in perpendicular shear





The front weld:

$$\tau_{//} = 0$$

$$\sigma_R = \frac{F}{a\,b} \longrightarrow \tau_\perp = \sigma_\perp = \frac{\sigma_R}{\sqrt{2}}$$

The plasticity criteria

$$\sqrt{\sigma_\perp^2 + 3\,\tau_\perp^2} \le \frac{f_u}{\beta_w\,\gamma_{M2}}$$

$$\sqrt{\left(\frac{\sigma_R}{\sqrt{2}}\right)^2 + 3\left(\frac{\sigma_R}{\sqrt{2}}\right)^2} = \sqrt{2\,\sigma_R{}^2} \le \frac{f_u}{\beta_w\,\gamma_{M2}} \longrightarrow \sigma_R \le \frac{f_u}{\sqrt{2}\,\beta_w\,\gamma_{M2}}$$

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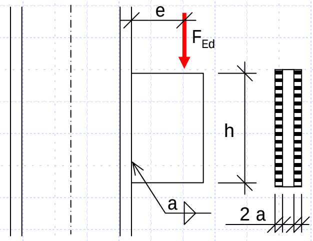
Example 3: Welded connection of a cantilever

Stress components from M_{Ed}

$$\sigma_R = \frac{M_{Ed}}{W_{we}} = \frac{F_{Ed}\, e}{2\,\frac{1}{6}\,a\,h^2}$$

$$\tau_\perp = \sigma_\perp = \frac{\sigma_R}{\sqrt{2}} = \frac{M_{Ed}}{\sqrt{2}\,W_{we}}$$



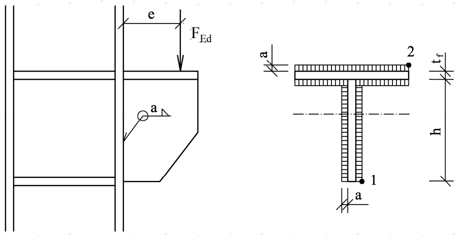
Stress from F_{Ed}

$$\tau_{II} = \frac{F_{Ed}}{2\,a\,h}$$

Resistance check

$$\sqrt{\sigma_\perp^2 + 3\left(\tau_\perp^2 + \tau_{II}^2\right)} \le \frac{f_u}{\beta_w\,\gamma_{M2}}$$

Example 4: Welded connection of T-cantilever



V – transferred by the web:

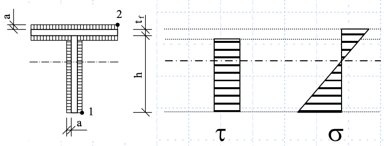
$$\tau_{II} = \frac{F_{Rd}}{2\,a\,h}$$

M – transferred by the whole weld cross-section section properties (I_{we}, W_{we}) of the weld shape are required

Stress components from M_{Ed}

$$\sigma_R = \frac{M_{Ed}}{W_{we}} = \frac{F_{Ed}\, e}{I_{we}}\, z$$

$$\tau_\perp = \sigma_\perp = \frac{M_{Ed}}{\sqrt{2}\,W_{we}}$$



Resistance check (application of plasticity criteria) is required at critical points

- Point 1: τ_{II}, $\tau_\perp$, $\sigma_\perp$
- Point 2: $\tau_\perp$, $\sigma_\perp$

Example 5: Welded connection of a gusset plate

Stress components from $F_{y,Ed}$

$$\sigma_R = \frac{F_{y,Ed}}{A_w} + \frac{M_{Ed}}{W_w} = \frac{F_{y,Ed}}{2\,a\,L} + \frac{F_{y,Ed}\,e}{2\frac{1}{6}\,a\,L^2} = \frac{F_{y,Ed}}{2\,a\,L}\left(1 + \frac{6\,e}{L}\right)$$

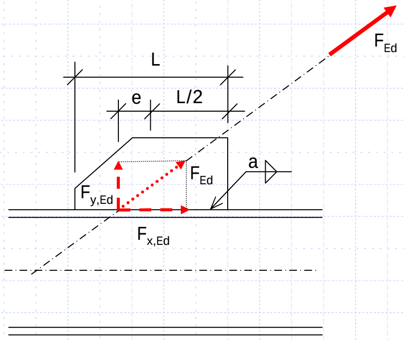
$$\tau_\perp = \sigma_\perp = \frac{\sigma_R}{\sqrt{2}} = \frac{M_{Ed}}{\sqrt{2}\,W_{we}}$$

Stress from $F_{x,Ed}$

$$\tau_{/\!/} = \frac{F_{x,Ed}}{2\,a\,L}$$

Resistance check

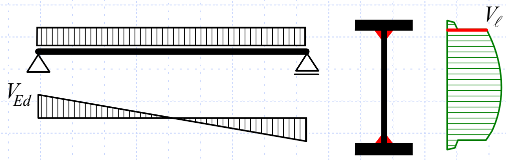
$$\sqrt{\sigma_\perp^2 + 3\left(\tau_\perp^2 + \tau_{II}^2\right)} \le \frac{f_u}{\beta_w\,\gamma_{M2}}$$



Example 6: Flange to web welds

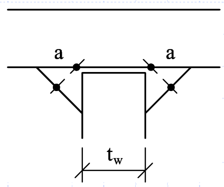
Longitudinal shear flow V_ℓ
(calculation is based on theory of elasticity)

$$V_\ell = \frac{V_{Sd}\,S}{I} \quad [kN/m]$$



Longitudinal shear stress

$$\tau_{/\!/} = \frac{V_\ell}{2\,a} = \frac{V_{Ed}\,S}{2\,I\,a} \le \frac{f_u}{\sqrt{3}\,\beta_w\,\gamma_{M2}}$$



the other stress components

$\tau_\perp = \sigma_\perp = 0$

(usually)

Long welds

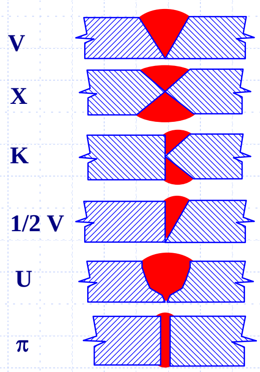
Longitudinal shear flow V_ℓ
(calculation is based on theory of elasticity)

Longitudinal shear stress

the other stress components

(usually)

Butt welds



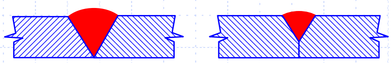
Types of the butt welds

Completely replace the cross-section

The type of the weld and and shape of the edge should be designed by specialist

Two basic types exist:

- Full penetration weld
  no separate check of the weld needs to be made, resistance is the same as the section
- Partial penetration weld
  resistance is evaluated in similar way as for the fillet welds


Full penetration (left) and partial penetration (right) V butt weld

Scope of the lecture

- Welded connections
- ➡ Bolted connections
- Distribution of forces among fasteners
- Connections in the structures
- Hybrid connections

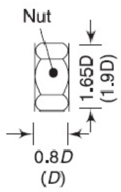
Nuts

Types

- Standard (height *m* is approx. 0,8 *d*)
- High (1,2 up to 2 *d*)

  used for bolts loaded by significant tension
- Low (0,4 *d*)

  for securing bolts - to avoid the bolts get loose



Washers

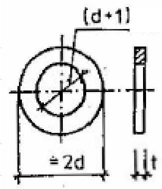
Washer is used on the part which rotate during bolt assembling (head or nut)

Purpose:

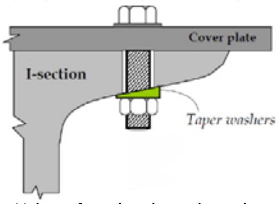
- to distribute the pressure evenly on the connected part
- to avoid surface damage during bolt rotation

Types:

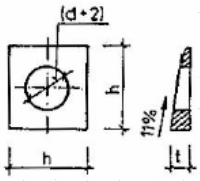
- Standard washers
- Standard but hardened for slip-resistant connections (see later)
- Wedge washers for connection to flanges of I sections



Standard washers



Using of wedge (taper) washers



Wedge washers

Bolted connections

Connection types according to behaviour:

- Normal (bearing type)
- Slip-resistant = friction type (with preloaded bolts)

Connection types according to transferred load:

- Loaded in shear
- Loaded in tension

Combination of behaviour and load gives the category of connection, see the next slide

Bolts loaded in shear

Category A:
- standard (no preloaded bolts)
- should be checked for the resistance in:
  - shear
  - bearing

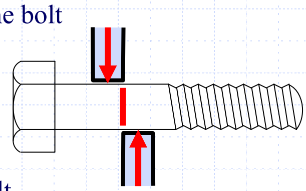
Category B
- preloaded bolts, slip in the connection is allowed at ULS but not at SLS
- at SLS, it should be checked for the resistance in:
  - slip
  - bearing
- at ULS, it should be checked for the resistance in:
  - shear
  - bearing

Category C:
- preloaded bolts, slip in the connection is not allowed at all
- it should be checked for the resistance in:
  - slip
  - bearing

Shear resistance

Shear plane is passing through unthreaded part of the bolt

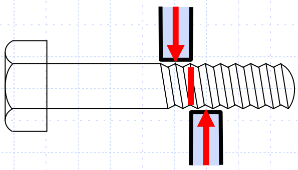
$$F_{v,Rd} = i\,\frac{0{,}6\;A\;f_{ub}}{\gamma_{M2}}$$



Shear plane passing through threaded part of the bolt

$$F_{v,Rd} = i\,\frac{0{,}5\;A_s\;f_{ub}}{\gamma_{M2}}$$ for bolt grades 4.8, 5.8, 10.9

$$F_{v,Rd} = i\,\frac{0{,}6\;A_s\;f_{ub}}{\gamma_{M2}}$$ for other bolt grades



A full area of the bolt, $A = \frac{\pi\,d^2}{4}$

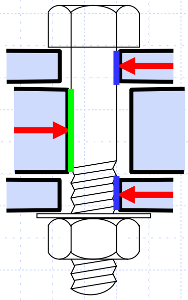
A_s stress area of the bolt, see the tables

f_{ub} ultimate strength of the bolt

i number of the shear planes

Bearing resistance

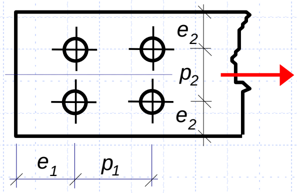
$$F_{b,Rd} = \frac{k_1\, \alpha_b\, d\, t\, f_u}{\gamma_{M2}}$$



Effect of the bolt spacing
stress concentration is more significant for small spacing
small bolt spacing = smaller resistance

$$\alpha_b = \min\left(\frac{e_1}{3\, d_0};\quad \frac{p_1}{3\, d_0} - \frac{1}{4};\quad \frac{f_{ub}}{f_u};\quad 1\right)$$

$$k_1 \leq 2{,}5$$



t smaller thickness of connected elements in one direction (either the green or both red parts)
d diameter of bolt
d_0 diameter of hole
f_{ub} ultimate strength of the bolt
f_u ultimate strength of the connected elements

Slip resistance

Slip resistance

$$F_{s,Rd} = \frac{k_s\, n\, \mu}{\gamma_{M3}} F_{p.C}$$

Required preloading force

$$F_{p,C} = 0{,}7\, A_s\, f_{ub}$$

A_s stress area of the bolt
f_{ub} ultimate strength of the bolt
n number of friction planes
μ friction coefficient
k_s factor depending on bolt hole size (= 1 for standard holes, < 1 for oversized holes
$\gamma_{M3} = 1{,}25$

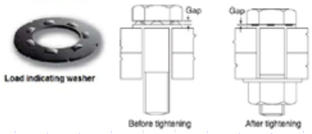
The friction coefficient depends on the surface preparation
$\mu = 0{,}2$ for surfaces without special treatment
$\mu = 0{,}2$ for surfaces cleaned with wire brush
$\mu = 0{,}5$ for grit-blasted surfaces spray-metallized with zinc or aluminium

Slip resistance - bolt tightening techniques

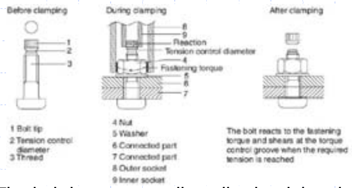
Three methods of control of the preloading force are used

- Turn of the nut method (the most common, cheap and reliable method)
  the nut is first snug-tight and then rotated by additional 1/3, 1/2 or 3/4 turn
  (depending on the bolt length)

- Direct tension indicator tightening



The bolt load is indicated by measurable change in gap between the bolt head and material



The bolt has a protruding nib, the tightening is continued until the nib is sheared off

- Calibrated wrench tightening (torque control method)
  Wrenches need to be calibrated in tension measuring device
  to set the torque to desired value. When the desired value
  is reached, the click sound is heard and felt.

The wrench

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Number of bolts in the connection

Category A

$$n = \frac{F_{Ed}}{\min\left(F_{v,Rd}, F_{b,Rd}\right)}$$ ← shear, bearing

Category B (no slip at SLS)

$$n = \frac{F_{Ed}}{\min\left(F_{v,Rd}, F_{b,Rd}\right)}$$ ← shear, bearing at ULS

and

$$n = \frac{F_{Ed,ser}}{\min\left(F_{s,Rd}, F_{b,Rd}\right)}$$ ← slip, bearing at SLS

Category C (no slip at ULS)

$$n = \frac{F_{Ed}}{\min\left(F_{s,Rd}, F_{b,Rd}\right)}$$ ← slip, bearing

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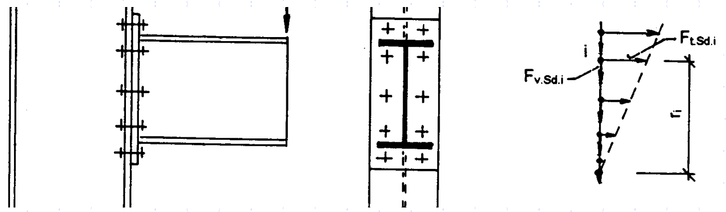
Bolts in tension



The connection can be designed with

- non-preloaded bolts (category D)
- preloaded bolts (category E)

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Ultimate Resistance in Tension

$$F_{t,Rd} = \frac{0{,}9\, A_s\, f_{ub}}{\gamma_{M2}}$$

A_s stress area of the bolt
f_{ub} ultimate strength of the bolt

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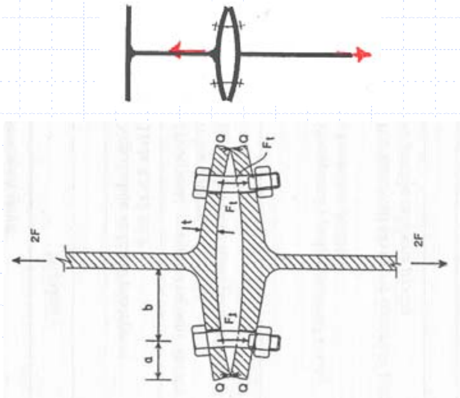
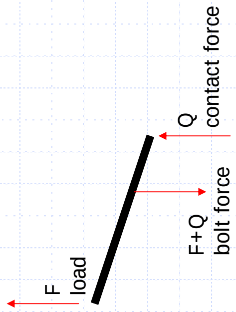
Bolts in tension – Prying of bolts



Prying of the bolts in rigid end plate connection
and the T-stub model



Equilibrium equation
showing the increased bolt force
because of prying of the bolts

Prying of the bolts increase the bolt force
Depends on thickness of connected plates

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Scope of the lecture

- Welded connections
- Bolted connections
- ➡ Distribution of forces among fasteners
- Connections in the structures
- Hybrid connections

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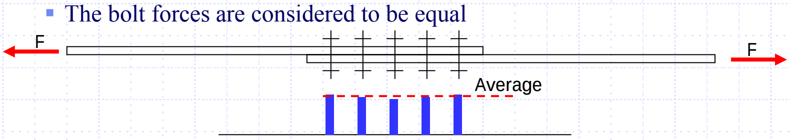
Distribution of forces among the fasteners

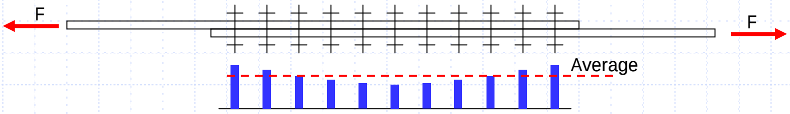
Lap joint – short connection

- The bolt forces are considered to be equal

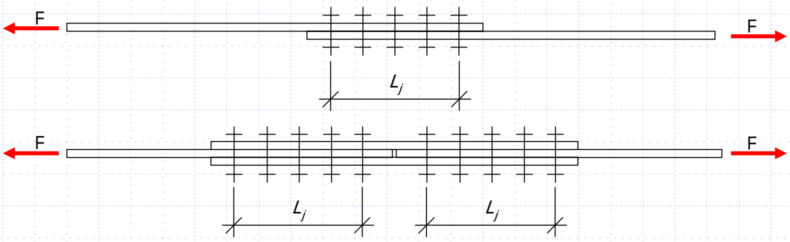


Lap joint – long connection

- The bolt forces are not equal, the end bolts carry higher load than those in the middle
- Reduction of resistance for long bolts is introduced (see EN 1993-1-8)



Long overlap joints – reduction of the resistance

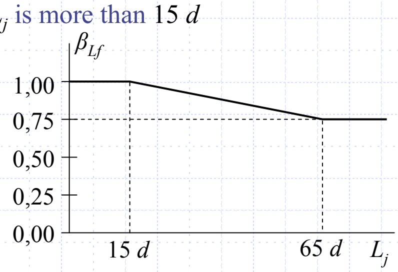


The design shear resistance of all the bolts $F_{v,Rd}$ should be multiplied by reduction factor β_{Lf} when the length L_j is more than 15 d

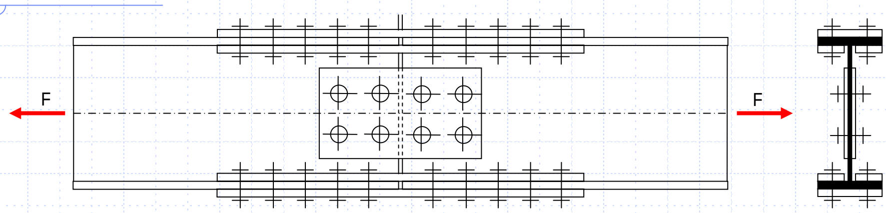
$$\beta_{Lf} = 1 - \frac{L_j - 15\,d}{200\,d}$$

but

$$0{,}75 \leq \beta_{Lf} \leq 1$$



Distribution of forces among the fasteners



The bolts in flanges and web are designed separately

The force is split according to area ratio

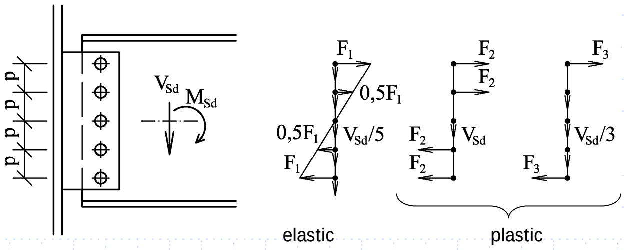
- forces in flanges

$$F_{flange} = F \frac{A_{flange}}{2\,A_{flange} + A_{web}}$$

- force in web

$$F_{web} = F \frac{A_{web}}{2\,A_{flange} + A_{web}}$$

Distribution of forces among the fasteners



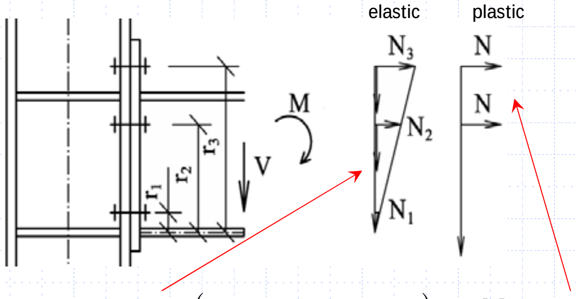
Elastic calculation

- One solution, based on equilibrium equation and compatibility equations
- Can always be used (no limitations)

Plastic calculation

- More possibilities of force distribution
- Rule: the bolts near the centre of rotation are considered to resist the shear force, the bolt far from the centre resist the bending moment
- Certain criteria should be met to use plastic distribution (sufficient ductility)

Distribution of forces on rigid end plate connection



$$M_{el,Rd} = 2\left(N_1\, r_1 + N_2\, r_2 + N_3\, r_3\right)$$

$$\frac{N_1}{r_1} = \frac{N_3}{r_3}$$

$$\frac{N_2}{r_2} = \frac{N_3}{r_3}$$

N_3 is equal to the resistance of one bolt in tension

$$M_{pl,Rd} = 2\, N\left(r_2 + r_3\right)$$

N is equal to the resistance of one bolt in tension

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Scope of the lecture

- Welded connections
- Bolted connections
- Distribution of forces among fasteners
- ➡ Connections in the structures
- Hybrid connections

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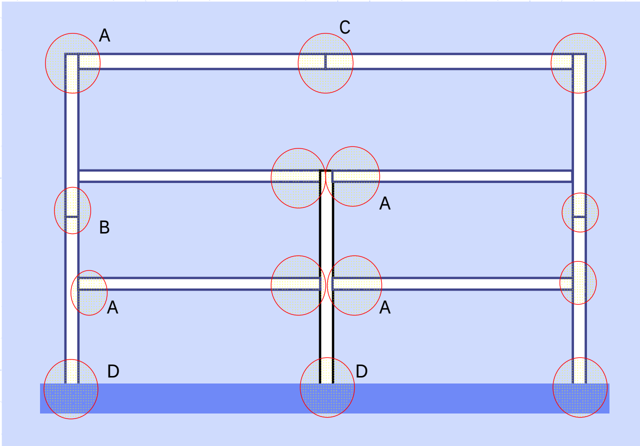
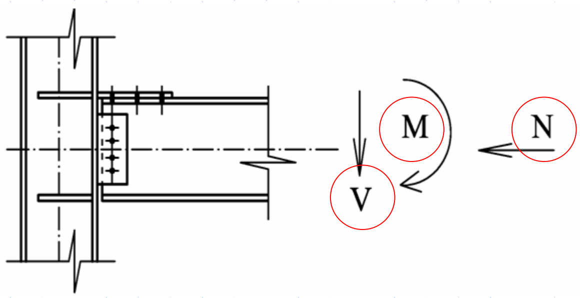
Connections at the structure



A - Beam to column joint
B - Column splice connection
C - Beam splice connection
D - Column base

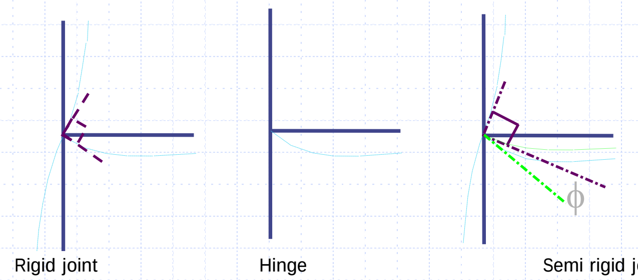
Acting internal forces



The connections are designed to:

- acting forces - the connection might be weak part of the structure and future increase of the load might be limited by the connections
- resistance of the connected elements - the connections are not weak part of the structure and the resistance can be increased up to the resistance of the connected elements (typical situation for bridge design)

Bending stiffness of joints



Design simplification

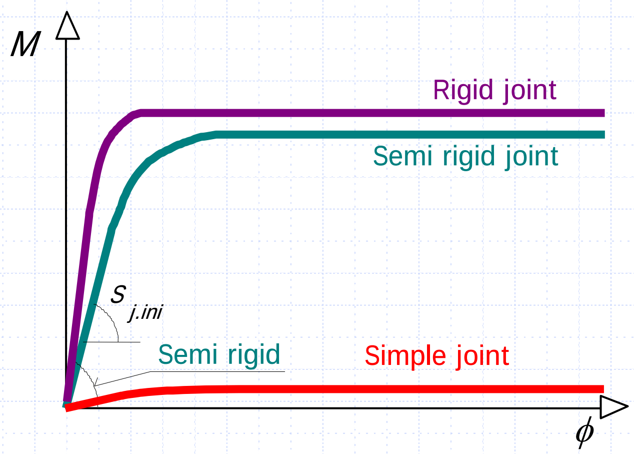
In reality, rigid joints and hinges do not exist but all joints are semi-rigid

Precise evaluation of joint stiffness is complicated

In most cases, simplified assumption is taken into account:

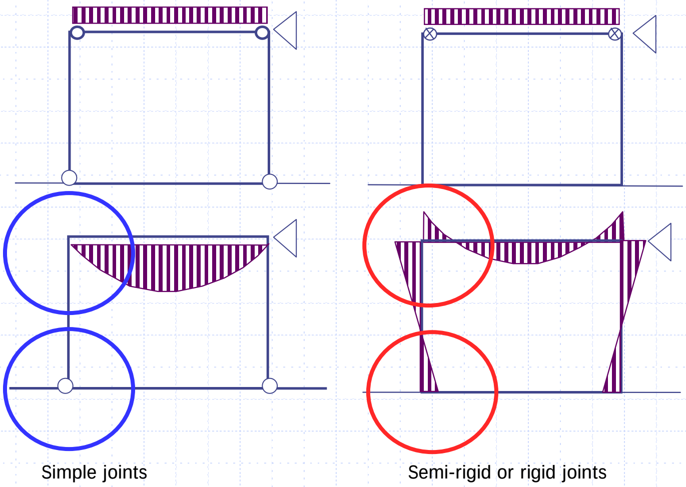
- Almost rigid joint is considered as rigid joint
- Joint with small stiffness and bending resistance (almost hinge) is considered as simple joint

Classification with respect to joint stiffness



Moment-rotation curve

Influence of stiffness on moment distribution



Simple connections

Perfect hinge would be very difficult and expensive to manufacture (it is only designed in rare situations for complicated structures - bridges, etc.)

Hinge for beam to column connection does not exist

Simple connections are used instead

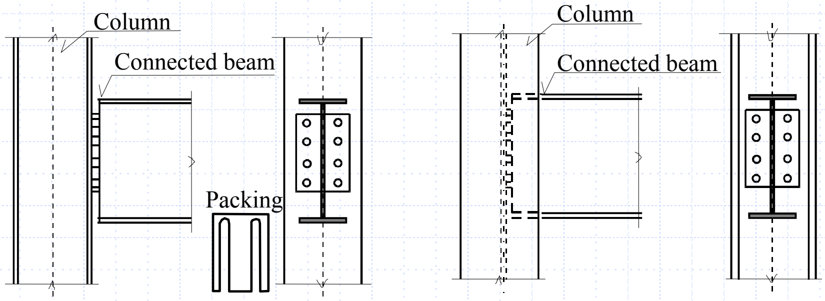
Simple connection have

- Small rotational stiffness
- Small bending moment resistance
- Satisfying rotation capacity

Three basic types exist (several modifications of each can be found)

- Simple end plate connection
- Web cleated connection
- Fin plate connection

End plate beam to column connection

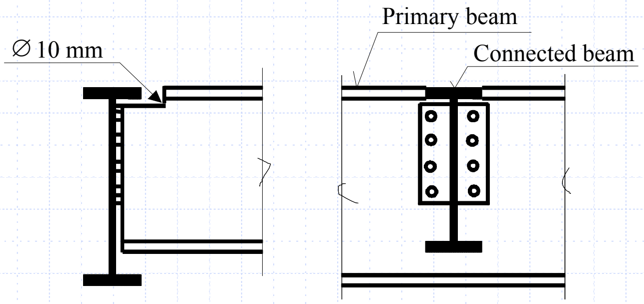


Simple connection

- Only negative tolerance of beam length is allowed, the packing plate is used to compensate it
- Thin plate should be used (8 or 10 mm)
- Sufficient horizontal bolt spacing should be designed to ensure the rotational capacity
- Beam flange must not be connected to the plate

The rotation is allowed by deformation of the end plate

End plate beam to beam connection

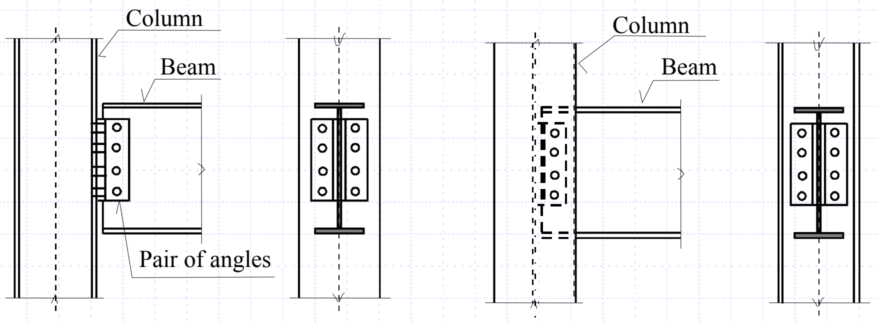


Simple connection

- Only negative tolerance of beam length is allowed, the packing plate is used to compensate it
- Thin plate should be used (8 or 10 mm)
- Sufficient horizontal bolt spacing should be designed to ensure the rotational capacity
- Beam flange must not be connected to the plate

The rotation is allowed by deformation of the end plate

Web cleated beam to column connection

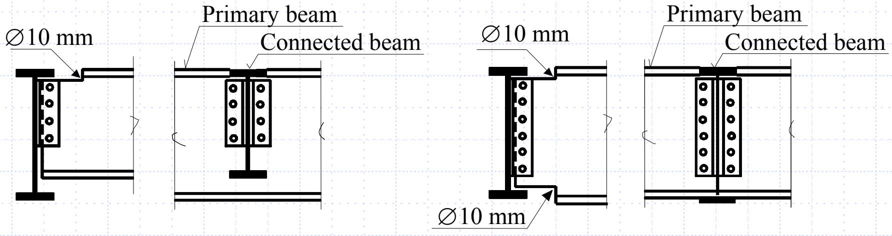


Simple connection

Gap should remain between the beam and the column to allow the rotation

The rotation is allowed by deformation of the angles and by slip of the bolts

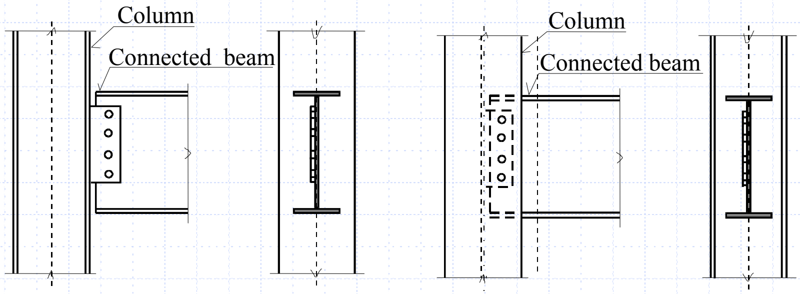
Web cleated beam to beam connection



Simple connection

The rotation is allowed by deformation of the angles and by slip of the bolts

Fin plate beam to column connection



Simple connection

Gap should remain between the beam and the column to allow the rotation

The rotation is allowed by slip of the bolts

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Scope of the lecture

- Welded connections
- Bolted connections
- Distribution of forces among fasteners
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- ➡ Hybrid connections

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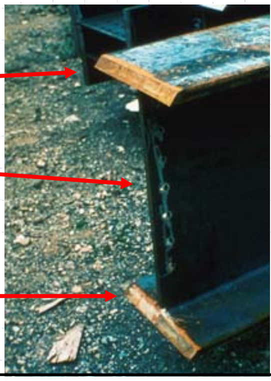
Hybrid Connections

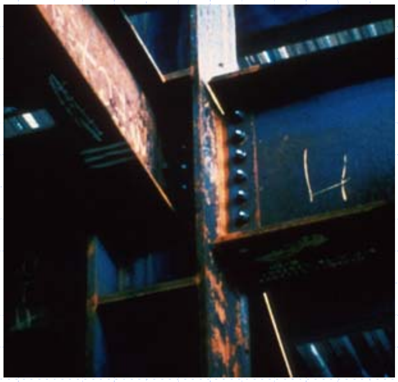
- Welds and bolts are combined together
- Equal stiffness is required
  - only slip-resistant bolts and welds are allowed to combine
- Not frequently used

butt welds

bolted connection

butt welds





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Thank you for your attention

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