Basic principles of steel structures

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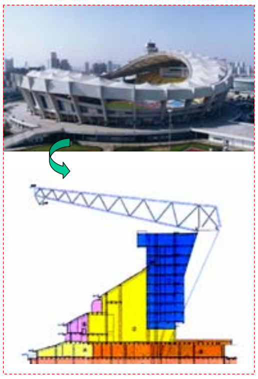
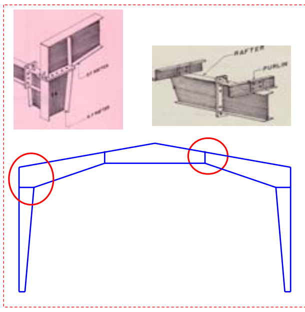
Members + connections = system



transfer forces supported by a member to others



Connections

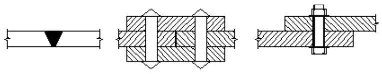
Outlines

- ✧ types of connections and their characteristics
- ✧ butt weld connections: details and calculation
- ✧ fillet weld connections: details and calculation
- ✧ bolted connections: details and calculation
- ✧ high-strength bolted connections: details and calculation

Types of structural connections

basic types of connections

- ☑ welded connections
  molten parent metals are fused with each other being together
  electric-arc/slag/resistance welding, gas welding
- ☑ riveted connections
- ☑ bolted connections
  ordinary structural bolt/ high strength bolt
- ☑ other connections…
  screw, glue…



weld rivet bolt

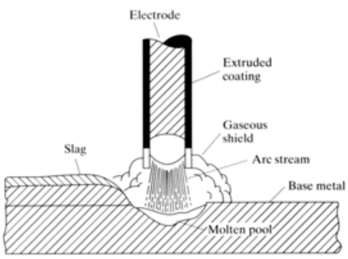
Types of structural connections

welded connections: types of welding

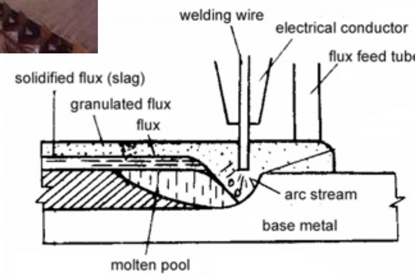
- ☑ electric arc welding: molten weld metal (welding wire or electrode) is fused with the base metal of the members being connected
- ☑ shielded metal arc welding (SMAW)
  Q235: E43 electrode / Q345: E50 / Q390, Q420: E55
  electrode matches with lower yield strength steel
- ☑ submerged arc welding (SAW) : auto-/ semi-automatic
  H08 welding wire, with Mn flux
- ☑ gas metal-arc welding (GMA): CO_2
  shielding gas (indoor weld)

Types of structural connections

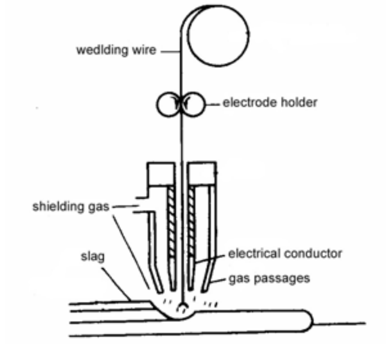
welded type: shielded metal arc welding



Types of structural connections
welded type: submerged arc welding

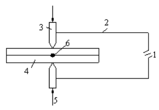


Types of structural connections
welded type: gas metal-arc welding

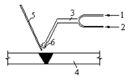


Types of structural connections
welded connections: types of welding

- ☑ electric slag welding
  - molten slag + base metal + welding wire
- ☑ electric resistance welding
  - Molten base metal + pressure

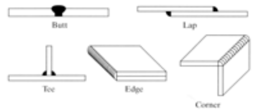


- ☑ gas welding
  - Acetylene + oxygen + electrode

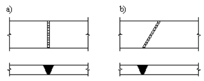


Types of structural connections
classification of welds

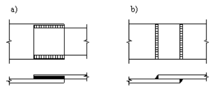
- ☑ Types of joint used: position of base metals
  - butt, lap, tee, edge, corner



- ☑ Types of weld made
  - butt weld: straight / bevel welds

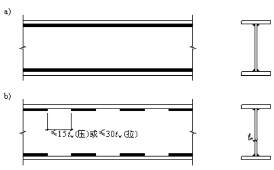


  - fillet weld: end / side welds

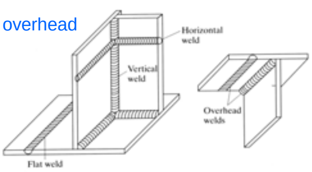


Types of structural connections
classification of welds

- ☑ Types of weld made
  - Continuous weld
  - Intermittent weld

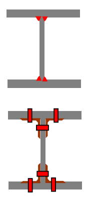


- ☑ Welding position
  - Flat, horizontal, vertical, overhead



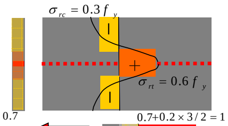
Types of structural connections
advantage and disadvantage of weld connections

- ☑ Efficiency: material saving and time saving
- ☑ Wider range of application
- ☑ More rigid, most truly continuous structures
- ☒ Residual stress: rigid, stability and fatigue
- ☒ Weld deformation
- ☒ HAZ: brittle failure
- ☒ Crack: propagation to members
- ☒ Qualified: skill dependent/ qualification of welding procedure
  - crack, blow hole, slag inclusion, undercut, overlap
  - incomplete penetration / fusion / filled groove

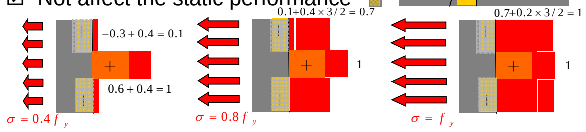


Types of structural connections
residual stress

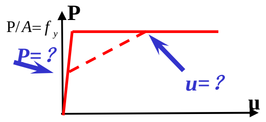
- ☑ Self balance system



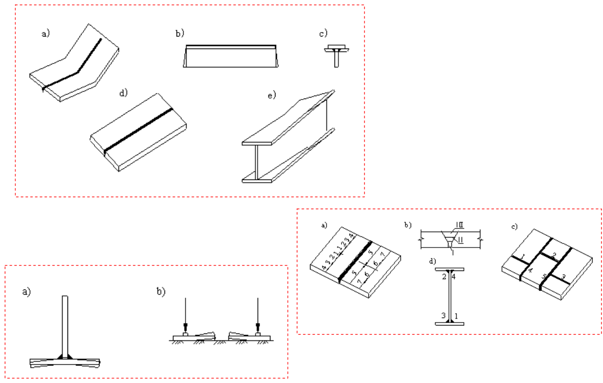
- ☑ Not affect the static performance



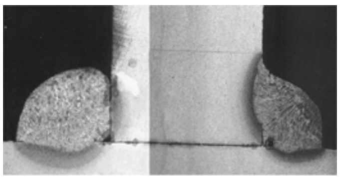
- ☑ Decrease the stiffness?
- ☑ Decrease fatigue?
- ☑ Decrease stability?



Types of structural connections
weld deformation



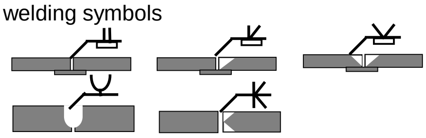
Types of structural connections
HAZ and weld crack



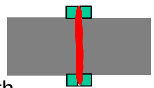
Butt weld connections
detailing

- ☑ Backup strip, back gouging and weld mending

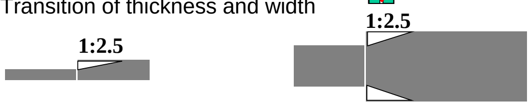
- ☑ Grooves and welding symbols



- ☑ Run-out plate



- ☑ Transition of thickness and width



Butt weld connections
design of butt welds

- ☑ design resistance of butt welds
  - Quality grade I & II : equal to the design strength of base metal
  - Quality grade III : decrease to 85% design strength of base metal
- ☑ how to classify the quality grade of butt weld
  - Quality grade III: visual inspection
  - Quality grade II: visual inspection + ultrasonic testing (20%)
  - Quality grade I: visual inspection + ultrasonic + radiographic (100%)
- ☑ cross-section of butt weld
  - (1) Area = thickness of plate (t) X effective length of weld (L)
  - (2) With run-out plate: L = length of weld
  - (3) Without run-out plate: L = length of weld – 2t

Butt weld connections
design of butt welds

- ☑ design principle of butt welds
  - a. Butt weld subject to compressive force: NO NEED
  - b. Butt weld under repeated load: Quality grade I
  - c. Butt weld under tension load: Quality grade II + run-out plate
  - d. Set the butt weld in the vicinity of lower stress
- ☑ Steps to design of butt weld
  - (1) Determine the internal force at the section to be checked
  - (2) Calculate the section properties of A, S, W, I
  - (3) Calculate the stress
  - (4) Check the strength of weld

Butt weld connections
design of butt welds

☑ Typical problem using butt welds

(1) butt-welded plates subject to axial load

(2) butt-welded plates subject to axial load (inclined welds)

(3) butt welds under shear force (plates and bracket)

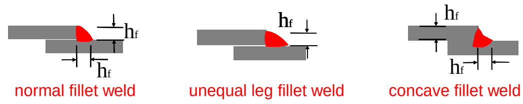
(4) butt welds under combined shear and moment

equivalent stress

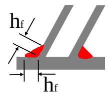
(5) butt welds under combined tensile, shear and moment

Fillet weld connections
detailing

☑ Orthogonal fillet weld

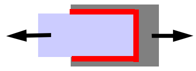


☑ Oblique (angle) fillet weld



☑ End weld: transversely loaded fillet weld

☑ Side weld: fillet weld loaded parallel to the weld's axis



Fillet weld connections
detailing

☑ Leg size of fillet weld

Minimum: 1.5Xsqrt(t_{thick}), prevent weld crack

Maximum: 1.2t_{thin}, prevent burn through

☑ Length of fillet weld

Minimum: 8h_f & 40mm, avoid mass imperfection

Maximum: 60h_f , avoid uneven stress distribution

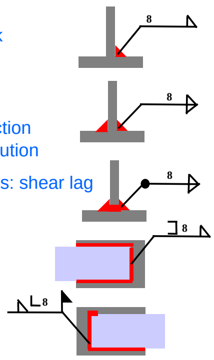
Distance between two longitudinal fillet welds: shear lag

☑ Weld symbols

Fillet weld on one side / on both side

Fillet weld all around joint (L, 3 or 4 sides)

Fillet weld in the field



Fillet weld connections
failure mode

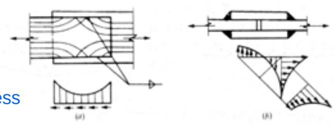
☑ Stress distribution

End weld: tri-axial stress

(brittle failure)

Side weld: mainly shear stress

(ductile failure)



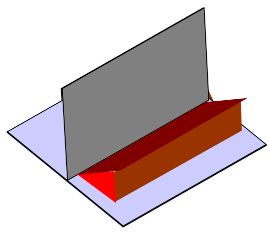
☑ Failure plane (assumption)

Effective plane = failure plane

(45 degree through the throat)

Effective thickness = 0.7 leg size

(weld throat)

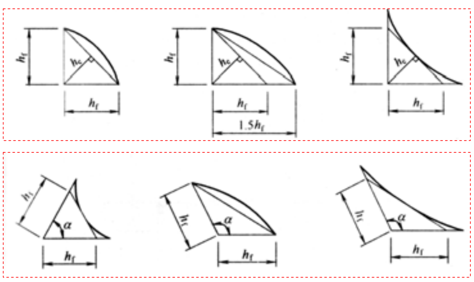


Fillet weld connections
failure mode

☑ Failure plane and theoretical throat

Orthogonal fillet weld

Oblique-angle fillet weld



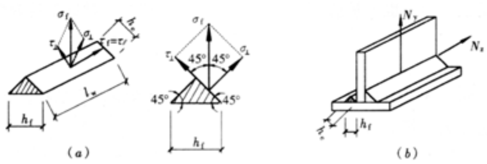
Fillet weld connections
failure mode

☑ Failure plane and stress distribution (assumption)

$\sigma_\perp$ Normal stress perpendicular to the throat plane

$\tau_\perp$ Shear stress (in the plane of the throat) perpendicular to the weld axis

$\tau_{//}$ Shear stress (in the plane of the throat) parallel to the weld axis

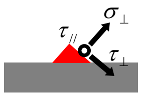


$$\frac{\sigma_\perp^2}{(f_u^w)^2}+\frac{\tau_\perp^2}{(0.75f_u^w)^2}+\frac{\tau_{//}^2}{(0.75f_u^w)^2}=1 \Rightarrow \sqrt{\sigma_\perp^2+3(\tau_\perp^2+\tau_{//}^2)}=\sqrt{3}f_f^w$$

Fillet weld connections
failure mode

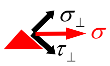
☑ Failure plane and stress distribution (assumption)

$$\sqrt{\sigma_\perp^2 + 3(\tau_\perp^2 + \tau_{//}^2)} = \sqrt{3} f_f^w$$



End weld: larger strength and rigid, less deformation ability

$$\sqrt{\sigma_\perp^2 + 3\tau_\perp^2} \approx \sqrt{0.5\sigma^2 + 1.5\sigma^2} = \sqrt{2}\sigma = \sqrt{3} f^w \rightarrow \sigma = 1.22 f^w$$



Side weld: 22% less than strength of end weld
larger deformation ability

$$\sqrt{3\tau_{//}^2} = \sqrt{3\tau^2} = \sqrt{3} f^w \rightarrow \tau = f^w$$

Fillet weld connections
simplified method

☑ simplified method for design resistance of fillet weld

$$\sqrt{\left(\frac{\sigma_f}{\beta_f}\right)^2 + \tau_f^2} \le f_f^w \quad \longleftarrow \quad \sqrt{\sigma_\perp^2 + 3(\tau_\perp^2 + \tau_{//}^2)} = \sqrt{3} f_f^w$$

β_f amplification factor for weld strength perpendicular to the weld axis, taken as 1.22 for static loading and 1.0 for dynamic loading

f_f^w design strength of fillet weld (same for shear, tension and compression)

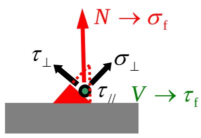
☑ stress on the failure plane

For applied force N perpendicular to the weld axis

$$\sigma_f = N / l_w h_e$$

For applied force V parallel to the weld axis

$$\tau_f = V / l_w h_e$$



$h_e = 0.7 h_f$ $\quad$ $l_w = l - 2h_f$

Fillet weld connections
procedure of fillet weld design

☑ Centroid of welds coincides with that of members

☑ Analysis of internal forces at weld connection
- Axial force, shear force or combined axial and shear force
- Combined bending moment, axial and shear forces
- Combined torsional moment, axial and shear forces

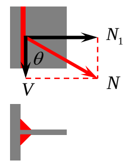
☑ Stress calculation under single force
- Focus on the distinguishing of stress perpendicular to the weld axis and stress parallel to the weld axis
- Calculation of weld section properties, A, S, I, W (weld length)

☑ Superposition of stress components at critical point, then check with practical equation

$$\sqrt{\left(\frac{\sigma_f}{\beta_f}\right)^2 + \tau_f^2} \le f_f^w$$

Fillet weld connections
typical problem (1)

☑ Axially loaded weld connections



(1) Internal force

$$N_1 = N \sin\theta$$
$$V = N \cos\theta$$

(2) Weld stress

$$\sigma_f = \frac{N_1}{\sum h_e l_w} = \frac{N_1}{A_f}$$

$$\tau_f = \frac{V}{\sum h_e l_w} = \frac{V}{A_f}$$

(3) Stress check

$$\theta = 90^0, \quad \frac{N}{A_f} \le \beta_f f_f^w$$

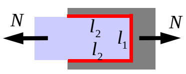
$$\theta = 0^0, \quad \frac{N}{A_f} \le f_f^w$$

$$\longleftarrow \quad \sqrt{\left(\frac{\sigma_f}{\beta_f}\right)^2 + \tau_f^2} \le f_f^w$$

Fillet weld connections
typical problem (2)

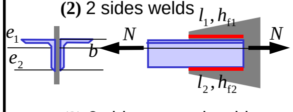
☑ Axially loaded weld connections (C & Angle)

(1) 3 sides around welds (cover plate of flange)



$$\frac{N}{\beta_f l_1 h_{e1} + 2(l_2 - h_{f2}) h_{e2}} \le f_f^w$$

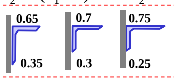
(2) 2 sides welds



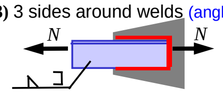
Internal force $N_1 = (e_2 / b) N = k_1 N$

$N_2 = (e_1 / b) N = k_2 N$

(root) k_1
(toe) k_2



(3) 3 sides around welds (angle)



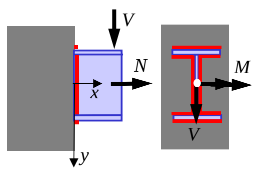
Internal force $N_1 = k_1 N - 0.5 N_3$

$N_2 = k_2 N - 0.5 N_3$

(4) L-shape welds (angle) ?

Fillet weld connections
typical problem (3)

☑ weld connections subject to bending moment, axial and shear forces



(1) Internal force

$$N, V \Rightarrow N, V, M$$

(2) Weld stress

$$\sigma_{fx}^N = \frac{N}{A_f}$$

$$\tau_{fy}^V = \frac{V}{A_{fw}}$$

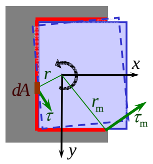
$$\sigma_{fx}^M = \frac{M\ y}{I_{fx}}$$

(3) Stress check

$$\sqrt{\left(\frac{\sigma_{fx}^N + \sigma_{fx}^M}{\beta_f}\right)^2 + (\tau_{fy}^V)^2} \le f_f^w$$

Fillet weld connections
typical problem (4)

☑ weld connections subject to torsional moment, axial and shear forces



assumption:
(1) The connected plate is perfectly rigid, thus the welds are assumed to be perfectly elastic
(2) $\frac{\tau}{r} = \frac{\tau_m}{r_m}$

Resultant force for any micro-element

$$dF = \tau dA = \frac{\tau_m}{r_m} r dA$$

Torsional moment about weld centroid for the micro-element

$$dM = r dF = \frac{\tau_m}{r_m} r^2 dA$$

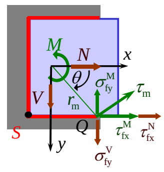
Total torsional moment for the weld connection

$$M = \int r_i dF = \int \frac{\tau_m}{r_m} r_i^2 dA = \frac{\tau_m}{r_m} \int (x^2 + y^2) dA$$

$$= \frac{\tau_m}{r_m}(I_{yf} + I_{xf}) = \frac{\tau_m J_f}{r_m}$$

Fillet weld connections
typical problem (4)

☑ weld connections subject to torsional moment, axial and shear forces



critical point, S or Q?

(1) Stress calculation for welds subject to torsional moment and axially force (taken Q point, how about S point?)

$$\tau_{fx}^M = \tau_m \sin\theta = \frac{M r_m}{J_f} \sin\theta = \frac{My}{J_f}$$

$$\sigma_{fy}^M = \frac{Mx}{J_f}$$

$$\tau_{fx}^N = \frac{N}{\sum l_{wi} h_{ei}} = \frac{N}{A_f} \qquad \sigma_{fy}^V = \frac{V}{A_f}$$

(2) Stress check

$$\sqrt{\left(\frac{\sigma_{fy}^V - \sigma_{fy}^M}{\beta_f}\right)^2 + (\tau_{fx}^N + \tau_{fx}^M)^2} \le f_f^w$$

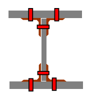
Fillet weld connections
comparison of butt weld with fillet weld

	Butt weld	**Fillet weld**
Manufacture	groove preparation	No groove
	less filler metal, just a few run-out plate	pretty much gusset plates
Weld strength	computing method of weld is similar with that of base metal	completely different in stress calculation compared to base metal
	design strength of weld equals to base metal	design strength of weld is less than base metal
Dynamic performance	base metal-weld-base metal connect smoothly, less stress concentration	performance is worse than that of butt welds

Fasteners connections
characteristics

✧ Machining

Position and hole machining: drill, punch
Surface treatment (for slip-resistant connection)
Assembly: snug-tight or pretensioned



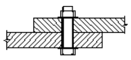
✧ Characteristics

- ☑ Ease to erect on site (less skill / facility dependent)
- ☑ Fatigue resistance (for slip-resistant connection)
- ☑ Easy to prevent the propagation of crack
- ☑ Easy to realize the removable structures
- ☒ Material and time waste
- ☒ Strongly depend on the machining accuracy
- ☒ Partially damnifying the base metal

Common-bolt connections
introduction

☑ Types of bolt

Unfinished, ordinary or common bolt
High-strength bolt (pretensioned)



☑ Bolt grade

Grade 4.6, 4.8: Q235BF (Grade C bolt)
Grade 5.6, 8.8: quality carbon steel (Grade A, B bolt)
➔ heat-treatment

Hexagonal bolt

Twist-ff bolt

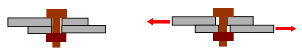
Common-bolt connections
introduction

☑ Drilled hole dimension

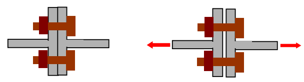
Hole dimension = bolt diameter + 1~1.5mm
Grade A, B bolt: hole quality, hole size deviation +0.25mm
Grade C bolt: relatively large tolerances in shank, thread dimensions and holes, hole size deviation + 1mm

☑ Load transfer

bolt loaded shear force



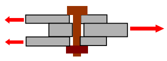
bolt loaded tension



Common-bolt connections
bolt for shear transfer

☑ Behaviour mechanism (load transfer)

friction → plate shear off the bolt and
the bolt push or bear against the hole



☑ Failure mode

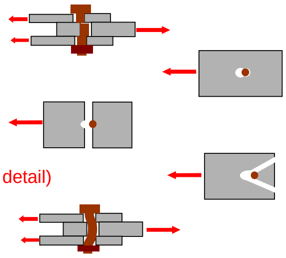
Shearing of the bolt (calc.)

Bearing of the bolt/hole (calc.)

Tension failure of plate (calc.)

Shearing out of part plate (calc. & detail)

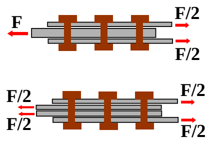
Bending of bolt (detail) $l \leq 5d$



Common-bolt connections
bolt for shear transfer

☑ Design resistance for individual bolt subjected to shear

(1) Shear resistance (shear plane)



$$N_v^b = n_v \cdot \frac{\pi}{4} \cdot d^2 \cdot f_v^b$$

(2) Bearing resistance (thickness for bearing same-direction force)

$$N_c^b = \sum t \cdot d \cdot f_c^b$$

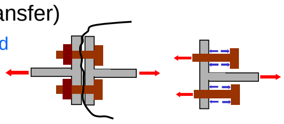
(3) Design resistance for individual bolt

$$[N]_v^b = \min\{N_v^b, N_c^b\}$$

Common-bolt connections
bolt for tension transfer

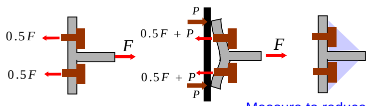
☑ Behaviour mechanism (load transfer)

The two contact plates tend to expand
and the bolt are tensioned



☑ Prying action

How prying action
affect the internal
force of the bolt?



Measure to reduce
prying action

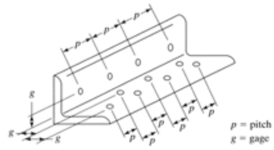
☑ Design resistance for individual bolt subjected to tension

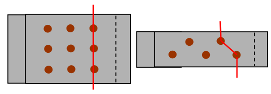
$$N_t^b = \frac{\pi}{4} \cdot d_e^2 \cdot f_t^b$$

Tension increase in bolt → decrease strength of bolt
Failure plane: effective section in thread

Common-bolt connections
spacing and edge distance of bolts

☑ Behaviour mechanism (load transfer)





Net area for
regular and staggered spacing bolt

Pitch: the center-to-center distance of bolts in a direction parallel to the member axis
Gage: the center-to-center distance of bolt lines perpendicular to the member axis
Edge distance: the distance from the center of bolt to the adjacent edge of a member

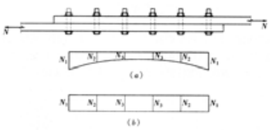
☑ Specification of spacing allowance (hole-size based)

requirement of capacity: cutting off and buckling
requirement of detail: anti-corrosion
requirement of construction: room for wrench

Common-bolt connections
typical problem (1)

☑ Uniformly shearing bolts

Long joint: uneven shear force in each bolt
Elastic and plastic period: uneven → uniform



☑ Procedure of design

(1) determine the shear force on the connect plane
(2) calculate the shear force of each bold endured
(3) ascertain the design resistance for individual bolt:

- single shear, double shear or multiple shear?
- shear resistance or bearing resistance?
- long joint need to reduce resistance by a reduction factor? $[N]_v^b \rightarrow \eta [N]_v^b$

$l_1 / d_0 \leq 15 \quad \eta = 1.0$

$15 < l_1 / d_0 \leq 60 \quad \eta = 1.1 - l_1 / 150 d_0$

$l_1 / d_0 \geq 60 \quad \eta = 0.7$

(4) check the capacity of net section

Common-bolt connections
typical problem (2)

☑ Bolted eccentric connection with torsional moment

assumption:
(1) The bolt is perfectly elastic and the connected plate is perfectly rigid
(2) The shear stress of a bolt at a centroidal distance d is proportional to d

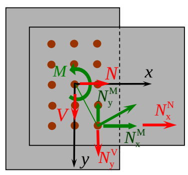
$$N_x^M = \frac{M y}{\sum (x_i^2 + y_i^2)}$$

$$N_y^M = \frac{M x}{\sum (x_i^2 + y_i^2)}$$

☑ Procedure of design

Same as procedure mentioned before, and pay attention to the superposition of shear force under torsion with that under axial load

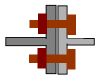
$$\sqrt{(N_x^M)^2 + (N_y^M)^2} \leq [N]_V^b$$



Common-bolt connections

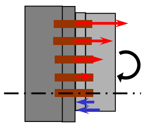
typical problem (3)

☑ Bolted connection subjected to tension



☑ Bolted connection subjected to bending moment

assumption:
(1) Location of neutral axis?
(2) The tension force of a bolt at a centroid distance d is proportional to d



Capacity check: (maximum loaded bolt)

$$N_1^{M} = \frac{My_1}{\sum y_i^2} \le N_t^b$$

Common-bolt connections

typical problem (4)

☑ Bolted connection subjected to combined tension and bending moment

The tension force of a bolt depends on the location of the neutral axis.

(1) Assume the neutral axis locates the centroid of bolt connection

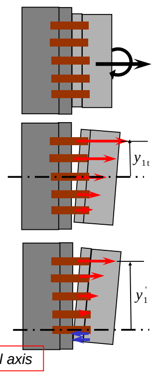
$$N_{1c}^{M} = -\frac{My_{1c}}{\sum y_i^2} \qquad N^{N} = \frac{N}{n}$$

(2) If $N_{1c}^{M} + N^{N} \ge 0$, the assumption is ok and the critical tension force

$$N_1^{M} = \frac{My_{1t}}{\sum y_i^2} + \frac{N}{n} \le N_t^b$$

(3) If $N_{1c}^{M} + N^{N} < 0$, the neutral axis locates the bottom line of bolts, the critical tension force

$$N_1^{M} = \frac{(M + Ne)y_1'}{\sum y_i'^2} \le N_t^b$$



Note: y value in item (2) & (3) away from corresponding neutral axis

Common-bolt connections

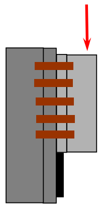
typical problem (5)

☑ Bolted connection subjected to combined shear and tension forces

(1) Correlation equation

$$\sqrt{\left(\frac{N_v}{N_v^b}\right)^2 + \left(\frac{N_t}{N_t^b}\right)^2} \le 1$$

$$N_v \le N_c^b$$



Q: replacing N_v^b with N_c^b is ok?
Q: do we need radical sign?

(2) Shear rest to avoid the shear force in bolt

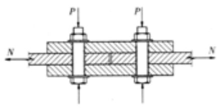
Q: weld detail of the rest?

High-strength bolt connections

introduction

☑ High-strength bolt

pretensioned



☑ Machining of high-strength bolt

Hole: hole size is larger than shank 1~1.5mm (bearing-type bolt)
1.5~2mm(slip-resistant bolt)

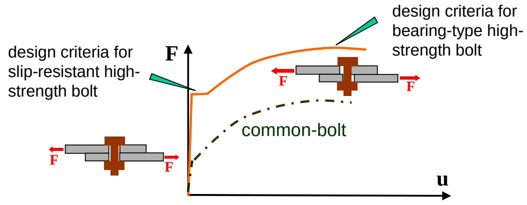
Surface treatment: only for slip-resistant bolt

Pretensioned: both slip-resistant and bearing-type bolt

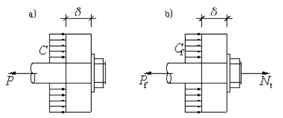
High-strength bolt connections

introduction

☑ Behaviour mechanism for shear transfer



☑ Behaviour mechanism for tension transfer



$$P_f = P + \frac{N}{1 + A_c/A_b}$$

high-strength bolt connections

bolt for shear transfer

☑ design resistance for individual slip-critical bolt subjected to shear

$$N_v^b = 0.9 n_f \cdot \mu \cdot P$$

(1) 0.9 — reciporical of resistance factor (1/1.111)

(2) n_f — number of slip planes

(3) μ — Slip coefficient for different surface (Table8-7)

(4) P — pretensioned force (Table 8-8)

$$P = 0.9 \times 0.9 \times 0.9 \times f_u \times A_e / 1.2 = 0.6075 f_u A_e$$

Q: do we need to check the bearing of the hole?

☑ design resistance for individual bearing-type bolt subjected to shear

$$[N]_v^b = \min\{n_v \frac{\pi}{4} d^2 \cdot f_v^b, \ \sum t \cdot d \cdot f_c^b\}$$

high-strength bolt connections
bolt for tension transfer

- ☑ design resistance for individual slip-critical bolt subjected to tension

$$N_t^b = 0.8P$$

Q: why use 0.8 reduction? (for the sake of shear transfer)

- ☑ design resistance for individual bearing-type bolt subjected to tension

$$N_t^b = \frac{\pi}{4} \cdot d_e^2 \cdot f_t^b$$

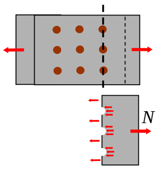
Q: why same as the common-bolt capacity?

High-strength bolt connections
typical problem (1)

- ☑ Uniformly shearing bolts

Slip-critical connection:
- shearing of bolt
- capacity of net section: $N' = N - 0.5 \times \frac{N}{n} \times n_1$

Bearing-type connection: same as common bolt



- ☑ Bolted connection subjected to combined shear and tension forces

For slip-critical connection:

$$\frac{N_v}{N_v^b} + \frac{N_t}{N_t^b} \le 1$$ (GB50017-2003)

$$N_v^b = 0.9 n_f \cdot \mu \cdot (P - 1.25 N_t)$$ (GBJ17-88)

For bearing-type connection:

$$\sqrt{\left(\frac{N_v}{N_v^b}\right)^2 + \left(\frac{N_t}{N_t^b}\right)^2} \le 1$$

$$N_v \le N_c^b / 1.2$$

Q: why use 1.2 not as common-bolt?

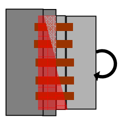
High-strength bolt connections
typical problem (2)

- ☑ Bolted eccentric connection with torsional moment/shear

Internal force at each bolt is ascertained as common bolt
Check the capacity: slip-critical or bearing-type bolt?

- ☑ Bolted connection subjected to bending moment

Internal force at each bolt is as common bolt
Location of neutral axis:
- Tongji: at centroid,
  max. tension in bolt less 0.8P, and the connected plate is always in compression
- Chen Shao-fan: as common bolt

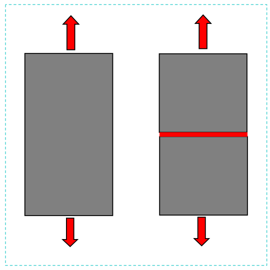


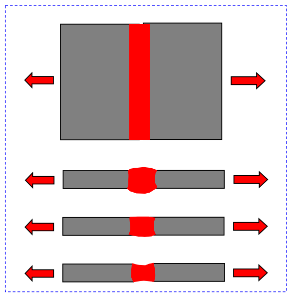
Test result: external force is smaller Tongji's is better; while larger, Chen's better

- ☑ Bolted connection subjected to bending moment & tension

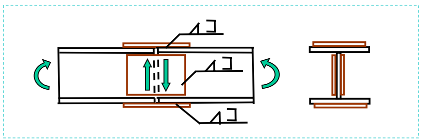
As subjected to bending moment

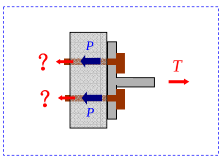
Question:

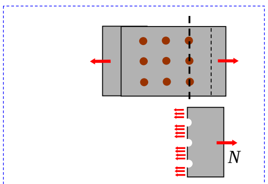




Question:







$$N / (b - 3d_0) t \le f_d = f_y / \gamma_R$$