Basic principles of steel structures

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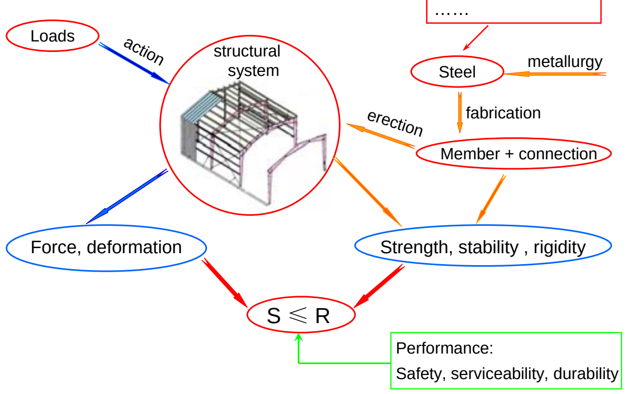
Design concept & rationale



Structural steel

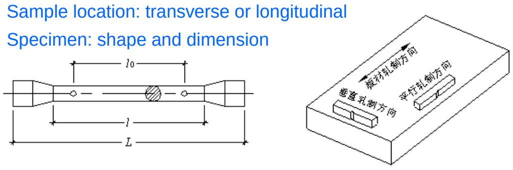
Outlines

- ✧ requirement of properties for structural steel
- ✧ factors affecting steel properties
- ✧ state of stress and stress concentration
- ✧ fatigue failure
- ✧ steel grade, steel products & steel selection
- ✧ recent advances of structural steel

Requirement of steel properties

uni-axial tensile test: preparation

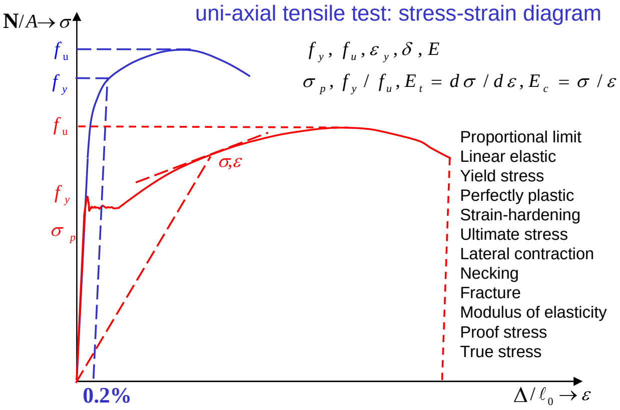
- ☑ tensile-test specimen
  - Sample location: transverse or longitudinal
  - Specimen: shape and dimension

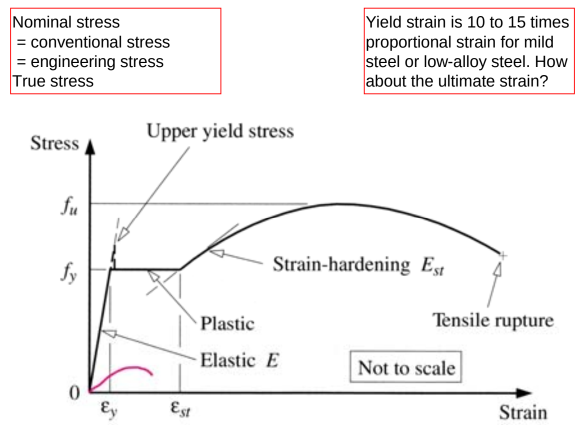


- ☑ loading method
  - Rate of stressing
- ☑ temperature
  - room temperature

Requirement of steel properties

uni-axial tensile test: stress-strain diagram





Requirement of steel properties

- ☑ strength
  - Proportional limit, yield point, tensile strength
  - Yield-to-tensile strength ratio (0.6~0.7 for mild steel)
- ☑ ductility
  - Percentage elongation at failure, reduction of area
- ☑ toughness
  - static toughness, impact toughness
- ☑ cold-forming
  - cold bent test
- ☑ weldability
  - for construction & usage
- ☑ durability
  - corrosion resistance, fatigue resistance

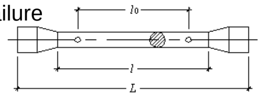
Requirement of steel properties

ductility: elongation & reduction of area

☑ ductility: occur remarkable residual strain (plastic deformation) without fracture after stress exceeding yield point

☑ percentage elongation at failure

$$\delta = \frac{l_1 - l_0}{l_0} \times 100\%$$



☑ percentage reduction of area

true assessment criteria but difficult to measure

through-thickness property

$$\psi = \frac{A_0 - A_1}{A_0} \times 100\%$$

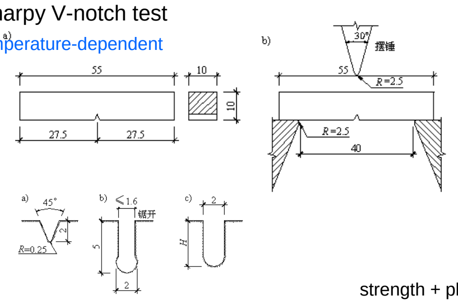
Requirement of steel properties

toughness: static & impact toughness

☑ impact toughness: measure of impact resistance or the ability to absorb sudden increase in stress at notch

☑ Charpy V-notch test

temperature-dependent



strength + plasticity

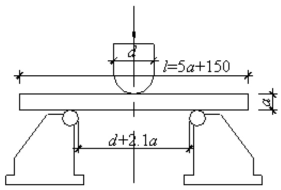
Requirement of steel properties

cold-forming ability

☑ cold-forming property: ability to resist crack while producing plastic deformation under cold-forming work

☑ Cold-bent test

assess ductility and weldability



Requirement of steel properties

weldability

☑ weldability

Construction: no crack in welds and HAZ area under normal weld condition

Usage: mechanical properties of welds and HAZ area are not less than the base metal

☑ Carbon Equivalent

$$= C + Mn + \left(\frac{C_r + Mo + V}{5}\right) + \left(\frac{Ni + Cu}{15}\right)$$

Requirement of steel properties

durability

☑ corrosion resistance

30-40% demolished

Corrosion-resist steel: Cu-P-Ti-Re

☑ fatigue resistance

No statement here

Factors affecting steel properties

- ☑ chemical composition
  Fe, C, Si, Mn, V, S, P, O, N, others
- ☑ process of metallurgy
  Smelt, cast, rolling, residual stress while cooling
- ☑ time effect
  time - hardening
- ☑ cold work
  history of strain & stress, cold work
- ☑ temperature
  elevated temperature and low temperature
- ☑ rate of stressing
  the higher rate, the higher stress

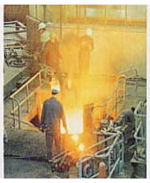
Factors affecting steel properties

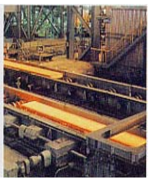
chemical composition

	strength	ductility	toughness	weldability	durability
Iron	↓	↑			
Carbon	↑	↓	↓	↓	↓
silicon	↑	-	-	-	-
manganese	↑	-	-	- (↓)	- (↓)
vanadium	↑	-	-	-	↑
Sulfur	↓	↓	↓	↓	↓
phosphorus	↑	↓	↓	↓	↑
oxygen	↓	↓	↓	↓	↓
nitrogen	↑	↓	↓	↓	↓

Factors affecting steel properties

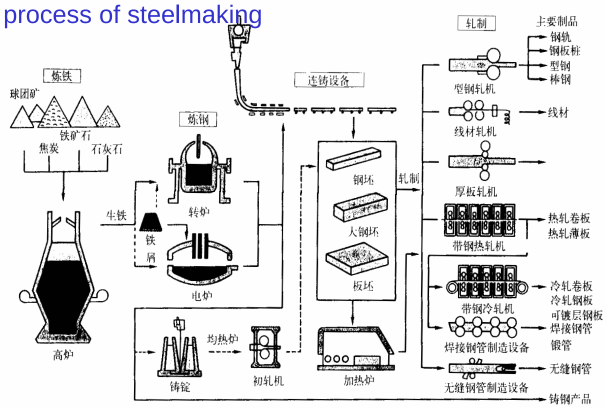
process of steelmaking





Factors affecting steel properties

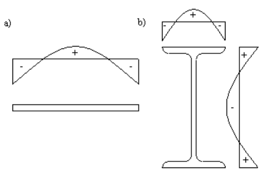
process of steelmaking



Factors affecting steel properties

process of steelmaking

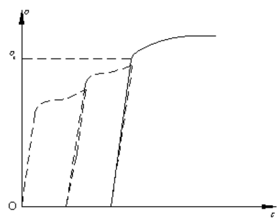
- ☑ produce - smelt
  Basic oxygen furnace, electric-arc furnace
- ☑ casting (ladle treatment)
  Rimming steel (Mn)
  Semikilled steel
  Killed steel (Si)
  Ultra-killed steel
- ☑ hot rolling
  1200-1300 degree
  transverse & longitudinal
- ☑ residual stress while cooling



Factors affecting steel properties

time-effect and cold work hardening

- ☑ time effect
  Strength increase, ductility decrease, crispy
  Heat treatment
- ☑ cold work hardening
  History of stressing
  Cold work: cut, punch,
  roll, press,
  fold, drill,
  plane, strike



- ☑ rate of stressing
  the higher rate, the higher stress

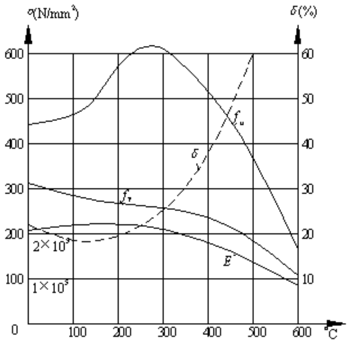
Factors affecting steel properties

temperature

☑ elevated temperature

250℃, brittle

600℃, soft

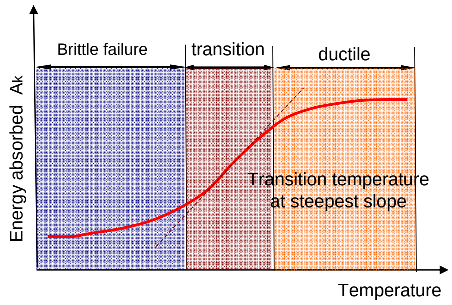


Factors affecting steel properties

temperature

☑ low temperature

toughness decrease suddenly

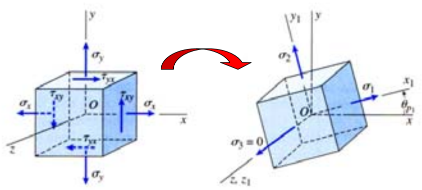


State of stress and stress concentration

combined stress and criteria of yield

☑ equivalent stress (von Mises stress)

$$\sigma_{zs} = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2 - \sigma_x\sigma_y - \sigma_y\sigma_z - \sigma_z\sigma_x + 3(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2)}$$



$$\sigma_{zs} = \sqrt{\frac{1}{2}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right]}$$

Plane stress?
Stress in beam?

State of stress and stress concentration

combined stress and criteria of yield

☑ criteria of elastic failure

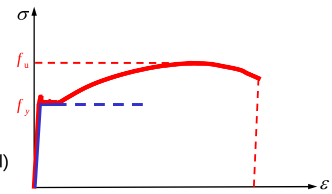
1st: The maximum-principal-stress theory
2nd: The maximum-principal-strain theory
3rd: The maximum-shear-stress theory
The maximum-strain-energy theory
4th: The maximum-distortion-energy theory

von Mises theory (4th):

$\sigma_{zs} < f_y$ Elasticity

$\sigma_{zs} = f_y$ Plasticity

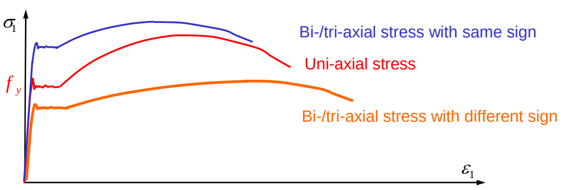
(perfect elasto-plastic model)



State of stress and stress concentration

yielding under biaxial or triaxial stresses

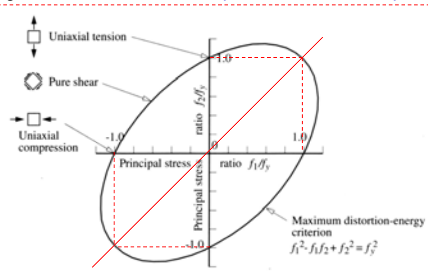
Effects of biaxial or triaxial stresses on yielding



State of stress and stress concentration

yielding under biaxial or triaxial stresses

Yielding under biaxial stresses: any stress is smaller than yield strength?



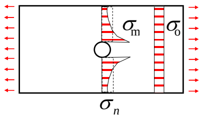
Pure shear condition: $\tau_y = f_y/\sqrt{3} \approx 0.58 f_y$

State of stress and stress concentration
stress concentration: definition

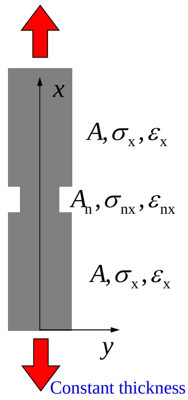
The uniform stress pattern is disruption and the intensity of stress increases greatly within a very short distance. The condition is described as STRESS CONCENTRATIONS.
It is due to the abrupt changes in geometry caused by imperfection of structural steel or manufacture. It includes holes, grooves, notches, keyways, threads, or abrupt changes in plate width or thickness.

Stress concentration factor:

$$K = \sigma_m / \sigma_n$$



State of stress and stress concentration
stress concentration and brittle failure



Steel bar with abrupt change of width at middle

$$A_n < A$$

Subjected to axial tensile load in x-direction, then

$$\sigma_{nx} > \sigma_x, \quad \varepsilon_{nx} > \varepsilon_x$$

Lateral strain is obtained by poisson's ratio,

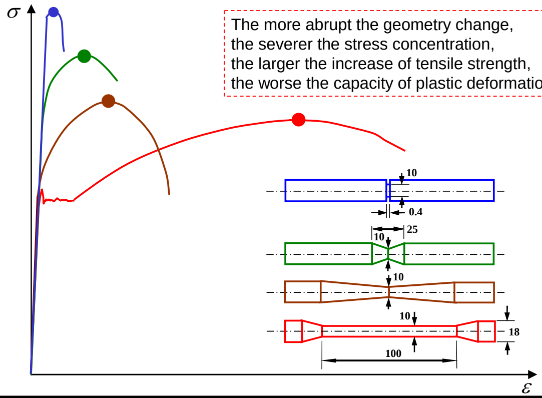
$$\varepsilon_{ny} = -\mu\varepsilon_{nx} < -\mu\varepsilon_x = \varepsilon_y$$

Lateral contraction at middle is larger than that at the ends, therefore, the lateral stress at middle must be tensile stress

$$\sigma_{nx} > 0, \quad \sigma_{ny} > 0$$

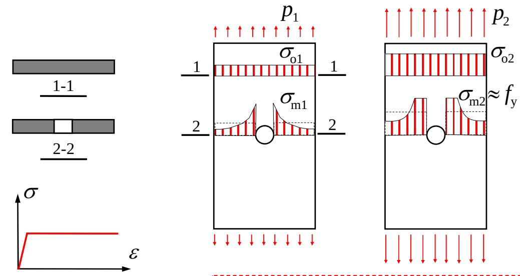
Abrupt change in width at middle →
stress concentration →
biaxial tensile stress field → brittle failure

State of stress and stress concentration
stress concentration and change of geometry



The more abrupt the geometry change,
the severer the stress concentration,
the larger the increase of tensile strength,
the worse the capacity of plastic deformation

State of stress and stress concentration
stress concentration and perfect plasticity of steel



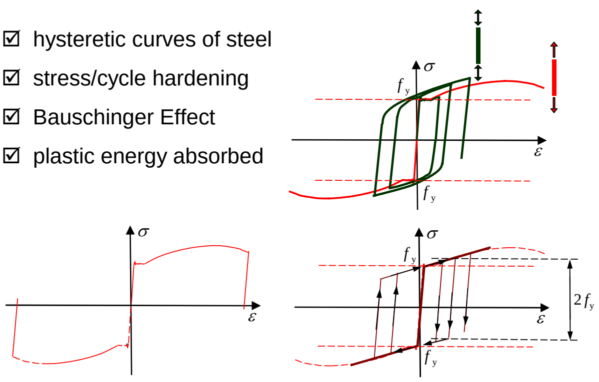
Idealized stress-strain plot for an elastoplastic material

$$K_1 = \frac{\sigma_{m1}}{\sigma_{n1}} > \frac{\sigma_{m2}}{\sigma_{n2}} = K_2$$

For a material with perfect elastoplastic constitutive relation, once the peak stress reaches yield point, its stress will remain this value and the stress concentration factor will decrease.

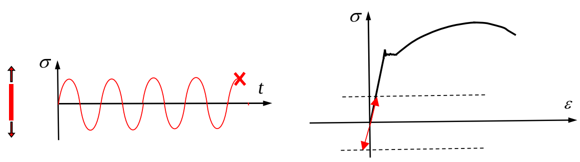
State of stress and stress concentration
stress beyond yield point: low-cycle fatigue

- ☑ hysteretic curves of steel
- ☑ stress/cycle hardening
- ☑ Bauschinger Effect
- ☑ plastic energy absorbed



Fatigue failure
high-cycle fatigue: basic concepts

- ☑ fatigue failure: steel material subjected to dynamic loads is likely to fail at a lower stress than when the same loads are applied statically, especially when the loads are repeated for a large number of cycles.

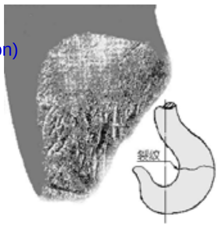


Number of cycles to failure
Nominal stress at failure

Fatigue failure
high-cycle fatigue: failure mechanism

☑ Progressive fracture:

imperfection of material (local damage)
⇩
microscopic crack forms (crack initiation)
⇩
crack gradually enlarges (crack propagation)
⇩
crack becomes unstable and sudden fracture of steel occurs (unstable crack growth and fracture)



☑ Characteristic of fracture

Fatigue failure
high-cycle fatigue: basic concepts

☑ fatigue life: number of stress cycles to failure under certain cycle symbol.

☑ Factors governing fatigue failure

- types of stress (tensile, compressive, shear or combined stress)
- cycle symbol
- number of cycles to failure
- stress concentration
- residual stress
- surface condition
- *range of stress*

Fatigue failure
fatigue research I: max. stress method

☑ research background

Small steel specimen for fatigue tests

☑ be applicable

Non-welded elements

☑ main concepts

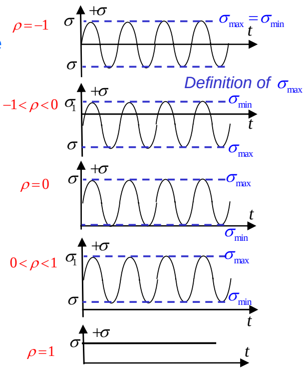
fatigue life = cycle numbers to failure

fatigue strength: (σ^P)

the max. stress (absolute value) → fatigue life under specified cycle symbol

endurance limit = threshold stress

stress ratio: $\rho = \sigma_{min} / \sigma_{max}$

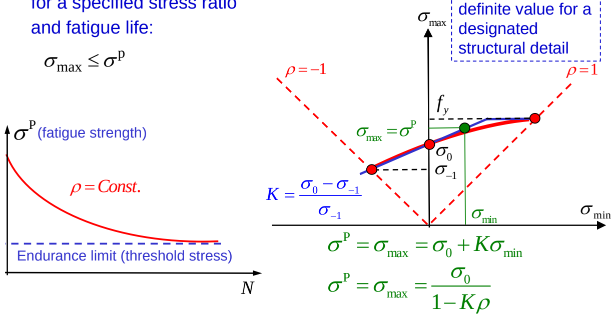


Fatigue failure
fatigue research I: max. stress method

☑ Engineering application: Goodman diagram

for a specified stress ratio and fatigue life:

$\sigma_{max} \le \sigma^P$



Fatigue failure
fatigue research II: stress range method

☑ research background

Full-scale structural specimen for fatigue tests

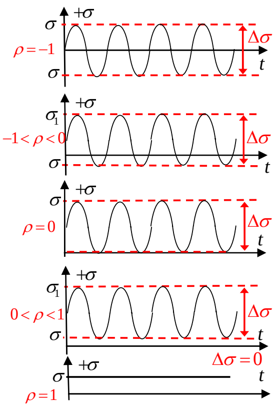
☑ be applicable

welded elements

☑ main concepts

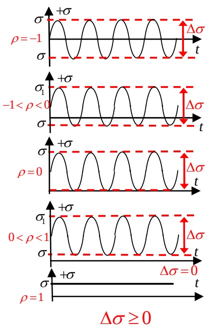
fatigue failure is governed by stress range of the part of the element, rather than stress ratio

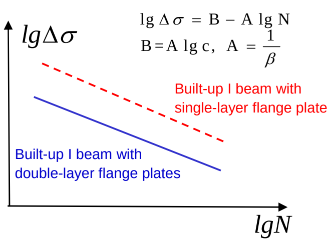
stress range: $\Delta\sigma = \sigma_{max} - \sigma_{min}$



Fatigue failure
fatigue research II: stress range method

☑ Engineering application: $\Delta\sigma \le [\Delta\sigma] = (c/N)^{1/\beta}$





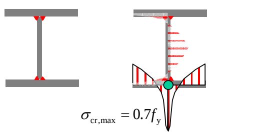
☒ stress ratio
☒ yield stress of steel
☑ structural details

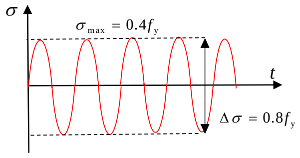
Fatigue failure

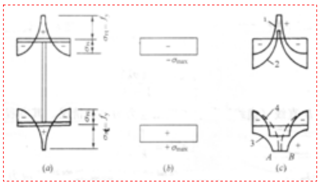
fatigue research II: stress range method

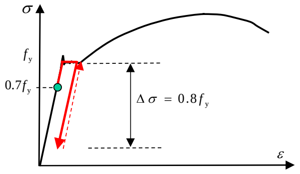
☑ Mechanism of stress range method

Stress range and residual stress





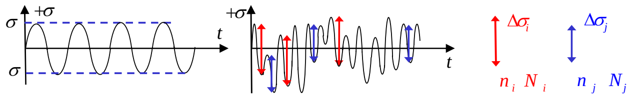




Fatigue failure

fatigue failure under variable amplitude stress cycles

☑ fatigue under constant and variable amplitude stress cycles



☑ Miner criteria:

$$\sum \frac{n_i}{N_i} = 1$$

Structural steel

classification & steel grade

☑ carbon structural steel
Q195, Q215, Q235, Q255, Q275

☑ low alloy structural steel
Q295, Q345, Q390, Q420, Q490

☑ quality carbon structural steel
31 types, 20, 45

☑ quality structural steel wires
high-strength

Structural steel

steel grade: carbon structural steel

☑ common used: Q235

☑ product quality documentation
Mechanical properties: yield strength, tensile strength, elongation
Chemical composition: C, Mn, Si, S, P

☑ expressed by:
quality grade: A, B, C, D
deoxidization: F, b, Z, TZ

Q235A[F,b,(z)]	No Ce Guarantee
Q235B[F,b,(z)]	20℃, Ak≥27J
Q235C [(z)]	0℃, Ak≥27J
Q235D [(TZ)]	-20℃, Ak≥27J

fy = 235MPa
fu = 400MPa
fvy = ?
E = ?

Structural steel

steel grade: high-strength low alloy structural steel

☑ common used: Q345, Q390, Q420 (alloy <5%)

☑ product quality documentation
Mechanical properties: yield & tensile strength, elongation, cold work
Chemical composition: C, Mn, Si, S, P, V, Nb, Ti

☑ expressed by:
quality grade: A, B, C, D, E
deoxidization: Z, TZ, plus heat treatment

Q345/390/420A	No toughness Guarantee
Q345/390/420B	20℃, Ak≥34J
Q345/390/420C	0℃, Ak≥34J
Q345/390/420D	-20℃, Ak≥34J
Q345/390/420E	-40℃, Ak≥27J

Q345:
fy = 345MPa
fu = ? 470~630MPa
fvy = ?
E = ?

Structural steel

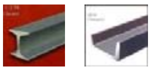
steel grade: quality carbon steel (wires)

☑ quality carbon steel
Heat treatment: thermal refining, tempering
Advantages: less impurity, less imperfection
Classification: 31 types, 20, 45 for high-strength bolts

☑ quality structural steel wires (rope)
wires: quality carbon steel → cold work
high strength: 1570~1770MPa
expressed by: 6×7, 8×19

Structural steel
steel products (shapes)

- ☑ steel plate
  - Steel sheet: 0.35 ~ 1mm ~ 4mm
  - Thicker steel plate: rolled steel plate 4.5~20mm, thicker plate 20~60mm
  - Super-thick steel plate: >60mm
  - Flat steel: 12~200mm width
- ☑ (hot rolled) shaped steel
  - I-section, channel, angle, H-section, T-section, tube



- ☑ cold-formed thin-wall sections
  - angle, channel, Z-section, hat-section, tubular

- ☑ welded sections (built-up)
  - I-section, box-section

Structural steel
design value of steel strength (design index)

- ☑ expression of design index
  - ASD (Allowable Stress Design): $[\sigma] = f_y / K$
  - LRFD (limit states design - factor): $f = f_y / \gamma_R$
- ☑ determination of design value
  - As mentioned in Introduction Part
- ☑ design value of structural steel
  - steel plate: steel grade, thickness
  - cast-steel: just authorized
  - weld: butt weld / fillet weld
  - bolt: ultimate strength

Structural steel
principles for selection of structural steel

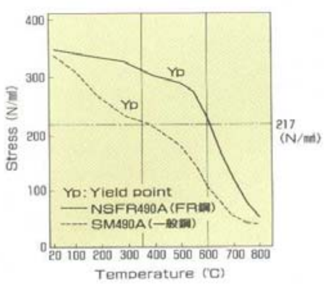
- ☑ structural types and importance
  - Important / normal / secondary
- ☑ characteristic of loads
  - Static load / dynamic load
  - Period of actions
- ☑ connection methods
  - weld / bolt
- ☑ temperature (steel located)
  - north / south, indoor / outdoor
- ☑ stress condition
  - tension / compression, through-thickness loading

Recent advances of Structural steel

- ☑ fire-resistant structural steel
- ☑ corrosion-resistant structural steel
- ☑ high-strength structural steel
  - High-strength, weldability (Ceq)
  - Through-thickness steel
- ☑ ultra-low yield point steel
- ☑ structural casting (steel)
- ☑ high friction factor steel plate
  - 0.3~0.5 → 0.9

Recent advances of Structural steel
fire-resistant structural steel

- ☑ traditional structural steel
  - 600℃:
  - remain one-third strength
- ☑ fire-resistant steel
  - 600℃:
  - remain two-third strength

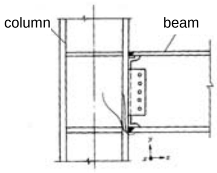


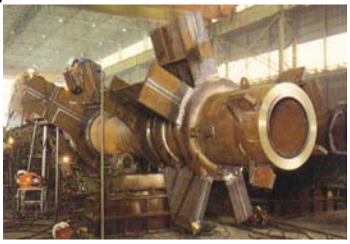
Recent advances of Structural steel
corrosion-resistant structural steel

- ☑ additional chemical constituent
  - Cu, Cr, Mn, RE
- ☑ USA Cro-Ten steel
  - 2~8 times corrosion resistance
- ☑ Baosteel 09CuPTiRE
  - 2~3 times corrosion resistance
- ☑ stainless steel
  - Strength, ductility, weldability

Recent advances of Structural steel
through-thickness structural steel

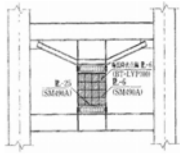
- ☑ thickness >100mm
- ☑ excellent toughness

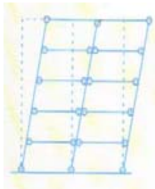




Recent advances of Structural steel
ultra-low yield point structural steel

- ☑ low yield point: 100~120MPa
- ☑ tensile strength: 250~260MPa
- ☑ elongation: approximate 60%
- ☑ aim: keep key members out of plasticity





Recent advances of Structural steel
structural casting steel