Basic principles of steel structures

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Design concept & rationale

- Loads
- Action
- Structural system
- Steel metallurgy
- Fabrication
- Member + connection
- Force, deformation
- Strength, stability, rigidity

S ≤ R

Performance:
- Safety
- Serviceability
- Durability

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

- Proportional limit
- Linear elastic
- Yield stress
- Perfectly plastic
- Strain-hardening
- Ultimate stress
- Lateral contraction
- Fracture
- Modulus of elasticity
- Proof stress
- True stress

Nominal stress
= Conventional stress
= Engineering stress
=True stress

Upper yield stress

Yield strain is 10 to 15 times proportional strain for mild steel or low-alloy steel. How about the ultimate strain?
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

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**ductility:**
- Occur remarkable residual strain (plastic deformation) without fracture after stress exceeding yield point
- Percentage elongation at failure
  \[ \varepsilon = \frac{\Delta L}{L_0} \times \frac{100}{\lambda} \]
- Percentage reduction of area

**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)

**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

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**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
  \[ C + Mn + \left( \frac{Cr + Mo + V}{5} \right) + \left( \frac{Ni + Cu}{15} \right) \]

**durability**
- Corrosion resistance
  - 30-40% demolished
  - Corrosion-resistant 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

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Factors affecting steel properties

- 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
  - 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

- **Elevated temperature**
  - 250°C: brittle
  - 600°C: soft

Factors affecting steel properties

- **Low temperature**
  - Toughness decreases suddenly

State of stress and stress concentration

- **Combined stress and criteria of yield**
  - *Equivalent stress* (von Mises stress):
    \[ \sigma_{eq} = \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} \]

State of stress and stress concentration

- **Elasticity**
- **Plasticity**
  - Perfect elasto-plastic model

State of stress and stress concentration

- **Yielding under biaxial or triaxial stresses**
  - Bi/tri-axial stress with same sign
  - Uni-axial stress
  - Bi/tri-axial stress with different sign

Energy absorbed, $A_k$

- **Transition temperature**
  - At steepest slope

State of stress and stress concentration

- **Elasticity**
- **Plasticity**
  - Pure shear condition:
    \[ \sigma = \frac{f}{\sqrt{3(\sqrt{3}/2)^2 + 1)} \]
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:

\[ K = \frac{\sigma_m}{\sigma_n} \]

where \( \sigma_m \) is the maximum stress at the concentration location and \( \sigma_n \) is the maximum stress elsewhere.

State of stress and stress concentration
stress concentration and brittle failure

Steel bar with abrupt change of width at middle

\( A_x < A \)

Subjected to axial tensile load in x-direction, then

\( \sigma_{mx} > \sigma_y, \quad \epsilon_{mx} > \epsilon_y \)

Lateral strain is obtained by Poisson's ratio,

\( \epsilon_y = -\mu \epsilon_x = -\mu \epsilon_m \)

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

\( \sigma_{mx} > 0, \quad \sigma_{my} > 0 \)

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

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.

\[ K = \frac{\sigma_y}{\sigma_m} - K \]

Idealized stress-strain plot for an elastoplastic material

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.
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 research I: max. stress method**

- **Research background**
  - Small steel specimen for fatigue tests
  - Non-welded elements

- **Main concepts**
  - Fatigue life = cycle numbers to failure
  - Fatigue strength: maximum stress (absolute value)
  - Fatigue life under specified cycle symbol
  - Endurance limit = threshold stress
  - Stress ratio: $\rho = \frac{\sigma_{\text{min}}}{\sigma_{\text{max}}}$

**Fatigue research II: stress range method**

- **Research background**
  - Full-scale structural specimen for fatigue tests
  - Welded elements

- **Main concepts**
  - Fatigue failure is governed by stress range of the part of the element, rather than stress ratio
  - Stress range: $\Delta \sigma = \sigma_{\text{max}} - \sigma_{\text{min}}$

- **Engineering application**: $\Delta \sigma \leq [\Delta \sigma] = (c/N)^{1/\beta}$
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:
\[ \sum \frac{N_i}{N_j} = 1 \]

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: 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
  - Deoxidization: F, b, Z, TZ

- Q345/390/420A [F] No Ce Guarantee
- Q345/390/420B [F] 20°C, A0 ≥ 34J
- Q345/390/420C [F] 0°C, A0 ≥ 34J
- Q345/390/420D [F] -20°C, A0 ≥ 34J
- Q345/390/420E [F] -40°C, A0 ≥ 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

**Expression of design index**
- ASD (Allowable Stress Design):
  \[ \sigma = f_y / K \]
- LRFD (Limit States Design - Factor):
  \[ f = f_y / \gamma_f \]

**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

**Recent advances of Structural steel**
- Fire-resistant structural steel
  - Traditional structural steel: 600°C; remain one-third strength
  - Fire-resistant steel: 600°C; remain two-third strength
- 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**