Fundamentals of Structural Design
Part of Steel Structures

Civil Engineering for Bachelors
133FSTD

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Syllabus of lectures

1. Introduction, history of steel structures, the applications and some representative structures, production of steel
2. Steel products, material properties and testing, steel grades
3. Manufacturing of steel structures, welding, mechanical fasteners
4. Safety of structures, limit state design, codes and specifications for the design
5. Tension, compression, buckling
6. Classification of cross sections, bending, shear, serviceability limit states
7. Buckling of webs, lateral-torsional stability, torsion, combination of internal forces
8. Fatigue
9. Design of bolted and welded connections
10. Steel-concrete composite structures
11. Fire and corrosion resistance, protection of steel structures, life cycle assessment

Scope of the lecture

- **Steel products**
- Properties of steel
- Testing of steel
- Steel grades

Semi-finished products

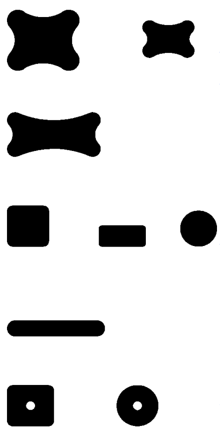
These are produced by continuous casting process and represent starting point for further processing

Blooms
- square cross section with slightly concave edges
- rectangular section with slightly concave edges

Slabs
- rectangular with slightly concave edges

Billets and Sheet billets
- rectangular with convex side edges

Hollow semi-finished products
- square
- circular



Processes for final steel products

The finished shapes are produced by one of the following method:

- Hot rolling

  the most common method for steel plates structural shapes, concrete reinforcements, etc.
- Cold rolling

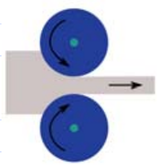
  to produce thin steel sheets delivered in coils for further processing (producing parts of car body by cold drawing, sections for civil engineering by cold forming)
- Cold forming

  bending of corrugated sheets and C sections from thin steel sheets
- Casting

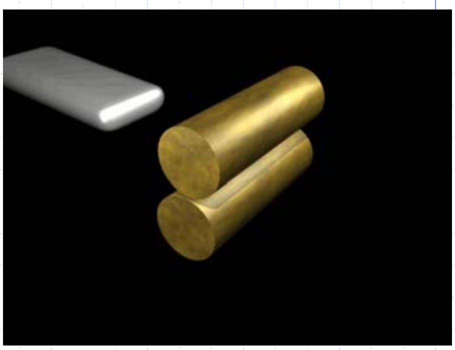
  for complicated shapes, i.e. bearings, complicated joints, etc.
- Forging

  for special elements, usually not for civil engineering

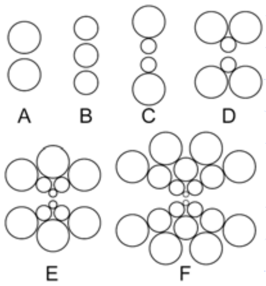
Hot Rolling



- Hot rollings used mainly to produce sheets of steel or simple cross sections, such as I, H, U and L sections, rail tracks
- The starting material is usually large pieces of steel, like semi-finished casting products, such as slabs, blooms, and billets
- They came from a continuous casting operation (the products are usually fed directly into the rolling mills at the proper temperature, or the material starts at room temperature and must be heated
- The process that occurs above the recrystallization temperature of steel (approx. 1000ºC). After the grains deform during processing, they recrystallize, which maintains an equiaxed microstructure and prevents the metal from work hardening



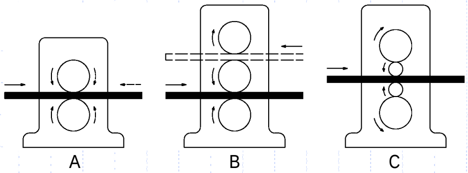
Hot Rolled Profiles



Various rolling configurations

Rolling mill

- A - two-high reversing mill has rolls that can rotate in both directions (disadvantage - the rolls must be stopped add reversed)
- B - three high - the rolls rotate the same direction, the piece can pass back and forth
- C-F - more complicated configuration to reduce bending of the rolls and heat loss



Hot Rolled Profiles

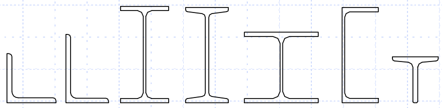
Tandem mill - can create the finished shape in single run by passing the material through several set of cylinders

Cross-sections of continuously rolled structural shapes, showing the change induced by each rolling mill

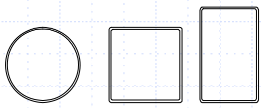
Hot rolled products

- Semi-finished products used for further processing
- Steel sheets
  various thickness from 5 to 80 mm
- Rods
  - flat, circular, square, rectangular, hexagonal, etc.

  - concrete reinforcement: with ribs, cold-twisted
- Rails
- Structural sections
- Sheet piles



- Tubes
  - circular
    - seamless
    - seamed (welded)
  - square and rectangular



Sheets and plates

supplied to the market in:
- plates (thick sheets) size up to 2,5 m × 12 m
- coils (thin sheets)

according to the method of production
- hot rolled (thick sheets), majority of sheets for structural application
- cold rolled (thin sheets)

according to the thickness
- thin (up to 3 mm)
- thick (3 mm and more)
- the range produced:
  5, 6, 8, 10, 12, 15, 18, 20, 22, 25, 28, 30, 35, 40, 50 mm
- other dimension are available on request, it is necessary to order minimum amount of steel (approx. 40 tones)

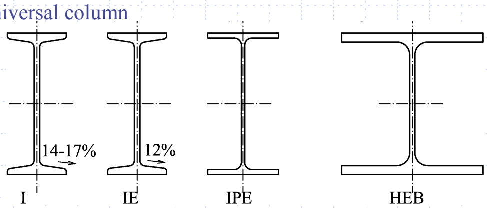
I sections

The most common sections

Length 6 - 14 m

- Traditional I sections
  - first produced in 1848
  - with sloped flanges (slope 14 to 17 %), easier to produce, more difficult to use - for bolted connection to flanges using of wedge washers is necessary
- Sections with parallel flanges – e.g. IPE
  - produced on special rolling machines with 4 cylinders, easy to use bolted connections
- Wide flange sections HEAA, HEA, HEB, HEM
  - e.g. for centrically loaded columns
- Sections in USA and UK are different, based on imperial units

  in UK: UB = universal beam, UC = universal column

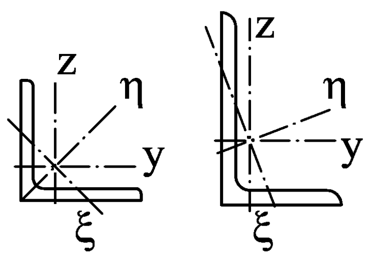


Angles

Typically used for elements loaded in tension / compression

- Equal leg angles
- Unequal leg angles

Biggest equal leg angle is L 200 × 20 mm



Tubes

- Seamless
  - thick walled tubes
  - suitable for gas pipes, etc. (high pressure inside, no risk that the seam will break)
  - more expensive than welded tubes
- Welded - seamed
  - Shaping of strip into slot tube and welding by electrical arc, resistance or inductive welding process
  - Spiral weld for tubes of large diameters (approx. 2500 mm),
- Circular
- Square or rectangular
- Elliptical

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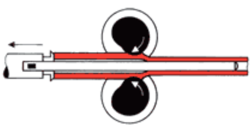
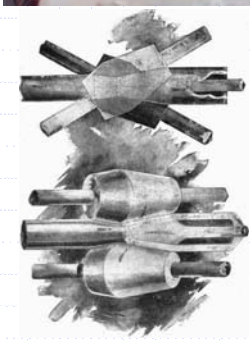
Seamless tubes

Two production methods invented by Mannesmann brothers at the end of 19th century

- pierce-rolling process - mandrel rolling
  - rolls arranged at an angle to each other can loosen the core of an ingot and cause it to break open
  - it is helped with a plug to ensure more uniform piercing and a smoother inside surface = the plug is "drilling" the hole into the billet as it passes through the mill
- pilger rolling process
  - a pair of conical-shaped rolls "stretches" and "makes thinner" the thick-walled hollow body, with a cylindrical mandrel inside it



Pilger-rolling process



Pierce-rolling process

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Production of seamless tubes

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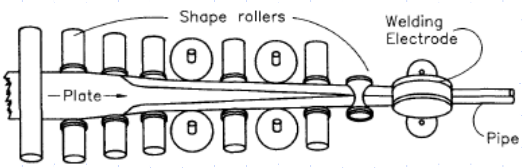
Seamed tubes

tubes are formed and welded from strip of steel sheet

Seamed tube
the weld is removed later
to have smooth surface



Making of butt-welded tube

Seamed tube
finished product (no weld is visible)

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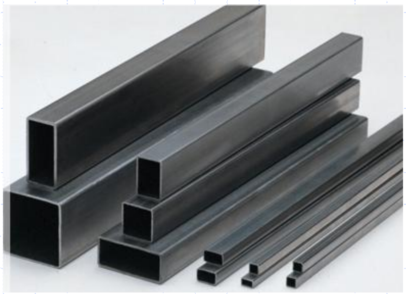
Square and rectangular tubes

tubes formed and welded from strip of steel sheet
size 20 - 500 mm, thickness 2 - 25 mm

Forming a square tube

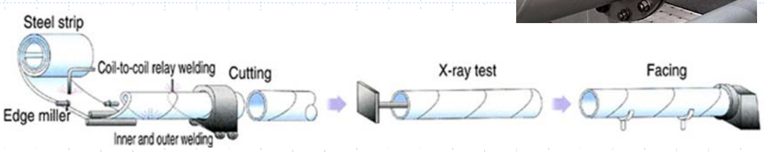


Square and rectangular tubes

Seamed square tubes

Spiral welded tubes

- spiral welded tubes of large diameters (up to 2500 mm, web thickness up to 20 mm)
- can be used for:
  - piping for oil, natural gas, etc. transport
  - piling (foundation in poor soils)
  - columns of large diameter, can be filled with concrete to increase load bearing capacity of column



Cold rolling

- is done with the metal below its recrystallization temperature (usually at room temperature)
- it which increases the strength via strain hardening up to 20%
- sheets, strips, bars, and rods are produced - smaller sizes than with hot rolling process
- produce sections with higher quality (smooth) surface and smaller manufacturing tolerances than hot rolling process

Coils of thin steel sheet

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Cold Forming

- Roll forming
  - for prismatic members - metal decking, Z, C shaped sections
- Drawing
  - solid or hollow sections of smaller dimensions, have better surface finish than hot rolled sections
- Pressing
  - Small number of more complicated cross-sections

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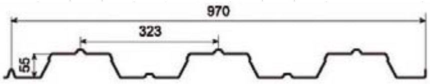
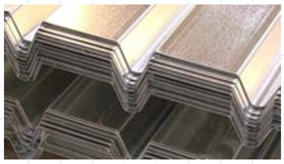
Roll forming

- metal decking sheets are produced from thin zinc-coated steel sheets supplied in coils
- thickness 0,7 - 1,2 mm, length up to 12 m, height 30 - 200 mm



Cold forming of steel metal decking



Cold forming of steel metal decking

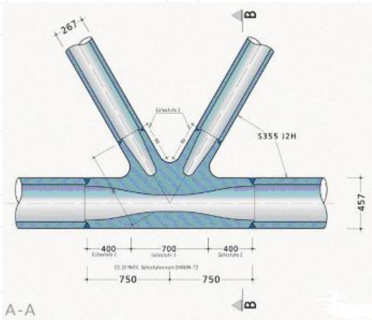
Casting

- Only for complicated shapes
- Moulds from forming mass (mixture of sand and clay)
- Usage
  - hinges
  - bearings
  - joints of tubular structures
- Steel for casting has different chemical composition than steel for rolling
- Cast elements can sometimes be replaced by welded parts

Cast joints for tubular structures

Used for

- complex shapes
- thick-walled tubes
- high loads



Cast joints for tubular structures

Application of cast joint in tubular columns, Stuttgart Airport

Tolerances of Hot Rolled Sections

- Dimension tolerances
  - Cross section tolerances
  - Length tolerances
- Weight tolerances
  - Theoretical weight of metallurgical products may differ from density of steel 7850 kg/m^3 (for sheets 8000 kg/m^3).
- Shape tolerances
  - Out of parallel shape of flanges of I profile, etc.
- Defects of material
  - On the surface
    - Cracks, shrinkage cavity, bubbles, porosity, milled scales, scoring and corrosion traces
  - Inside of the product
    - Inclusions, segregates, layering of material
- The limits are given by standards

Scope of the Lecture

Steel products

➡ Properties of steel

Testing of steel

Steel grades

Properties of Steel

Material constants

- Modulus of elasticity — $E = 210\ 000$ MPa
- Elastic Shear Modulus — $G = 81\ 000$ MPa
- Poisson's ratio — $\nu = 0{,}3$
- Specific weight — $\rho = 7\ 850$ kg/m^3
- Coefficient of thermal expansion — $\alpha = 0{,}000012$ deg^{-1}

Other important parameters (strength, weldeability) are specific for each steel grade and steel batch and need to be tested

Scope of the Lecture

Steel products

Properties of steel

➡ Testing of steel

Steel grades

Testing of steel

- yield stress f_y
- ultimate strength f_u ⇐ Tensile test
- ductility

- fracture toughness ⇐ Bending impact test
- weldeability ⇐ Weldeability test
- fatigue resistance ⇐ Fatigue test (cyclic)

- hardness (~ linear relation to strength)

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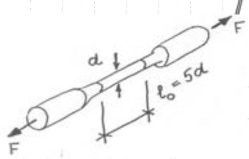
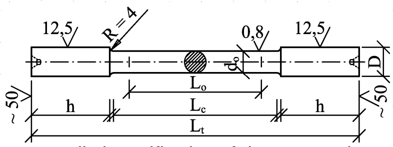
Tensile test

The most important test on mechanical properties of steel

The specimens are either circular or rectangular cross sections (special sections can be used when necessary)



Principle of the tensile test



Detailed specification of the test specimen

The values obtained:

- yield limit, f_y

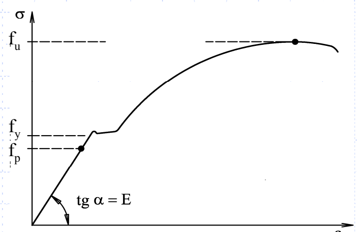
  is the point when strain increase without increasing of the load
- proportional limit

  is the point up to which Hook's law is applicable

  it is very close to yield limit, in most cases these are considered to be identical
- ultimate strength, f_u

  corresponding to maximum tensile load transmitted by the specimen
- ductility, δ

  is the amount in % to which the specimen extends until failure



Stress-strain diagram of structural steel

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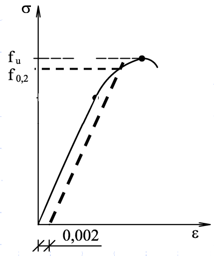
Tensile test

Some steels do not have “visible” yield point

These include stainless steels and cold formed steels

In that case the yield limit is replaced by conventional limit $f_{0,2}$



Stress-strain diagram of cold-formed steel

The values obtained:

- conventional limit, $f_{0,2}$

  is the point when the plastic strain (i.e. permanent strain) is equal to 0,2%
- ultimate strength, f_u

  corresponding to maximum tensile load transmitted by the specimen
- ductility, δ

  is the amount in % to which the specimen extends until failure

Bending impact test

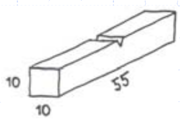
To find the ability a crack can create and grow in a specimen after impact

The propagation of the crack is helped by a notch created on the tension side of the specimen

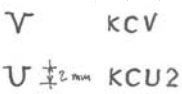
In real structures, notch represents non-homogeneity in structure (sudden change of dimensions - these should be avoided) or in material (defects), where high stress concentration may occur

Result of the test is expressed as notch toughness = impact energy required to break the specimen

Low notch toughness = brittle steel



Test specimen



Shape of the notch

Testing equipment - Charpy's hammer

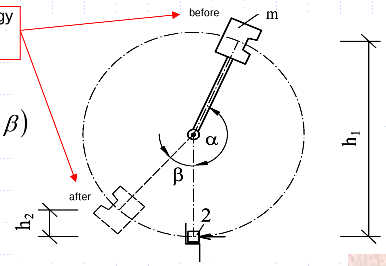
Bending impact test

Notch toughness = the energy necessary to break the specimen

The results significantly depend on the notch shape
(either U-shaped notch - KCU, or V-shaped notch - KCV)

Difference in potential energy
=
notch toughness

$$E = m\,(h_1 - h_2) =$$
$$= m\,r\,(\cos\alpha - \cos\beta)$$



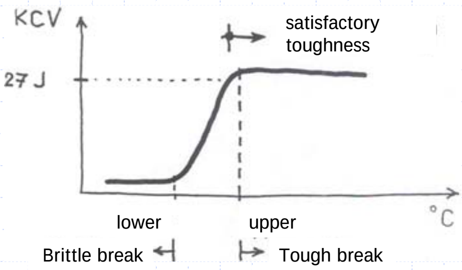
Principle of test

Specimens before and after the test

Junction Temperature

The toughness decrease at low temperatures, therefore it is performed at room temperature (+20 ºC) but also at 0ºC and -20 ºC

Notch toughness rapidly decrease at junction temperature



Hardness Tests

Specific volume (indentor) is pressed by known force to the brushed surface of the material

The shape or depth of the mark on the surface is measured

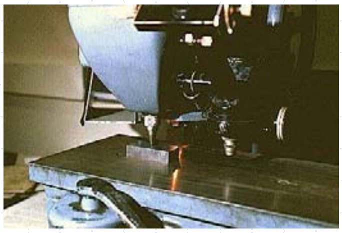
- Brinell, steel sphere, quenched (HB)
- Rockwell, diamond conus or steel sphere (HR)
- Vickers, diamond tetrahedral pyramid (HV)
- Koop's, diamond elongated pyramid (HK)

Relation between hardness and ultimate strength of steel

$$f_u = 3{,}6\ \text{HB [MPa]}$$

(Approximate evaluation from Brinell test)

Can be used for non-destructive testing of steel

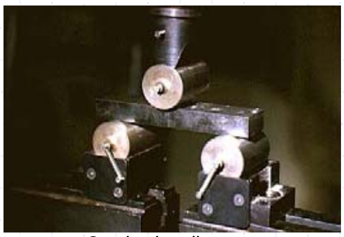


Hardness test

Weldability Tests

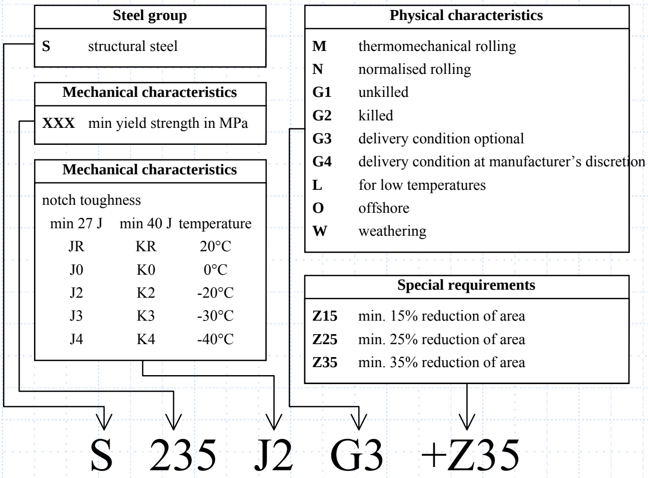
- Test of weld metal added from the electrodes – tensile test
- Test of weldability of the material
  - Impact test at bending with the notch created in the heat affected zone. This is the zone which was heated but not melted and cooled rapidly, this can lead to change of crystalline structure of the material - might become brittle. It is required the notch toughness is not reduced by welding process
  - Overlay bending test. The weld is bended, ductility of the weld and possible cracks are observed
- Carbon equivalent (chemical composition is checked on chromatograph, the limit value 0,4 should not be exceeded)

$$C_{ekv} = C + Mn/6 + (Cr+Mo+V)/5 + (Ni+Cu)/15 \quad \leq 0{,}4$$



Overlay bending test

European marking of steel grades (EN 10 025)



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Common steel grades

Standard steel grades

S235 "low quality" steel, yield limit 235 MPa

S275 similar to S235 but less common

S355 probably the most common structural steel in future

S420 becoming more and more popular

S460 becoming more and more popular

Trend – when increasing f_y, only small increase of price - using higher steel grades will be more common in near future

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High strength steels

S690

S960

These are only used for special applications - pre-stressed tendons, heavily loaded elements, etc.

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Example - S235 JR G3

S - structural steel
235 - minimum yield limit 235 MPa

J - min. notch energy 27 J
R - measured at room temperature = 20°C

G3 - steel killed, normalized

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High strength steels

Example - S460 NK

- They might have worse weldeability
- They have smaller ductility
- Price is about 15% higher than of steel S355 (i.e.1,15)
  but the ratio of yield limits is 460/355 = 1,30
  therefore it brings economic profit
- Yield limit f_y depends on thickness (see tables) and load direction

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Special alloy steels

- Weathering steels
  - alloyed with small amount of copper
  - compact layer of corrosion products creates on the surface and stops further corrosion
  - in US named CORTEN, in CZ Atmofix
- Stainless steels
  - austenitic steels
  - alloyed by chrome and nickel
  - expensive, used only for special elements

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Thank you for your attention

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