Fundamentals of Structural Design
Part of Steel Structures

Civil Engineering for Bachelors
133FSTD

Teacher: Zdeněk Sokol
Office number: B619

Scope of the lecture

- Introduction, studying of steel structures at CTU
- History of steel structures
- Properties of steel, advantages and disadvantages
- Applications of steel structures
- Interesting structures in Czech Republic
- Production of steel
- Video about steel production

Study of steel structures at faculty of Civil Engineering, CTU in Prague

- **Fundamentals of …** 4 lectures + 2 seminars per week
  basic principles, design of structural elements loaded by tension, compression, bending, design of connections
  visit in material testing laboratory and welding workshop
- **Steel Structures 01** 2 lectures + 2 seminars per week
  design of multi-storey office buildings, single storey industrial buildings, prediction of loads, interaction of structural elements, design of typical structural details
- **Optional courses**
  - WCS - Thin walled and composite structures
  - FSTS - Fire design of steel, composite and timber structures
  - GSTR - Glass structures
  - STB - Steel bridges
- **Structural project design 2**
  complete design of building, focused on structural design
- **Bachelor Project**

bachelor course

- **Steel Structures 3** 2 lectures + 1 seminars per week
  advanced course on design of steel structures, extension of the previous
- **Structural project design 3**
  complete design of building, focused on structural design
- **Diploma Project**

master course

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

References

- Wald F., Macháček J., Jandera M., Dolejš J., Sokol Z., Hájek P., Structural Steel Design According to Eurocodes, CTU Prague, 2012
- Studnička J., Design of Composite Steel Concrete Structures with Worked Examples , CTU Prague, 2011
- Studnička J., Ocelové konstrukce, ČVUT 2004 (in Czech)
- Eliášová M., Sokol Z. Ocelové konstrukce, Příklady, ČVUT 2005 (in Czech)
- Sokol Z. Steel Structures, Tables, ČVUT 2005

Lectures and Seminars

Lectures

- production of steel, properties of steel, manufacturing of steel structures, theoretical background to design of steel structures

Seminars

- practical application of your knowledge
- 6 examples - design of simple elements and connections
- visit to the material testing laboratory
- the credit is obtained at the end of the course

requirements: attend the seminars (you are allowed to miss 2 seminars)
attend the classes and laboratory
complete the calculation in time

the requirements will be precised by the teacher of the seminar

Exam

- You must complete the seminar first, i.e. get the credit from the teacher of the seminar
- After that, you must register for a date of the exam using KOS system
  The dates will be available approx. at the end of April
  Registration without credit from seminar is not possible
- And last, you must study hard

- The exam consists from these parts:

1. Theoretical knowledge of Steel Structures – 6 questions
   books, lecture notes, computers, mobile phones, etc. are not allowed
2. Exam of Concrete Structures will be organized by Mr. Štemberk
   rules will be given by Mr. Štemberk

You pass when you get at least 50% from each part (not the average from these)
The final mark is then obtained as average of the steel and concrete part
If you do not get over 50% in either steel or concrete, both parts must be repeated

Knowledge requirement for FSTD

It is required you have basic knowledge of structural mechanics and theory of elasticity

- Global analysis of statically determinate structures
  ability to calculate internal forces on simply supported beams and cantilever for any (reasonable) load, to draw bending moment diagrams, to get axial forces in lattice structures
- Calculation of deformation
  ability to calculate mid-span deformation of simply supported beam, end span deformation of cantilever using any method except using computer software
- Cross-section properties (elastic, plastic)
  ability to calculate centre of gravity, moment of inertia, radius of gyration, elastic and plastic section modulus of any (reasonable) cross section
- Stress distribution on cross-sections
  ability to draw/calculate axial and shear stress distribution

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History of steel

- First production of iron approx 2000 BC
- Around 1400 - blast furnace heated with charcoal
- Complicated production of steel as the furnaces were not able to produce sufficient temperature to melt iron
- Usage only for tools and weapons
- In 1784 modern steel is produced by reduction of carbon (Cort , England)
- First use for civil engineering around 1780
- In 1813 production of coke was invented which allowed large amount of steel to be produced (Derby, England)

History of steel

- Common use of steel in civil engineering started about 1850
- 1848 hot rolled I beams were produced (Zorès, France)
- 1855 steel was produced in molten state (Bessemer process, Thomas)

Development of steel structures

- composed (battened) profiles ⇒ hot rolled compact profiles
- latticed structures ⇒ plated structures
- rivets ⇒ bolts, welds

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History of steel

Iron Bridge, 1779

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Advantages and Disadvantages of Steel Structures

☺ The best common structural material
- ⇒ convenient for large spans, tall buildings
- ⇒ allows building of slender and light structures
- ⇒ replaces concrete every time the task is too ambitious for concrete structures :-)

☺ Relatively low weight v.s. carrying capacity

steel	7850/355	= 22 (standard),	7850/800	= 10 (high strength)
concrete	2500/50	= 50	2500/100	= 25
timber	600/15	= 40	600/30	= 20
aluminium	2700/180	= 15	2700/300	= 9

☺ Fast development, production, assembling, ready to carry load (no need for hardening)

☺ Easy recycling (about 60% of steel is made from scrap)

☹ Low corrosion resistance, need for protection

☹ Low fire resistance, need for protection

☹ High cost (also because of the protection)

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Amount of produced steel

- Steel is no more the labour-intensive industry , a modern steel plant employs very few people
- Steel consumption of 300 kg per man per year can be considered a fair level of economic development
- The biggest steel producers
  - Europe
    - ArcelorMittal — Luxembourg — 97,2 mil. tons steel in 2011
    - ThyssenKryp — Germany — 17,6
    - Evraz — Russia — 16,8
  - oversea
    - Hebei Iron and Steel — China — 44,4
    - Baosteel group — China — 43,3
    - Posco — South Korea — 39,1
    - Wuhan Iron and Steel — China — 37,7
    - Nippon Steel — Japan — 33,4
- Czech Republic is one of the big producers → 600 kg steel per man per year

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Amount of produced steel

Rank (2012)	Country / Region	2007	2008	2009	2010	2011	2012
---	World	1351,3	1326,6	1219,7	1413,6	1490,1	1547,8
1	People's republic of China	494,9	500,3	573,6	626,7	683,3	716,5
---	European Union	210,2	198,2	139,3	172,8	177,7	169,4
2	Japan	120,2	118,7	87,5	109,6	107,6	107,2
3	United States	98,1	91,4	58,2	80,6	86,2	88,6
4	India	53,5	57,8	62,8	68,3	72,2	76,7
5	Russia	72,4	68,5	60,0	66,9	68,7	70,6
6	South Korea	51,5	53,6	48,6	58,5	68,5	69,3
7	Germany	48,6	45,8	32,7	43,8	44,3	42,7
…							
27	Czech Republic	7,1	6,4	4,6	5,2	5,6	5,1

Crude steel production in million tonnes (Wikipedia)

Application of steel

Europe

- 8 % of produced steel is used for civil engineering
  - 3 % for concrete reinforcement
  - 5 % for steel structures

Czech Republic

- 15 % of produced steel is used for civil engineering
  - 10 % for concrete reinforcement
  - 5 % for steel structures

Large amount of steel is used for reinforcement, this is caused by tradition of building reinforced concrete structure and by aim to save the steel for military application in 1960-1990

It is expected the amount of steel for steel structures will increase slowly to level observed in Europe

Types of Steel Structures in Civil Engineering

Use of steel in Europe

Buildings (consume 70% of steel)

- Building frames
- Industrial and storage halls
- Sport and exhibition centers
- Tribunes

Bridges (5%)

Special structures (25%)

- Structures for the hydro-engineering
- Masts and Towers
- Power plants and power engineering structures
- Bunkers, silos, gas tanks
- Blast furnaces, chemical processing plants, etc.

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Scope of the lecture

Introduction, studying of steel structures at CTU

History of steel structures

Properties of steel, advantages and disadvantages

Applications of steel structures

➡ Typical examples of steel structures

Interesting structures in Czech Republic

Production of steel

Video about steel production

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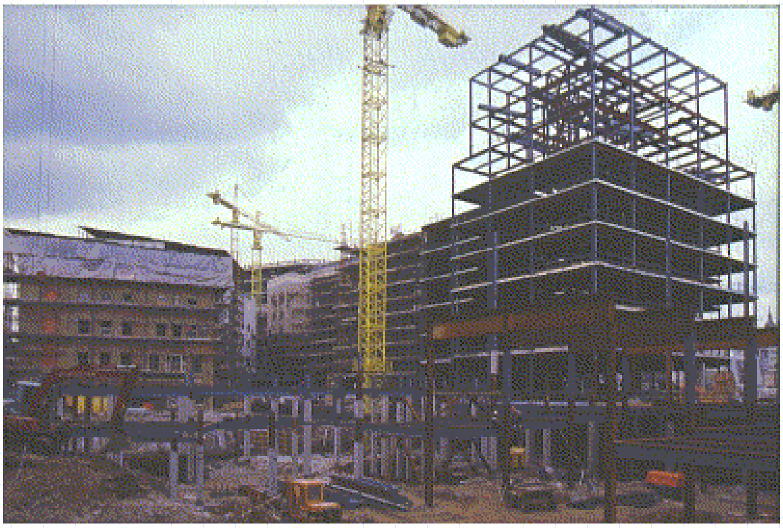
Building frames



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Building frames

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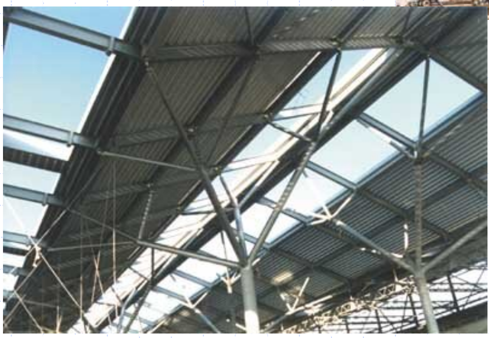
Industrial halls



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Industrial halls

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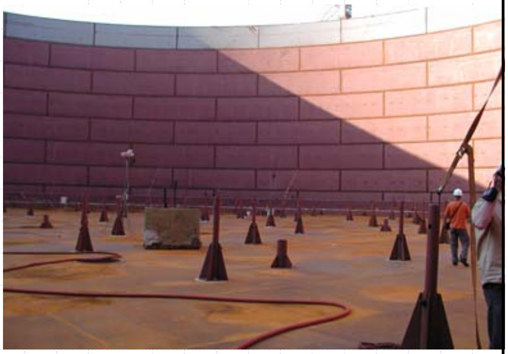
Stadiums

Sheds

Towers

Oil tanks

Capacity 125 000 m^3
The largest in Europe



Bridges

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Bridges

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Pedestrian bridges

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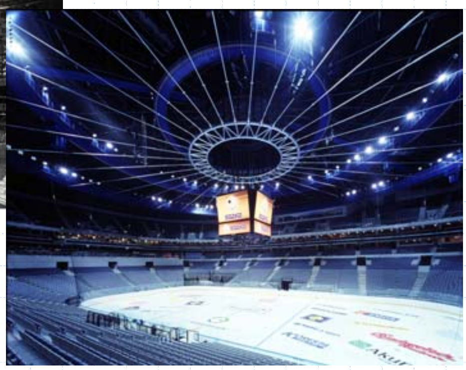
Interesting steel structures in Czech Republic
Sazka Arena (Praha)

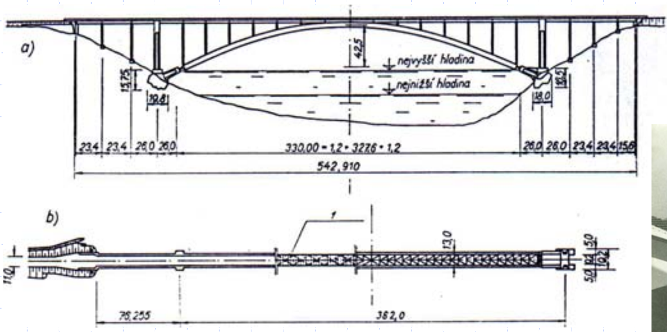
Now O_2 Arena
Build for Ice hockey championship in 2004
Elliptical plan
Diameter 135 m
Capacity 18 000 people
Bears several awards for design

Interesting steel structures in Czech Republic
Sazka Arena (Praha)

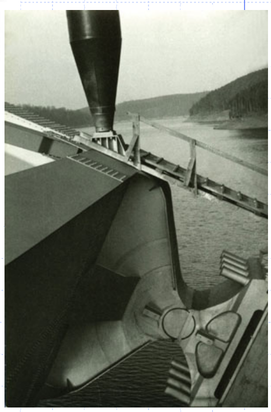


Interesting steel structures in Czech Republic
Žďákovský most - Žďákov Bridge

Interesting steel structures in Czech Republic
Žďákovský most - Žďákov Bridge



Crossing Vltava river in South Bohemia
Completed in 1967
At that time the largest steel arch in the world, replaced only in 2002



The bearing of the arch

Interesting steel structures in Czech Republic
Dlouhý most (České Budějovice)

Crossing Vltava river
Town bridge
Completed in 1998
Span 49 + 49 m

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Interesting steel structures in Czech Republic
Bridge in Stádlec

Chain suspension bridge near Stádlec (south Bohemia), span 91 m, completed in 1848, moved in 1975 from Podolsko, still in service

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Steel - what is it?

Steel - best structural material considering the weight to strength ratio

Steel is an alloy of iron (Fe) and carbon (C). Other elements are also included to influence various properties of steel

Steel = malleable iron → $C \leq 2{,}1\%$

Steel for civil engineering → $C < 0{,}2\%$

Mechanical properties

- modulus of elasticity $E = 210\,000$ MPa
- shear modulus $G = 81\,000$ MPa
- Poisson's ratio $\nu = 0{,}3$
- coefficient of thermal expansion $\alpha = 12\times10^{-6}\ K^{-1}$
- density $\rho = 7850\ kg/m^3$

Production of pig iron

Steel is produced in a two-stage process.

First, iron ore is reduced or smelted with coke and limestone in a blast furnace

iron ore = hematite (Fe_2O_3) and magnetite (Fe_3O_4)

coke = almost pure carbon (produced from black coal)

The coke reacts with oxygen (O_2) to produce carbon monoxide (CO)

$$2\,C + O_2 \rightarrow 2\,CO$$

Part of the iron ore (here the reactions are shown for hematite) reacts directly with the carbon (at high temperture, in the lower part of the furnace)

$$2\,Fe_2O_3 + 3\,C \rightarrow 4\,Fe + 3\,CO_2$$

The rest of the iron ore reacts with the carbon monoxide (at lower temperture)

$$Fe_2O_3 + 3\,CO \rightarrow 2\,Fe + 3\,CO_2$$

The flux (limestone) is used to remove impurities (mainly silicon dioxide, SiO_2) → slag

Products: pig iron (contains approx. 4 - 5% of carbon and impurities (sulphur - S, manganese - Mn, magnesium - Mg, phosphorus - P), used for further processing to obtain steel)

slag (used for road construction, etc.)

Production of steel

In the second stage, known as steelmaking, the impurities such as sulphur (S), phosphorus (P), and excess carbon are removed.

Alloying elements such as manganese (Mn), nickel (Ni), chromium (Cr) and vanadium (V) are added to influence the properties of steel

The process is performed by one of these methods

- in oxygen converters (the most common method)
- in electrical furnaces (only for high quality steels, usually not for civil engineering)

Products: various types of steel

The full process (from iron ore and black coal to final products - steel sheets and sections) is often integrated to a single factory - steel mill

Production of steel - steel mill

An integrated steel mill has all the functions for primary steel production

- iron making (conversion of iron ore to liquid iron - pig iron using blast furnaces),
- coke furnace to produce coke from black coal (and other chemicals as by-products)
- steelmaking (conversion of pig iron to liquid steel by removing the excess carbon),
- casting (solidification of the liquid steel, molten steel is cast into large blocks called ingots), or continuous casting
- roughing rolling/billet rolling (reducing size of blocks)
- product rolling (to get finished shapes).

Production of steel - steel mill

Sintering - pre-processing of the iron ore

Coke oven - to produce coke from black coal by distillation at approx. 1000ºC (other products as coal gas, ammonium, benzen, xylen and coal tar are produced, but these are not used in steel making)

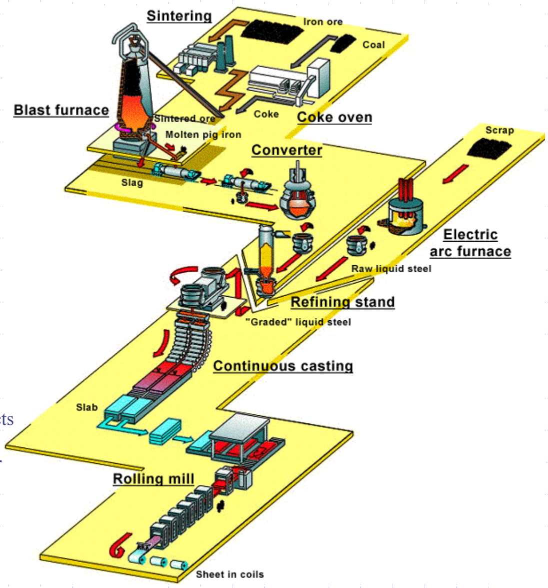
Blast furnace - to produce pig iron (high carbon content and impurities)

Converter - to remove excess carbon (alloying elements can be added)

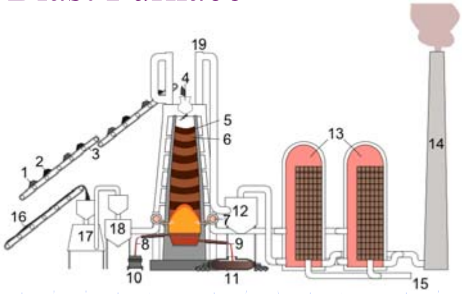
Electric arc furnace - another method to produce steel from pig iron mostly from scrap (pig iron can be added)

Continuous casting - to allow the liquid steel to solidify, slabs are produced for further processing - rolling

Rolling mill - to produce the final products (steel sheets in coils are shown here, but many different products can be obtained - steel sheets, I, H, L etc. sections, reinforcing bars for concrete, etc.)



Blast Furnace



1 Iron ore + Calcareous sinter
2 Coke
3 Conveyor belt
4 Feeding opening, with a valve that prevents direct contact with the internal parts of the furnace and outdoor air
5 Layer of coke
6 Layers of sinter, iron oxide pellets, ore,
7 Hot air (around 1200˚C) is injected into the furnace
8 Slag
9 Liquid pig iron
10 Mixers
11 Tap for pig iron
12 Dust cyclon for removing dust from exhaust gasses before burning them in 13.
13 Air heater
14 Smoke outlet (can be redirected to carbon capture & storage (CCS) tank)
15 Feed air for Cowper air heaters
16 Powdered coal
17 Cokes oven
18 Cokes bin
19 Pipes for blast furnace gas

Blast furnace Antiguo Alto horno de Sestao, Spain; technical cultural monument

From left to right
- chimney
- air pre-heaters
- gas pipe with dust bag
- blast furnace
- inclined elevator to feed the furnace
- winch house

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Steel production

Goal: to eliminate the of excess carbon

Discontinued methods

- **in Bessemer converters, 1855-1968**
- **in open hearth furnace (Siemens-Martin process), 1865-1990**
  the older method, now is rarely used and replaced by other methods

Modern methods

- **basic oxygen steelmaking in oxygen converters, 1952-present**
  the most common method at present, approx. 60% of steel is produced this way
- **in electric arc furnaces , 1907-present**
  only for special types of steel - high electricity consumption, therefore expensive, not used for steel for civil engineering

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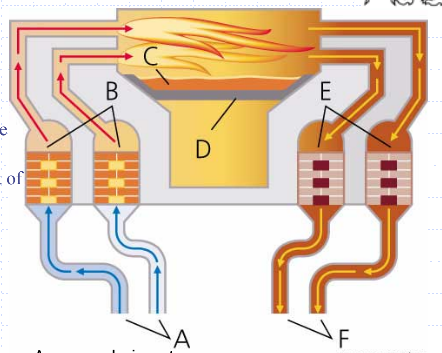
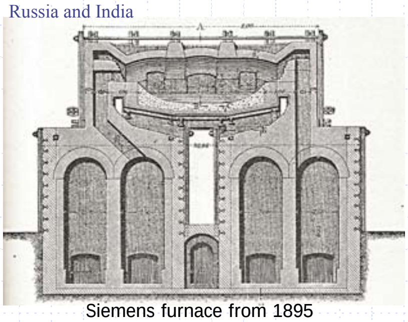
Open hearth furnace
Siemens – Martin process

- furnace is heated by gas
- need of additional source of energy (gas), quite expensive and slow (approx 8-12 hours/batch) = not efficient
- can take 50 to 100 tons of steel, can process high amount of scrap or cold pieces of pig iron (up to 80% of volume)
- hot air is blown into the molten iron to burn the carbon (carbon dioxide is created) and the impurities (various oxides are created which flow atop the steel and create slag)
- most furnaces were closed in 1990', now used only in Russia and India



A gas and air enter
B pre-heated chamber
C molten pig iron
D hearth
E heating chamber (cold)
F gas and air exit



Siemens furnace from 1895

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Basic oxygen steelmaking
Oxygen converter process

- invented by Henry Bessemer in 1858 but introduced into industry in 1950' when pure oxygen was available at large quantities and low price
- converter = thick walled vessel with calcium or magnesium oxide lining to withstand high temperature
- it is filled with liquid pig iron and scrap which melts there
- the oxygen is driven into the molten iron at high pressure and high velocity (exceeding 1 Mach) through water cooled jet
- carbon included in the iron is burned producing carbon monoxide and dioxide → carbon content is reduced
- no additional heat source, heat is released from carbon oxidation (proper ratio of pig iron and scrap is important)
- silicon and phosphorus oxides flow on top of the molten iron forming the slag
- can take 200 to 300 tons of steel, fast process, it takes approx. 40 minutes
- other substances could be added to the molten steel when conversion is complete
- the most common method at present, more than 70 % of steel in CR was produced in oxygen converters in 2004

Bessemer converter, Kelham Island Museum, Sheffield, England

Oxygen converter is similar in shape, oxygen is blown instead of air (used in past)

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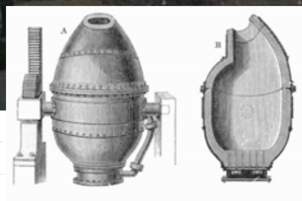
Basic oxygen steelmaking
Oxygen converters

Charging the oxygen converter,
steel mill Maxhütte, Germany

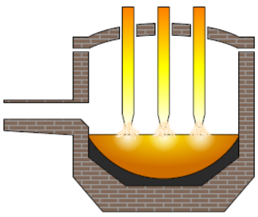


Bessemer converter,
schematic diagram

Bessemer converter in operation
Youngstown, Ohio, 1941

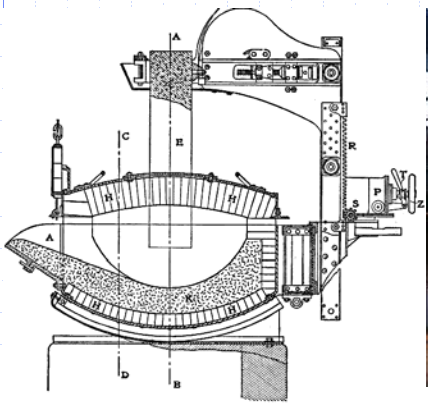
Electric arc furnace

- high production cost, huge consumption of energy (furnace often operate off peak hours to use cheap electricity)
- used for high quality (alloyed) steel, stainless steel
- not used for structural steel
- typical capacity is 80 tons, the largest has capacity 300 tons (in Turkey)
- the furnace is filled with scrap and pig iron (solid or liquid), which are heated and melted by electric arc
- oxygen is blown into the molten metal to oxidize the impurities (they form slag flowing atop) and reduce carbon content
- alloying elements can be added to molten steel
- fast process, takes approx. 70 minutes



The roof of an arc furnace removed,
showing the three carbon electrodes

Electric arc furnace



A schematic cross section through arc furnace.
E is an electrode (only one shown), raised and lowered by the rack and pinion drive R and S. The interior is lined with refractory brick H, and K denotes the bottom lining. A door at A allows access to the interior. The furnace shell rests on rockers to allow it to be tilted for tapping

White-hot steel pours like water from a 35-ton electric furnace into a small ladle car.
The transformer vault can be seen at the right side of the picture. For scale, note the operator standing on the platform at upper left. This is a 1941-era photograph and so does not have the extensive dust collection system that a modern installation would have, nor is the operator wearing a hard hat or dust mask

Chemical composition of steel
The Influence of Carbon

Carbon is the main alloying element in steel

- it increases tensile strength and hardness
- it reduces ductility and fracture toughness

- steel → carbon content < 2,1% (carbon is diluted in iron forming various crystalline structures)
- cast iron → carbon content > 2,1% (carbon is presented in cementite = iron carbide - Fe_3C, which is very hard and brittle)
- steel for civil engineering → carbon content < 0,2%

- weldability

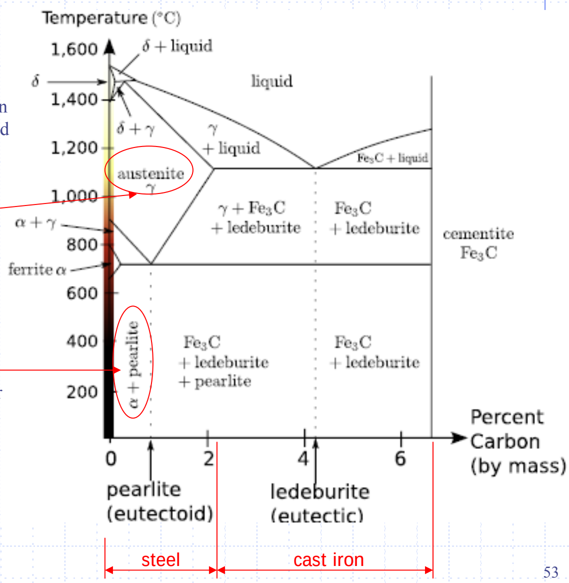
  can be expressed as carbon equivalent (substitute content of the alloying elements in percents by mass)

$$CEV = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

$CEV < 0,4$ to ensure good weldability

Iron-carbon equilibrium phase diagram

- iron alloy crystallizes in various modifications with very different properties
- the most important (for the steels used in civil engineering) are ferrite, pearlite and austenite
- austenite = γ iron (which can dissolve considerable amount of carbon) forms at temperatures above 750 °C
  → soft, strong, ductile
- when slowly cooled, austenite will change to ferrite and pearlite
- ferrite = α iron can not dissolve carbon (=pure iron), therefore pearlite (lamellar structure of ferrite and cementite = iron carbide - Fe_3C) forms to accommodate the carbon
  → soft, strong, ductile



Heat treatment

Heat treatment is used to influence the mechanical properties of steel

- when steel is cooled naturally in the air, it is normalised, ferrite and pearlite are formed
  → soft, strong, ductile
- annealing is the process of heating the steel to a sufficiently high temperature to soften it. This process occurs through three phases: recovery, recrystallization, and grain growth. It is used to recover "damaged grains" after forming, rolling, etc.
- when steel is cooled rapidly (quenched) austenite will not change to ferrite and pearlite as the atoms do not "have time" to form the pearlite
  instead, martensite forms, it has long thin lens-shaped crystal (not shown on the phase diagram, it is not an equilibrium phase)
  → hard, brittle, usually not desired
- martensite can be easily "destroyed" by heat = steel needs to be heated below the transformation temperature and allowed to cool slowly = tempering
- many high strength steels require certain amount of martensite (to get desired hardness and strength) - they are quenched and tempered until only the desired amount of martensite exists

Chemical composition of steel
The Influence of other alloying elements

- **nickel** - Ni and **manganese** - Mn add to tensile strength and make austenite more chemically stable, increase the resistance to brittle fracture
- **chromium** - Cr increases hardness and melting temperature
- **vanadium** - V increases hardness while reducing the effects of metal fatigue
- **copper** - Cu increase corrosion resistance (weather resistant steel steel Corten, Atmofix), but decrease the mechanical properties (max. content 0,4%)

- **sulphur** - S, **nitrogen** - N, and **phosphorus** - P make steel more brittle, needs to be removed
- **oxygen** - O, **nitrogen** - N, undesirable, contribute to aging of steel (decrease of toughness over time)
these gases are presented as small bubbles, when oxygen is removed by adding aluminum powder, the steel is "killed"

- the chemical composition has influence on the weldeability (shown before) expressed as carbon equivalent

$$CEV = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

Deoxidation of steel

- Deoxidized steel is steel that has some or all of the oxygen removed from the melt during the steelmaking process.
- Liquid steels contain dissolved oxygen after their conversion from molten iron, but the solubility of oxygen in steel decreases with temperature. As steel cools, excess oxygen escapes (the steel seems to be "boiling"because of the bubbles escaping), can cause blowholes or precipitate FeO → not desired.
- Adding metallic deoxidizing agents to the melt will remove the oxygen

- Types of steel:
  - **Killed steel** - steel with all oxygen removed, quietly solidify in the mould, with no gas bubbling out
  - **Semi-killed steel** - mostly deoxidized steel, but the carbon monoxide is presented as smal bubbles creating a porosity. This is removed after rolling. Mostly used for structural steel.
  - **Rimmed**
  - **Capped**

  } - no deoxidizing agents, used for cold forming and drawing

Chemical composition of steel
Types of steel

- **carbon steel**, composed simply of iron and carbon, accounts for 90% of steel production. It has small additions (usually < 2% by weight) of other elements, typically 1,5% manganese - Mn, to provide additional strength for a modest price increase.
- **low alloy steel** is alloyed with other elements, usually molybdenum - Mo, manganese - Mn, chromium - Cr, or nickel - Ni, in amounts of up to 10% by weight to improve the hardenability of thick sections.
- **stainless steels** and surgical stainless steels contain a minimum of 11% chromium, often combined with nickel, to resist corrosion (rust). It is used mainly for because of architect wishes, it is very expensive (there are other methods of corosion protection, much cheaper).
- **weathering steels** such as Corten, Atmofix, which weather by acquiring a stable, rusted surface, and so can be used un-painted. It contains small amount of copper - Cu.

- many other types exist which **are not used in civil engineering**
  - **tool steels**, which are alloyed with large amounts of tungsten and cobalt, used in axes, drills, and other devices that need a sharp, long-lasting cutting edge
  - **dual-phase steel**, which is heat treated to contain both a ferritic and martensitic microstructure for extra strength
  - etc.

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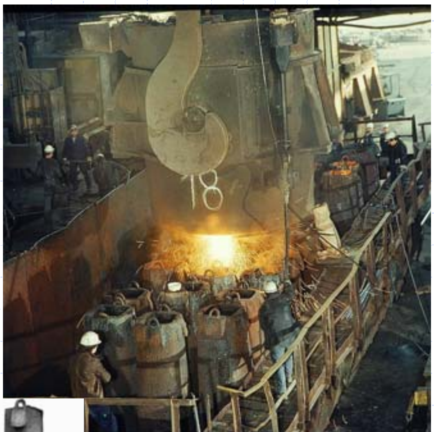
Ingots casting

- an **ingot** is steel, that is cast into a shape suitable for further processing
- the mold is conical to allow stripping
- crack creates on top, approx. 20% of the ingot must be cut of and melted again - not efficient method
- old method, now replaced by continuous casting, only 4% of steel is cast into ingots at present



Teeming ingots at a steel mill


Ingots stripped from the moulds


Ingot moulds on a car

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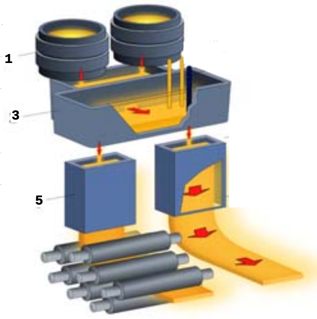
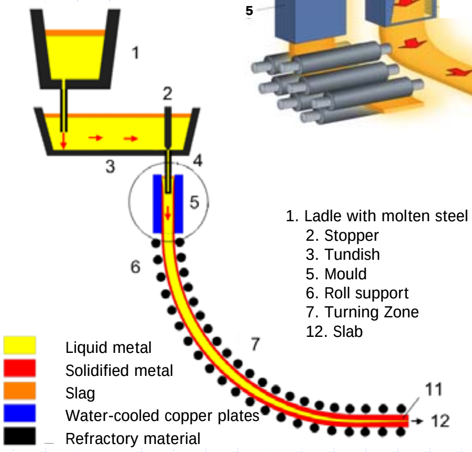
Continuous casting

- molten metal is tapped into the ladle from furnaces
- after treatment (alloying and degassing) it is transferred to tundish (a reservoir)
- then it is poured to water cooled mould, where the surface of the steel solidifies
- it is passed to a set of rollers which transport it away from the mould (as new steel is being poured into the mold), it is sprayed with water for additional cooling
- at the end, the continuous strip is cut to pieces
- typically, slabs thickness 180-250 mm, width up to 1600 mm, length up to 12 m are produced at velocity 1,4 m/min
- other products are available
- this method is used for 96% of steel





The continuous casting process

Scope of the lecture

Introduction, studying of steel structures at CTU
History of steel structures
Properties of steel, advantages and disadvantages
Applications of steel structures
Typical examples of steel structures
Interesting structures in Czech Republic
Production of steel
→ Video about steel production

Thank you for your attention