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

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Scope of the lecture

- **Corrosion protection**
  - Corrosion
  - Protection: painting, metal coating, duplex systems
  - Stainless and weathering steels
  - Economy of corrosion protection
- Fire resistance
  - Design principles
  - Fire protection
- Life cycle assessment

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Corrosion

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Corrosion

Eiffel Tower Maintenance

- The Eiffel Tower is built of riveted wrought iron, a material that will last virtually forever if it is painted regularly. Since it was built (for the International Exhibition of Paris in 1889), the tower has been painted once every seven years.
- Maintenance on the tower includes applying 50 metric tons of three graded tones of paint every 7 years to protect the 200,000 square meters of iron lattice work from rust.
- The darkest paint is used at the bottom and the lightest shade at the top. Each repainting, by 25 painters working for 15 months, requires 1500 brushes, 5000 sanding disks and 1500 sets of work clothes.
- On occasion, the color of the paint is changed. The tower is currently painted to a shade of brown.
- Corrosion damage is a major consideration in the maintenance / refurbishment requirements. The 1989 refurbishment costs of 200 million FF.

Repainting of the Eiffel tower

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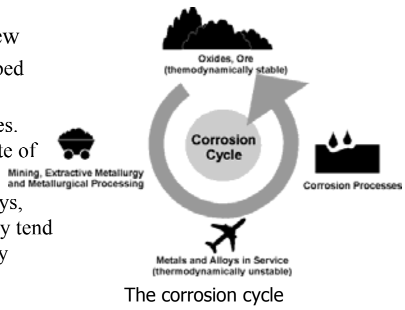
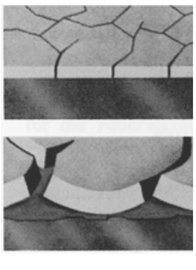
Corrosion

Corrosion from thermodynamics point of view

- In view of this cycle, corrosion has been described "extractive metallurgy in reverse".
- Thermodynamics is concerned with energy states. The original metallic ores are said to be in a state of low energy. External energy is applied in the conversion of the ores to usable metals and alloys, transforming them to a higher energy state. They tend to revert to a lower (more stable) energy state by reacting with a corrosive environment.



The corrosion cycle



- The paint contains micro cracks which allow the water and oxygen access to the steel surface
- Iron in the steel is oxidized to produce rust, which occupies approximately 6 times the volume of the original material. As the volume increase, the paint is peeled of

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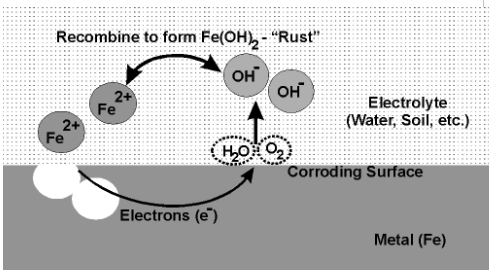
Corrosion

Electrochemical reaction

Iron + Oxygen

Electrolyte = water

Critical humidity 60 to 75 %



Principle of electrochemical corrosion

Protection of structures = stopping the reaction

Separation of steel from atmosphere - painting

Electrochemical – coated with zinc or aluminum layer

Using special alloyed steels – stainless, weathering steel

Take care of structural detailing – proper detailing avoids accumulation of water and dust which increase the risk of corrosion

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Surface treatment before application of the protection

Proper cleaning of the surface has significant effect on the quality and durability of the corrosion protection – paint, zinc coating – as it provide perfect bond to the steel surface

De-greasing

Removing rust and iron scales

- By hand (mechanical brushes) – not very effective
- By flame
- Cure in acid
- Blasting the surface – the most effective
  - Steel grit
  - Siliceous sand
  - → these are blown in air stream at high velocity, as they hit the steel surface, any loose particles (rust, scales, old paint, etc.) are removed

Making rough surface to get sufficient bond of paint layers

After surface treatment the protection must be applied "immediately" as the corrosion starts again quickly

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Grit blasting

Grit blasting of steel beams on-site
suitable for repairing of existing structures

Grit blasting in the workshop
takes place in "chamber" to reduce
health risk and polution

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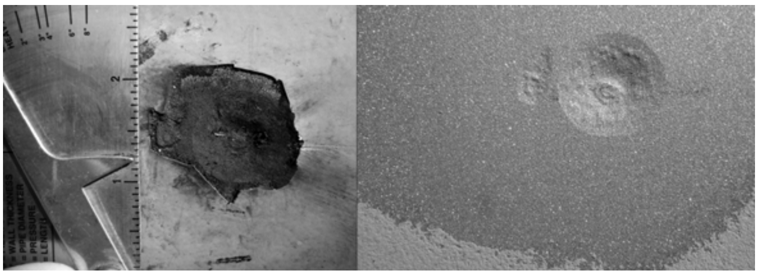
Cleaning of surface



Corrosion pit before and after abrasive blasting (scale in inches)

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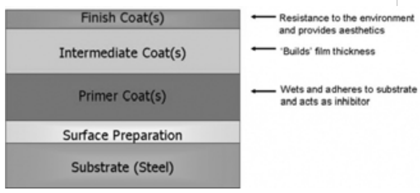
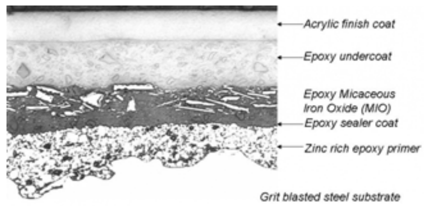
Painting

Paint systems – set of layers of paint to provide the protection (from bottom to top):

- Prime coat
  - To bond the paint to the surface
  - Two to three layers are applied
- Intermediate / build coats
  - It provides the protection to corrosion
  - The thicker the coating the longer the life
  - Three to four layers are applied
  - Thickness of single layer of paint - 25 μm up to 100 μm in aggressive environment
- Sealing coat
  - Aesthetic purpose – it gives the final colour
  - Protects the underlying layers from wear
  - One layer (sometimes two layers) is applied
  - Might be applied on site
  - Thickness of layer from 25 to 100 μm





Cross section through a multi-coat paint system

Application of paint

- Brush
  - slow, therefore expensive
  - suitable for small areas, repair
- Roller
  - for large flat areas
- Air spray
  - the most common method
  - the paint creates fine droplets which are transported by compressed air (pressure about 7 bars)
  - adjustments of the spray nozzle and air pressure must be made by a skilled operator
- Airless spray
  - the paint is driven at high pressure to the nozzle where the droplets are created and fly to the painted surface (similar way like watering within garden hose)
  - high pressure (up to 280 bar) is required
  - expensive equipment, skilled operator is required

Coating application in the fabrication factory

Durability of paint - corrosivity category

Corrosivity category and risk	Low-carbon steel thickness loss (μm after first year)	Examples of typical environments in a temperate climate (informative only)	
		Exterior	Interior
C1 very low	⩽ 1,3	-	Heated buildings with clean atmospheres, e.g. offices, shops, schools, hotels
C2 low	> 1,3 to 25	Atmospheres with low level of pollution Mostly rural areas	Unheated buildings where condensation may occur, e.g. depots, sports halls
C3 medium	> 25 to 50	Urban and industrial atmospheres, moderate sulphur dioxide pollution Coastal area with low salinity	Production rooms with high humidity and some air pollution e.g. food-processing plants, laundries, breweries, dairies
C4 high	> 50 to 80	Industrial areas and coastal areas with moderate salinity	Chemical plants, swimming pools, coastal, ship and boatyards
C5-I very high (industrial)	> 80 to 200	Industrial areas with high humidity and aggressive atmosphere	Buildings or areas with almost permanent condensation and high pollution
C5-M very high (marine)	> 80 to 200	Coastal and offshore areas with high salinity	Buildings or areas with almost permanent condensation and high pollution

Durability of paint

The durability is affected by:

- Environment (corrosivity of the atmosphere)
- Surface preparation
- Conditions of application (temperature, humidity)
- Dry film thickness

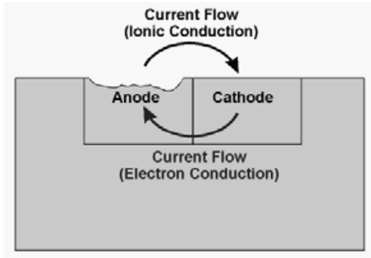
Painting system lasts usually 10 years

- Renovation of paints usually takes place after 20 to 30 years, when about 5 % of surface is attacked by corrosion

Guarantee period is not longer than 5 years

Electrochemical corrosion - principle

Magnesium
Zinc
Aluminum
Carbon steel
Cast iron
Lead
Tin
Copper, brass, bronze
Nickel
Stainless steel
Silver
Gold



Principle of electrochemical corrosion

When two metals are joined together, the metal placed above the other (in this table) serves as anode

The anode corrodes preferentially

Consumption of anode ⇒ protection of cathode

Anode is aluminum or zinc in practical application (they corrode very slowly and are cheap)

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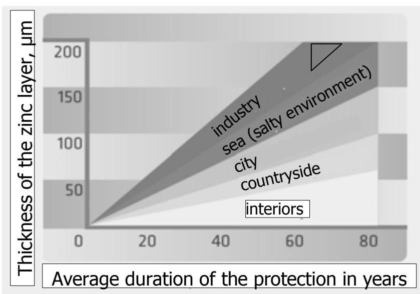
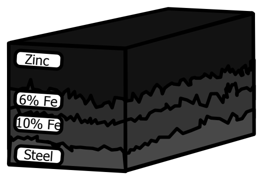
Hot dip zinc coating (galvanizing)

Submerging the element in molten zinc bath (temperature approx. 450°C)

- At least 275 g/m² is required, which corresponds to thickness 40 μm
- Normally, 70 - 80 μm is applied, up to 140 μm is used in aggressive environment
- Zinc creates zinc-iron alloys, which create the bond to the surface
- Size of the elements is limited by the bath, the largest in CZ is 15,2×1,7 ×2,8 m





The layers of zinc-iron alloys on the protected surface

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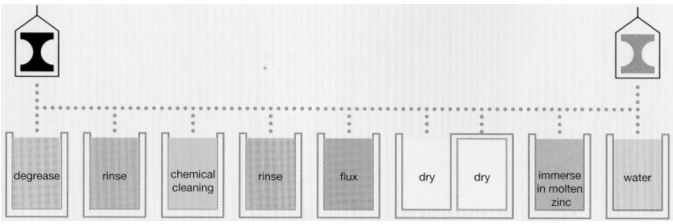
Hot dip zinc coating - the process

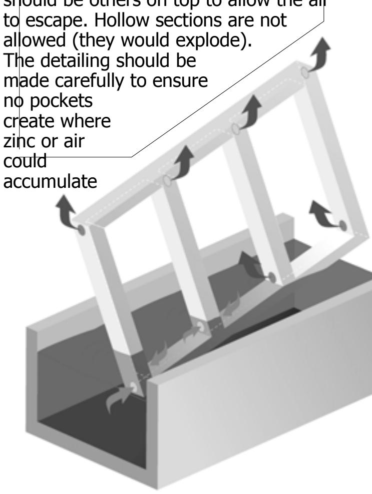
The process requires several steps:

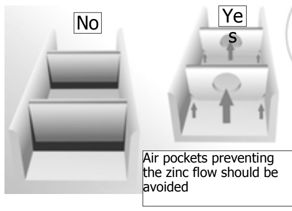
- degreasing and removing surface contamination (only special markers should be used during production otherwise the zinc layer is not created at these spots)
- curing in acid (HCl) to remove rust and scales
- washing away the acid
- flux bath: ammonium chloride (NH_4Cl) and zinc chloride ($ZnCl$) to increase the wettability
- submerging in the molten zinc
- cooling in water or in air
- control and repairing the surface with zinc-rich paint (at the spots where the zinc coating is not present), if necessary



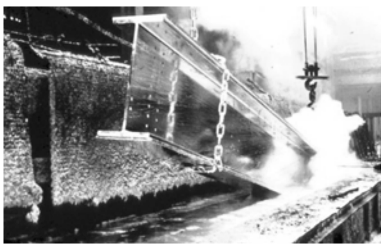
Hot dip zinc coating - the process

Submerging the structure into zinc: openings allow the zinc to flow in, there should be others on top to allow the air to escape. Hollow sections are not allowed (they would explode). The detailing should be made carefully to ensure no pockets create where zinc or air could accumulate





Air pockets preventing the zinc flow should be avoided



Steel beam being withdrawn from hot-dip galvanizing bath

Duplex systems

Hot-dip galvanizing plus painting

Reasons

- future maintenance is likely to be difficult to carry out
- the zinc coating is thin, as on continuous galvanized thin steel sheets
- aesthetic reasons
  - giving the matt grey zinc surface a more pleasing appearance
  - warn of the existence of a structure
  - to camouflage the structure

Durability

$$LT = K\left(LT_{Zn} + LT_p\right)$$

where

LT service life of the protection

K factor (1,5 to 2,3) depending on the environment

LT_{Zn} estimated life of the zinc coating

LT_p estimated life of the paint coating

The lighthouse Pater Noster is one of the first duplex treated steel constructions in Sweden. It was galvanized in 1868, and after that painted

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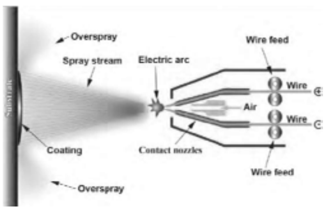
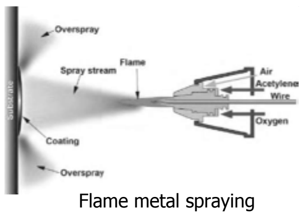
Metal spraying

Metal spraying

- Spray of molten metal (zinc, zinc alloys or aluminum) by special gun
- The metal is heated by electric arc or flame
- The droplets of molten metal solidify rapidly and are attached to steel surface by mechanical interlocking (no diffusion bonding)
- Creates “porous-like” surface protection, sealing layer is often applied to give a smoother surface, reducing the pickup of dirt and other contaminants
- Thickness 80 up to 150 μm, but 300 μm can be achieved
- Can be applied on site or in the workshop
- Does not bring significant heat input to the steel structure, therefore material properties are not modified by heating/cooling



Twin wire arc spraying



Flame metal spraying

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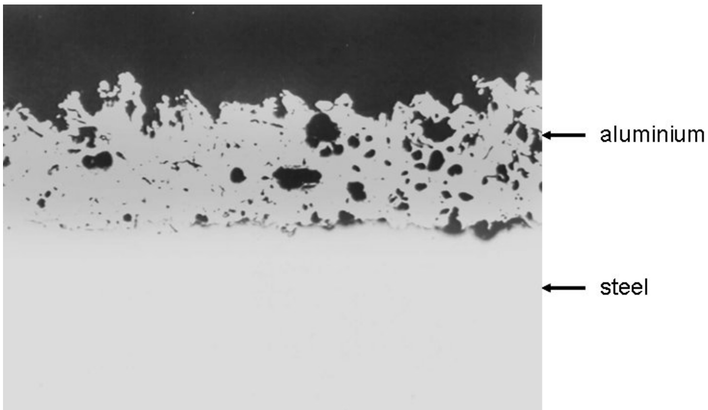
Metal spraying



Cross-section through a thermally sprayed aluminum coating

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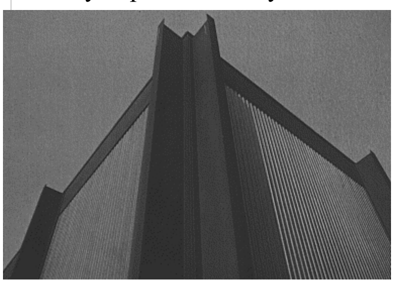
Stainless steel

Steel alloyed by chrome (more than 14%) and nickel

Very expensive - only used for facades and interior elements



Stainless steel used for façade elements

Interior stainless steel elements

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Weathering steel

- Developed in USA in about 1930
- Low alloyed steel (alloyed by chrome, nickel,copper and phosphorus, total approx. 1%)
- About 30 types produced worldwide
  - Europe – Corten A, Corten B
  - Czech Republic - Atmofix A, Atmofix B
- Layer of compact protective rust creates on the surface after 2-4 years
  - The corrosion is significantly reduced (but not stopped) after about 4 years
  - Alternating of wet and dry atmosphere is required to create the protective layer
  - The layer does not increase in volume
- No need for any corrosion protection (painting, zinc coating, etc.)
- Design: increase the thickness by 1,5 mm to allow for the corrosion of the element
- Can be used only in situations when stains from the rust do not damage other structures
- Application
  - Bridges
  - Transmission lines
  - Facade - metal sheets

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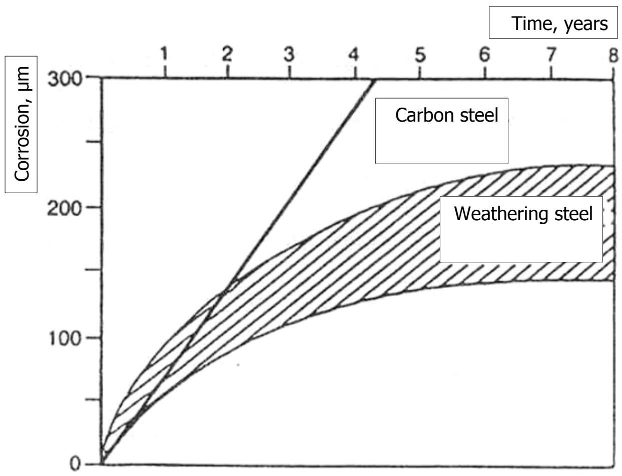
Corrosion of weathering steel



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Weathering steel

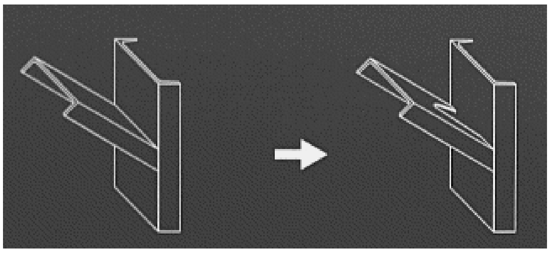
Steel-concrete composite bridge on highway D47
under construction from weathering steel

Weathering steel

Example of structures from weathering steel

Structural detailing

- Design of structural details is important, zones where water and dust may accumulate should be avoided
- Contact of different metals should be avoided – electrochemical corrosion
- Sharp edges, corners and narrow spaces should be avoided
- Inspection and maintenance should be carried out periodically
- Zinc coated bolts are normally used (bolts normally cannot be painted as the structure is painted in advance)



Modification of structural detailing to avoid water accumulation

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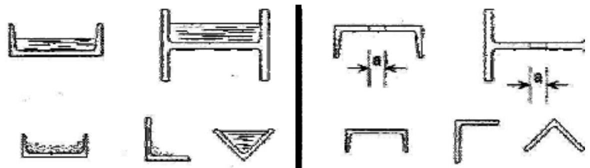
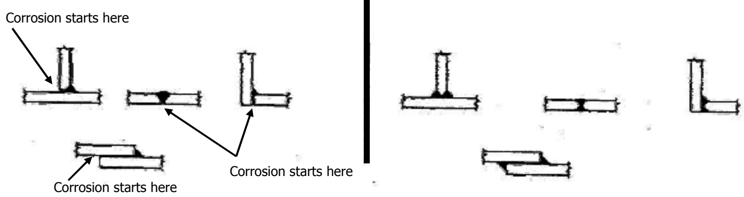
Structural detailing



Not suitable, water and dust can accumulate

Suitable, water is drained away



Not suitable weld arrangement

Suitable weld arrangement

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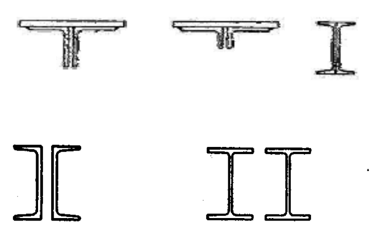
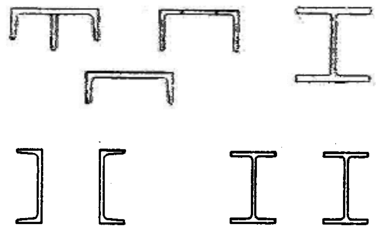
Structural detailing



Not suitable, narrow spaces do not allow proper maintenance



Suitable, narrow spaces are avoided

Cost optimization

Total cost of the structure:

Production + <u>Maintenance</u> + Dismantling

Design lifetime of structures is 50-100 years

The maintenance cost might be high when the corrosion protection is not designed properly

Maximum allowed loss of material due to corrosion is 150 μm (to calculate nominal dimensions of the elements)

Scope of the lecture

- Corrosion protection
  - Corrosion
  - Protection: painting, metal coating, duplex systems
  - Stainless and weathering steels
  - Economy of corrosion protection
- ➡ Fire resistance
  - Design principles
  - Fire protection
- Life cycle assessment

Requirements to structures at fire

Design at fire:
- limit states are also taken into consideration
- time period while the requirement is satisfied gives the people the chance to escape

The requirements
- Resistance (strength) - R 15, R 30, R 45, R 60 or even more (in minutes)
- Integrity - E (no cracks appear or no joints open which prevents the smoke and flames to pass through the structure)
- Insulation - I (maximum temperature of the unexposed face of the slab, wall, etc. must not exceed 180°C and the average temperature must not exceed 140°C)

The requirements can be combined when applicable – REI 60

Examples:
- multi-storey building (many people, long escape routes) → R60 to R90
- single storey industrial building (few people, easy to escape) → R15 (R30)

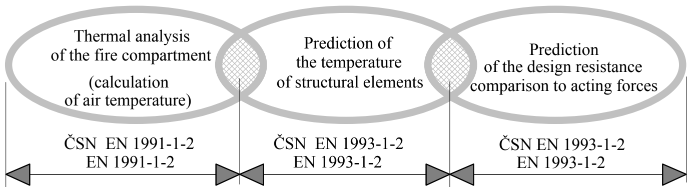
Design at fire situation

At fire, the resistance of the structure is evaluated for accidental load combination, i.e. the fire is the accidental load and the other loads (dead, variable, snow, wind) are considered as average values – partial safety factors are equal to 1 → the load is smaller than load at ULS

The effect of fire is introduced by increasing temperature → various time–temperature curves are used, these represent increase of the air temperature

The temperature of structural elements needs to be evaluated, it is based on the air temperature

At high temperatures, all materials loose strength and stiffness, the resistance is reduced



Three steps of design to fire

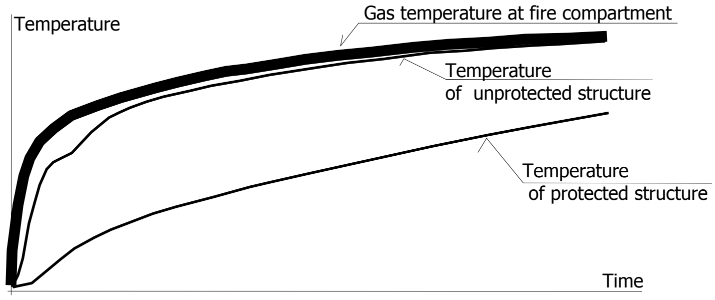
Thermal analysis - standard fire

Traditional method (often conservative)

Standard fire takes the gas temperature from formula $\theta_g = 20 + 345 \log_{10}(8\,t + 1)$

Does not correspond to “real” fire

No data are necessary



Time-temperature curve of standard fire
and temperature of unprotected and protected steel elements

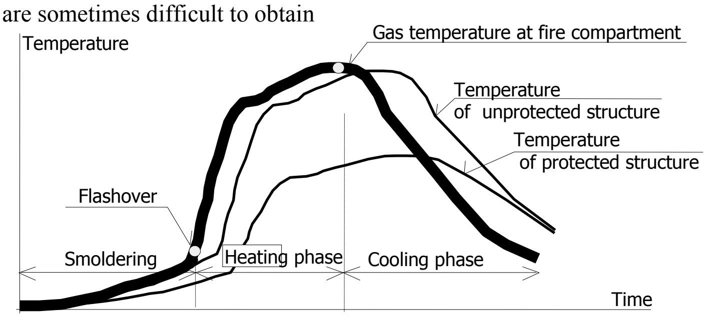
Thermal analysis - natural fire

Modern method – performance method to predict the behaviour of the fire

Natural fire takes into account "real" conditions at fire

- amount of combustible materials
- size of opening (bring fresh air - oxygen - necessary for burning)
- size of the fire compartment
- thermal properties of walls, and more

The data are sometimes difficult to obtain



Time-temperature curve of natural fire
and temperature of unprotected and protected steel elements

Prediction of temperature of steel elements

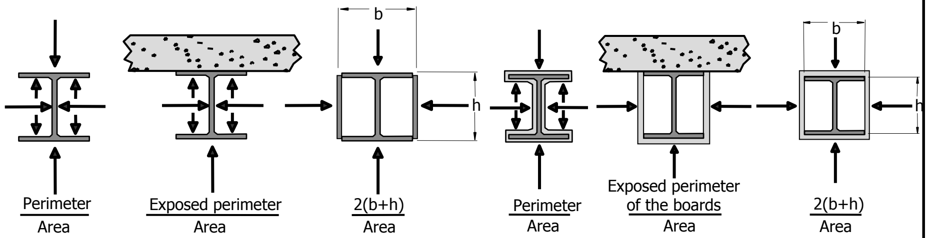
The temperature is calculated from the air temperature

It depends on the section factor *A*/*V*

A perimeter of the section exposed to fire

V section area of the section

Sections with higher *A*/*V* heat up faster



Definition of section factor A/V for unprotected and protected steel elements

Prediction of temperature of steel elements

Temperature of steel structure recorded by thermo camera during fire test

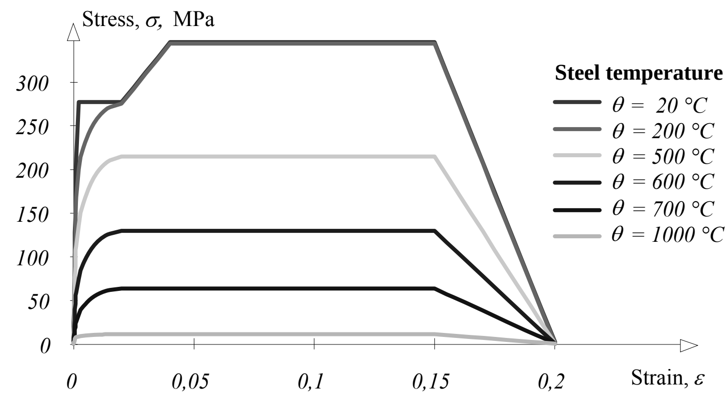
Note: Secondary beams (smaller section, higher *A*/*V*) heat up and cool down faster than the primary beam (bigger section, lower *A*/*V*)

Heating phase (30 min)

The maximum temperature (54 min)

The end (240 min)

Stress-strain diagram of steel at high temperature

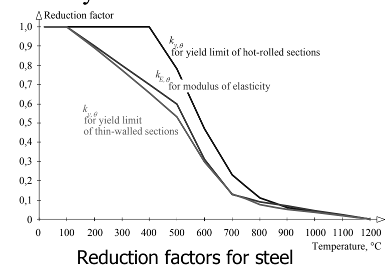


Reduction factors for steel and concrete

Change of material properties is introduced by reduction factors

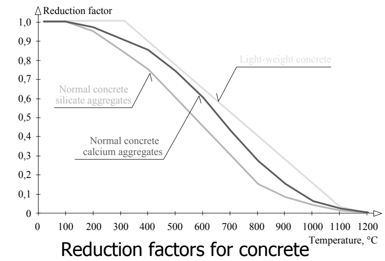
for yield limit $f_{y,\theta} = k_{y,\theta}\ f_y$

for elastic modulus $E_{a,\theta} = k_{E,\theta}\ E_a$



Reduction factors for steel

for concrete $f_{c,\theta} = k_{c,\theta}\ f_{ck}$



Reduction factors for concrete

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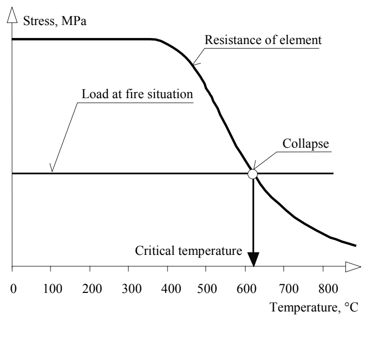
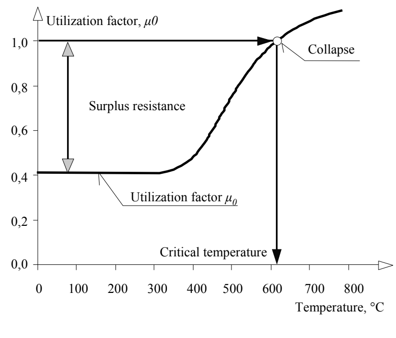
Critical temperature

At critical temperature, the resistance is reduced to the applied load

When the temperature is (even slightly) increased, the structure will collapse

It is not a constant value, for smaller utilization factor μ_0 higher critical temperature is obtained





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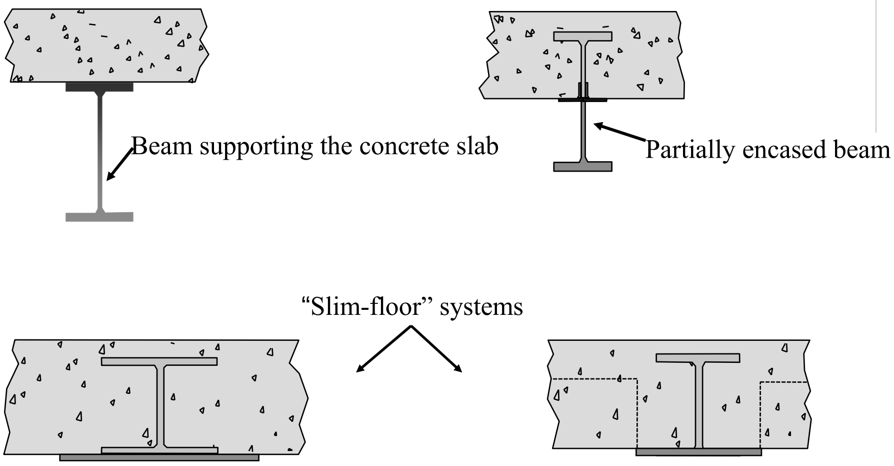
Fire protection - concrete encasement

Concrete is perfect material for thermal insulation of steel elements at fire



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Fire protection - board protection

Board fire protection at fire test in Mokrsko, 18 September 2008

- in preparation
- the joints are not sealed
- the column and the diagonals are not protected
- only the castellated beam should remain unprotected

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Fire protection - board protection

Fire test in Mokrsko, 18 September 2008

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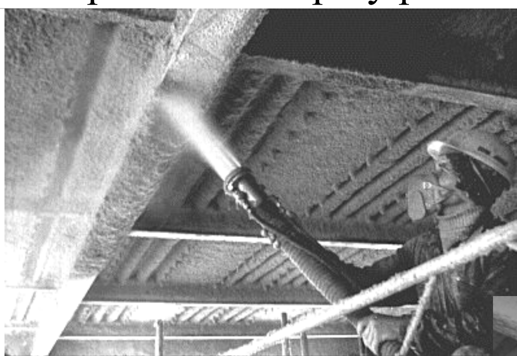
Fire protection - spray protection



Spray protection is the cheapest way of fire protection

Not very aesthetic, it is usually hidden by suspended ceiling

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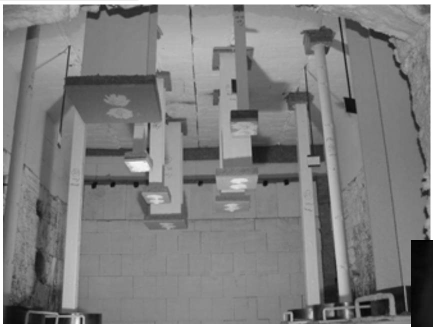
Fire protection - intumescent paint



Before test

During the test

- Intumescent paint increase volume by creating porous material
- It protects the steel elements from fire
- It is aesthetic and can be applied on visible parts of structures
- Can be easily damaged

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Fire protection - intumescent paint

After the test

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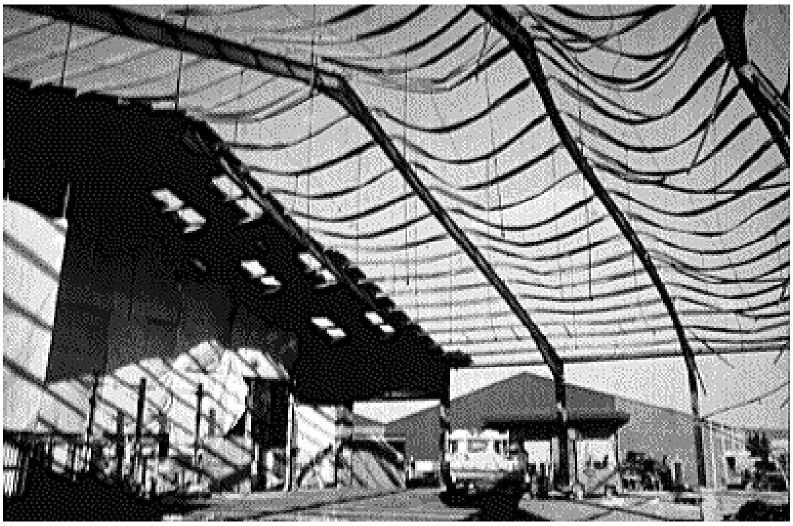
Fire safe structure



Fire safe structure – no collapse was observed, people were not in danger when escaping / fighting with fire

Scope of the lecture

- Corrosion protection
  - Corrosion
  - Protection: painting, metal coating, duplex systems
  - Stainless and weathering steels
  - Economy of corrosion protection
- Fire resistance
  - Design principles
  - Fire protection
- ➡ Life cycle assessment

Life cycle thinking

The way to identify possible improvements to goods and services in the form of lower environmental impacts and reduced use of resources across all life cycle stages

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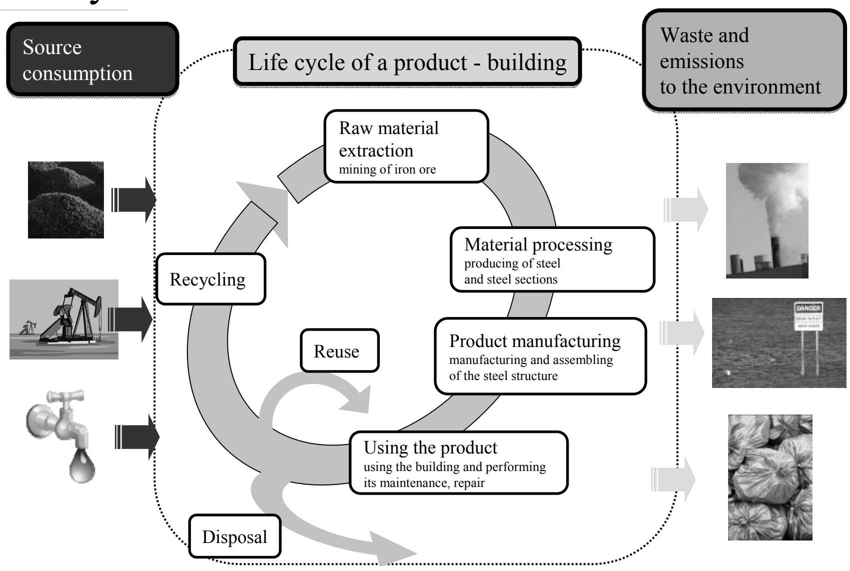
Life Cycle Assessment



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Life Cycle Assessment
Comparison of steel and concrete structures

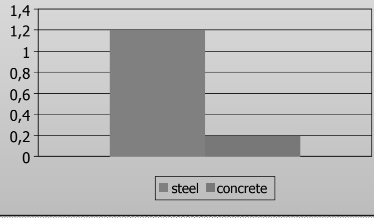
Life Cycle Assessment is applied to functional unit

Example: 1m² of tiles, 1 beam designed for particular load and span, 1 kg of cement

only products with equal parameters can be compared

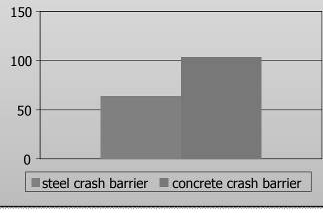
compare to

1 kg of steel — 1 kg of concrete



compare to

1 m of steel crash barrier — 1 m of concrete crash barrier



Conclusion: steel is more demanding material, but less amount is needed for 1 m of the crash barrier

Life Cycle Assessment

Free software AMECO v.3 can be downloaded from:
http://steel.fsv.cvut.cz/LVS3/index.htm

Thank you for your attention