2E14

Design of aluminium and stainless steel structures

František Wald
List of lessons

1) Aluminium structures
2) HAZ softening
3) Design of aluminium elements
4) Design of aluminium connections
5) Design beyond the elastic limit
6) Aluminium advanced design
7) Stainless steel structures
8) Stainless steel material and material properties
9) Specialty in design of stainless steel structural elements
10) Connection design
11) Erection and installation of stainless steel structures
12) Stainless steel advanced design
Objectives of the lecture

- Introduction to aluminium design
- References
- Examples
- Material selection
- Eurocodes for aluminium design

Objectives

- Introduction
- Examples of structures
- Structural alloys
- Designation system
- Assessment 1
- Products
- Assessment 2
- Material selection
- Eurocodes
- Assessment 2
- Summary
- Notes
Advantages

- Weight (2700 kg/m³)

- Corrosion

- Mon magnetic and low toxic

- Fatigue, low ductility transaction temperature
Corrosion

Rate of corrosion in a marine environment:

Steel: \( v_{St} = k_{St} \cdot t \)
Aluminium: \( v_{Al} = k_{Al} \cdot t^{1/3} \)

Consequence:
Virtually maintenance free construction

After 20 years in sea water:
Average corrosion rate/year: St52/Al 10-40/1
References

**European recommendation** for aluminium alloy structures, ECCS publication, No. 26, Brusel, 1978.

Bulíček V.: Rules for design, production and erection, *Směrnice pro navrhování*, výrobu a montáž konstrukcí z hliníkových slitin, Technický zpravodaj r.11 č.4, Vítkovice, 1975.


Educational program TALAT [www.eaa.net/eaa/education/TALAT](http://www.eaa.net/eaa/education/TALAT)
History –
Bridge Quebec 1947
History – Bridge for airport terminal 1948
History – Aluminium ship 1948
History – Sceleton of car, Landover 1990
History – Offshore helimodule, 1986

Helideck, Helihangar, Stairtowers and Support Structure
History –
Couch for subway 1992
Examples of application

- **Scaffolds**
- **Platforms**
- **Roofing**
- **Mobil structures**
Aluminium and its alloys

- Pure Aluminium
- Aluminium Alloys
  - Wrought alloys
  - Casting alloys
  - Non-heat treatable alloys
  - Heat treatable alloys
Pure aluminium

- Electrolytic smelters
- Cast into different shapes or forms suitable for manufacturing of semifinished products
- Level of purity a distinction is made between
  - commercial purity (99,5 - 99,8% aluminium) and
  - high purity (up to 99,98% aluminium)
Alloying elements

- **Improve its strength** (from 20 MPa to 350 MPa)
- **Commonly used**
  - Copper (Cu)
  - Magnesium (Mg)
  - Zinc (Zn)
  - Silicon (Si)
  - Manganese (Mn)
- **Other alloying elements**
  - Bismuth (Bi), boron (B), chromium (Cr), lithium (Li), iron (Fe), lead (Pb), nickel (Ni), titanium (Ti), zirconium (Zr), strontium (Sr) and sodium (Na)
  - in small quantities to achieve special metallurgical effects or properties, e.g. grain refining, machinability etc.
Adding lithium (Li)

- Quantities of 3 to 5%
  - Improves the elastic modulus
  - Decreases the density.

- Structural aluminium-lithium alloys
  - restricted to aerospace applications
  - special care and attention at
    - casting,
    - fabrication,
    - use
    - scrap recycling stages
Heat treatable and not treatable alloys

Structural alloys

- Designation system
- Assessment 1
- Products
- Assessment 2

Material selection

Eurocodes

Assessment 2

Summary

Notes
Heat treatment

Structural alloys
- Designation system
- Assessment 1
- Products
- Assessment 2
- Material selection
- Eurocodes
- Assessment 2
- Summary
- Notes
The nature of heat treatment

• Heating for a prescribed period
  – at a prescribed temperature, then cooling rapidly from this temperature,
  – usually by quenching (solution heat-treatment).

• Ageing
  – spontaneously at ordinary temperatures (natural ageing)
  – by heating for a prescribed period at a prescribed low temperature (artificial ageing).

The application of both solution heat-treatment and artificial ageing is often termed “full heat treatment”
Solution treatment

Heating, quenching, artificial ageing, re-heat treatment

• Heating
Specified temperature range and heating length. Alloying constituents tend to diffuse from the core into the aluminium cladding. Cast aluminium alloys need to be solution heat-treated for longer periods than wrought aluminium alloys.

• Quenching
Plate, extrusions and strip may be discharged from a furnace horizontally and quenched by water sprays to minimise distortion. Distortion can also be reduced by decreasing the cooling rate using hot water or oil as a quenching medium and this is often helpful with castings and forgings.
Solution treatment
Heating, quenching, artificial ageing, re-heat treatment

- **Artificial ageing**
  Hardening can be accelerated by heating the solution heat-treated alloy in the range 100 - 200 °C for a suitable period.
  Maximum strength is generally achieved by prolonged ageing at low temperature rather than by rapid ageing at high temperature.

- **Re-heat treatment**
  Alloys which have been incorrectly heat-treated can be re-solution treated and then precipitation treated again to enable optimum properties to be achieved.
  Clad material should not be re-heat treated.
Heat treatment

- Non heat treatable (Non-age hardening) alloys
  - AlMg
  - AlMn
  - AlMgMn
  - AlSiCu
  - AlSi

- Heat treatable (Age hardening) alloys
  - AlMgSi (6000 series)
  - AlZnMg(Cu) (7000 series)
  - AlCuMg (2000 series)
  - AlLi (8000 series)
Four digit alloy designation system

- The first digit indicates the alloy group as follows:
- The second digit indicates modifications of the original alloy or impurity limits.
- The last two digits identify the aluminium alloy or indicate the aluminium purity.
  - A letter used as a prefix indicates an experimental alloy.
  - A letter used as a suffix indicates national variations.
The first digit indicates the alloy group

- Al. 99,00 % purity and above 1xxx
- Copper (Cu) 2xxx
- Manganese (Mn) 3xxx
- Silicon (Si) 4xxx
- Magnesium (Mg) 5xxx
- Magnesium and Silicon (MgSi) 6xxx
- Zinc (Zn) 7xxx
- Other element (eg. Li, Fe) 8xxx
- Unused series 9xxx
### Classification examples of commonly used alloys

<table>
<thead>
<tr>
<th>Int. reg. record EN 573</th>
<th>ISO</th>
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<tbody>
<tr>
<td>1050A</td>
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<td>AlSiMgMn</td>
</tr>
<tr>
<td>7020</td>
<td>AlZn4,5Mg1</td>
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</table>
Temper Designation

**F as-fabricated**
Fabricated products without special control

**O annealed**
Wrought products which are annealed to obtain the lowest strength temper

**H strain hardened**
Wrought products which have been cold worked

**W solution heat treated**
Unstable temper applicable only to alloys which spontaneously age at room temperature

**T thermally treated to produce stable tempers other than F, O, and H**
Products which are thermally treated, with or without supplementary strain hardening.
The T is always followed by one or more digits.
**H-temper - strain hardened**

**H1 strain hardened only**

The number following this designation indicates the degree of strain hardening.

**H2 strain hardened and partially annealed**

Applies to products that are strain hardened more than the desired final amount and then reduced in strength to the desired level by partial annealing.

**H3 strain hardened and stabilized**

Applies to products which are strain hardened and whose mechanical properties are stabilized by a low temperature thermal treatment which results in slightly lower tensile strength and improved ductility. This designation is applicable only to those alloys which, unless stabilized, gradually age-soften at room temperature.
H-temper - strain hardened

Three-digit H temper designation

**H111** to products strain hardened less than the amount required for a controlled H11

**H112** acquire some temper from shaping processes

**H311** to products which are strain hardened less than the amount required for a controlled H31 temper.

**H321** to products which are strain-hardened less than the amount required for a controlled H32 temper

**H323/H343** to products which are specially
**T temper - thermally treated**

**T4 solution heat treated and naturally aged to a substantially stable condition**
- to products which are not cold worked after solution heat treatment, or
- in which the effect of cold work in flattening or straightening

**T5 cooled from an elevated temperature shaping process and then artificially aged**
- to products which are not cold worked after cooling from an elevated temperature shaping process, or
- in which the effect of cold work in flattening or straightening

**T6 solution heat treated and then artificially aged**
- to products which are not cold worked after solution heat treatment, or
- in which the effect of cold work in flattening or straightening may not be recognized in mechanical property limits.
Assessment 1

- What are the advantages of aluminium structures?
- What is nature of heat treatment?
- How is indicated the heat treatment?
Aluminium products for structural applications

- **Extrusions**
  - The extrusion process
  - Direct extrusion
  - Indirect and hydrostatic extrusion
  - Extrusions for structural applications

- **Sheet and plate**
  - The cold rolling process
  - Hot rolling
  - Alloys for rolled products

- **Casting alloys**
Processing aluminium alloys

Objectives
Introduction
Examples of structures
Structural alloys
Designation system
Assessment 1

Products
Assessment 2

Material selection
Eurocodes
Assessment 2

Summary
Notes
Wrought alloys

- For fabrication by hot and cold forming processes
  - rolling, forging and extrusion.

- Principal alloying elements
  - Magnesium strengthening element
    - added up to 5% by weight.
  - Zinc, copper and/or silicon + magnesium
    - very high strength alloys special heat treatments.
  - Lead and bismuth
    - The machinability is increased by adding.
  - Copper and/or nickel, manganese or iron
    - High temperature strength properties
Casting alloys

- For the fabrication of cast parts
- High fluidity in the liquid state
- Good resistance to hot cracking during solidification.

Castability
- addition of silicon (7 to 13% Si)
- the silicon content further up to 25% reduces the thermal expansion down to levels of iron and steel
Extrusion process

- At temperatures 400° - 500° C
  - using a pre-heated billet

- Direct Extrusion
- Indirect and Hydrostatic Extrusions

- Extrusion alloys
  - 6000-series (AlMgSi), and the

- Extrusion speed for the 6063 alloy
  - between 20 and 70 m/min.
Extrusion process
Extrusion - examples

• **AlMn - 3000-series for drawn tubes**
  - due to very high formability
  - excellent dimensional tolerance abilities

• **2000-series or the 7000 series**
  - strength performance
  - no weldability (Cu alloys)
  - potential danger of stress corrosion (Zn alloys).

• **AlMgSi 6000-serie**
  - majority of extrusions good overall performance i.e.
    - relatively easy to extrude
    - medium to high strength in the T6 condition
    - good corrosion resistance in marine and industrial environments
    - good weldability by all welding methods
    - good availability on the market, both as standard and special sections

6082 (AlMgSi1Mn) T6 In Europe normal
Sections

- Extrusion
- Extrusion
- Extrusion
- Casting
- Cold forming
- Hot rolling
Sections

- Extrusion
- Extrusion
- Extrusion
- Casting
- Cold forming
- Hot rolling
Extrusion

- Bulbs
- Stiffners
- Locks
Extrusion – preparation for welding

A: Extruded profiles
B: Fillet welds
C: Extruded flat bar or rolled plate
# Extrusion - thicknesses

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Profile type</th>
<th>25</th>
<th>50</th>
<th>75</th>
<th>100</th>
<th>150</th>
<th>200</th>
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<td>50</td>
<td>80</td>
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</table>

- **a:** Solid / semi-hollow sections
- **b:** Hollow sections with equal wall thicknesses
- **c:** Hollow sections with unequal wall thicknesses
# Extrusion – recommended shapes

<table>
<thead>
<tr>
<th></th>
<th>Instead of this</th>
<th>This is recommended</th>
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</thead>
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<tr>
<td>Equal wall thickness</td>
<td><img src="image1" alt="Diagram" /></td>
<td><img src="image2" alt="Diagram" /></td>
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<tr>
<td>Sharp edges</td>
<td><img src="image3" alt="Diagram" /></td>
<td><img src="image4" alt="Diagram" /></td>
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<tr>
<td>Profile symmetric</td>
<td><img src="image5" alt="Diagram" /></td>
<td><img src="image6" alt="Diagram" /></td>
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<tr>
<td>Better dimensional control</td>
<td><img src="image7" alt="Diagram" /></td>
<td><img src="image8" alt="Diagram" /></td>
</tr>
<tr>
<td>Avoid hollow sections if possible</td>
<td><img src="image9" alt="Diagram" /></td>
<td><img src="image10" alt="Diagram" /></td>
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<tr>
<td>Increased strength of weak points</td>
<td><img src="image11" alt="Diagram" /></td>
<td><img src="image12" alt="Diagram" /></td>
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</tbody>
</table>
Hot rolling

- Thick sheetings
Hot rolling

- Non heat treatable alloys
  - 5052 (AlMg2.5)
  - 5083 (AlMg4.5Mn)
  - 5054 (AlMg2.7Mn)

- Heat treatable alloys
  - 6082 (AlMgSi1)
  - 7020 (AlZn4.5Mg1)
Reverze hot rolling

- Thin sheetings
Casting Alloys for Structural Applications

• The typical alloys AlSiMg, AlSiCu, AlMg, AlCuTi and AlZnMg,
  • AlSi-alloys are preferred with respect to castability.

• Sand casting
  • produced by pouring molten metal into a sand mold and allowing it to solidify.

• Permanent mold casting
  • produced by feeding molten metal by force of gravity or low pressure into a mold constructed of durable material (iron or steel), and allowing it to solidify.

• Die casting
  • produced by injecting molten metal under high pressure into a metal mold or die and allowing it to solidify.
Advanced sheetings

Objectives

Introduction

Examples of structures

Structural alloys

Designation system

Assessment 1

Products

Assessment 2

Material selection

Eurocodes

Assessment 2

Summary

Notes
Sandwitch panels - principle

- Thin sheetings

**Products**

- Core (e.g. Plastic, Foam, Honey Comb)
- Adhesive Bond
- Aluminium Sheet or Plate
Sandwitch panels - advantages

Normal stresses are taken by the faces.

Transverse shear stress is taken by the core.

The core must have sufficient resistance against compression.

The panel must resist compression loading without buckling.

The adhesive joint must resist tension and peeling stresses.

Adequate load transfer joints between different structures to be considered.

Thermal insulation capacity for the complete panel construction.
Assessment

- What are the major processes for aluminium products?
- What are the advantages of extrusion?
- What is the reason for limits of size and thickness in extrusion?
Choice of alloy and temper

- The available semi product range
- Delivery time from stock or plant
- Prices, etc
Costs

- Main relevant factors,
  - type of alloy
  - quantity and price
  - material dimensions
  - delivery time/eventual need for own internal stock
  - demands for special material control/certificates and traceability

- Type of Alloy

\[ \text{AlMn1} < \text{AlMg2,5} < \text{AlMg4,5Mn} < \text{AlMgSi1} \]
Design

- Steel as a reference material

- Material property
  \[ E = 70000 \text{ MPa} \]
  \[ \rho = 2700 \text{ kg/m}^3 \]
  ductility 0.1% to 12% (structural above 4%)
  (steel min 15%, commonly 40% and more)
# Standards

**Eurocode 9 - Design of Aluminium Structures**

<table>
<thead>
<tr>
<th>Pre-standars</th>
<th>Eurocode</th>
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<tbody>
<tr>
<td>ENV 1999-1-2</td>
<td>EN 1999-1-2</td>
<td>Structural fire design</td>
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<td>ENV 1999-2</td>
<td>EN 1999-1-3</td>
<td>Structures susceptible to fatigue</td>
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<td>EN 1999-1-4</td>
<td>Cold-formed structural sheeting</td>
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<td>EN 1999-1-5</td>
<td>Shell structures.</td>
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</table>
Structure of EN 1999-1-1

Chapters

1. General
2. Basis of design
3. Materials
4. Durability
5. Structural analysis
6. Ultimate limit states for members
7. Serviceability limit states
8. Design of joints
Annexes to EN 1999-1-1

A. Execution classes
B. Equivalent T-stub in tension
C. Materials selection
D. Corrosion and surface protection
E. Analytical models for stress strain relationship
F. Behaviour of cross section beyond elastic limit
G. Rotation capacity
H. Plastic hinge method for continuous beams
I. Lateral torsional buckling of beams and torsional or flexural-torsional buckling of compression members
J. Properties of cross sections
K. Shear lag effects in member design
L. Classification of connections
M. Adhesive bonded connections
# Material
## EN 1991-1-1 Chapter 3

Table 3.2b - Characteristic values of 0.2% proof strength \( f_o \) and ultimate tensile strength \( f_u \) (unwelded and for HAZ), min elongation \( A \), reduction factors \( r_{o,haz} \) and \( r_{u,haz} \) in HAZ, buckling class and exponent \( n_p \) for wrought aluminium alloys – Extruded profiles, extruded tube, extruded rod/bar and drawn tube

<table>
<thead>
<tr>
<th>Alloy EN-AW</th>
<th>Product form</th>
<th>Temper</th>
<th>Thickness ( t ) mm</th>
<th>( f_o ) 1) N/mm(^2)</th>
<th>( f_u ) 1) N/mm(^2)</th>
<th>( A ) 2) %</th>
<th>( f_{o,haz} ) 4) N/mm(^2)</th>
<th>( f_{u,haz} ) 4) N/mm(^2)</th>
<th>HAZ-factor4)</th>
<th>( \rho_{o,haz} )</th>
<th>( \rho_{u,haz} )</th>
<th>BC 6)</th>
<th>( n_p ) 7)</th>
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<td>T4</td>
<td>( t \leq 25 )</td>
<td>110</td>
<td>205</td>
<td>14</td>
<td>100</td>
<td>160</td>
<td>0,91</td>
<td>0,78</td>
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<tr>
<td>6082 EP/O,EP/H</td>
<td>T6</td>
<td>( t \leq 5 )</td>
<td>250</td>
<td>290</td>
<td>8</td>
<td>5 ( &lt; t \leq 15 )</td>
<td>260</td>
<td>310</td>
<td>10</td>
<td>0,50</td>
<td>0,64</td>
<td>A</td>
<td>32</td>
</tr>
<tr>
<td>6082 ER/B</td>
<td>T6</td>
<td>( t \leq 20 )</td>
<td>250</td>
<td>295</td>
<td>8</td>
<td>20 ( &lt; t \leq 150 )</td>
<td>260</td>
<td>310</td>
<td>8</td>
<td>0,50</td>
<td>0,63</td>
<td>A</td>
<td>27</td>
</tr>
<tr>
<td>6082 DT</td>
<td>T6</td>
<td>( t \leq 5 )</td>
<td>255</td>
<td>310</td>
<td>8</td>
<td>5 ( &lt; t \leq 20 )</td>
<td>240</td>
<td>310</td>
<td>10</td>
<td>0,49</td>
<td>0,60</td>
<td>A</td>
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</tbody>
</table>
Linear/multi-linear model of material
Nonlinear model of material
# Steel and aluminium sections

<table>
<thead>
<tr>
<th>Moment of inertia in mm$^4$</th>
<th>Steel</th>
<th>Aluminium Alloy</th>
<th>Aluminium Alloy</th>
<th>Aluminium Alloy</th>
</tr>
</thead>
<tbody>
<tr>
<td>EI (N/mm$^2$)</td>
<td>8.17 E12</td>
<td>8.16 E12</td>
<td>8.17 E12</td>
<td>8.21 E12</td>
</tr>
<tr>
<td>h (mm)</td>
<td>240</td>
<td>240</td>
<td>300</td>
<td>330</td>
</tr>
<tr>
<td>b (mm)</td>
<td>120</td>
<td>240</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>t (mm)</td>
<td>9.8</td>
<td>18.3</td>
<td>12.9</td>
<td>10</td>
</tr>
<tr>
<td>w (mm)</td>
<td>6.2</td>
<td>12</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>g (kg/m)</td>
<td>30.7</td>
<td>30.3</td>
<td>18.4</td>
<td>15.8</td>
</tr>
</tbody>
</table>
Aluminium and steel

Biegesteifigkeit

Stahl-Querschnitt

Al-Querschnitt

E × I = \(898 \times 10^6\) kNm²

Gewicht = 18.84 Kg/m

Torsionssteifigkeit

Stahl-Querschnitt

Al-Querschnitt

E × Iₜ = \(1.05 \times 10^9\) kNm²

Gewicht = 8.68 Kg/m

E × Iₜ = \(1.05 \times 10^9\) kNm²

Gewicht = 17.71 Kg/m
Aluminium and steel

Objectives
Introduction
Examples of structures
Structural alloys
Designation system
Assessment 1
Products
Assessment 2
Material selection
Eurocodes
Assessment 2
Summary
Notes

Aluminium and steel structures comparison:

- **Aluminium (Al)** vs. **Steel (Stahl)**
- **Designation System**
- **Assessment 1**
- **Assessment 2**
- **Summary**
- **Notes**

**Materials**
- Aluminium: I = 5304 cm^4, G = 24.35 kg/m^3, +15%
- Steel: I = 1786 cm^4, G = 21.10 kg/m^3, -5%

**Properties**
- Aluminium: I = 735.5 cm^4, G = 8.43 kg/m^3, -26%
- Steel: I = 245.4 cm^4, G = 11.37 kg/m^3, -5%

**Comparative Analysis**
- **Lightweight and High-Performance**
Assessment

• What affects the cost of aluminium structures?
• What knowledge in EN 1999-1-1 supports the other Eurocodes?
• How are described the material properties of alloys?
Summary

- Weight (2700 kg/m³)
- Corrosion
- Mon magnetic and low toxic
- Fatigue, low ductility transaction temperature
Extrusion - examples

- AlMgSi 6000-serie
  - majority of extrusions good overall performance i.e.
    - relatively easy to extrude
    - medium to high strength in the T6 condition
    - good corrosion resistance in marine and industrial environments
    - good weldability by all welding methods
    - good availability on the market, both as standard and special sections

6082 (AlMgSi1Mn) T6 In Europe normal
Extrusion

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Thank you for your kind attention
Notes to users of the lecture

• This session is a basic information about the fire design and requires about 90 min lecturing.

• Further readings on the relevant documents from website of www.eaa.net/eaa/education/TALA.

• The use of relevant standards of national standard institutions are strongly recommended.

• Formative questions should be well answered before the summative questions completed within the tutorial session.

• Keywords for the lecture:
aluminium structures, material, production, examples, Eurocodes.