Introduction to aluminium structures

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Mechanical material properties

Steel – reference material

- Modulus of elasticity E = 70 000 N/mm^2
- Shear modulus G = 27 000 N/mm^2
- Poisson's ratio ν = 0,3
- Coefficient of linear thermal expansion $\alpha = 23 \times 10^{-6}$ per ^{o}C;
- Unit mass ρ = 2 700 kg/m^3
- Min elongation from 0,1 % till 14 %
  - Structural alloys more than 4 %
  - Steel min 15 %, mostly 40 % and more

Material properties at elevated temp.

For service temperatures between 80°C and 100°C reduction of the strength should be taken in account.

All characteristic aluminium resistance values (f_o, f_u, $f_{o,haz}$ and $f_{u,haz}$) may be reduced according to

$$X_{kT} = [1 - k_{100}(T - 80) / 20]\, X_k$$

where:

X_k is the characteristic value of a strength property of a material

X_{kT} is the characteristic strength value for the material at temperature T between 80°C and 100 °C

T is the highest temperature the structure is operating

k_{100} = 0,1 for strain hardening alloys (3xxx-alloys, 5xxx-alloys and EN AW 8011A)

k_{100} = 0,2 for precipitation hardening material (6xxx-alloys and EN AW-7020)

Pros and cones

+ Low weight 2700 kg\m^3 – mobile str.
+ Unlimited choice of cross sections
+ Corrosion resistant
+ Low transition temperature
+ Toughness at low temperatures

– Low modulus of elasticity
– Round 70 000 MPa
– Low fire resistance
– Melting point about 530 °C

Criteria for Selecting Aluminium

- Weight reduction
- Maintenance aspects
- Product costs
- Load criteria

History as material

16th cent. BC mentions in Egypt

1808 - Sir Humpry Davy (England), extra insulation aluminum, aluminum named

1821 - Frenchman P. Berthier, near the town of Les Baux, hard reddish and clayey material containing 52 percent aluminum oxide, named as Bauxit.

1825 - Dane Hans Christian Oersted, metal dust grains

1827 - German chemist Friedrich Wohler's first aluminum nugget

1854 - Henri Sainte-Claire (France) improved Wöhler method for initial procurement, Napoleon III flagship spear tip

1870 - Sainte-Clare Deville melting furnace

1886 - electrolytic production process Hall-Heroult, Paul Louis

Civil Engineering Industry

1930s

roof structures, building systems, stairs, stairtowers, gangways, masts, silos, cranes, pylons, towers, pedestrian bridges

1940s

road bridges, particularly in the USA

1963

20 road bridges in the USA

the longest 100 m

Stage

for Pope John Paul II. in Hradec Králové in 1997

Stage

for Pope John Paul II. in Hradec Králové in 1997

- Installing the altar

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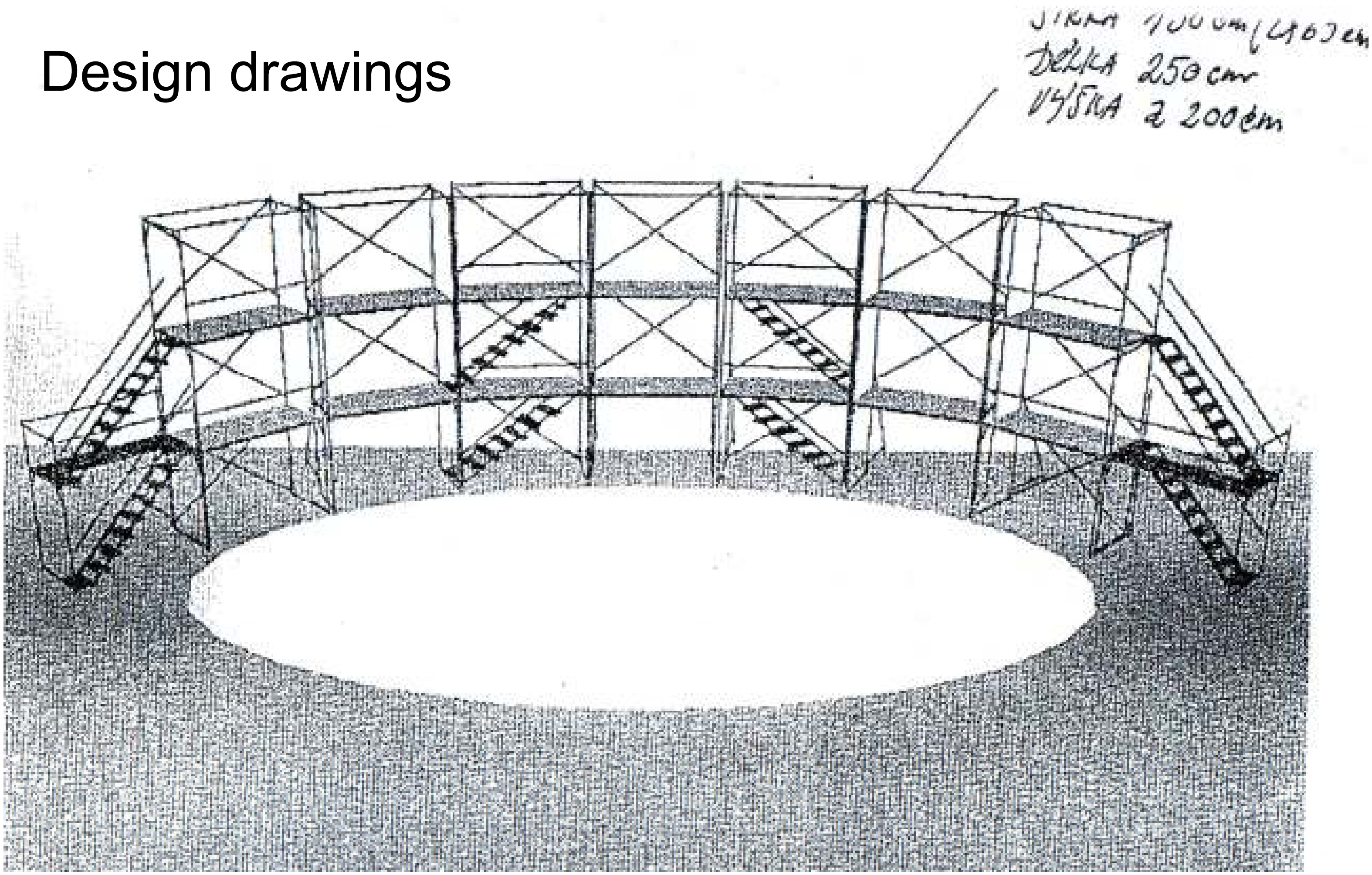
Stage backdrop
for Carmen at the National Theatre Brno

Design drawings



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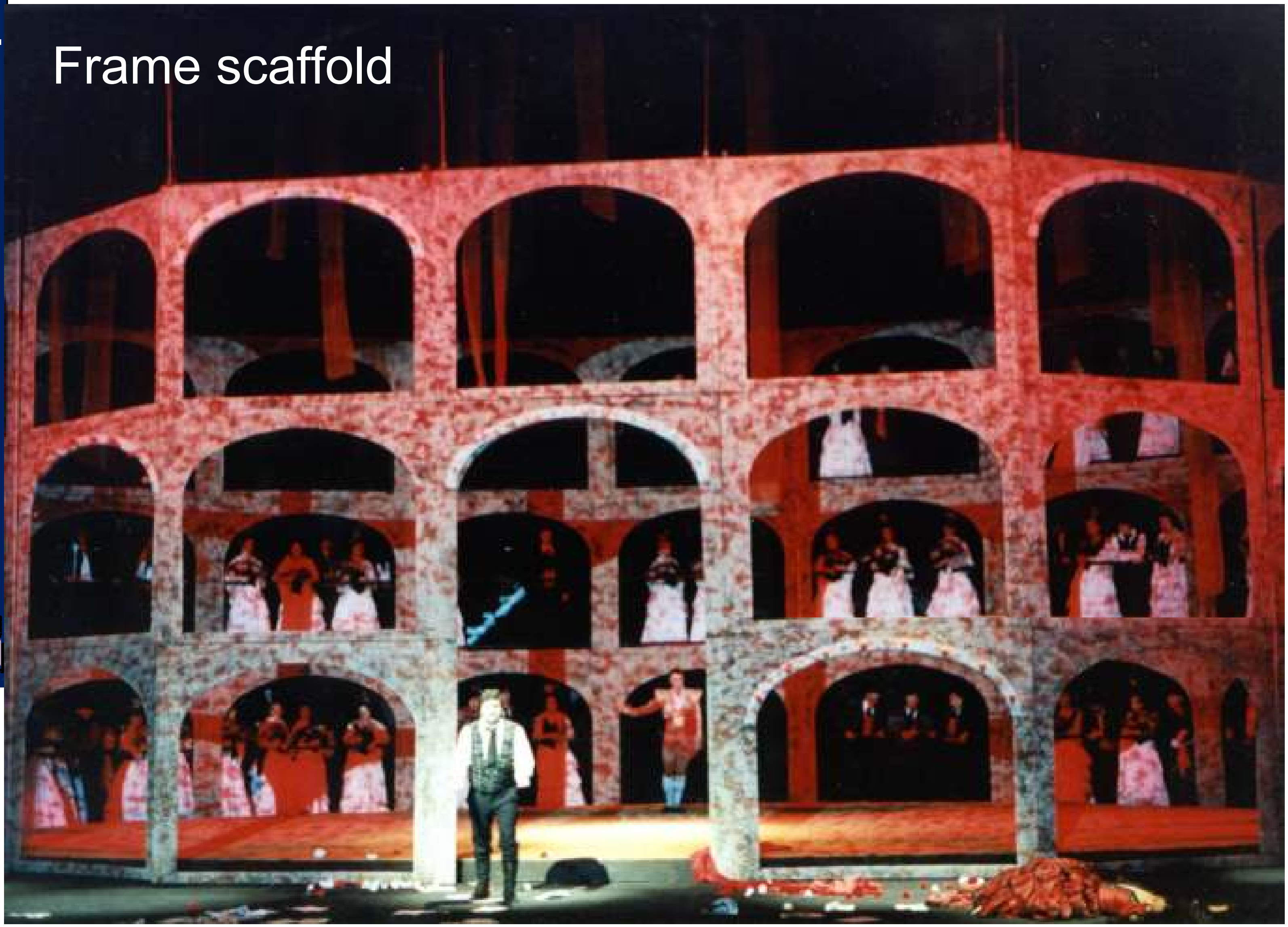

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Stage backdrop

for Carmen at the National Theatre Brno

Movable roof
on the second courtyard in castel Litomyšl

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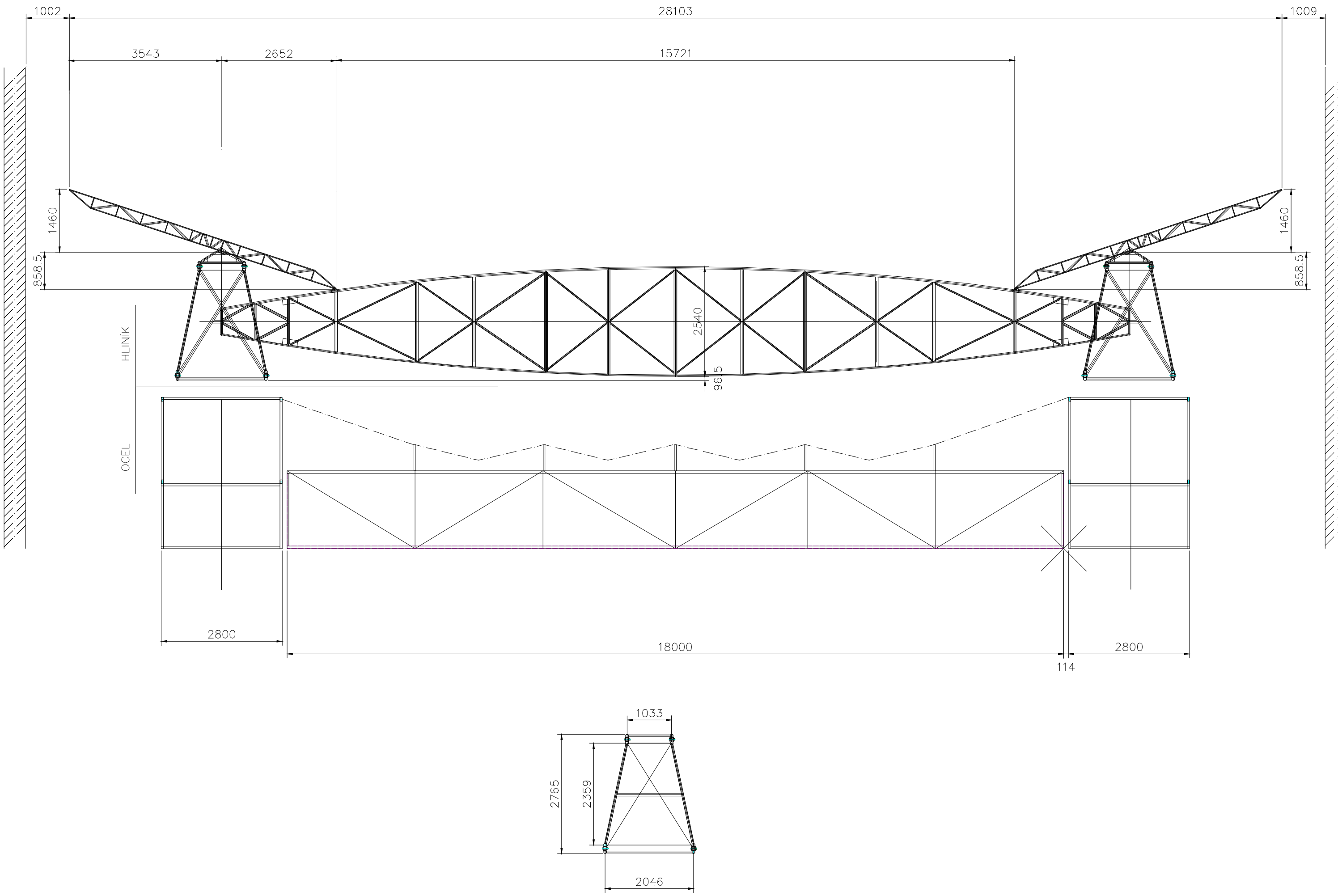
Cross section of aluminum part



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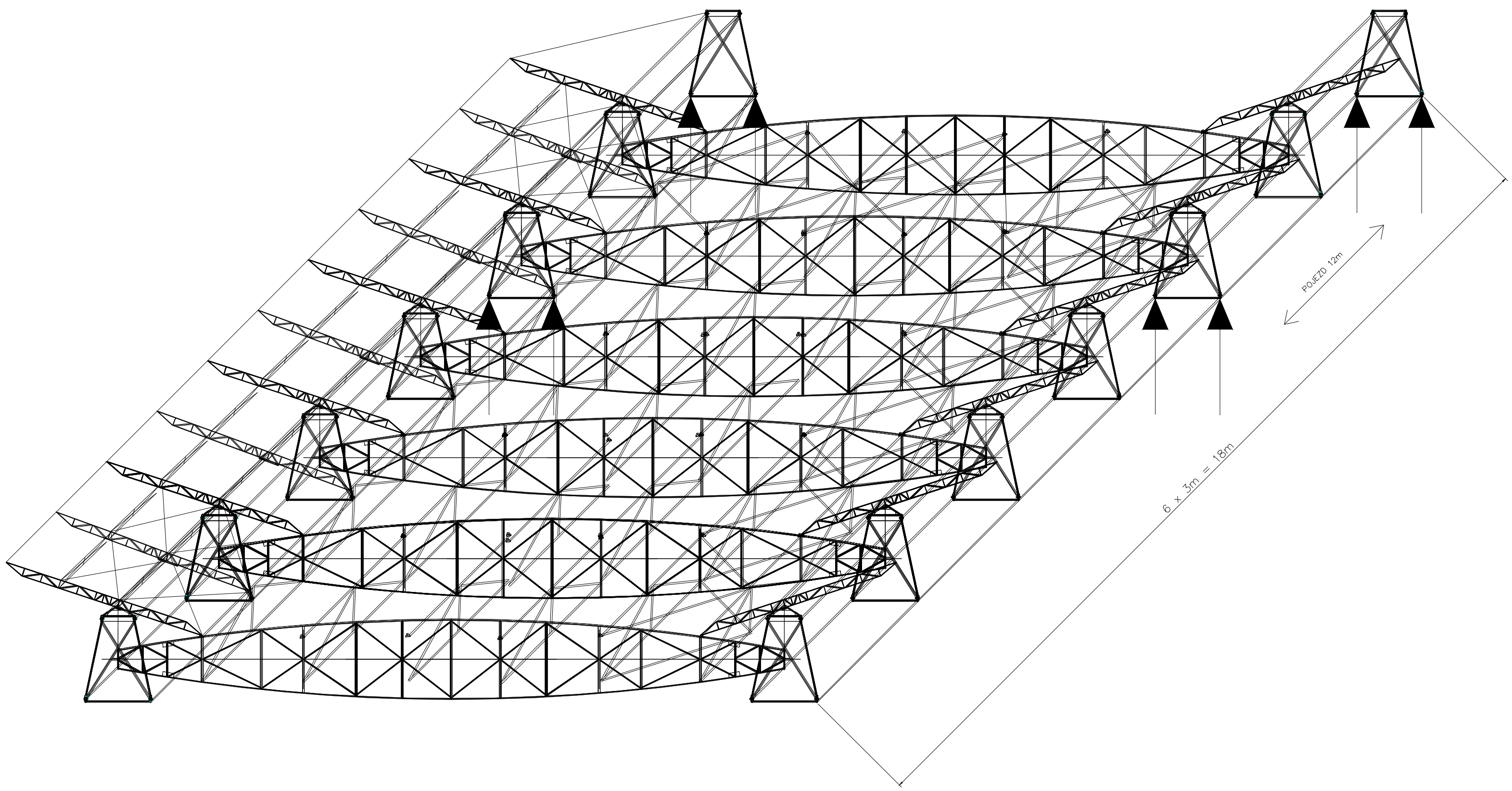
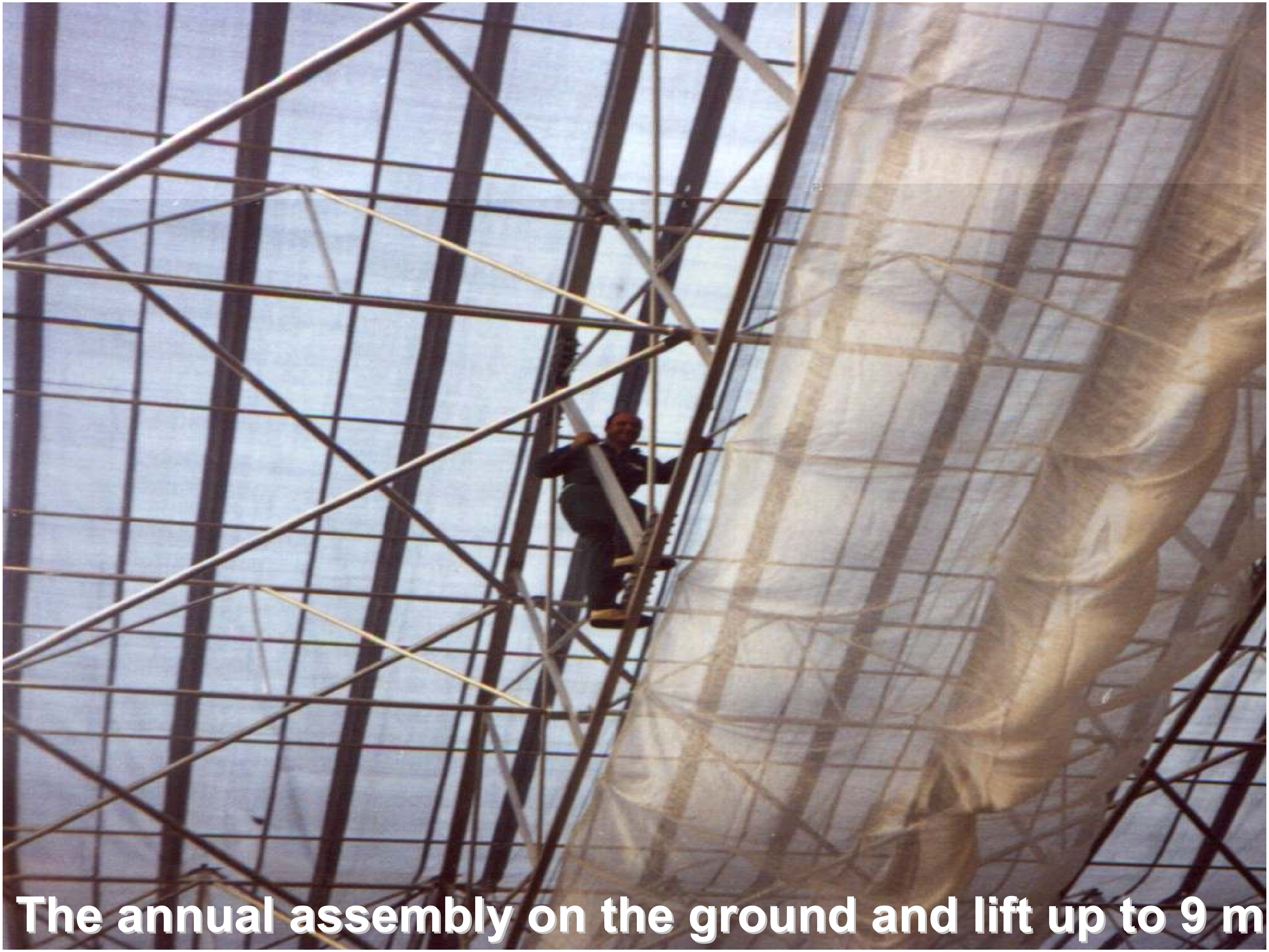
Structural diagram of sliding aluminum parts



The annual assembly on the ground and lifting up to

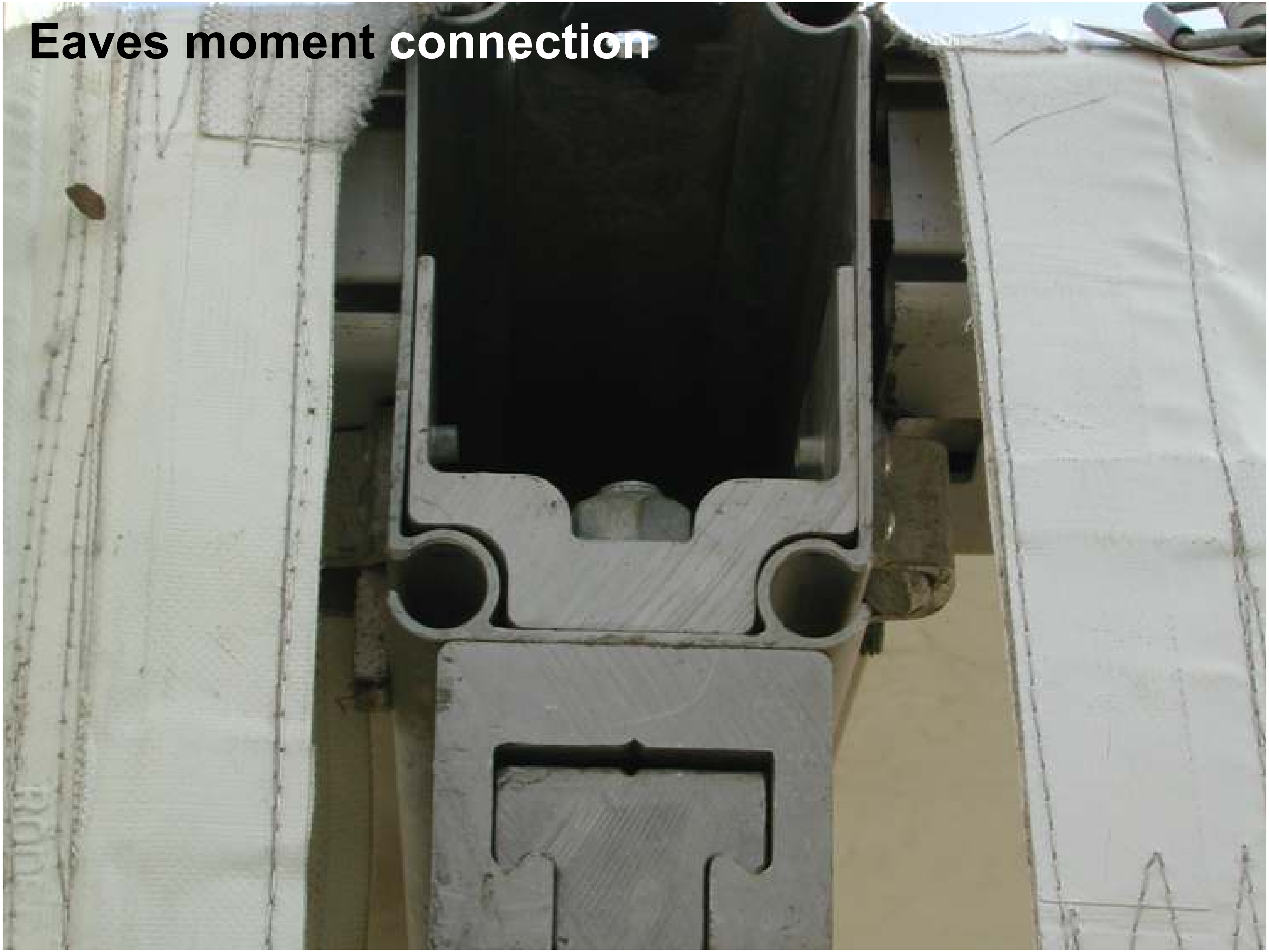

The annual assembly on the ground and lift up to 9 m

Protection against rain and sun

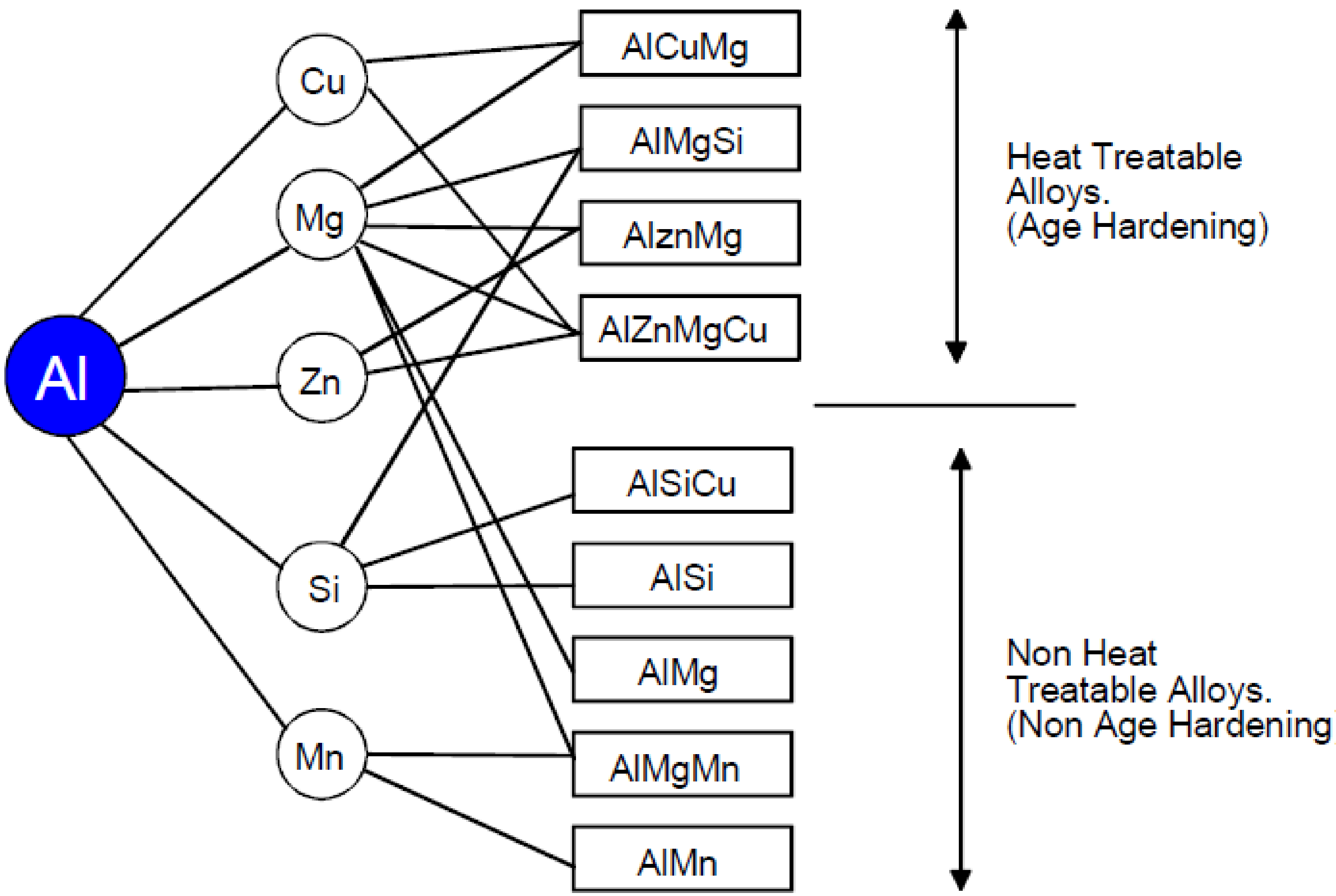
Albeny, UK

Eaves moment connection

Eaves moment connection



Principal groups of aluminium alloys



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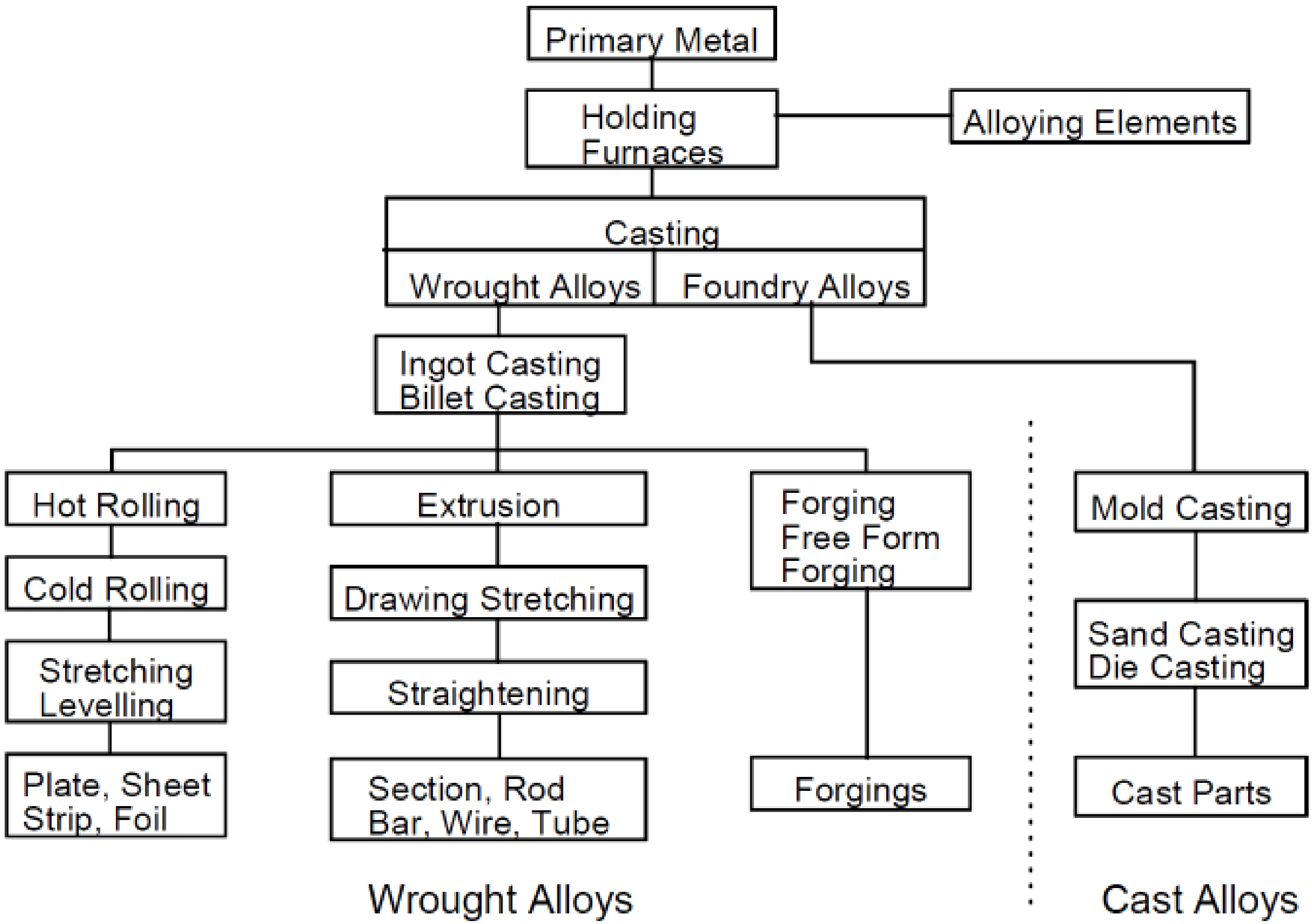
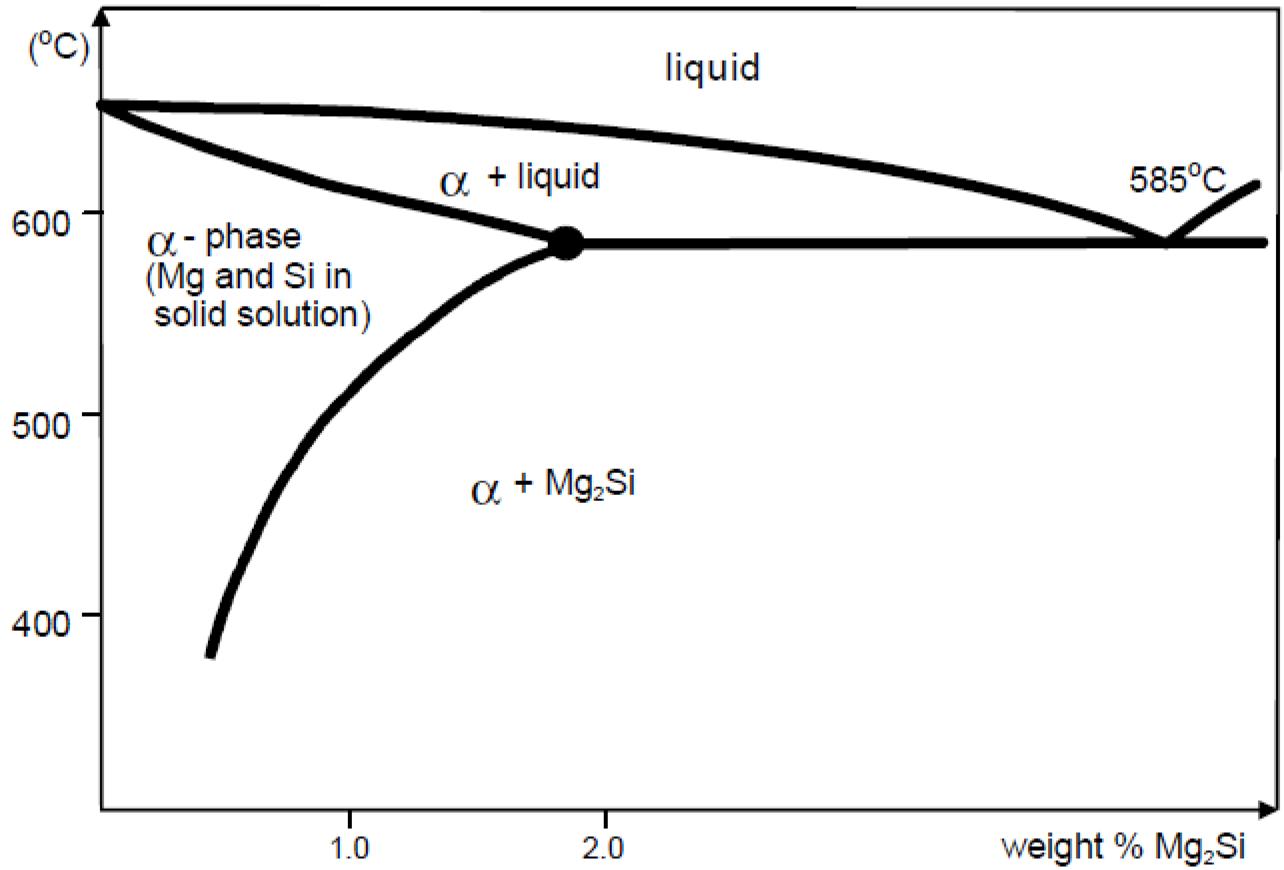
Processing aluminium alloys



Heat treatable alloys



Example of phase diagram for Mg_2Si in aluminium

Classification examples of commonly used alloys

	EN573	**ISO**
1050A	Al 99,5	
1070A	Al 99,7	
2017A	AlCu4MgSi	
3103	AlMn1	
5052	AlMg2,5	
5454	AlMg2,7Mn	
5083	AlMg4,5Mn	
6060	AlMgSi	
6063	AlMg0,5Si	

Temper designation

F as-fabricated

O annealed

H strain hardened

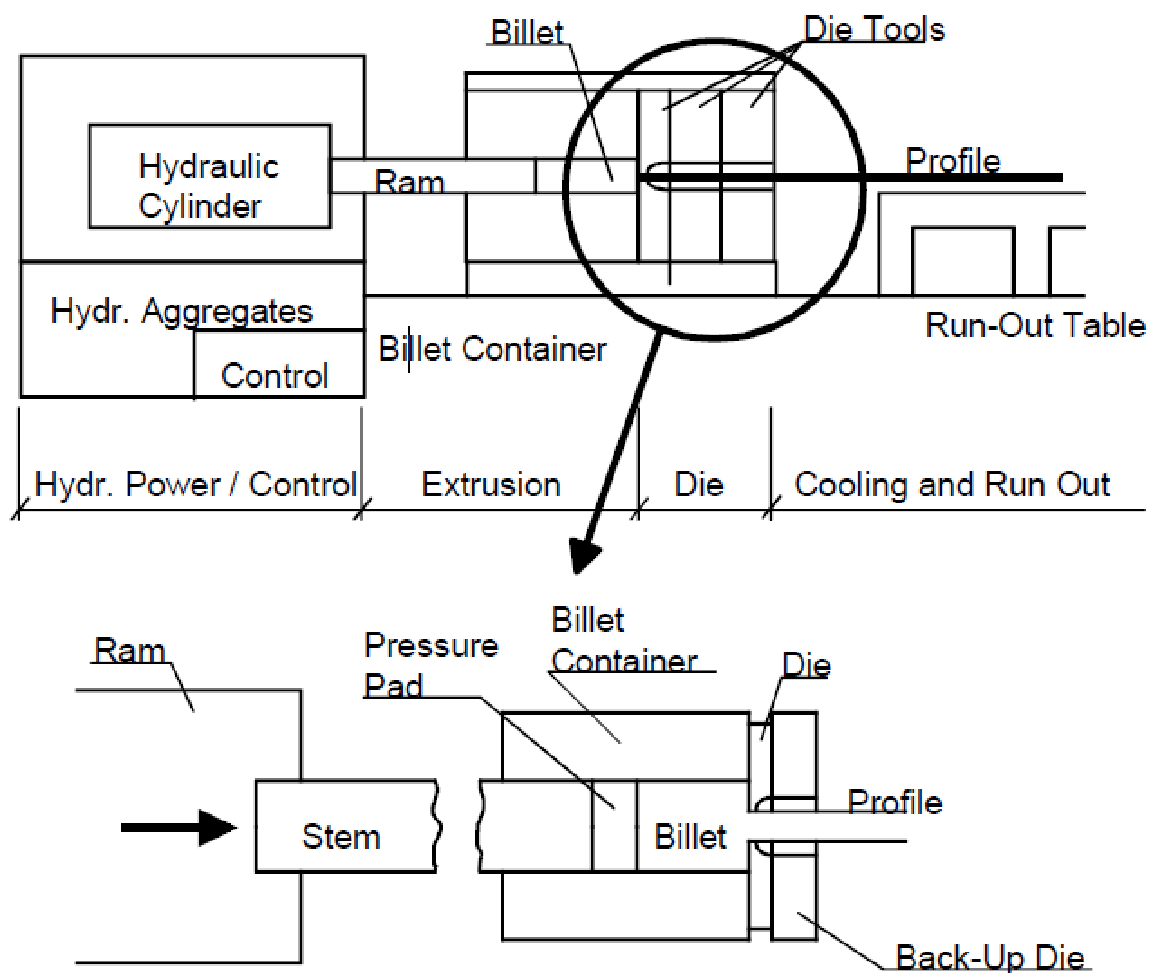
W solution heat treated

T thermally treated to produce stable tempers other than F, O, and H

EN 515 (1993)

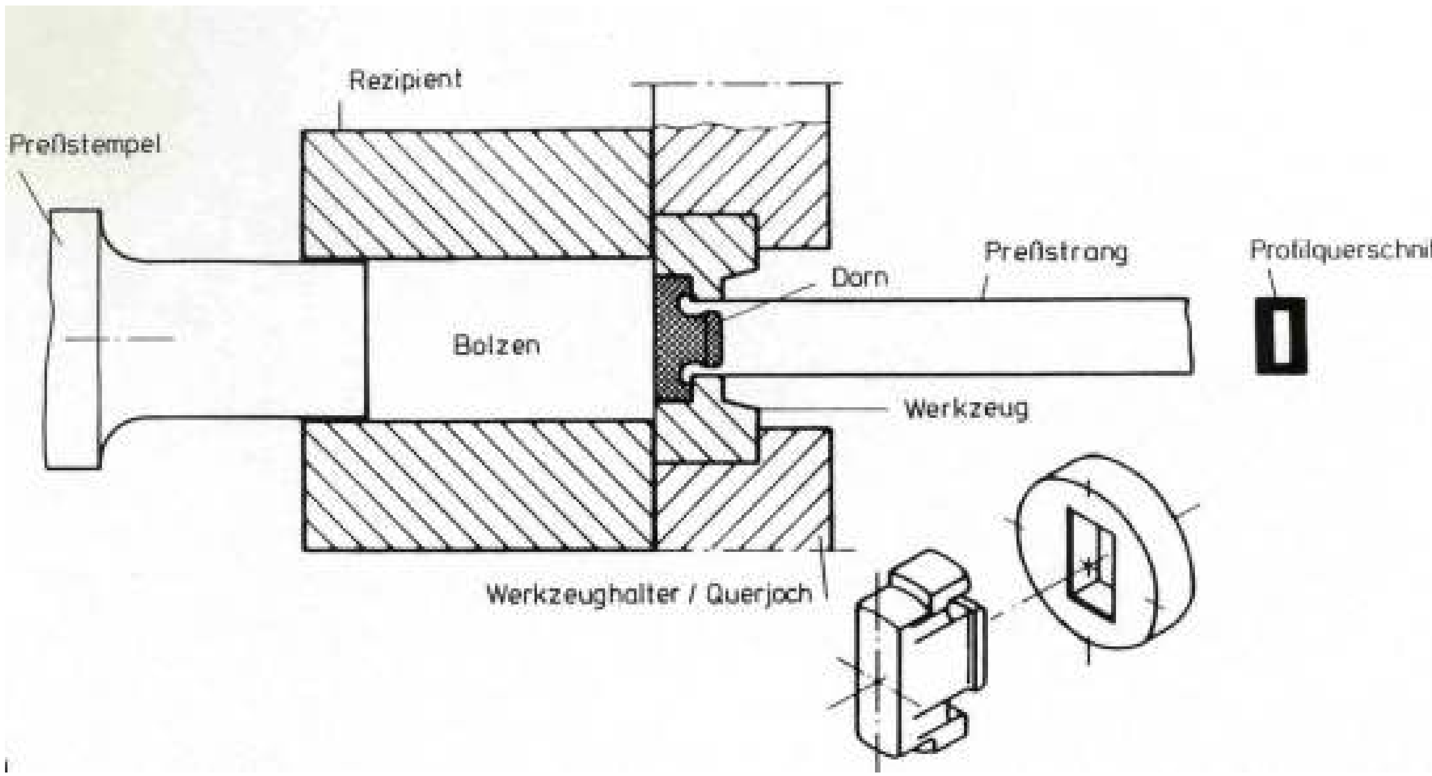
URL: http://aluminium.matter.org.uk/aluselect/

Extrusions for structural applications

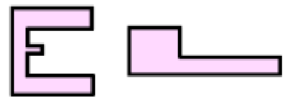
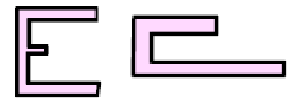
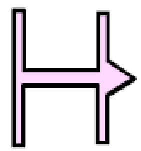
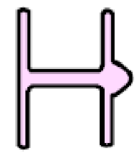
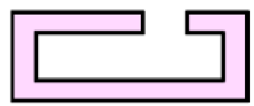
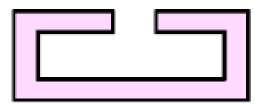
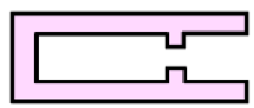
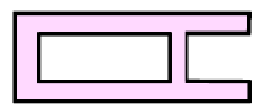
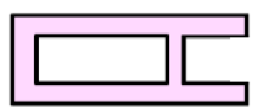
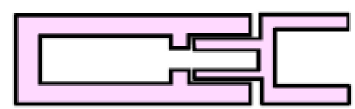
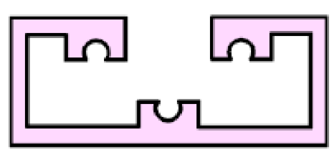
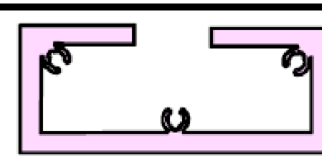


- The direct extrusion press arrangement

Direct extrusion of hollow sections



Optimising extruded section design

	Insteads of this	This is recommended
Equal wall thickness		
Sharp edges		
Profile symmetrie		
Better dimensional control		
Avoid hollow sections if possible		
Increased strength of weak points		

Wall thickness

Min. possible wall thickness for extrusion presses 10 - 80 MN.

Alloy	Profile type	25	50	75	100	150	200	250	300	350	400	450
Al 99-99,9	a	0,8	1	1,2	1,5	2	2,5	2,5	3	4	4	5
AlMgSi 0,5	b	0,8	1	1,2	1,5	2	2,5	2,5	3	4	4	5
AlMn 1	c	1	1	1,5	2	2,5	2,5	2,5	4	5	5	6
AlMg 1												
AlMgSi 1	a	1	1,2	1,2	1,5	2	2,5	3	4	4	5	6
	b	1	1,2	1,5	2	2	2,5	3	4	4	5	6
	c	2	1,5	2	2	3	4	4	5	5	6	6
AlMg 3	a	1	1	1,2	1,5	2	2,5	3	4	4	5	6
AlMg 5	b	1	1	1,2	1,5	2	2,5	3	4	4	5	6
AlCuMg 1	a	1,2	1,2	1,2	1,5	2	3	5	5	6	7	8
AlCuMg 2												
ALZnMgCu	a	2	2	2,5	3	3	5	6	8	12	12	14

Press capacity (MN) 10 → 25 → 35 → 50 → 80 →

a: Solid / semi-hollow sections
b: Hollow sections with equal wall thicknesses
c: Hollow sections with unequal wall thicknesses

0,2% proof strength f_o and ultimate tensile strength f_u

EN 1999-1-1 Table 3.2

Alloy EN-AW	Product form	Temper	Thickness t mm 1) 3)	f_o 1)	f_u 1)	A 5) 2)	$f_{o,haz}$ 4)	$f_{u,haz}$ 4)	HAZ-factor 4)		BC 6)	n_p 7)
				N/mm²		%	N/mm²		$\rho_{o,haz}$	$\rho_{u,haz}$		
6061	EP,ET,ER/B,DT	T4	t<25	110	**180**	**50**	95	150	0,86	0,83	B	8
	EP,ET,ER/B,DT	T6	$t \leq 20$	240	**260**	**8**	115	175	0,48	0,67	A	55

Characteristic values of
0,2% proof strength f_o
and ultimate tensile strength f_u (unwelded and for HAZ),
min elongation A,
reduction factors $\rho_{o,haz}$ and $\rho_{u,haz}$ in HAZ,
buckling class and exponent n_p
for wrought aluminium alloys - Extruded profiles, extruded tube, extruded rod/bar and drawn tube

EP	- Extruded profiles	EP/O	- Extruded open profiles
EP/H	- Extruded hollow profiles	ET	- Extruded tube
ER/B	- Extruded rod and bar	DT	- Drawn tube

Material properties up to 80°C

- Characteristic values of
  - the 0,2% proof strength f_o
  - the ultimate tensile strength f_u
  - are applicable for structures subject to service temperatures up to 80°C

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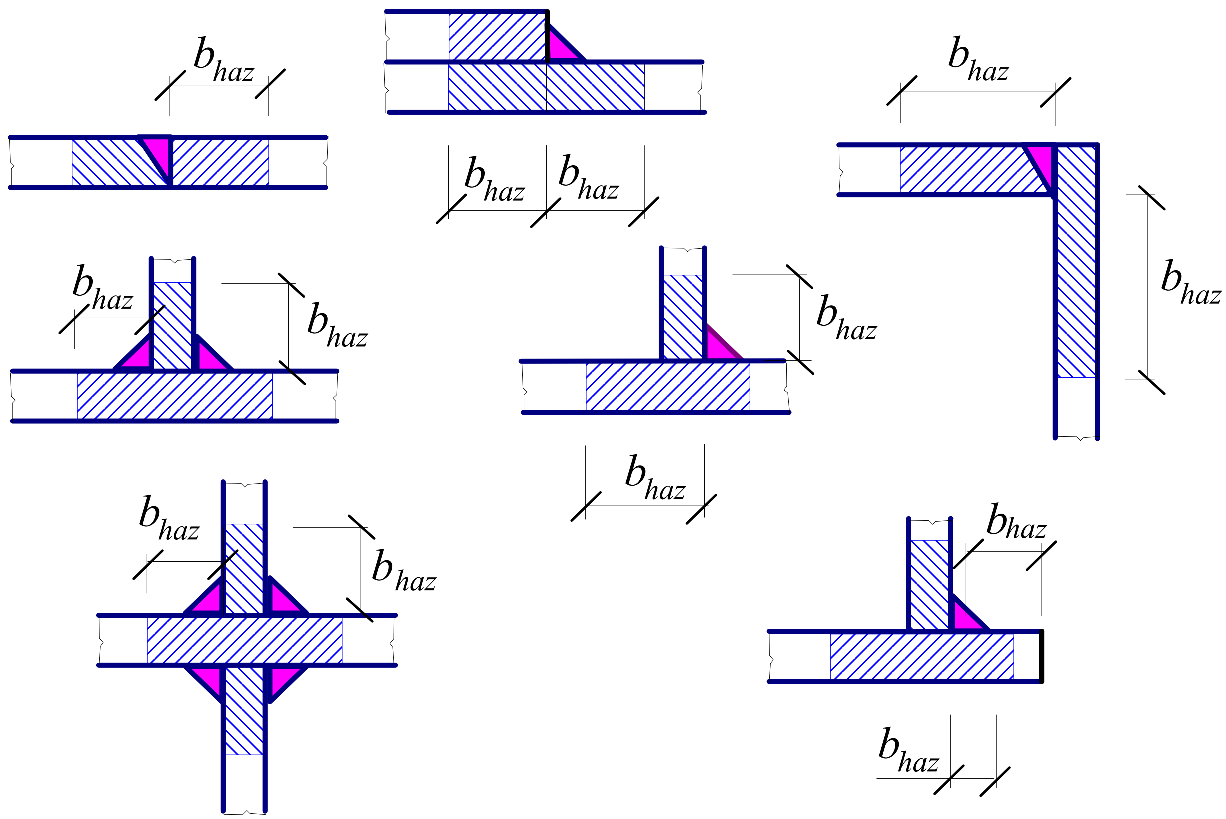
Heat affected zone HAZ softening adjacent to welds b_{haz}

- The extent of heat-affected zones softening adjacent to welds b_{haz}



Extent of heat-affected zones softening adjacent to welds b_{haz}

- For a MIG weld laid on unheated material, and with interpass cooling to 60ºC or less when multi-pass welds are laid, values of are as follows:

$0 < t$ 6 mm = 20 mm

$6 < t$ 12 mm = 30 mm

$12 < t$ 25 mm = 35 mm

$t > 25$ mm = 40 mm

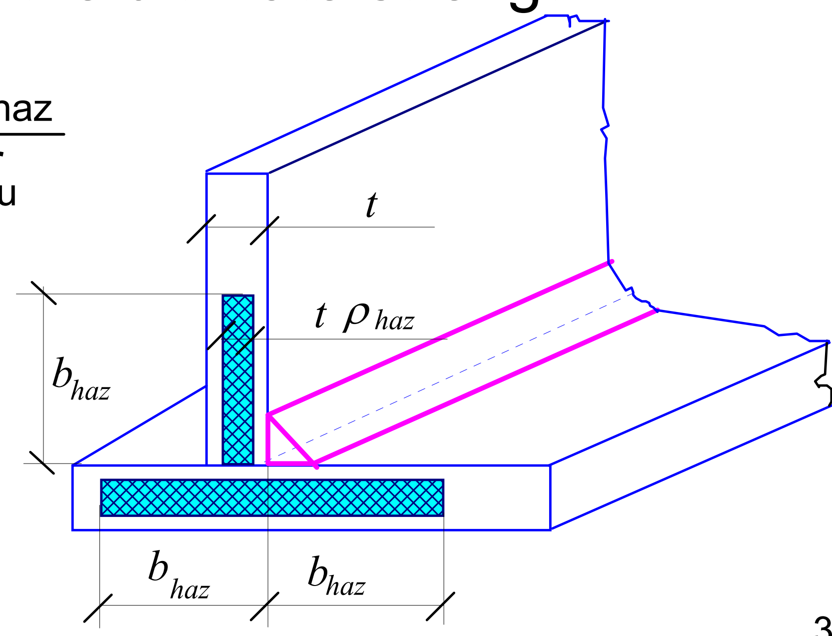
Severity of softening ρ_{haz}

- Reduction factor in the heat affected zone for the characteristic value of the 0,2 % proof strengths

$$\rho_{\mathrm{o,haz}} = \frac{f_{\mathrm{o,haz}}}{f_{\mathrm{o}}}$$

- Reduction factor for the ultimate strength

$$\rho_{\mathrm{u,haz}} = \frac{f_{\mathrm{u,haz}}}{f_{\mathrm{u}}}$$



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Reduction factor in the heat affected zone

EN 1999-1-1 Table 3.2

Alloy EN-AW	Product form	Temper	Thick-ness t mm	f_o	f_u	A	$f_{o,haz}$	$f_{u,haz}$	HAZ-factor		BC	n_p
				N/mm²		%	N/mm²		$\rho_{o,haz}$	$\rho_{u,haz}$		
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Characteristic values of
0,2% proof strength f_o and ultimate tensile strength f_u (unwelded and for HAZ), min elongation A,
reduction factors $\rho_{o,haz}$ and $\rho_{u,haz}$ in HAZ,
buckling class and exponent n_p

for wrought aluminium alloys –
Extruded profiles, extruded tube, extruded rod/bar and drawn tube

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The design buckling resistance of a compression member

$$N_{b,Rd} = \kappa \, \chi \, A_{eff} \, f_o / \gamma_{M1}$$

where:

χ is the reduction factor for the relevant buckling mode

κ is a factor to allow for the weakening effects of welding

A_{eff} is the effective area allowing for local buckling for class 4 cross-section

$A_{eff} = A$ for class 1, 2 or 3 cross-section

Buckling curves

- Two buckling curves
- Formulas as for steel

$$\chi = \frac{1}{\phi + \sqrt{\phi^2 - \overline{\lambda}^2}}$$

$$\phi = 0{,}5\,(1 + \alpha\,(\overline{\lambda} - \overline{\lambda}_0) + \overline{\lambda}^2)$$

where: $$\overline{\lambda} = \sqrt{\frac{A_{eff}\, f_o}{N_{cr}}}$$

α is an imperfection factor

$\overline{\lambda}_0$ is the limit of the horizontal plateau

N_{cr} is the elastic critical force for the relevant buckling mode based on the gross cross-sectional properties

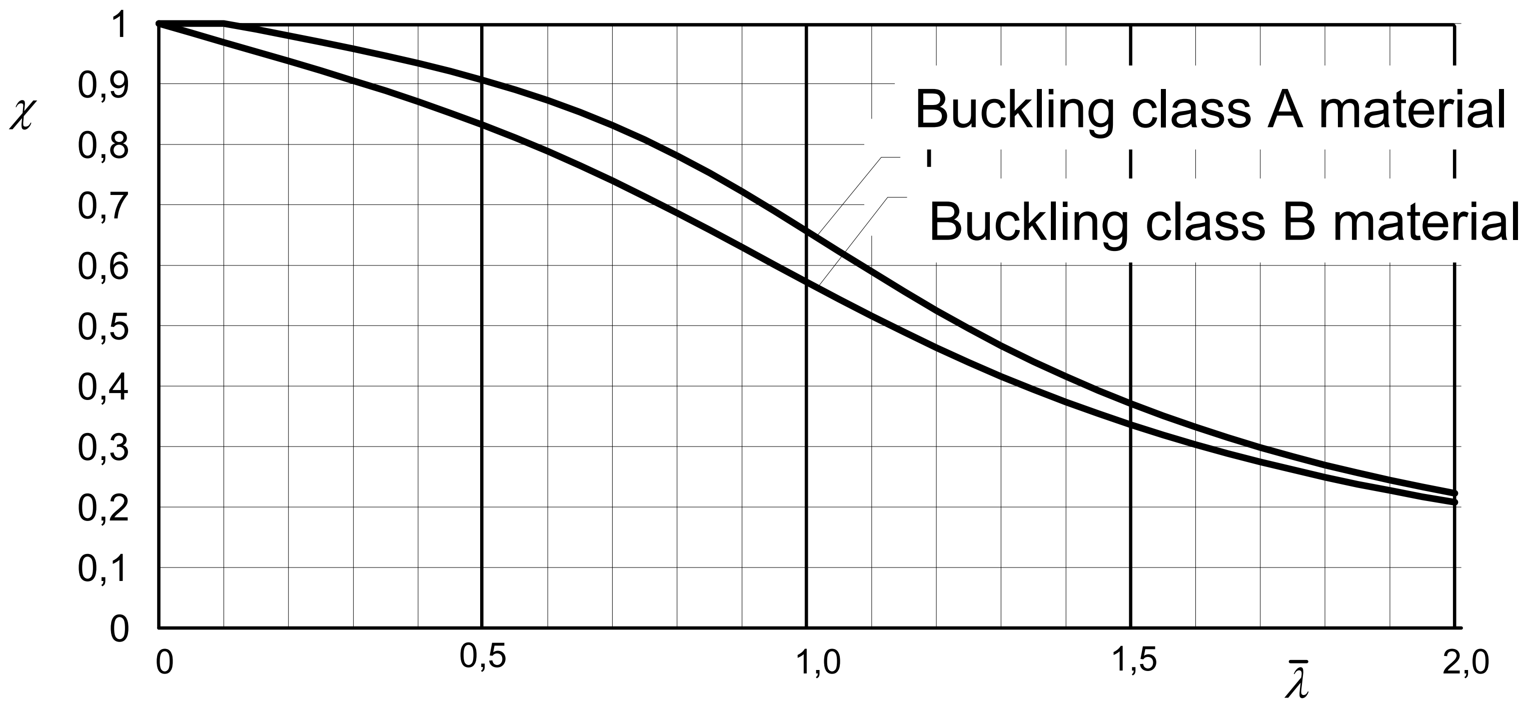
Imperfection factor and limit of the horizontal plateau

Material buckling class	α	$\overline{\lambda}_0$
Class A	0,20	0,10
Class B	0,32	0,00

- Class A usually
  - **T6** solution heat treated and then artificially aged
- Class B usually
  - **T5** cooled from an elevated temperature shaping process and then artificially aged
  - **T4** solution heat treated and naturally aged to a substantially table condition

Reduction factor χ for flexural buckling

Reduction factor
for flexural buckling



Relative slenderness

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Material buckling class

EN 1999-1-1 Table 3.2

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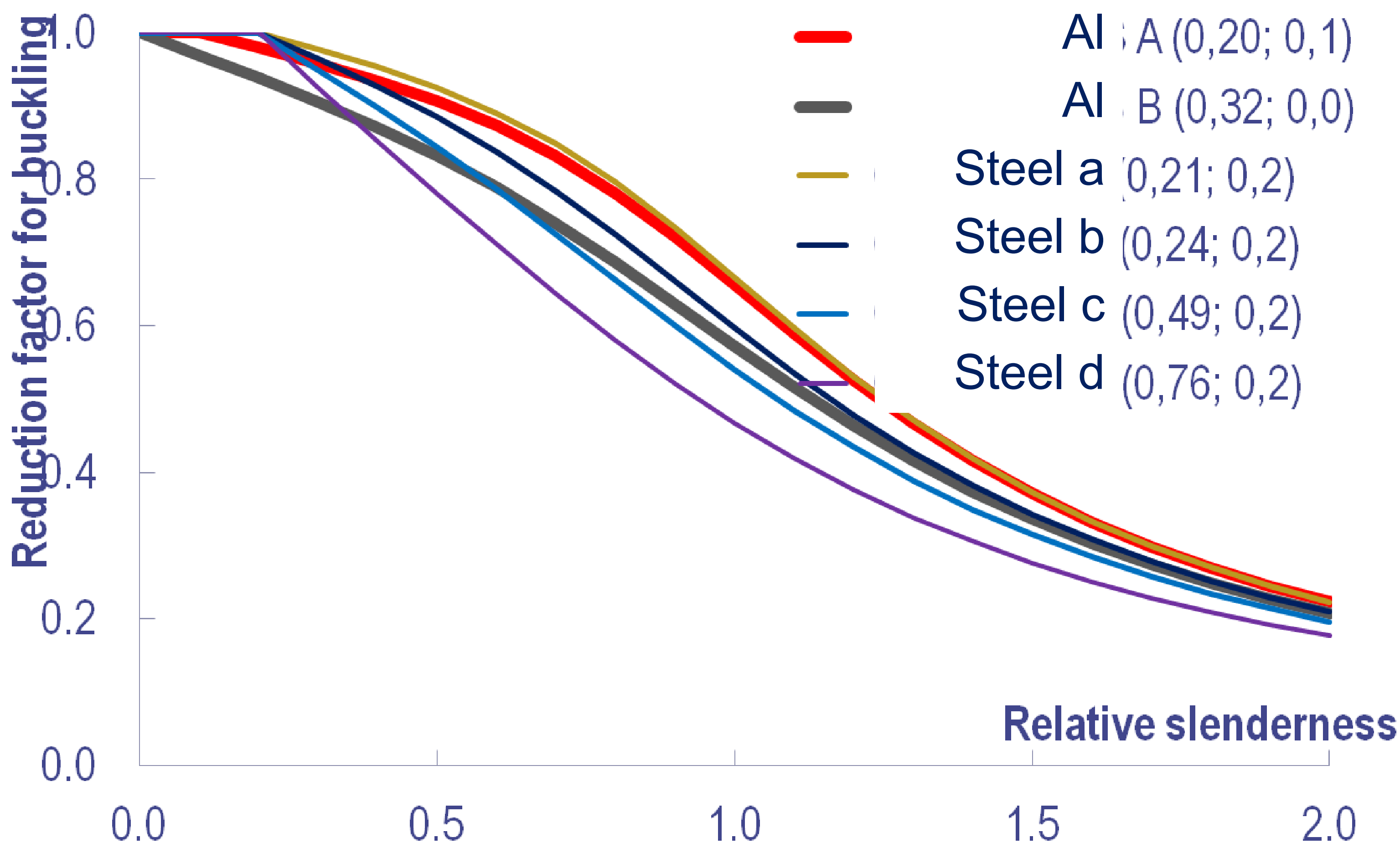
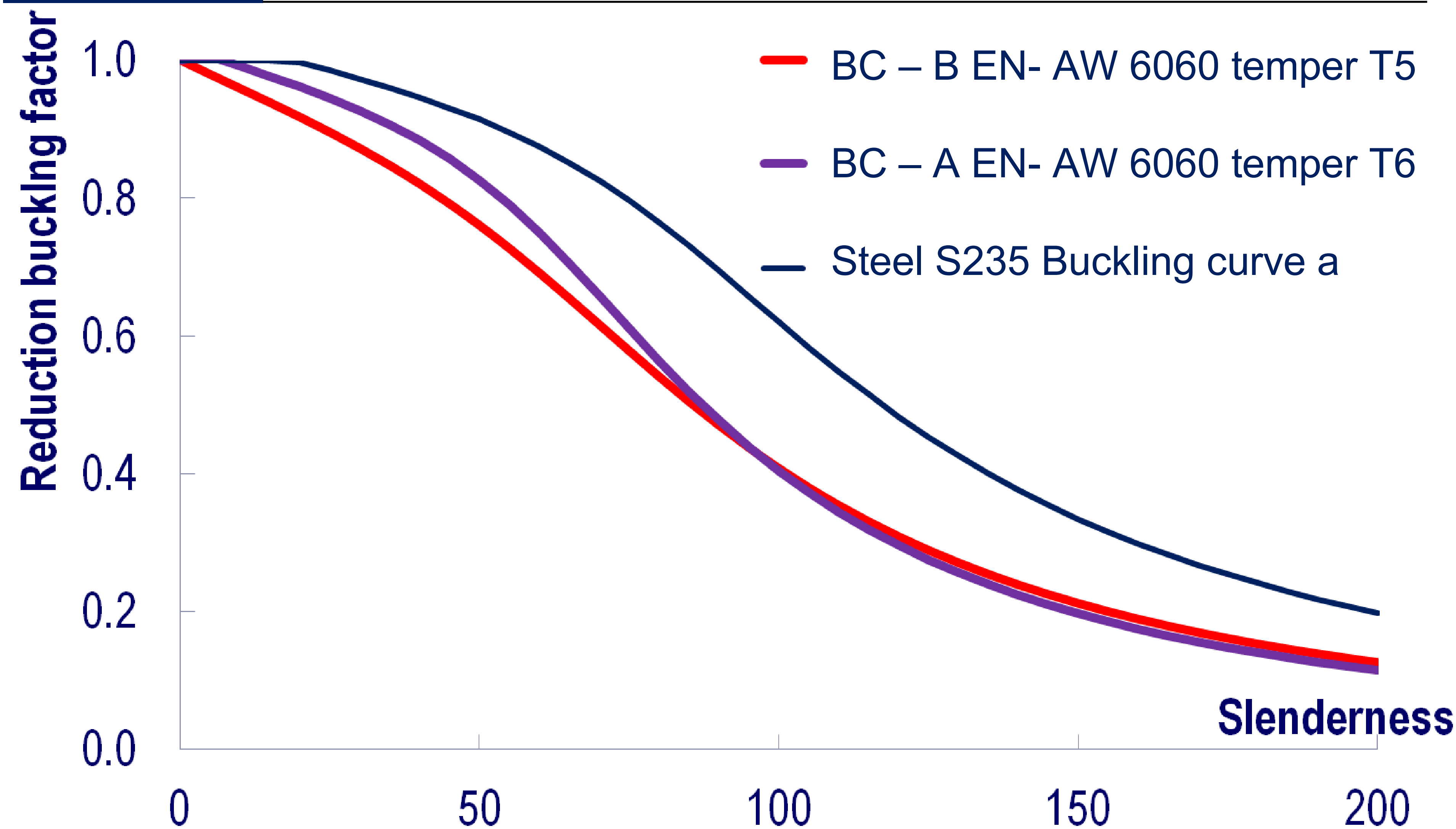
Comparison to steel



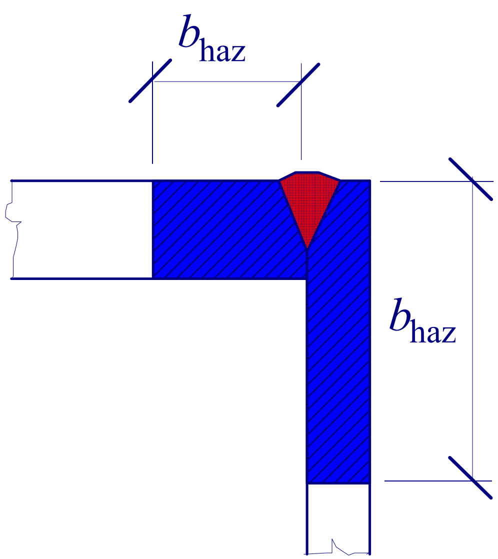
Cross section 60 x 3 – 40 x 2



Buckling resistance of member with longitudinal welds

$$N_{b,Rd} = \kappa \, \chi \, A_{eff} \, f_o / \gamma_{M1}$$

Class A material	Class B material
$\kappa = 1 - \left(1 - \frac{A_1}{A}\right) 10^{-\bar{\lambda}} - \left(0{,}05 + 0{,}1 \frac{A_1}{A}\right) \bar{\lambda}^{1{,}3(1-\bar{\lambda})}$ with $A_1 = A - A_{haz}(1 - \rho_{o,haz})$ in which A_{haz} = area of HAZ	$\kappa = 1$ if $\bar{\lambda} \leq 0{,}2$ $\kappa = 1 + 0{,}04(4\bar{\lambda})^{(0{,}5-\bar{\lambda})} - 0{,}22\bar{\lambda}^{1{,}4(1-\bar{\lambda})}$ if $\bar{\lambda} > 0{,}2$



Buckling resistance of member with localized welds

- Member subject to HAZ softening, should generally be based on the *ultimate* strength of the HAZ softened material

$$N_{b,Rd} = \kappa \, \chi \, A_{eff} \, f_o / \gamma_{M1}$$

- In case of transversally welded member $\kappa = \omega_x$
- The reduction factors

$$\omega_0 = \omega_x = \omega_{xLT} = \frac{\rho_{u,haz} f_u / \gamma_{M2}}{f_o / \gamma_{M1}} \quad \text{but} \le 1{,}00$$

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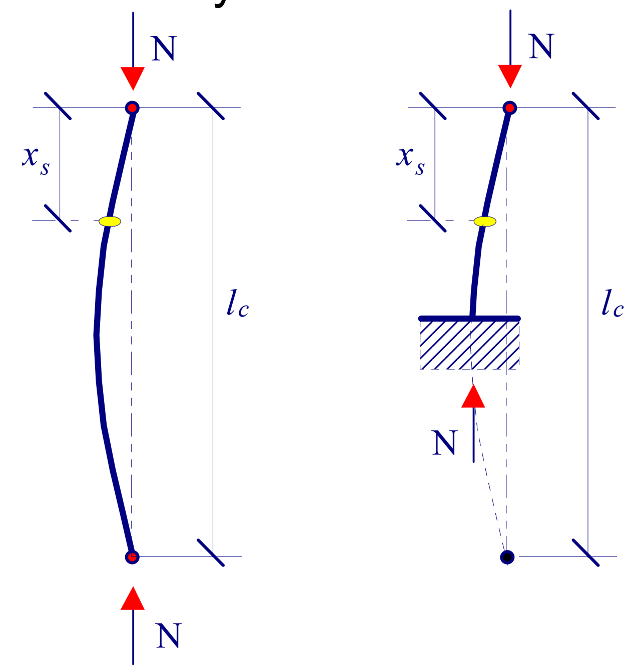
Members containing localized welds

- HAZ softening occurs close to the ends of the bay

$$\omega_0 = \frac{\rho_{u,haz} f_u / \gamma_{M2}}{f_o / \gamma_{M1}} \quad \text{but } \omega_0 \leq 1{,}00$$

$$\omega_x = \frac{\omega_0}{\chi + (1-\chi)\ \sin \dfrac{\pi\ x_s}{l_c}}$$



where

χ is depending on buckling direction

x_s is the distance from the localized weld to a support or point of contra flexure for the deflection curve for elastic buckling of axial force only

l_c is the buckling length

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Characteristic strength values of weld metal f_w

Characte-ristic strength	Filler metal	Alloy								
		3103	5052	5083	5454	6060	6005A	6061	6082	7020
f_w [N/mm²]	5356	-	170	240	220	160	180	190	210	260
	4043A	95	-	-	-	150	160	170	190	210

- Combinations of parent metal and filler metal
  - Approximatelly $f_w \cong (2\, f_u + f_f)/3$

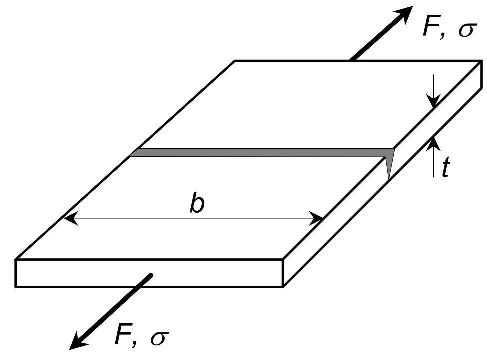
    f_u strength of basic material

    f_f strength of filler metal
- Strength of the weld metal is usually lower than the strength of the parent metal except for the strength in the HAZ

Full Penetration Butt Welds

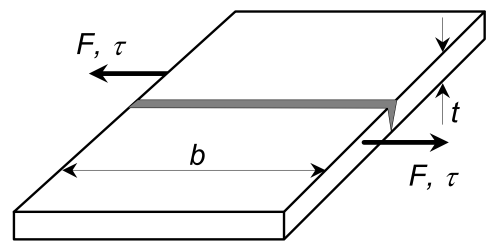
- normal stress, tension or compression, perpendicular to the weld axis

$$\sigma_{\perp Ed} \leq \frac{f_w}{\gamma_{Mw}}$$



- shear stress

$$\tau_{Ed} \leq 0{,}6 \frac{f_w}{\gamma_{Mw}}$$



- combined normal and shear stresses:

$$\sqrt{\sigma_{\perp Ed}^2 + 3\,\tau_{Ed}^2} \leq \frac{f_w}{\gamma_{Mw}}$$

where:

f_w	characteristic strength weld metal
$\sigma_{\perp Ed}$	normal stress, perpendicular to the weld axis
τ_{Ed}	shear stress, parallel to the weld axis
γ_{Mw}	partial safety factor for welded joints

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Design resistance in HAZ

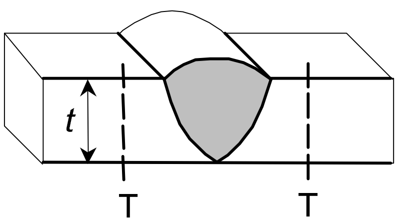
Tensile force perpendicular to the failure plane

- HAZ butt welds:

$\sigma_{haz,Ed} \leq f_{u,haz} / \gamma_{Mw}$

at the toe of the weld (full cross section)

- HAZ fillet welds:



$\sigma_{haz,Ed} \leq f_{u,haz} / \gamma_{Mw}$

at the fusion boundary

and at the toe of the weld (full cross section)

where:

$\sigma_{haz,Ed}$	design normal stress perpendicular to the weld axis;
t	thickness connected member
$f_{u,haz}$	characteristic strength HAZ
γ_{Mw}	material factor for welded joints

Design resistance in HAZ

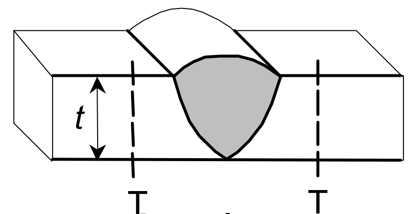
Shear force in failure plane

- HAZ butt welds:

$\tau_{haz,Ed} \leq f_{v,haz} / \gamma_{Mw}$

at the toe of the weld (full cross section)

- HAZ fillet welds:



$\tau_{haz,Ed} \leq f_{v,haz} / \gamma_{Mw}$

at the toe of the weld (full cross section)

where:

$\tau_{haz,Ed}$ shear stress parallel to the weld axis

$f_{v,haz}$ characteristic shear strength HAZ

γ_{Mw} material factor for welded joints

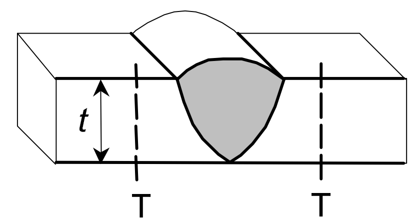
Design resistance in HAZ

Combined shear and tension

- HAZ butt welds:

$$\sqrt{\sigma_{haz,Ed}^2 + 3\,\tau_{haz,Ed}^2} \le f_{u,haz} / \gamma_{Mw}$$

at toe of the weld (full cross section)



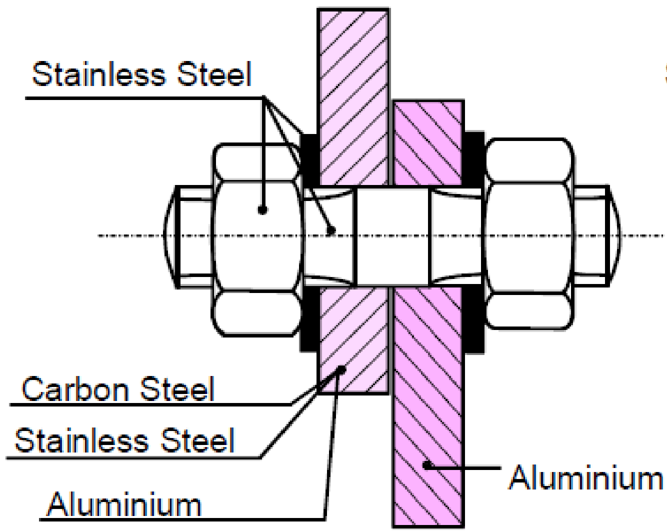
- HAZ fillet welds:

$$\sqrt{\sigma_{haz,Ed}^2 + 3\,\tau_{haz,Ed}^2} \le f_{u,haz} / \gamma_{Mw}$$

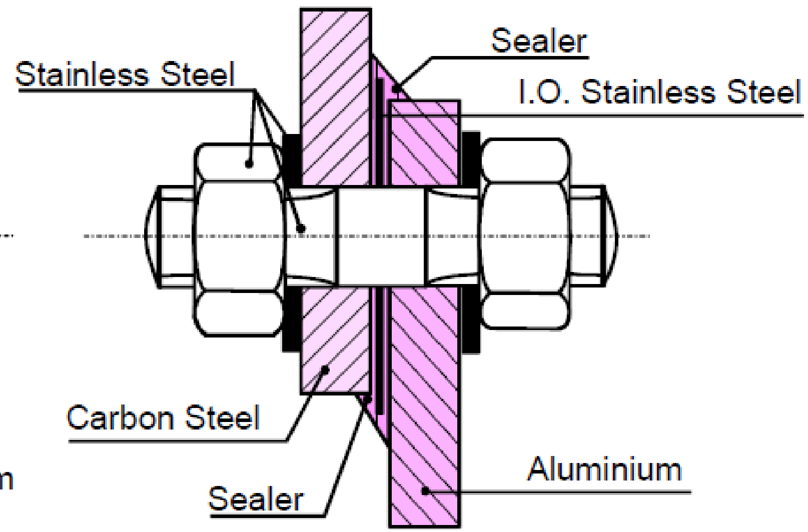
at the toe of the weld (full cross section)

Bolting

- Design of bolted joints
  for dry and severe corrosive environments



Dry Conditions



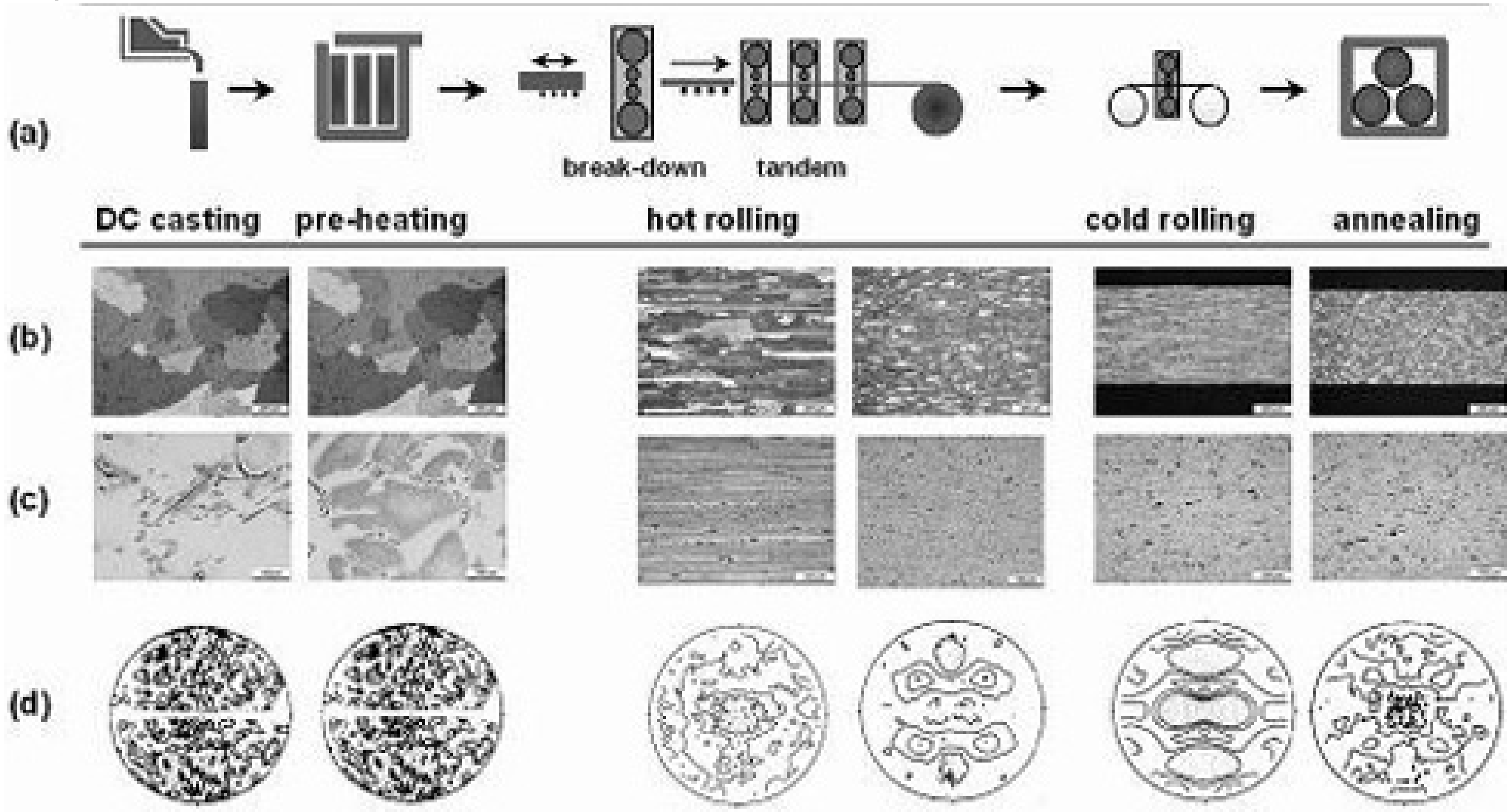
Saliferous Atmosphere

0,2 % proof strength f_o and ultimate strength f_u **for bolts and solid rivets**

Material	Type of fastener	Alloy Numerical designation: EN AW-.	Temper or grade	Diameter	f_o N/mm²	f_u N/mm²
Stainless Steel	Bolts	A2, A4	50	≤39	210	**500**
		A2, A4	70	≤39	450	**700**
		A2, A4	80	≤39	600	**800**

Summary

a) Principle processing steps
b) Grain structure,
c) Constituent and dispersoid particles
d) Texture



Summary

Non-heat treatable alloys : examples

Strengthened by combination of solution hardening and work hardening

- 1xxx : pure Al — eg electrical conductors, chemical plant and architectural panels
- 3xxx : Al-Mn — eg beverage cans, car radiators
- 5xxx : Al-Mg — eg car trim

Summary

Heat treatable alloys : examples

Strengthened by precipitation hardening.

2xxx : Al-Cu-Mg	eg aircraft structures
6xxx : Al-Mg-Si	eg extrusions, wide application
7xxx : Al-Zn-Mg	eg high strength
8xxx : specials	eg 8001(Al-Ni-Fe) for nuclear plant

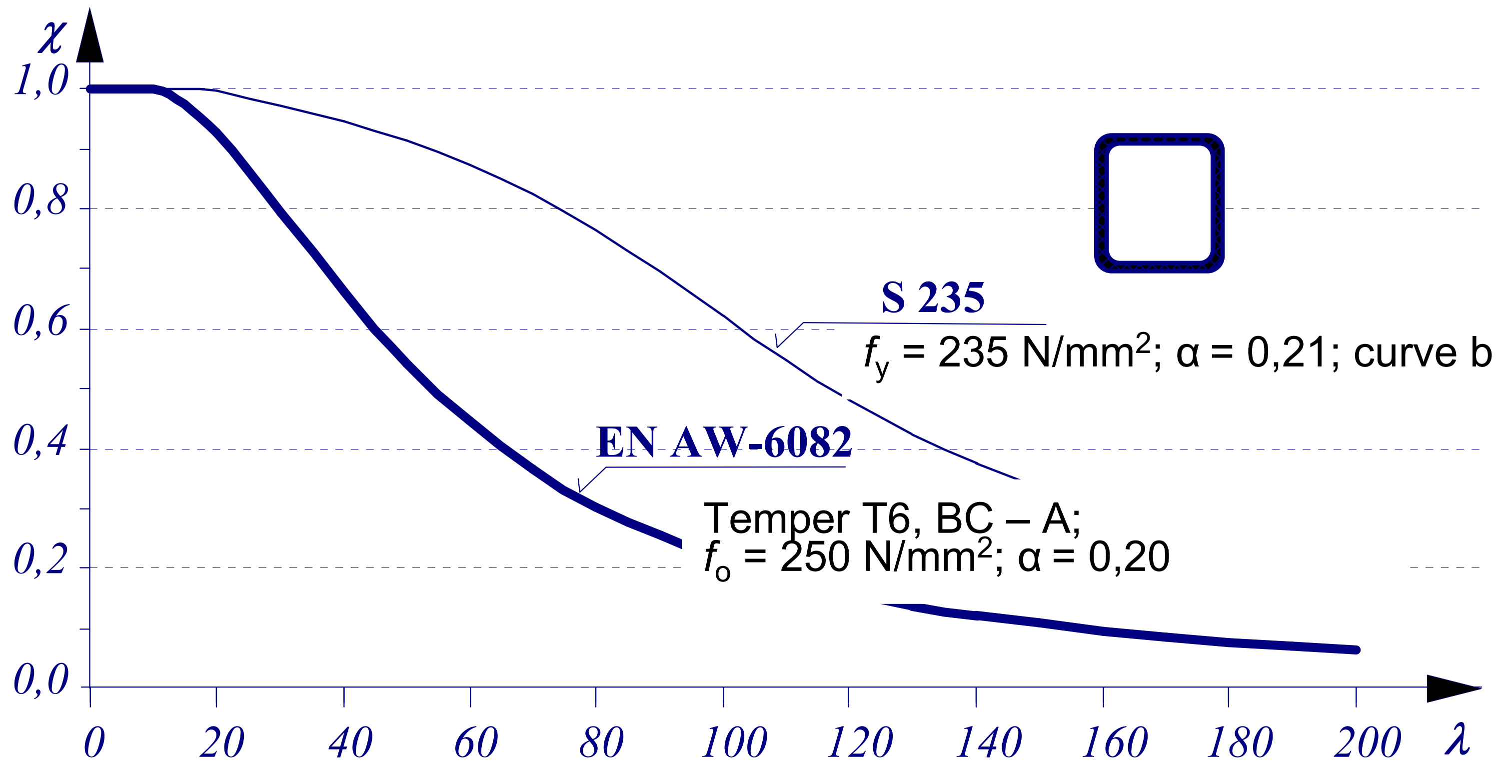
Summary

- Temper influences the HAZ

Alloy EN-AW	Product form	Temper	Thick-ness t mm	f_o	f_u	A	$f_{o,haz}$	$f_{u,haz}$	HAZ-factor		BC	n_p
				N/mm²		%	N/mm²		$\rho_{o,haz}$	$\rho_{u,haz}$		
5083	ET, EP,ER/B	O / H111, F, H112	$t \leq 200$	**110**	**270**	12	110	270	1	1	B	5
	DT	H12/22/32	$t \leq 10$	200	280	6	135	270	0,68	0,96	B	14
		H14/24/34	$t \leq 5$	235	300	4			0,57	0,90	A	18

Summary

- Buckling influenced by Modulus of elasticity



Thank you
for your attention

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Notes to users of the lecture

- Text books

Hodlung T., Tindall P., Design guide to Eurocode 9: **Design to aluminium structures,** EN 1999-1-1 and -1-4, ICE Publishing, London, 2012, ISBN 978-0-72277-5737-1.

Valtinat G., **Aluminium im Konstruktiven Ingenierbau**, Bauingeniering–Praxis, Ernst&Sohn, 2003. ISBN 3-433-01784-0.

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Mazzolani F. M.: **Aluminium alloy structures** (second edition), E & FN SPON, London, 1995.

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Sources

- EN 1999-1-1 Design of Aluminium Structures: General structural rules, CEN, Brussels, 2008.
- Bulson P.S.: Aluminium structural analysis: recent European advances, Elsevier, London, 1992, ISBN 1-85166-660-5.
- Educational programme TALAT www.eaa.net/eaa/education/TALAT

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