ALUNORD
Week 41, 2009

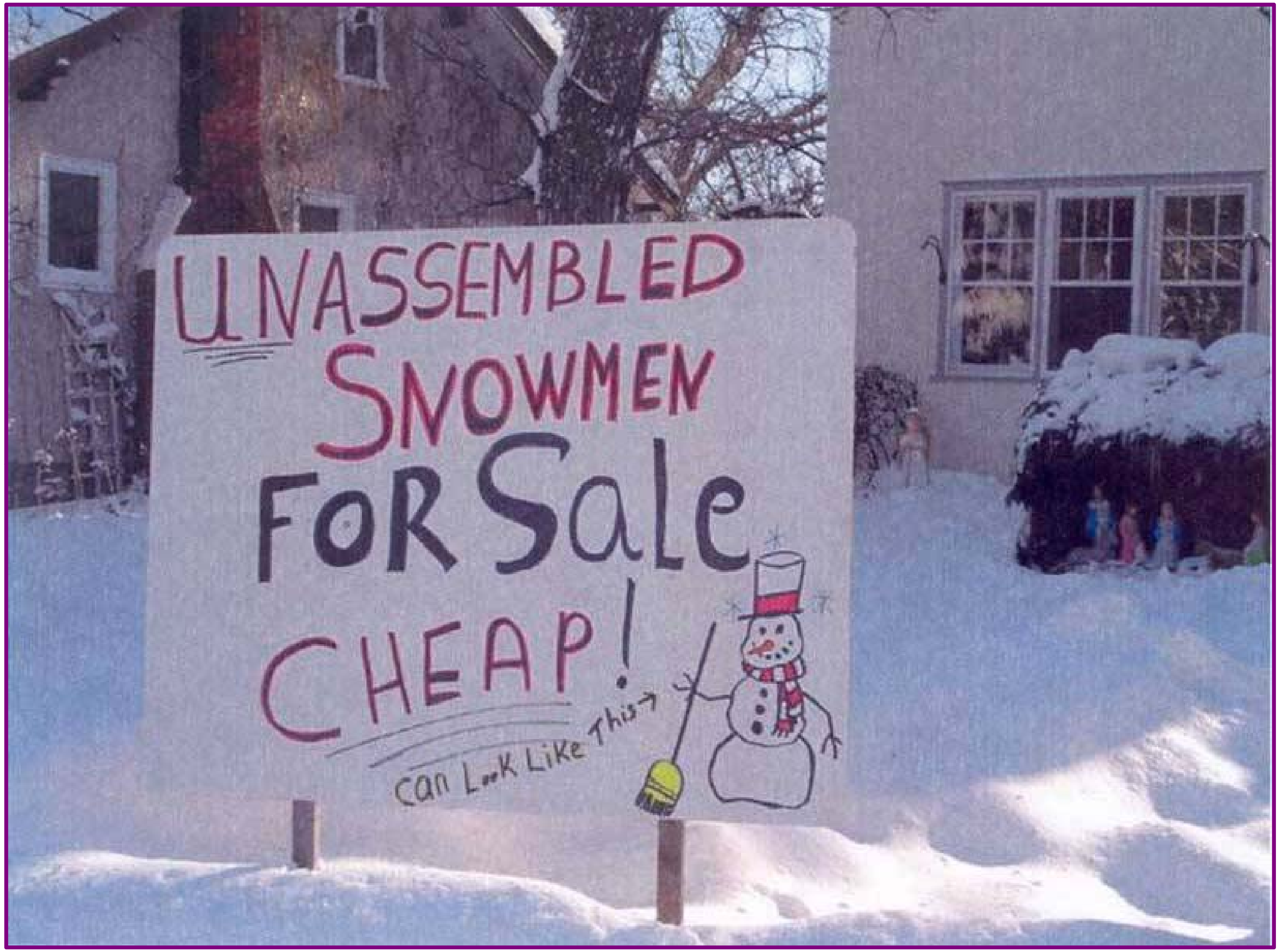
CONSTRUCTION in ALUMINIUM – Part I

by Anders Kristensen

Program

- The design process
- Structural design issues
- Example – helideck support structure
- Example – luggage lift
- Example – simulation

A good idea!



Product Development Stages

Scope of product development team

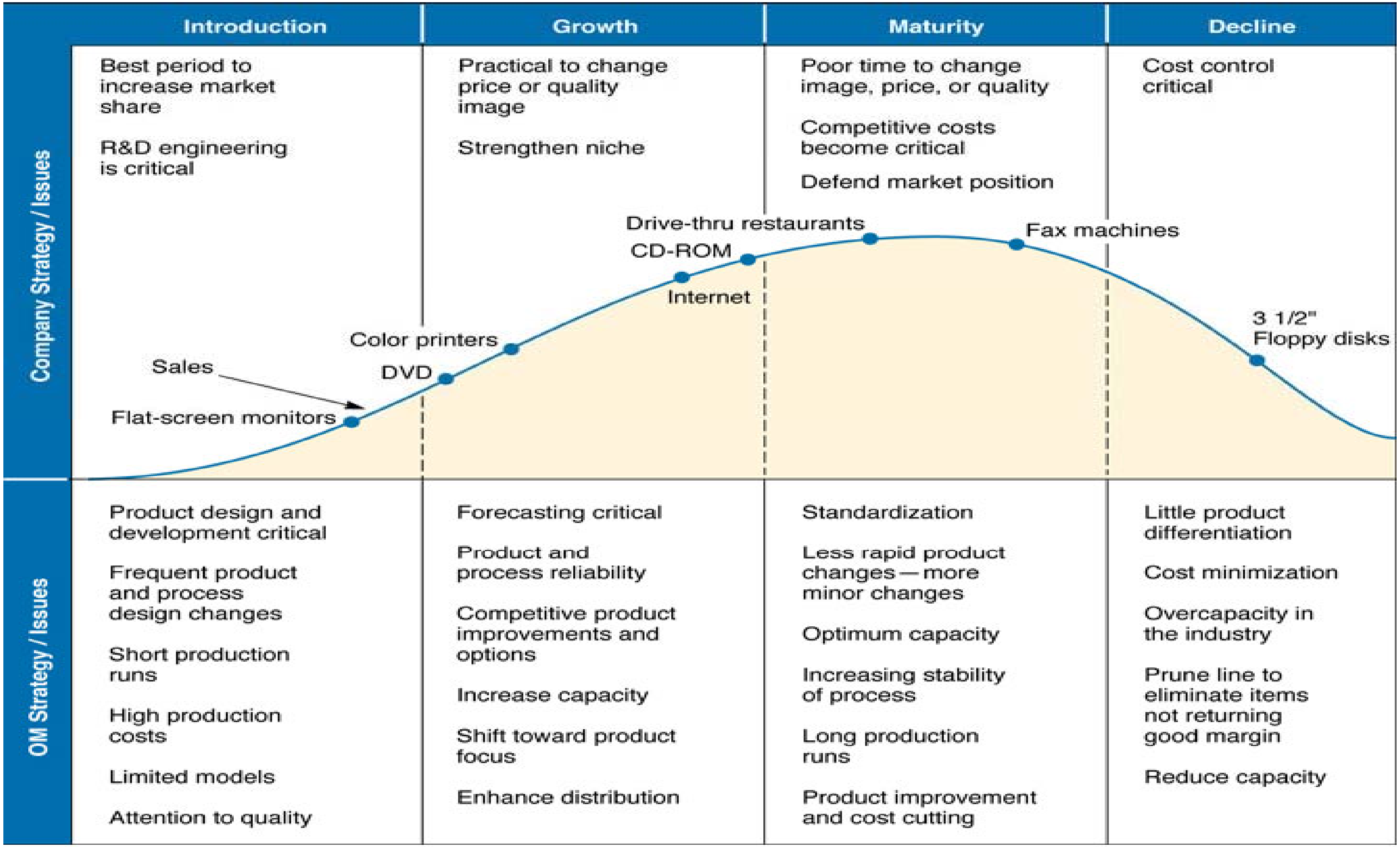
- Idea generation
- Assessment of firm's ability to carry out
- Customer Requirements
- Functional Specification
- Product Specifications
- Design Review
- Test Market
- Introduction to Market
- Evaluation

Scope of design for manufacturability and value engineering teams

Issues for Product Development

- Robust design
- Time-based competition
- Modular design
- Computer-aided design
- Value analysis
- Environmentally friendly design

Strategy and Issues During a Product's Life



Improving The Design Process: Design For Manufacture (DFM)

- Design a product for easy & economical production
- Consider manufacturability early in the design phase
- Identify easy-to-manufacture product-design characteristics
- Use easy to fabricate & assemble components
- Integrate product design with process planning

DFM Guidelines

1. Minimize the number of parts
2. Develop a modular design
3. Design parts for multi-use
4. Avoid separate fasteners
5. Eliminate adjustments
6. Design for top-down assembly
7. Design for minimum handling
8. Avoid tools

DFM Guidelines (continued)

9. Minimize subassemblies
10. Use standard parts when possible
11. Simplify operations
12. Design for efficient and adequate testing
13. Use repeatable & understood processes
14. Analyze failures
15. Rigorously assess value

Structural design issues

- Some design considerations:
  - Structural design criteria – failure modes
  - Stress concentration – notch sensitivity
  - Buckling/instability – modal analysis
  - Eigen-frequency – modal analysis
  - Contact with dissimilar metals
  - Welding and temperature affect mechanical properties
  - Corrosion
  - Fatigue considerations:
    - No endurance limit for Aluminum in S-N diagram
    - Consider fracture toughness properties for the material

Failure Modes

- Deformation
  - Modulus of Elasticity (E [MPa])
  - Moment of inertia
- Yielding
  - Yielding Stress (R_e [MPa])
  - Modulus of Elasticity (E [MPa])
- Ductile rupture
  - Yielding Stress (R_e [MPa])
  - Modulus of Elasticity (E [MPa])
- Brittle fracture
  - Ultimate Tensile Stress (R_m [MPa])
  - Modulus of Elasticity (E [MPa])
- Fatigue
  - Endurance limit
  - Design approach, e.g. Fail-safe, Damage Tolerant
  - Fracture toughness
- Corrosion
- Wear
- Impact
- Creep
- Buckling
  - Moment of inertia
  - Modulus of Elasticity (E [MPa])
- Stress corrosion (synergistic)

Mechanical Properties

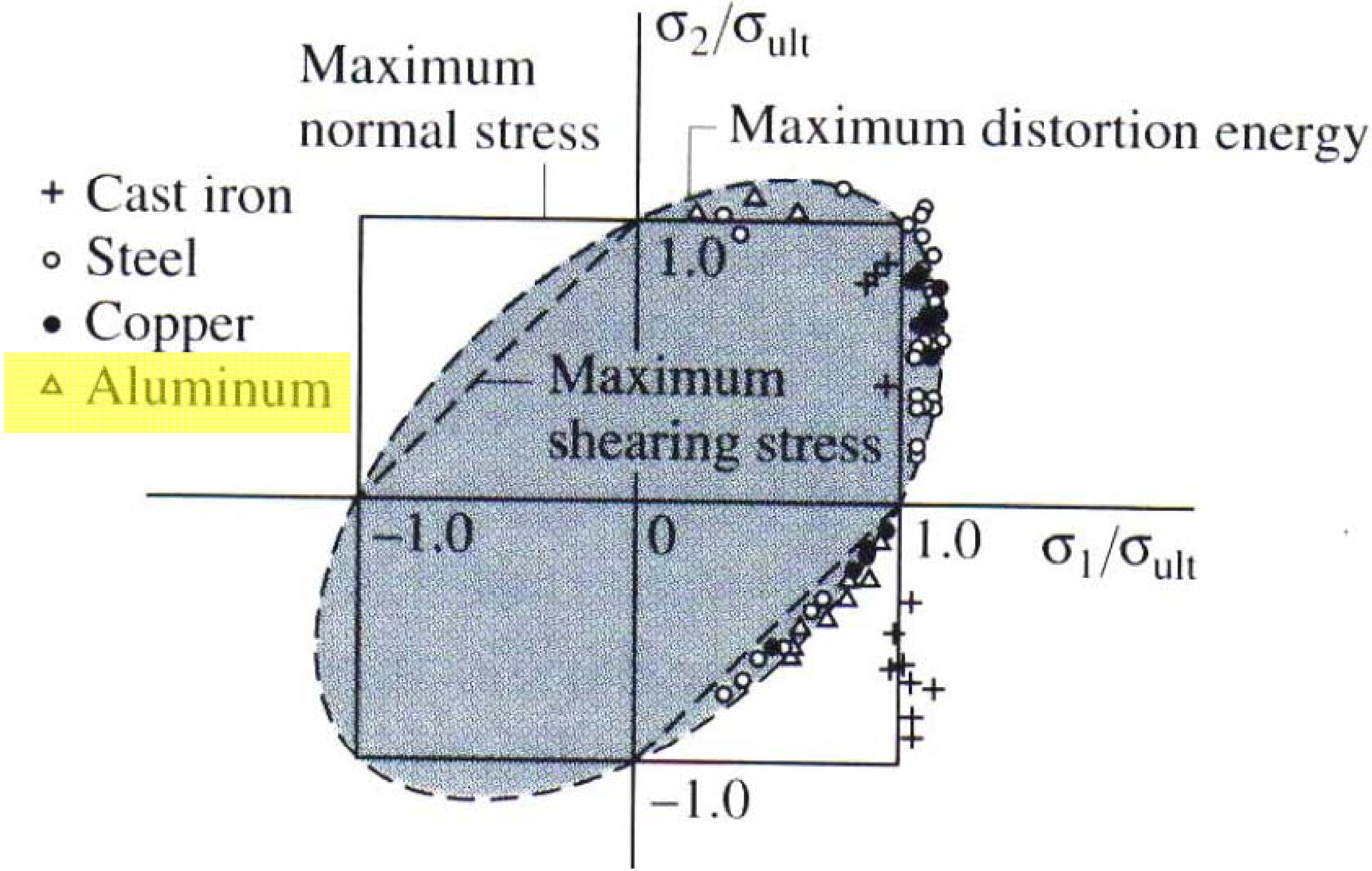
Material	Yield Stress (MPa)	Ultimate Stress (MPa)	Ductility EL%	Elastic Modulus (MPa)	Poisson's Ratio
1040 Steel	350	520	30	207000	0.30
1080 Steel	380	615	25	207000	0.30
2024 Al Alloy	100	200	18	72000	0.33
316 Stainless Steel	210	550	60	195000	0.30
70/30 Brass	75	300	70	110000	0.35
6-4 Ti Alloy	942	1000	14	107000	0.36
AZ80 Mg Alloy	285	340	11	45000	0.29

Mechanical Properties

Table 4.5 Mechanical properties of 357 aluminium alloy produced by different casting processes (from Lavington, M. H., *Metals and Materials*, 2, 713, 1986)

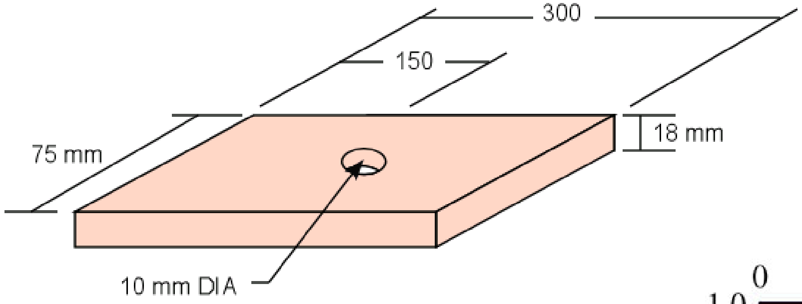
Process	0.2% proof stress MPa	Tensile strength MPa	Elongation %
Sand cast	200	226	1.6
Chill cast	248	313	6.9
Squeeze cast	283	347	9.3
Cosworth	242	312	9.8

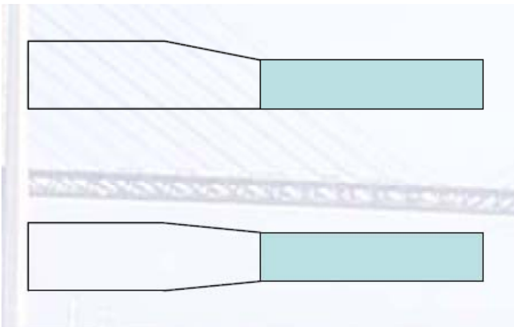
Design criteria

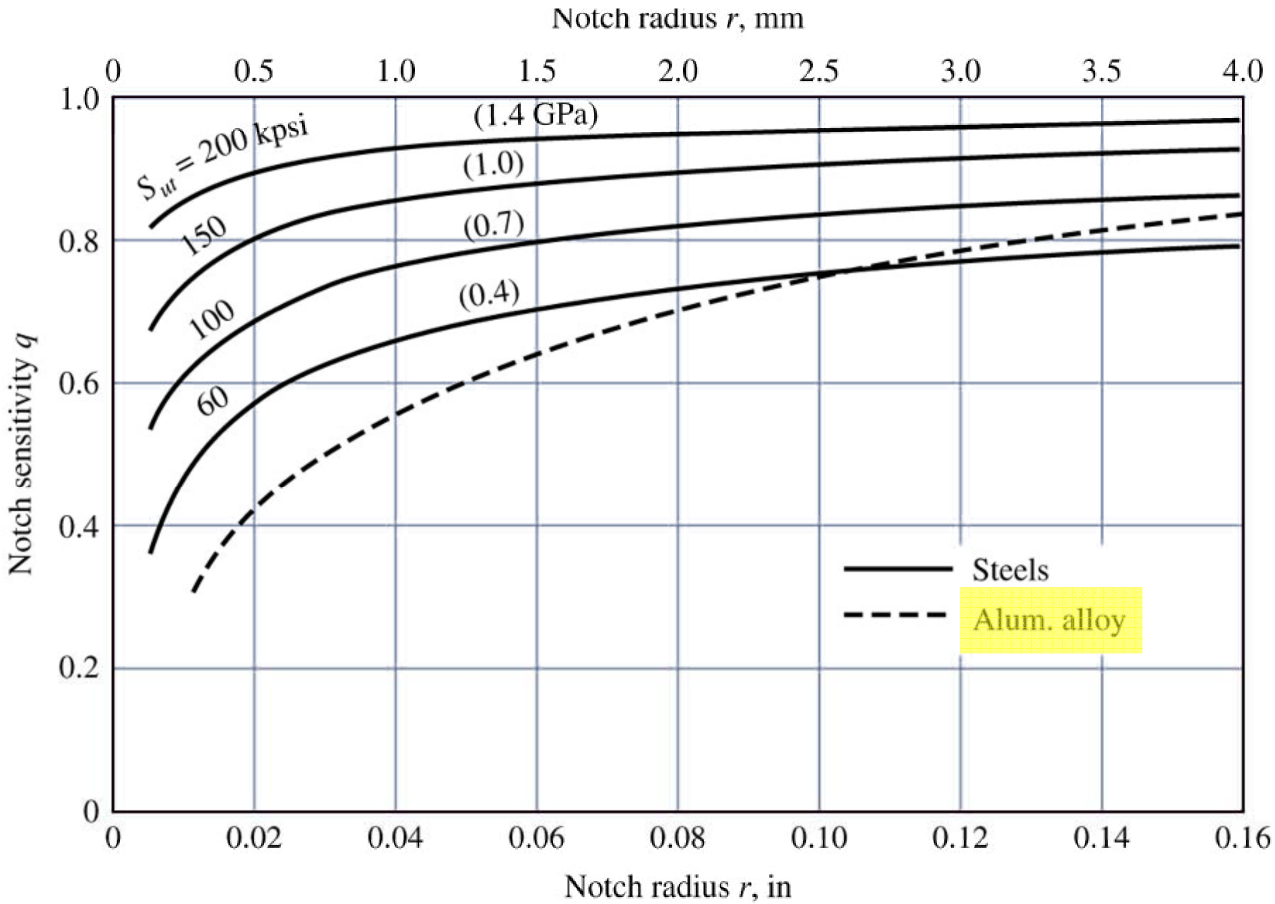


Hamrock, Fig. 6-17

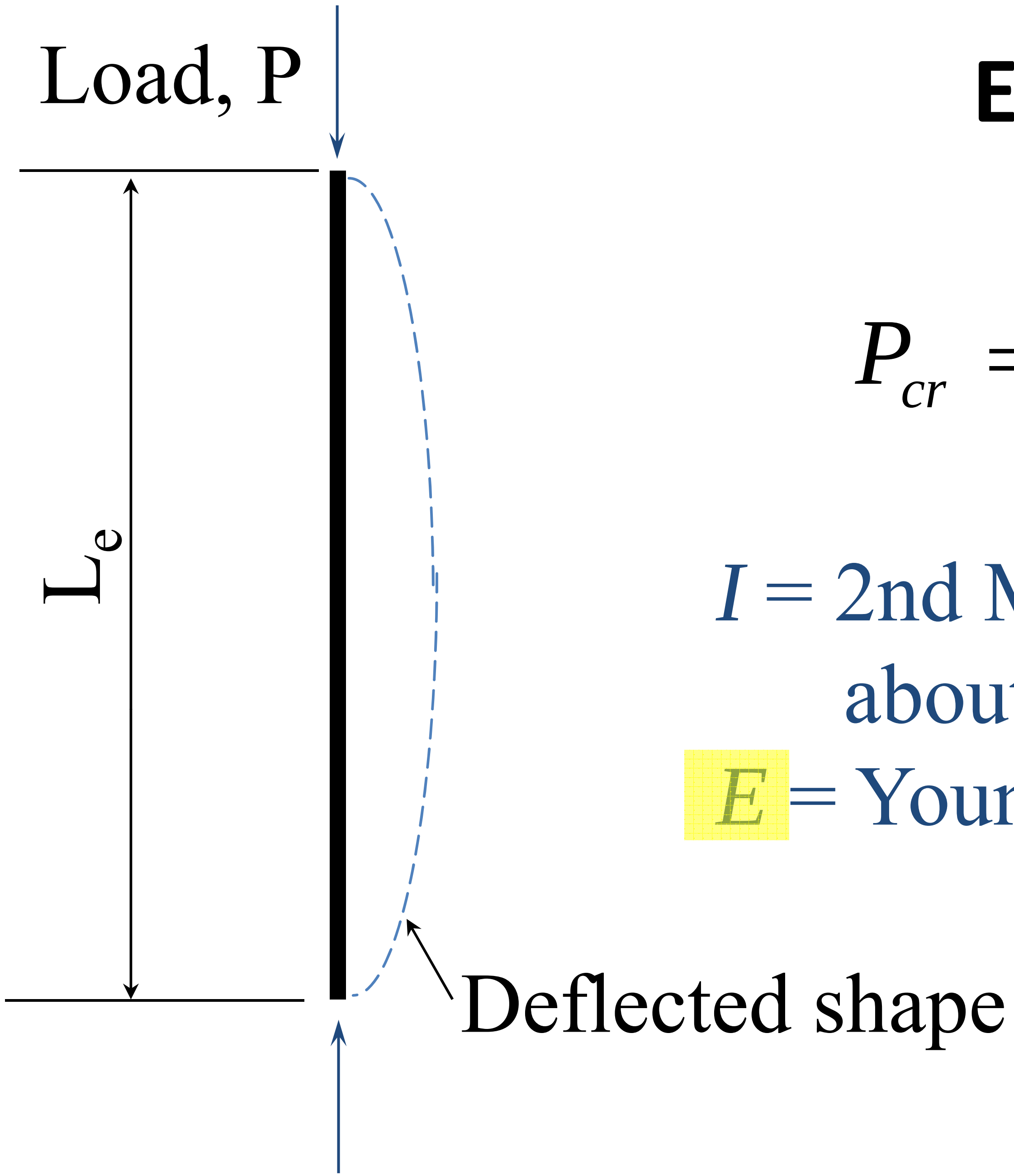
Stress concentration – notch sensitivity







EIGEN BUCKLING

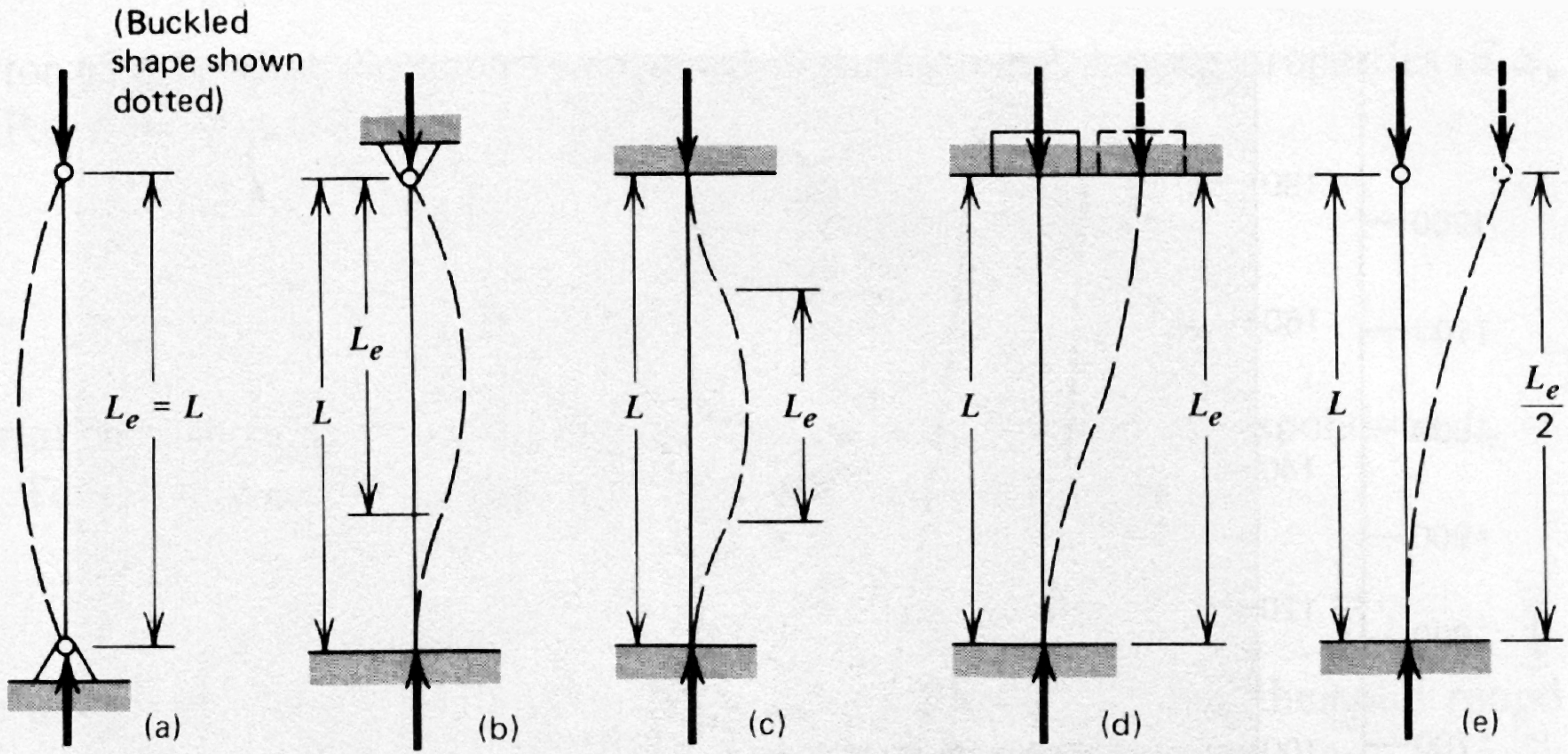


$$P_{cr} = \frac{\pi^2 EI}{\left(L_e\right)^2}$$

I = 2nd Moment of Area about weak axis.

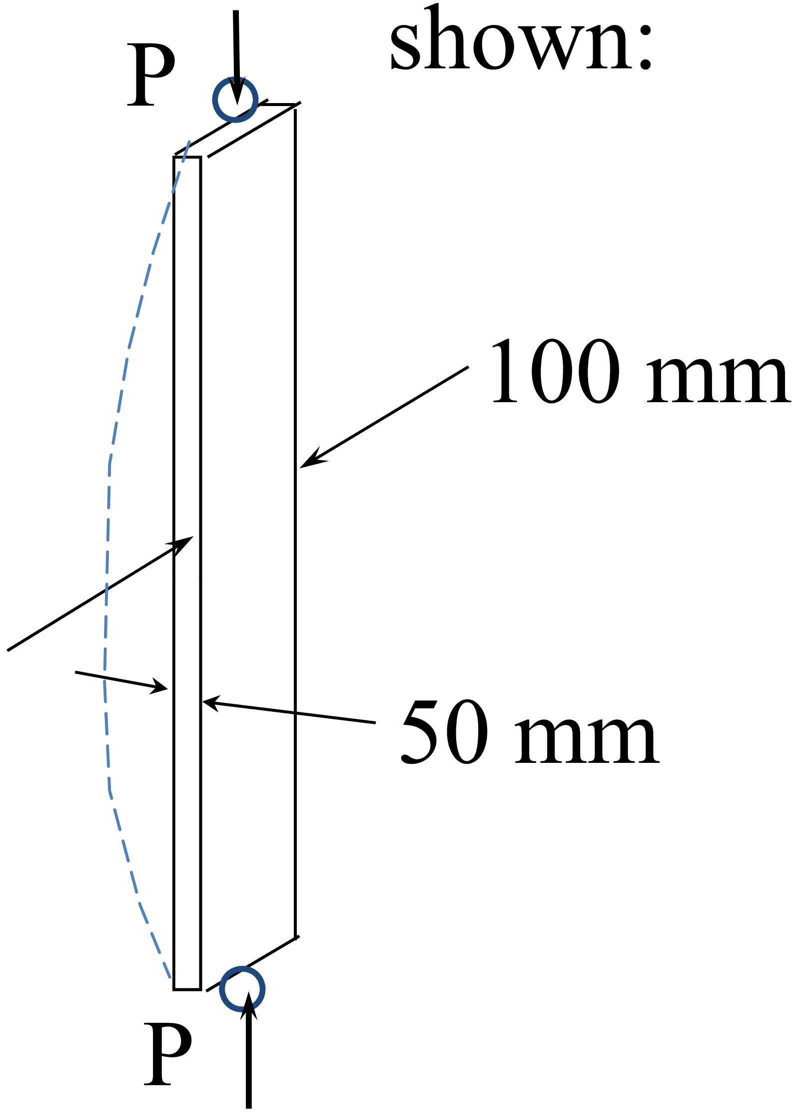
E = Young's Modulus

The effective length, L_e, depends on the Boundary Conditions:



	(a)	(b)	(c)	(d)	(e)
Theoretical	$L_e = L$	$L_e = 0.707L$	$L_e = 0.5L$	$L_e = L$	$L_e = 2L$
Minimum AISC Recommend.	$L_e = L$	$L_e = 0.80L$	$L_e = 0.65L$	$L_e = 1.2L$	$L_e = 2.1L$

Find the ***Buckling load*** for a pin-ended aluminum column 3m high, with a rectangular x-section as shown:



Weak axis:

$$I_{yy} = 100\,(50)^3/12$$
$$= 1.04\text{x}10^6\ \text{mm}^4$$

$$P_{cr} = \frac{\pi^2 (72000)(1.04x10^6)}{(3000)^2}$$

$= 82246$ N

Dynamic Effects

Static, i.e. acceleration ≈ 0

$$\mathbf{KD} = \mathbf{F}$$

Dynamic, i.e. acceleration ≠ 0

$$\mathbf{M\ddot{D}} + \mathbf{C\dot{D}} + \mathbf{KD} = \mathbf{F}$$

$$[\mathbf{k}] = \begin{bmatrix} \frac{12EI}{L^3} & \frac{6EI}{L^2} & -\frac{12EI}{L^3} & \frac{6EI}{L^2} \\ \frac{6EI}{L^2} & \frac{4EI}{L} & -\frac{6EI}{L^2} & \frac{2EI}{L} \\ -\frac{12EI}{L^3} & -\frac{6EI}{L^2} & \frac{12EI}{L^3} & -\frac{6EI}{L^2} \\ \frac{6EI}{L^2} & \frac{2EI}{L} & -\frac{6EI}{L^2} & \frac{4EI}{L} \end{bmatrix}$$

- Inertia force – mass times acceleration
- Damping force – damping times velocity
- Elastic Force – stiffness times deformation
- External force
- Dynamic Effects

Modal Analysis

- Avoid resonance
- Exploit resonance
- Assess structural stiffness
- Structural modal degrees of freedom
- Further dynamic analyses
- etc.

Contact with dissimilar metals

Table 2.3 Electrode potentials of various metals and alloys with respect to the 0.1 M calomel electrode in aqueous solutions of 53 g l^{-1} NaCl and 3 g l^{-1} H_2O_2 at 25°C (from *Metals Handbook*, Volume 1, American Society for Metals, Cleveland, Ohio, 1961)

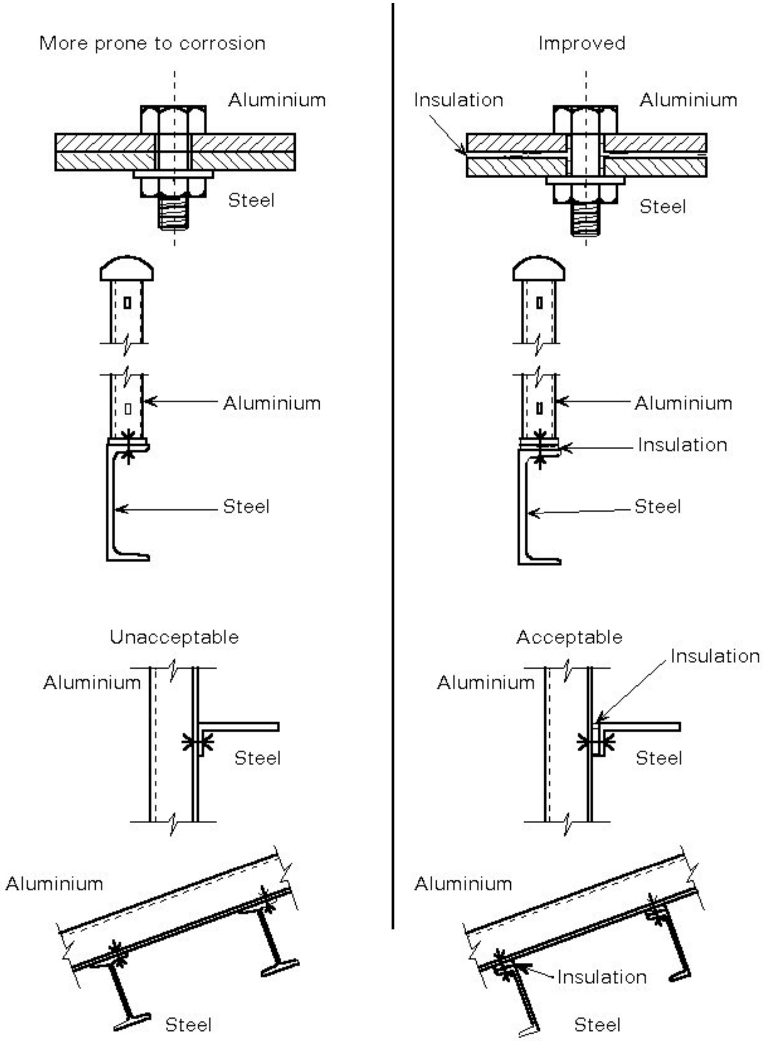
Metal or alloy		Potential (V)
Magnesium		− 1.73
Zinc		− 1.10
Alclad 6061, Alclad 7075	aluminium alloys*	− 0.99
5456, 5083	aluminium alloys*	− 0.87
Aluminium (99.95%), 5052, 5086	aluminium alloys*	− 0.85
3004, 1060, 5050	aluminium alloys*	− 0.84
1100, 3003, 6063, 6061, Alclad 2024	aluminium alloys*	− 0.83
2014-T4	aluminium alloys*	− 0.69
Cadmium		− 0.82
Mild steel		− 0.58
Lead		− 0.55
Tin		− 0.49
Copper		− 0.20
Stainless steel (3xx series)		− 0.09
Nickel		− 0.07
Chromium		− 0.49 to + 0.18

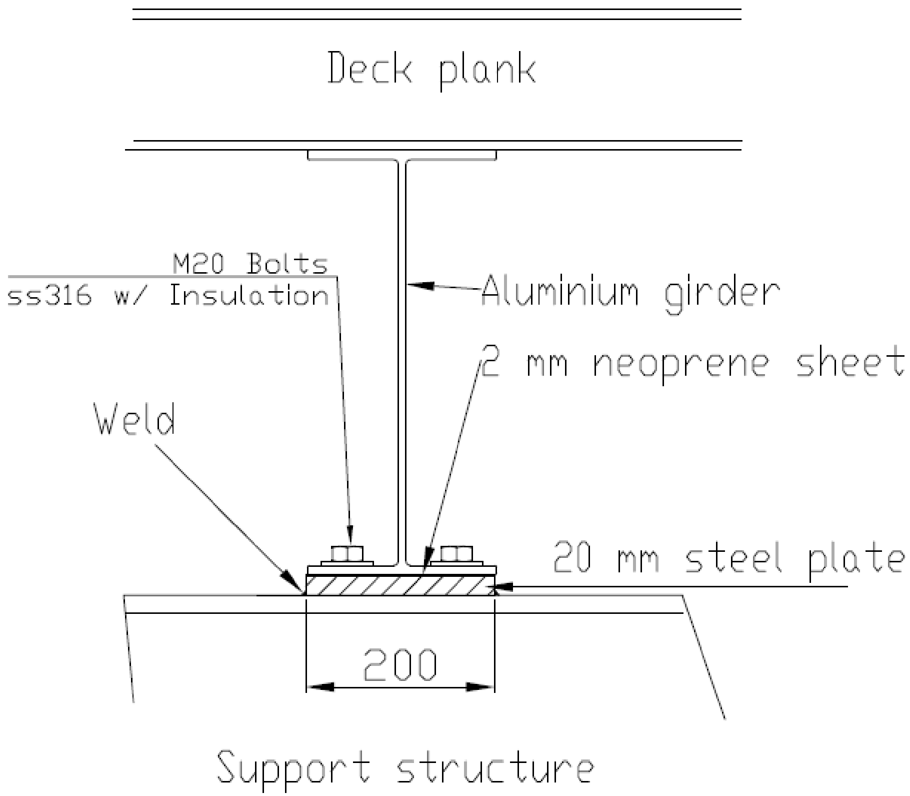
* Compositions corresponding to the numbers are given in Tables 3.2 and 3.4

Table 2.4 Electrode potentials of aluminum solid solutions and micro-constituents with respect to the 0.1 M calomel electrode in aqueous solutions of 53 g l^{-1} NaCl and 3 g l^{-1} H_2O_2 at 25°C (from *Metals Handbook, Volume 1, American Society for Metals, Cleveland, Ohio, 1961)*

Solid solution or micro-constituent	Potential (V)
Mg_5Al_8	− 1.24
Al-Zn-Mg solid solution (4% $MgZn_2$)	− 1.07
$MgZn_2$	− 1.05
Al_2CuMg	− 1.00
Al-5% Mg solid solution	− 0.88
$MnAl_6$	− 0.85
Aluminium (99.95%)	− 0.85
Al-Mg-Si solid solution (1% Mg_2Si)	− 0.83
Al-1% Si solid solution	− 0.81
Al-2% Cu supersaturated solid solution	− 0.75
Al-4% Cu supersaturated solid solution	− 0.69
$FeAl_3$	− 0.56
$CuAl_2$	− 0.53
$NiAl_3$	− 0.52
Si	− 0.26

Contact with dissimilar metals



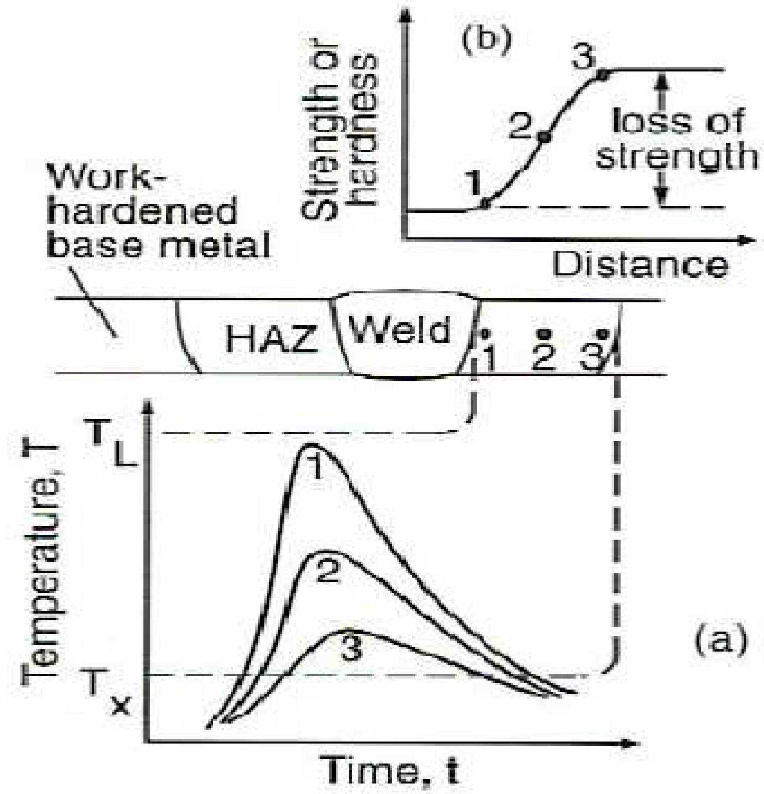


http://www.kappaluminium.no/

Welding

- If the base material has been cold worked prior to welding, the effect of work hardening is completely gone in the fusion zone due to remelting and is partially lost in HAZ due to recrystallisation and grain growth.

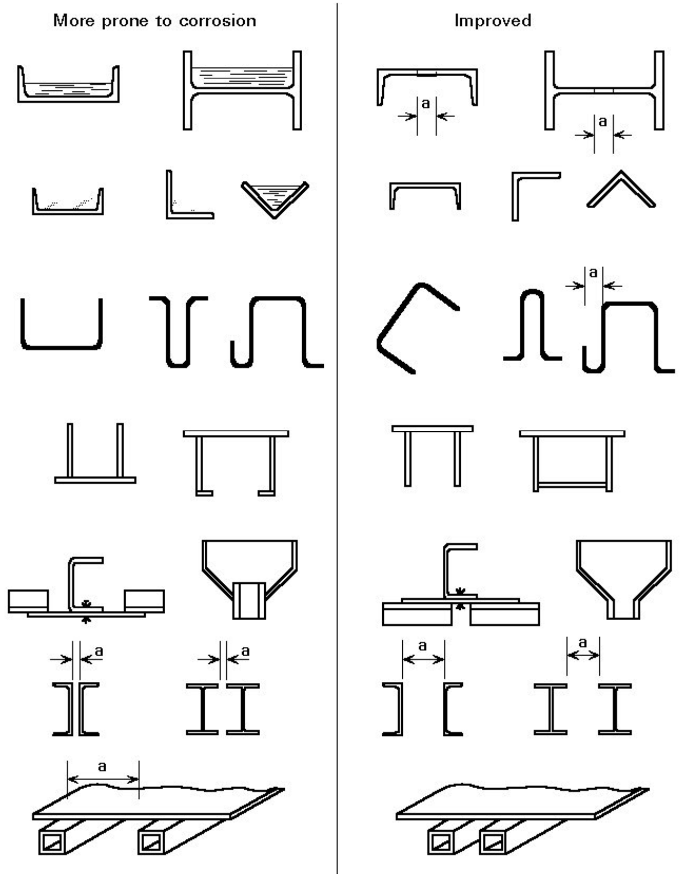
- Note: Strength loss should be taken into account in structural designs. (even Toughness) The harder the base metal, the greater the strength loss is.

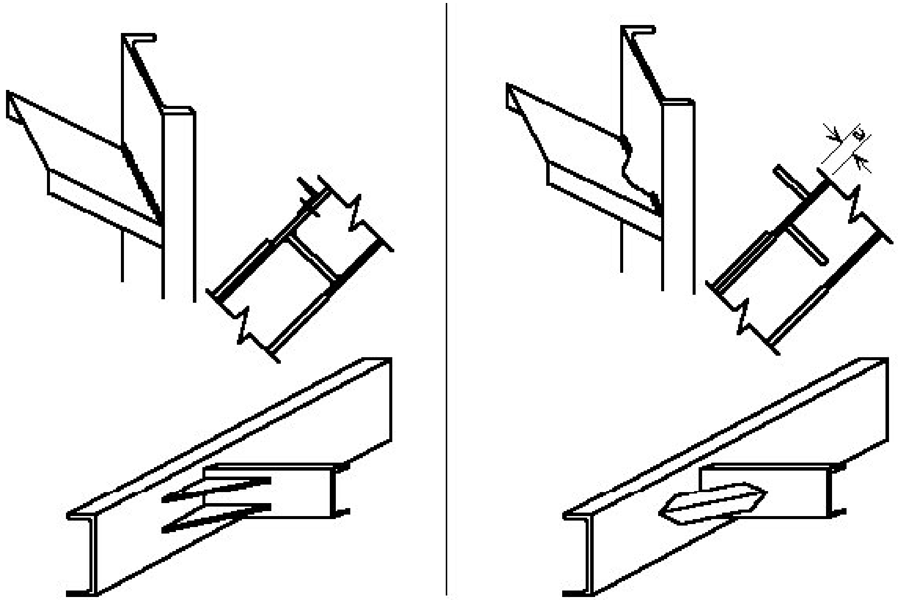


Softening of workhardened Material caused by welding
(a) thermal cycles
(b) strength or Fusion hardness profile.

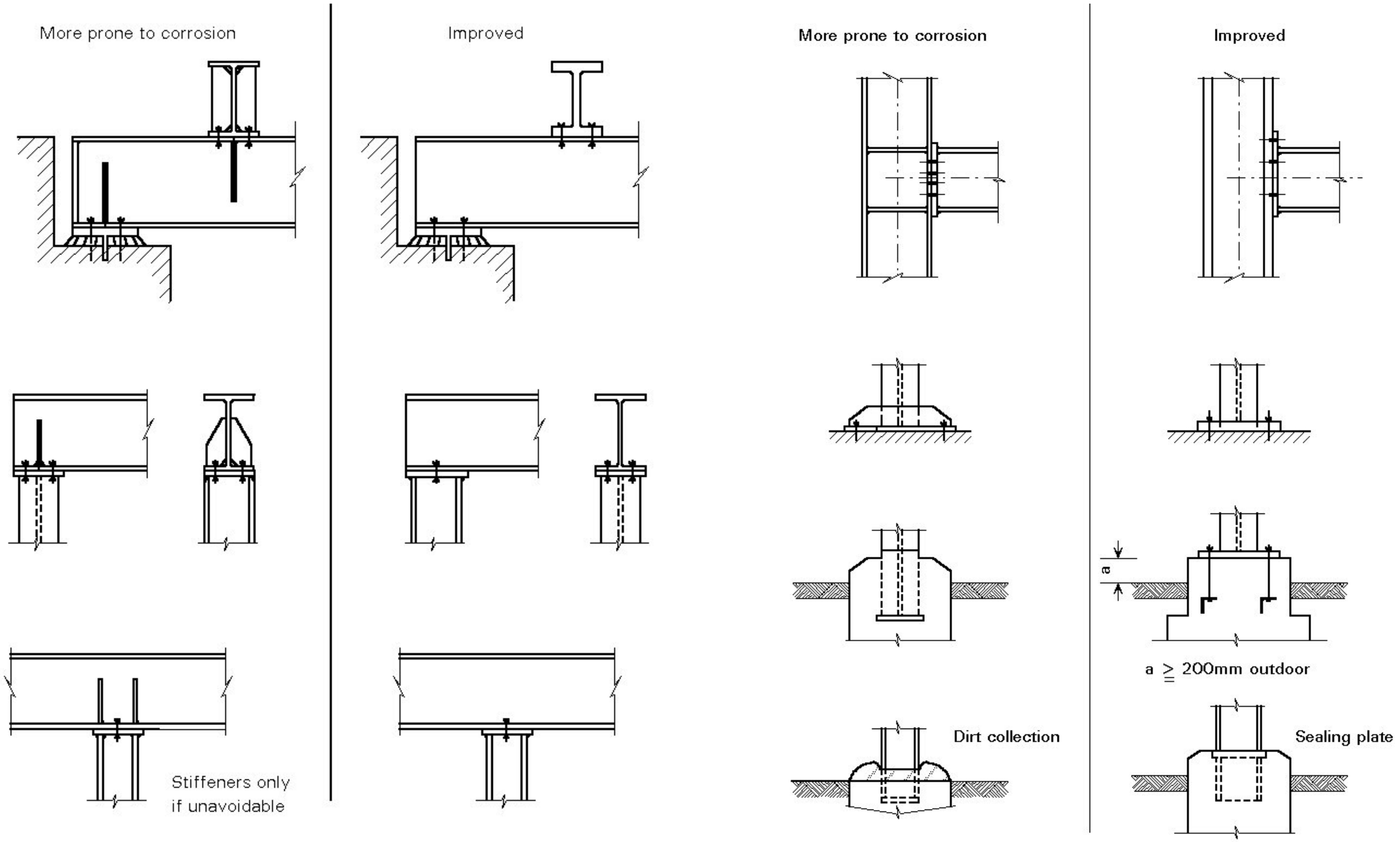
Corrosion

- Constructive prevention of corrosion the most inexpensive and the most effective





Corrosion


More prone to corrosion
Improved
More prone to corrosion
Improved
a ≥ 200mm outdoor
Dirt collection
Sealing plate
Stiffeners only
if unavoidable

Fatigue considerations

- Aluminum alloys
  - S_e' (S_f at 10^8 cycles) $= 0.4\ S_{ut}$ for $S_{ut} < 330$ MPa
    $= 130$ MPa for all other values of S_{ut}

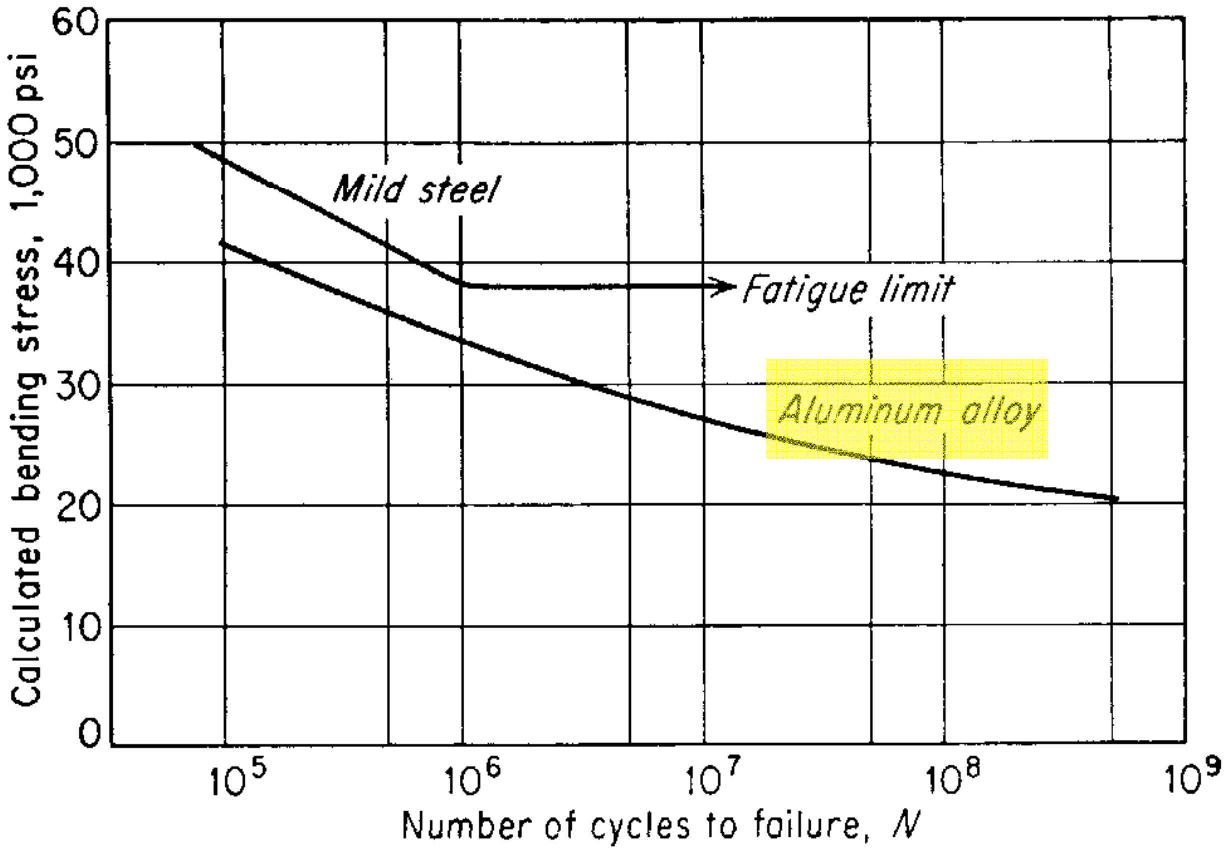
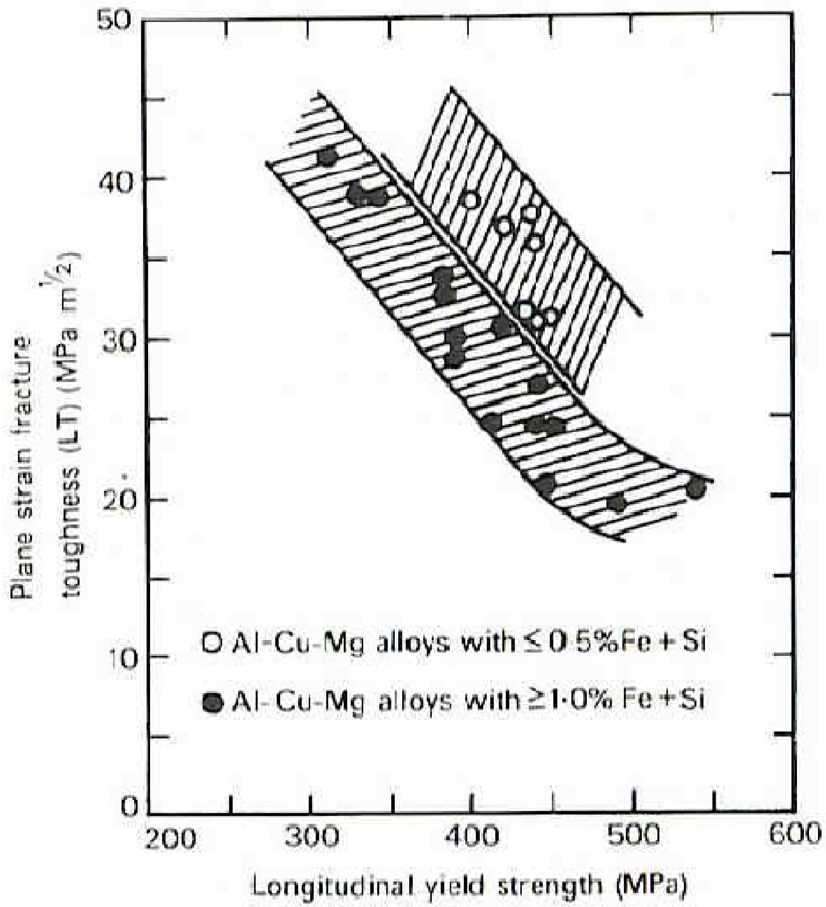


Figure 12-3 Typical fatigue curves for ferrous and nonferrous metals.

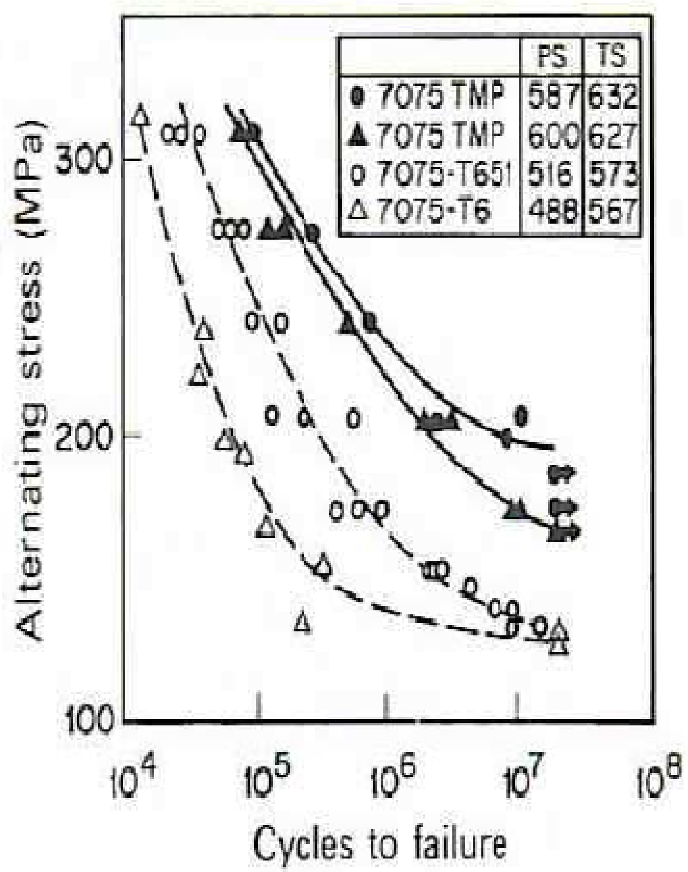
Fatigue considerations

- Toughness is resistance of material to fracture (in the presence of cracks).
- Crack extension is due to nucleation of crack by decohesion at second phase particle-matrix interface.
- Toughness is greatest in underaged condition and decrease as ageing proceeds to peak strength.
- Note: Reducing Fe and Si (impurities) greatly improves the toughness.



Fatigue considerations

- The improvement in tensile strength is not always accompanied with increased fatigue strength in non-ferrous alloys.
- The more an alloy is dependent upon precipitation-hardening for its tensile strength, the lower its fatigue ratio (endurance limit : tensile strength) becomes.
- Age-hardened aluminium alloys possess disappointing fatigue properties due to localised straining of precipitates under cyclic stressing. Improved by more uniformly dispersed precipitates to prevent coarse slips formation.
- An increase in dislocation density by thermo mechanical processing helps to improve fatigue performance



Microstructure-Fatigue Relationships

- Three major factors.

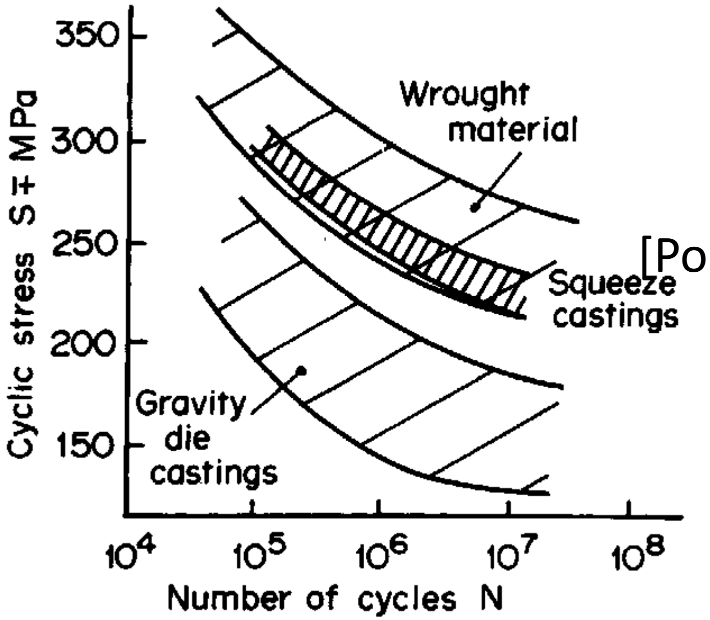
  1: geometry of the specimen (previous slide); anything on the surface that is a site of stress concentration will promote crack formation (shorten the time required for nucleation of cracks).

  2: defects in the material; anything inside the material that can reduce the stress and/or strain required to nucleate a crack (shorten the time required for nucleation of cracks).

  3: dislocation slip characteristics; if dislocation glide is confined to particular slip planes (called planar slip) then dislocations can pile up at any grain boundary or phase boundary. The head of the pile-up is a stress concentration which can initiate a crack.

Casting porosity affects fatigue

Gravity cast versus squeeze cast versus wrought Al-7010



[Polmear]

Fig. 4.9 Fatigue (*S/N*) curves for alloy 7010 in wrought, gravity diecast and squeeze-cast conditions (from Chadwick, G. A., *Metals and Materials*, **2**, 693, 1986)

- Casting tends to result in porosity. *Pores are effective sites for nucleation of fatigue cracks*. Castings thus tend to have lower fatigue resistance (as measured by S-N curves) than wrought materials.
- Casting technologies, such as *squeeze casting*, that reduce porosity tend to eliminate this difference.

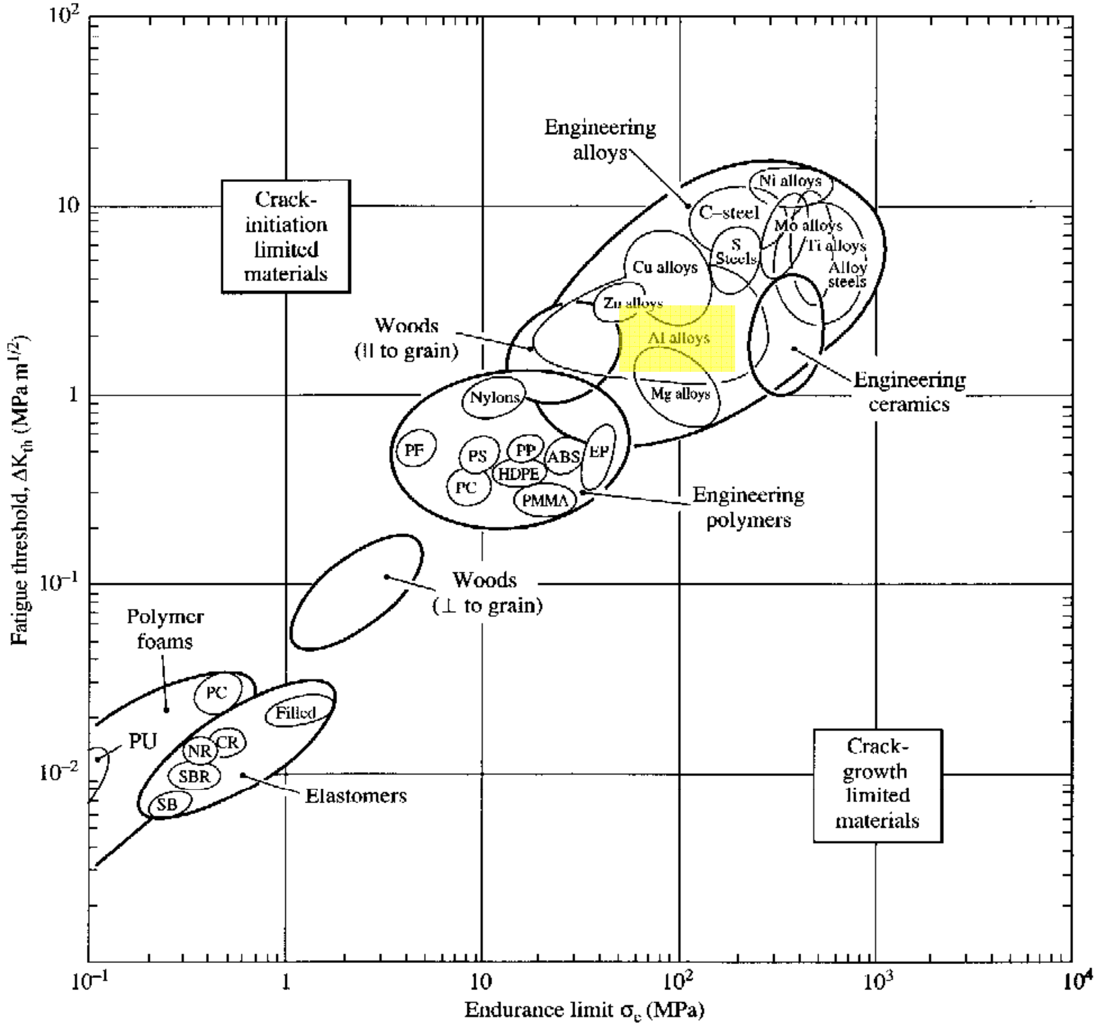


Figure 12.22

A material property chart displaying the fatigue threshold stress intensity (ΔK_{th}, obtained at $R = 0$) vs. endurance limit (σ_e, appropriate for $R = -1$). Although these two properties correlate for the several material classes, there are some subtleties. Ceramics, for example, have relatively high values of the ratio $\sigma_e/\Delta K_{th}$. Thus, they are more prone to crack-growth-limited fatigue fracture (extrinsic fatigue, cf. Fig. 12.21). Conversely, materials having high values of ΔK_{th} vis-à-vis σ_e (e.g., some of the tough metals) are more prone to intrinsic fatigue, which involves nucleation of the fatigue cracks that result in fracture (also see Fig. 12.21). (*Adapted from N. A. Fleck, K. J. Kang, and M. F. Ashby, "The Cylic Properties of Engineering Materials," Acta Metall. et Mater., 42, 365, Copyright 1994, with permission from Elsevier Science.*)

Example – Helideck support structure

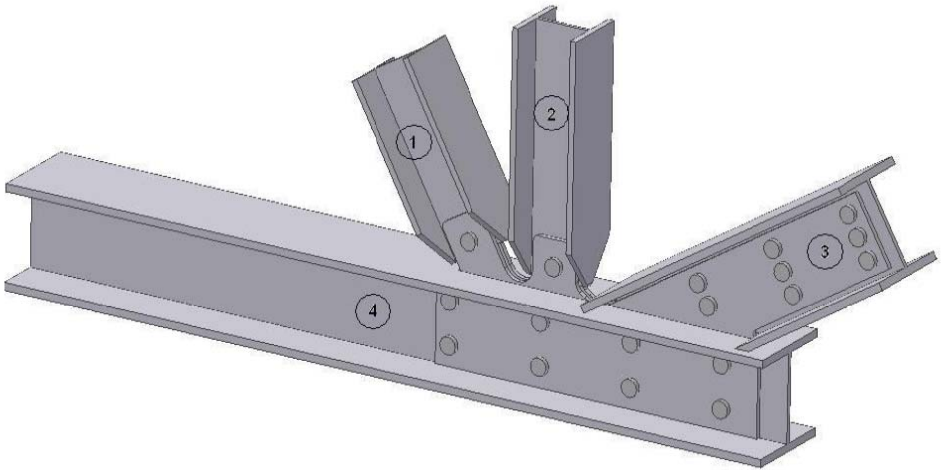
http://aluminium-offshore.com/

Example – Helideck support structure

Aluminium

EN AW 6082-T6

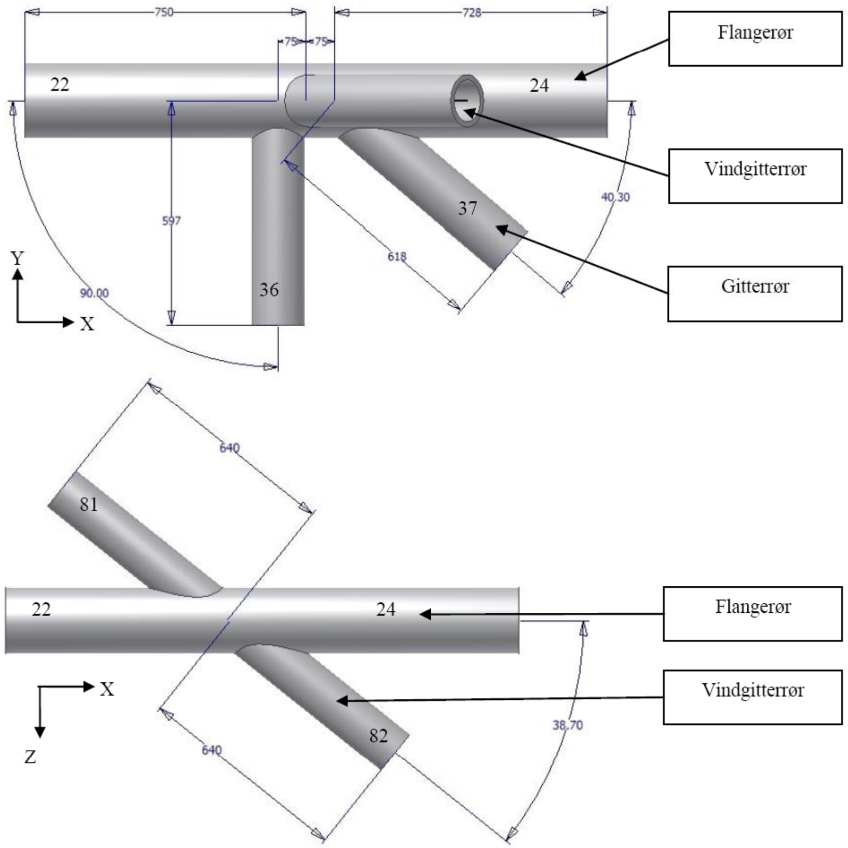
AlSi1MgMn alloy



Steel

EN 10 025 S355 K2 G3

Mn, Si, P, S alloying elements



Example – Helideck support structure

Aluminium

- Welding reduce strength in HAZ up to 30-50% and it is difficult to improve
- Inspection is required (NDT)
- SCF, i.e. welding and geometrical sharp edges (notches) increase the stress level significantly
- Price
  - Can be increased by introducing welding, i.e. increased requirements to inspection
- Weight
  - Depends on the structural behaviour – in this case the use of bolts provide a very effective load-carrying structure
  - Resulting weight = 12000kg
- Serviceability
  - Easier to transport
- Manufacturability
  - No additional corrosion considerations
- Resale

Steel

- Welding require special considerations in respect to HAZ
- Inspection is required (NDT)
- SCF, i.e. welding and geometrical sharp edges (notches) increase the stress level significantly
- Price
  - Can be increased by introducing welding, i.e. increased requirements to inspection
- Weight
  - Depends on the structural behaviour – in this case the use of cylindrical members provide a very effective load-carrying structure
  - Resulting weight = 24000kg
- Serviceability
  - Structural analysis on base structure required
- Manufacturability
  - Require additional corrosion considerations
- Resale

Example – Helideck support structure

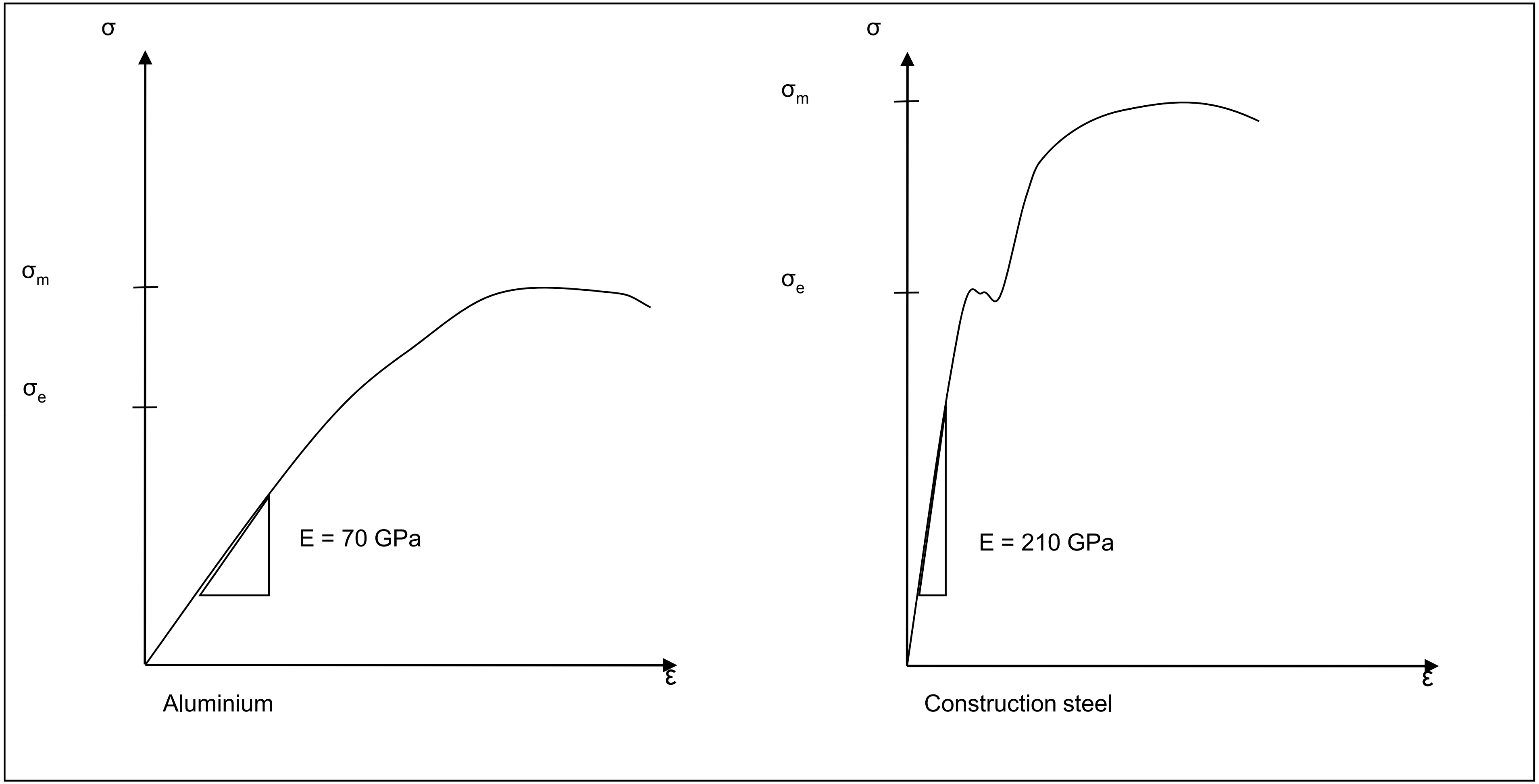
Materiale	Al 6082 T4	S355JR
Flydespænding, σ_{flyde} [MPa]	162	355
Brudspænding, σ_{brud} [MPa]	247	500
Elasticitetsmodul, E [MPa]	70.000	210.000
Densitet, ρ [kg/m³]	2.700	7.850
Pris [$/ton][]	1.120	335

TABLE 4 - Charpy impact test data, estimated yield strength and calculated fracture toughness values

Samples	Notch location	Charpy V impact data (average)	Vickers hardness (average)	Estimated yield strenght	Estimated Fracture toughness K_{IC}
		J	HV	MPa (*)	MPa$\sqrt{m}$ (**)
1..6 (unwelded)	Base material	10.6	100	242	32.5
7..12 (welded)	WM	6.9	60	132	20.2
13..18 (welded)	HAZ	13.0	70	162	32.9

(*) *Estimated using the regression formula (2)*
(**) *Calculated from empirical relation (1)*

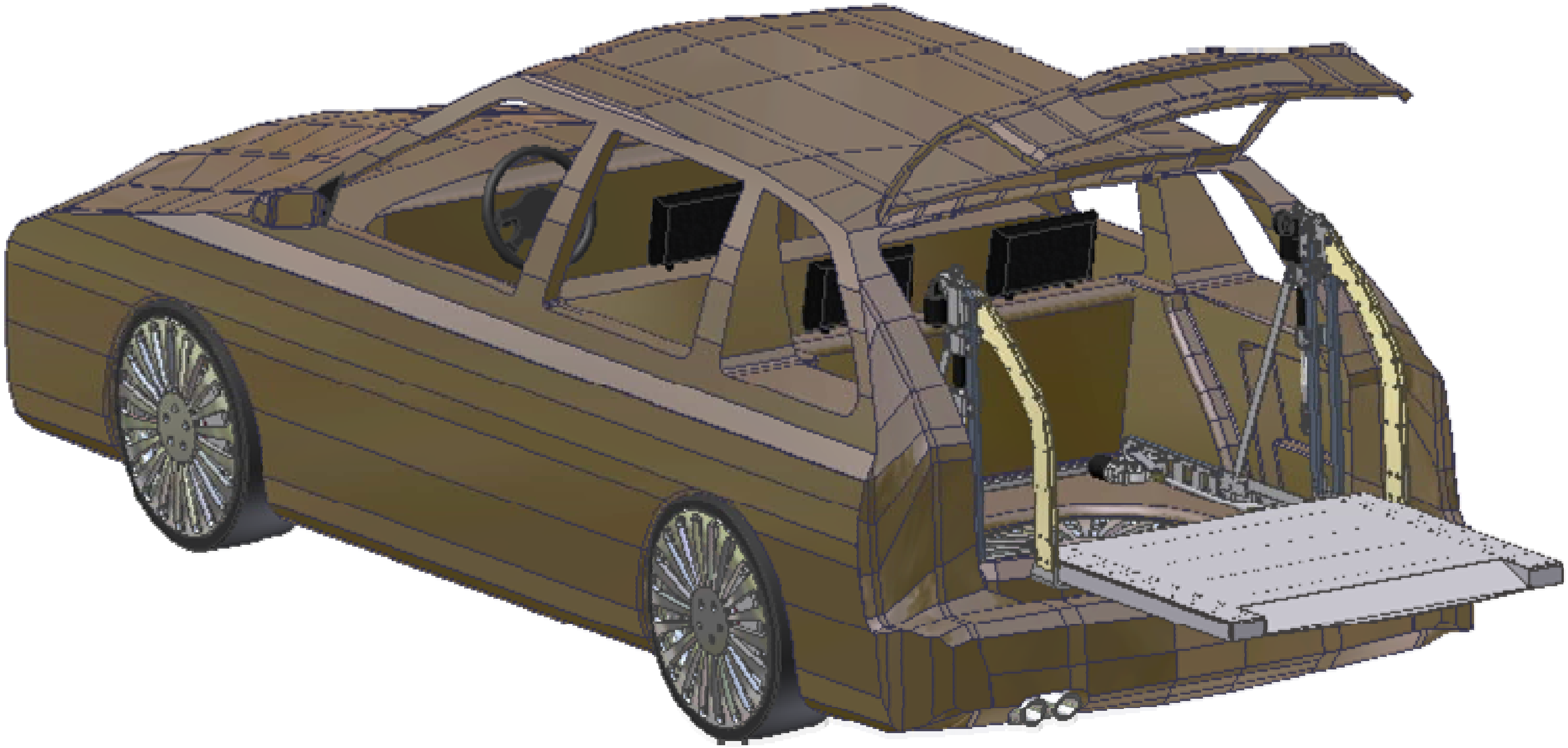
Example – Helideck support structure



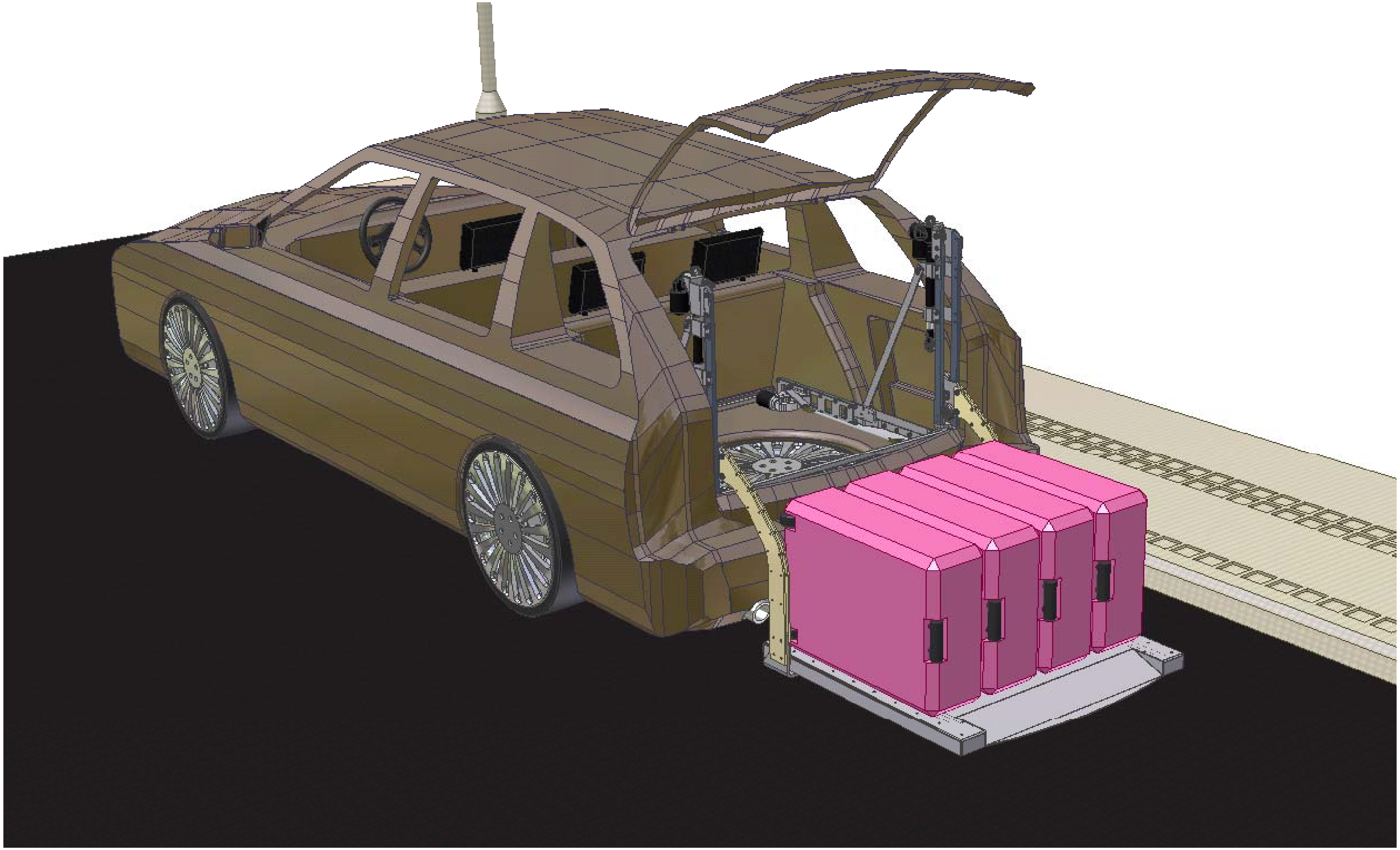
Stress-strain curve for aluminium and construction steel.

Example – Luggage lift

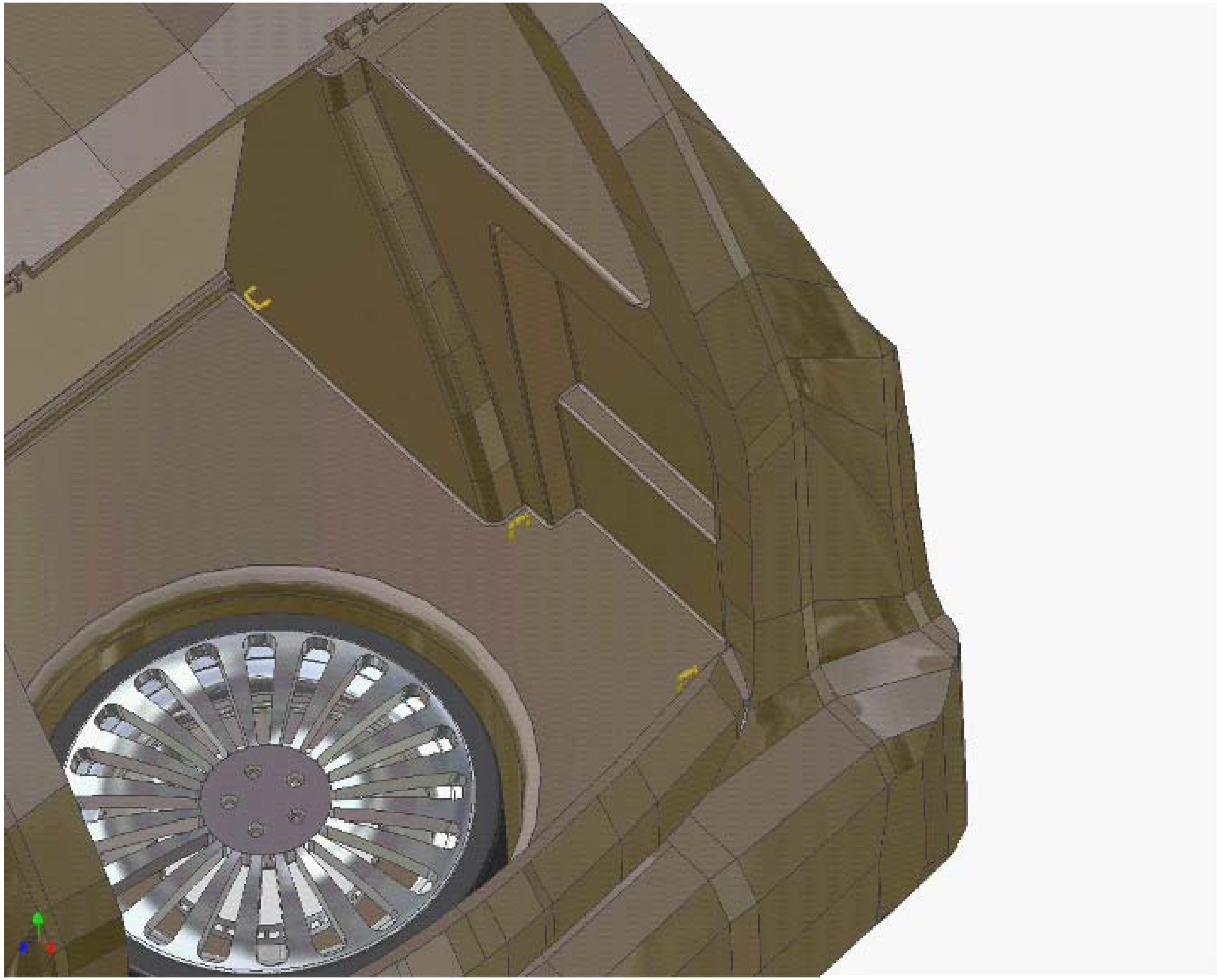
Example – Luggage lift



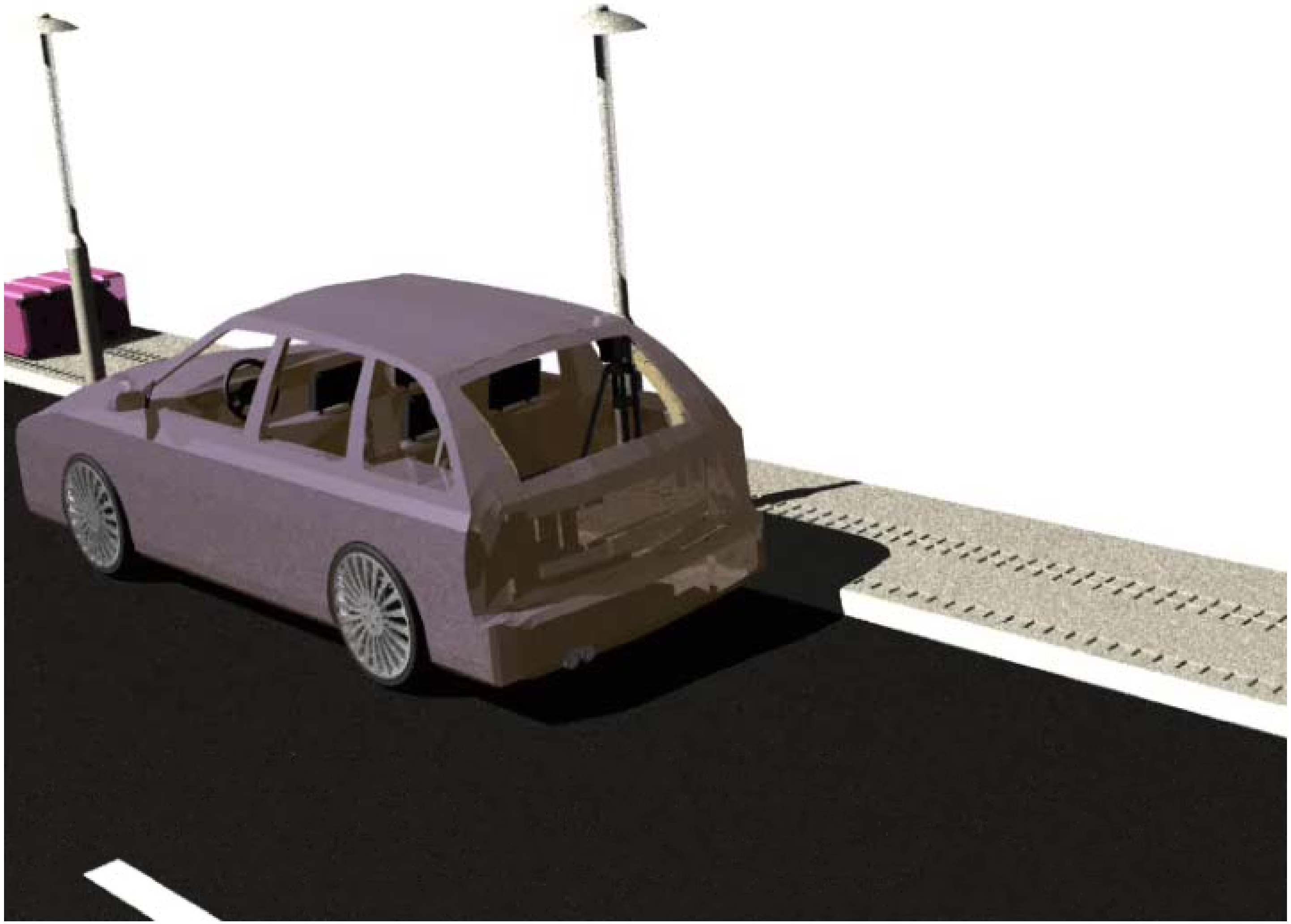
Example – Luggage lift



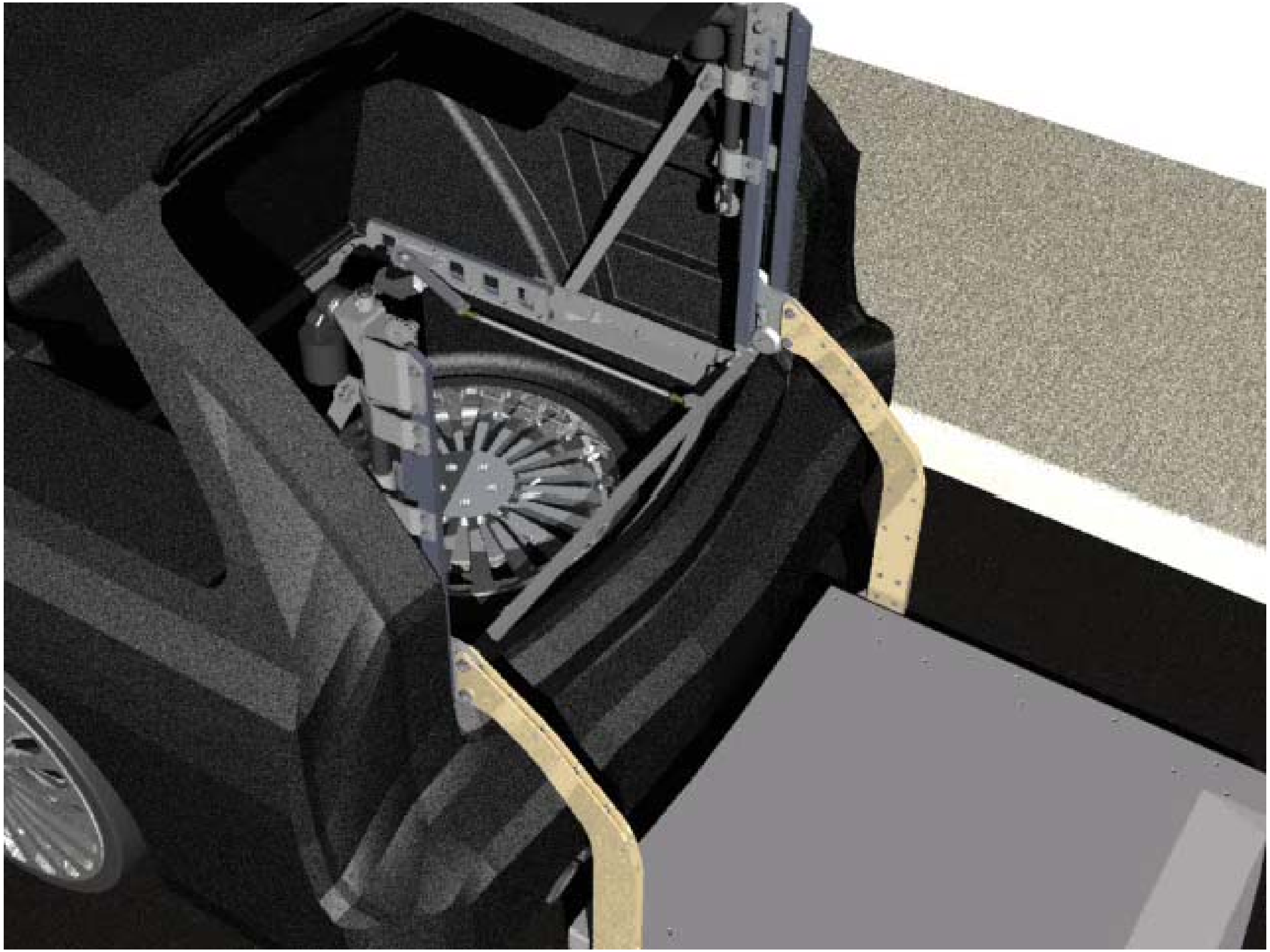
Mounting of lift



Timecycle



Operation cycle



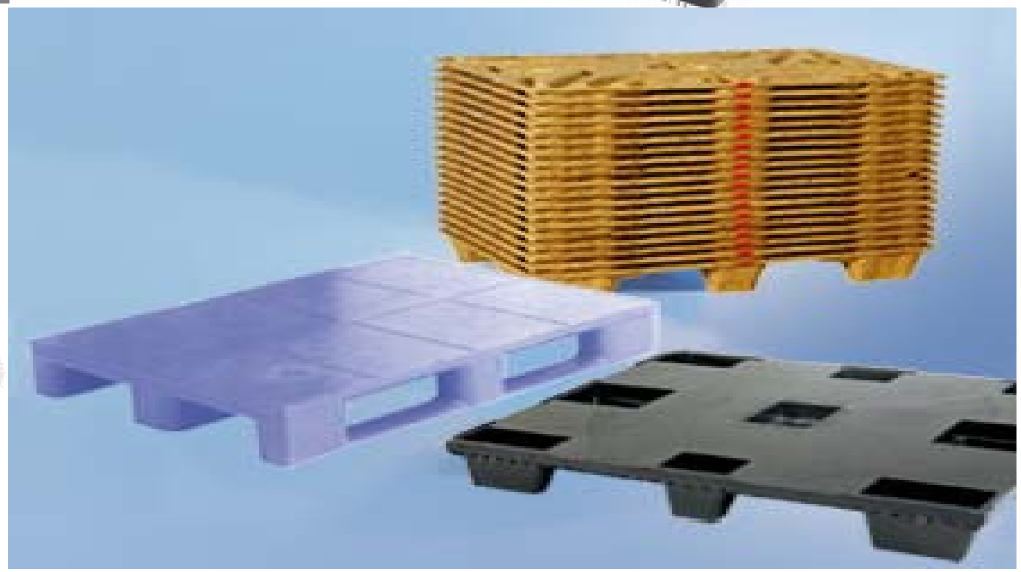
Other opportunities

- Elderly/disabled

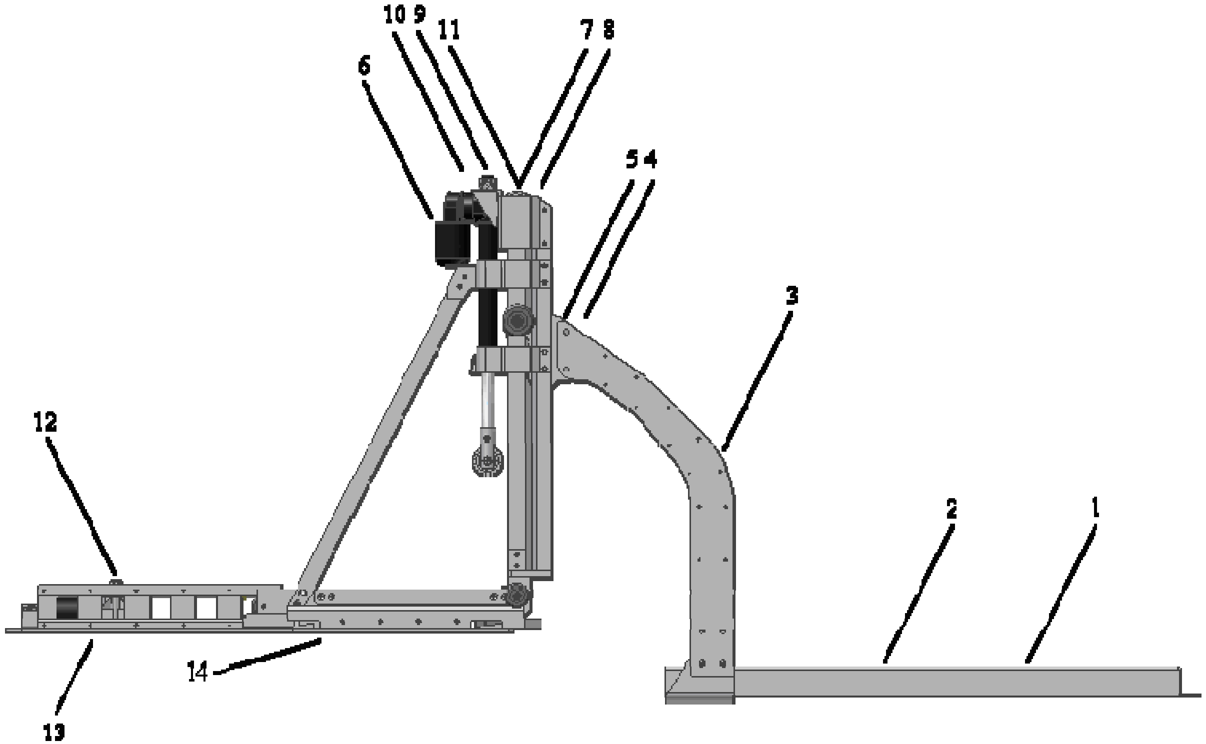
Freight







Material selection

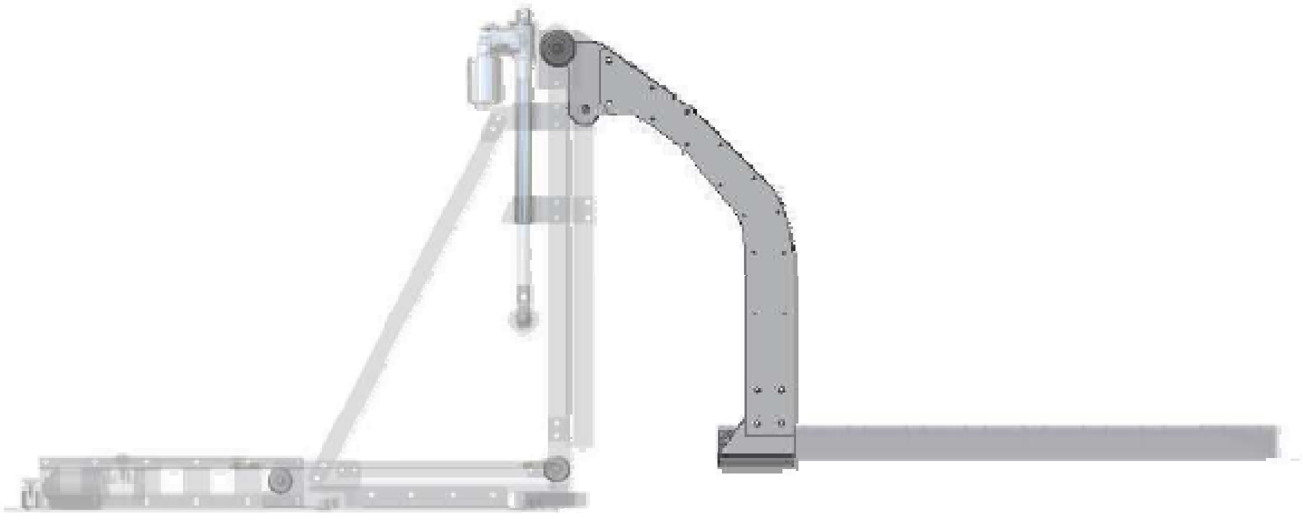


- Designcheck of structural components
- Critical areas
- Manufacturing

Loading area

- Material – aluminium chosen
- Profil chosen (area moment of inertia)
- Wear
- Coating on rail

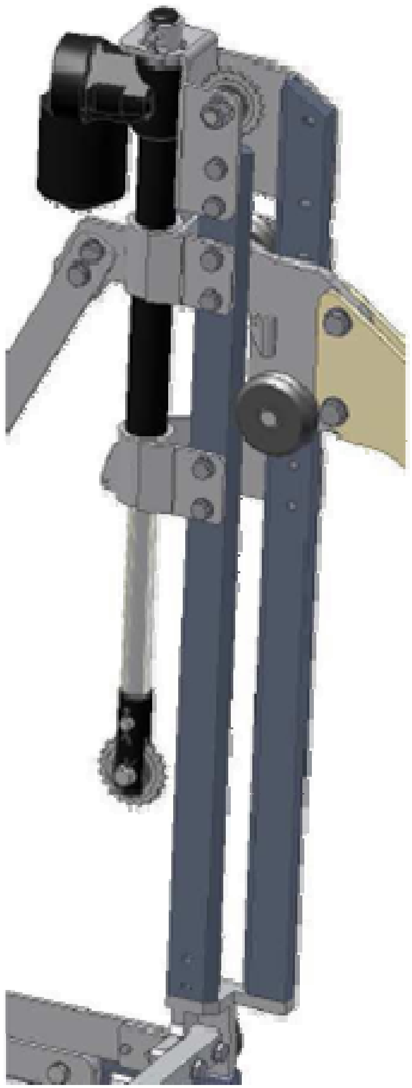
Liftarm



- Material – aluminium chosen
- No wear
- Designed as a structural loadcarrying member

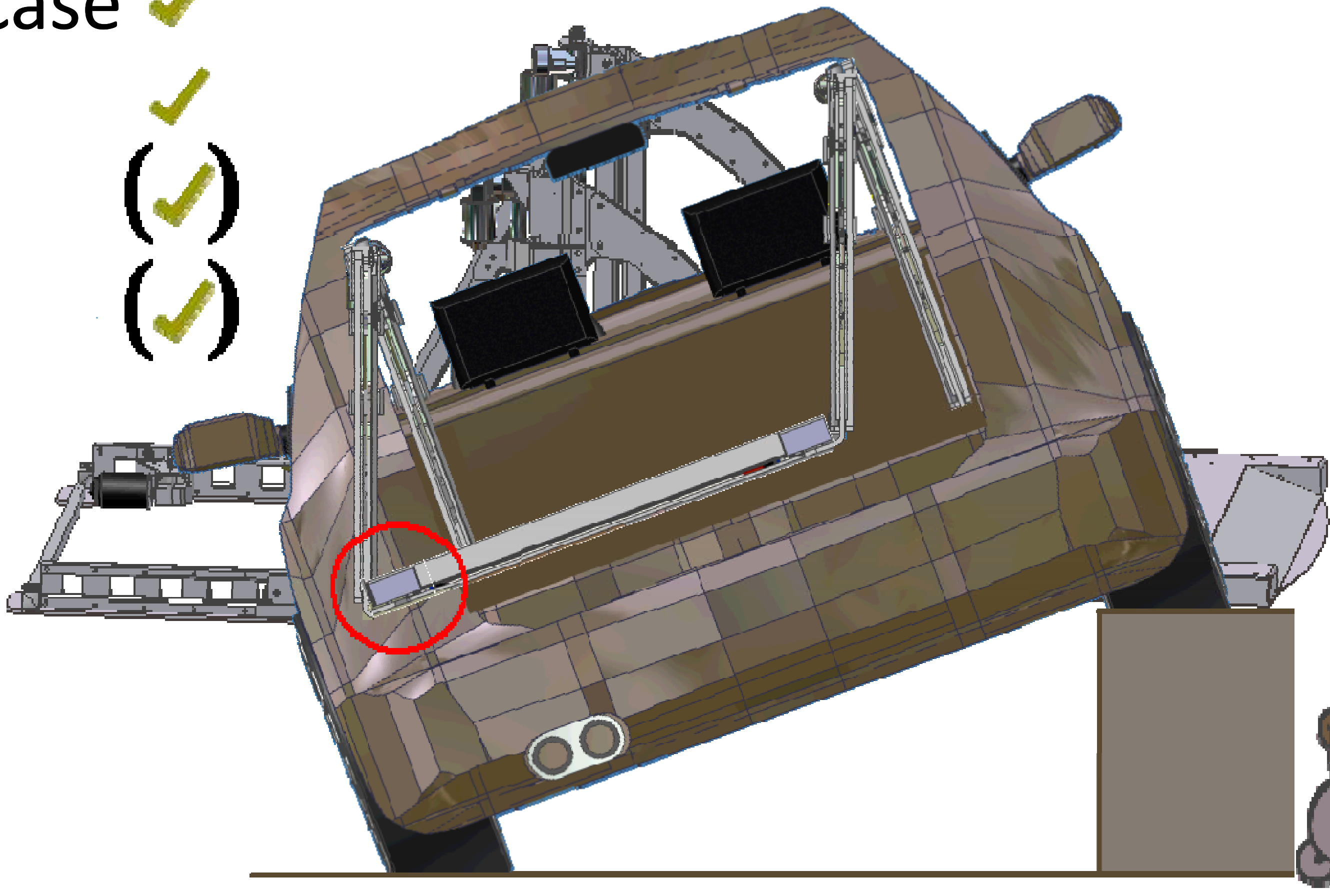
Vertical rail

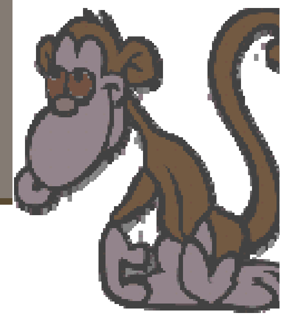
- Material – steel chosen
- Critical loads
- Weight



Critical issues

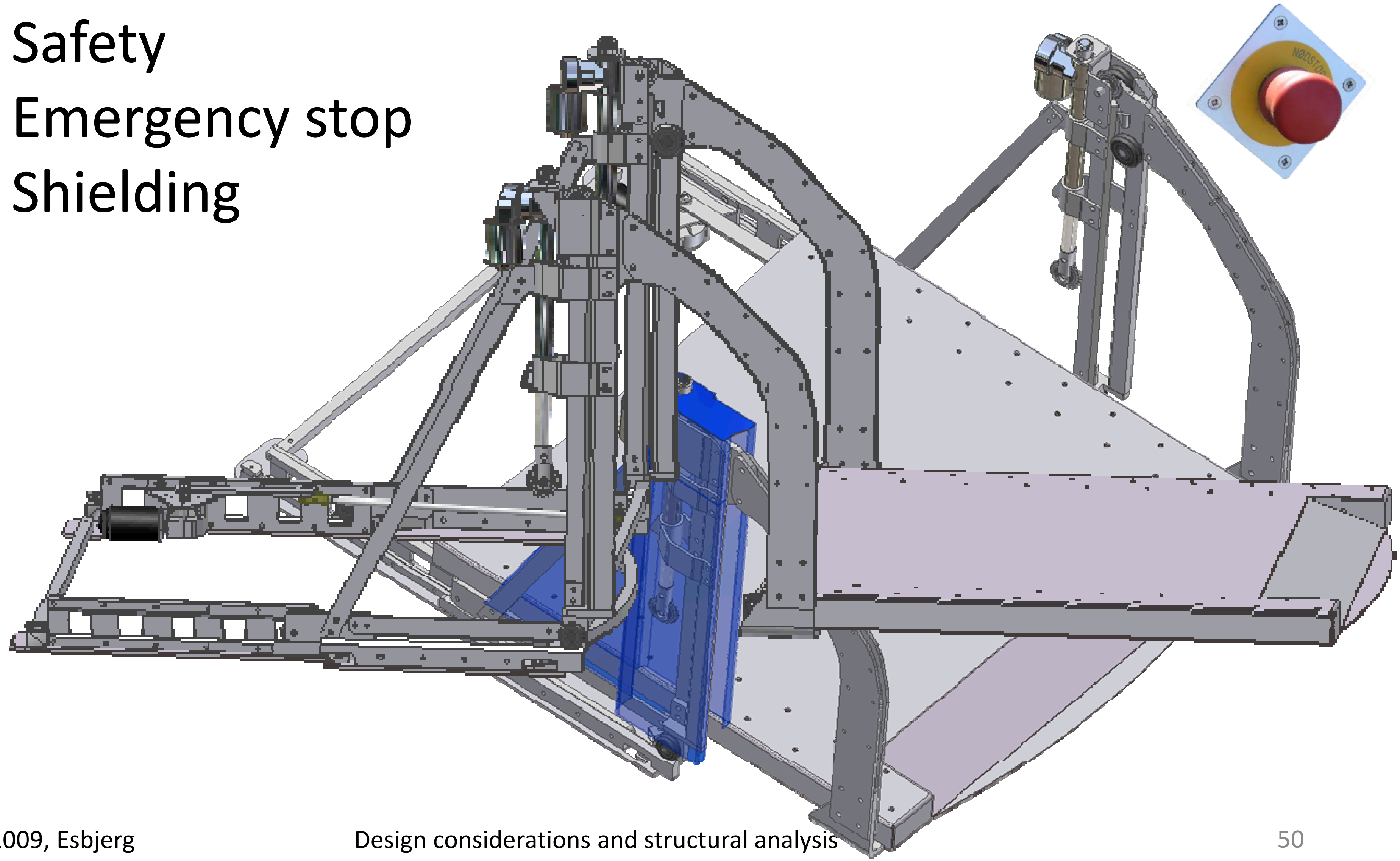
- Critical points ✓
- Unusual loadcase ✓
- Inclined lift ✓
- Inclination (✓)
- Overload (✓)





Safety

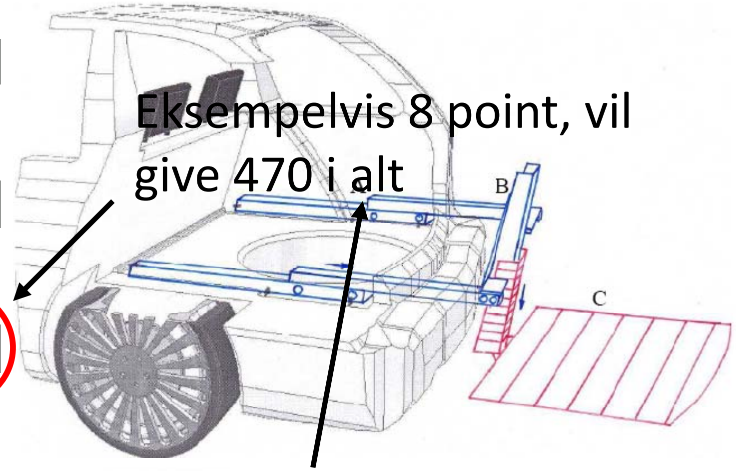
- Safety
- Emergency stop
- Shielding



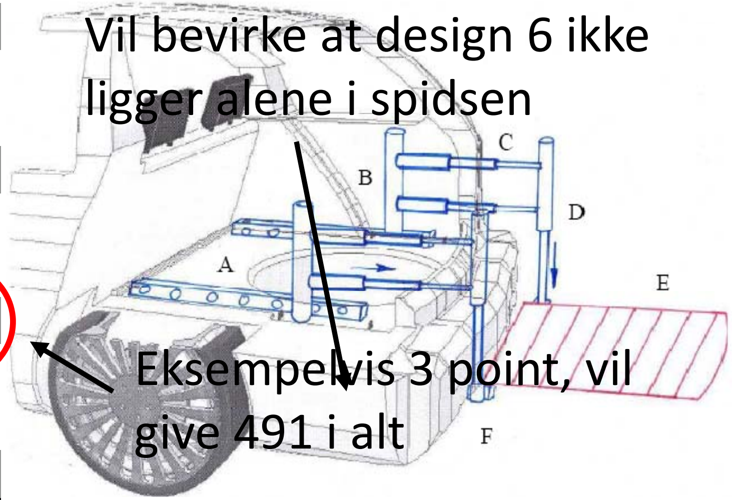
design phase

	løfteevne	pladskrav	konstruktionens ...	egenvægt	løftecyklus	montering	sikkerhed	materielle skader	arbejdshøjde	adgang til reservehjul	**Simpel konstruktion**	
Vægtning (1-10) [V]	***10***	***8***	***7***	***5***	***3***	***2***	***10***	***7***	***7***	***6***	***8***	
Design 1												
Point (1-10) [P]	3	8	3	2	2	1	2	3	3	8	-	
P x V	**30**	**64**	**21**	**10**	**6**	**2**	**20**	**21**	**21**	**48**		**243**
Design 2												
Point (1-10) [P]	7	6	7	9	7	8	4[1]	6	5	6	-	
P x V	**70**	**48**	**49**	**45**	**21**	**16**	**40**	**42**	**35**	**36**		**402**
Design 3												
Point (1-10) [P]	8	5	6	7	7	5	7	8	5	3[2]	-	
P x V	**80**	**40**	**42**	**35**	**21**	**10**	**70**	**56**	**35**	**18**		**406↑**
Design 4												
Point (1-10) [P]	4	2	2	2	7	3	6	8	5	1	-	
P x V	**40**	**16**	**14**	**10**	**21**	**6**	**60**	**56**	**35**	**6**		**264**
Design 5												
Point (1-10) [P]	6	6	4	6	8	7	5	2	5	8	-	
P x V	**60**	**48**	**28**	**30**	**24**	**14**	**50**	**14**	**35**	**48**		**351**
Design 6												
Point (1-10) [P]	8	7[3]	8	8	7	6	7	7	5	8	-	
P x V	**80**	**56**	**56**	**40**	**21**	**12**	**70**	**49**	**35**	**48**		**467↓**
Design 7												
Point (1-10) [P]	5	6	3	6	8	7	5	5	5	8	-	
P x V	**50**	**48**	**21**	**30**	**24**	**14**	**50**	**35**	**35**	**48**		**355**

Eksempelvis 8 point, vil give 470 i alt

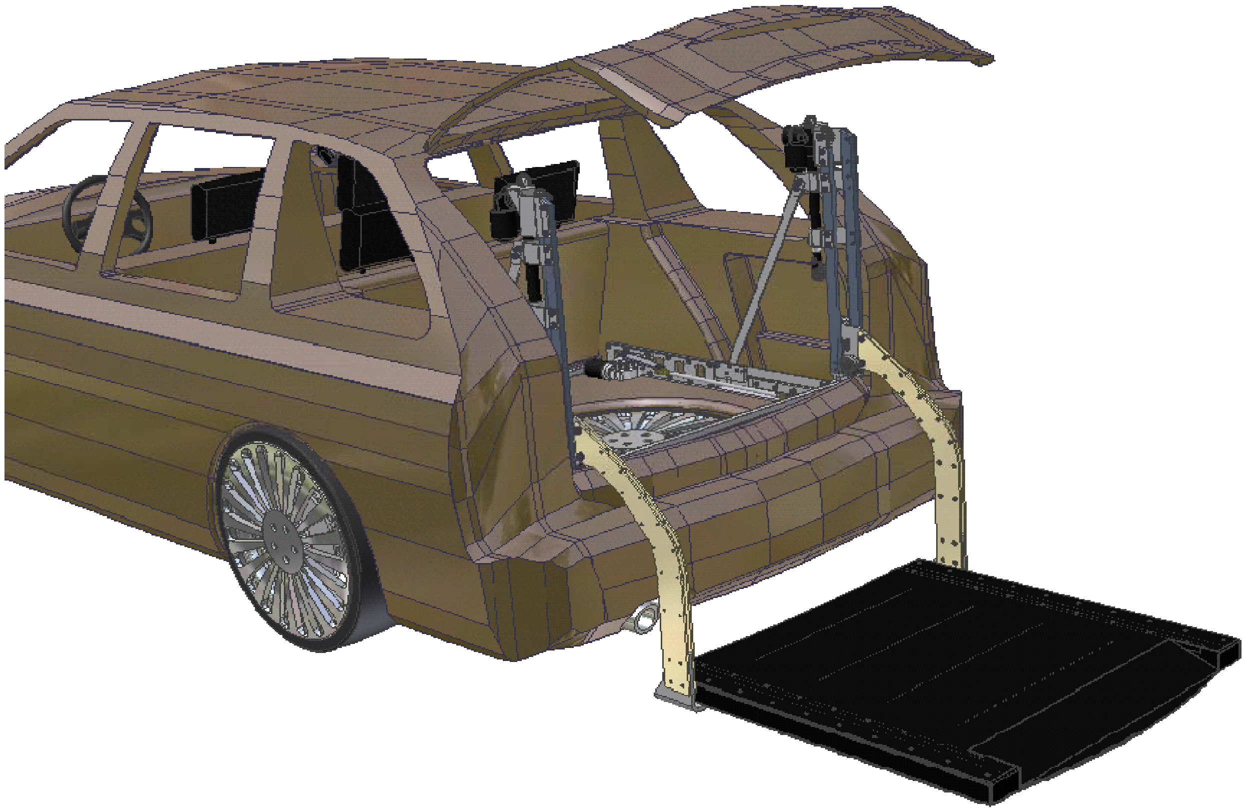


Vil bevirke at design 6 ikke ligger alene i spidsen



Eksempelvis 3 point, vil give 491 i alt

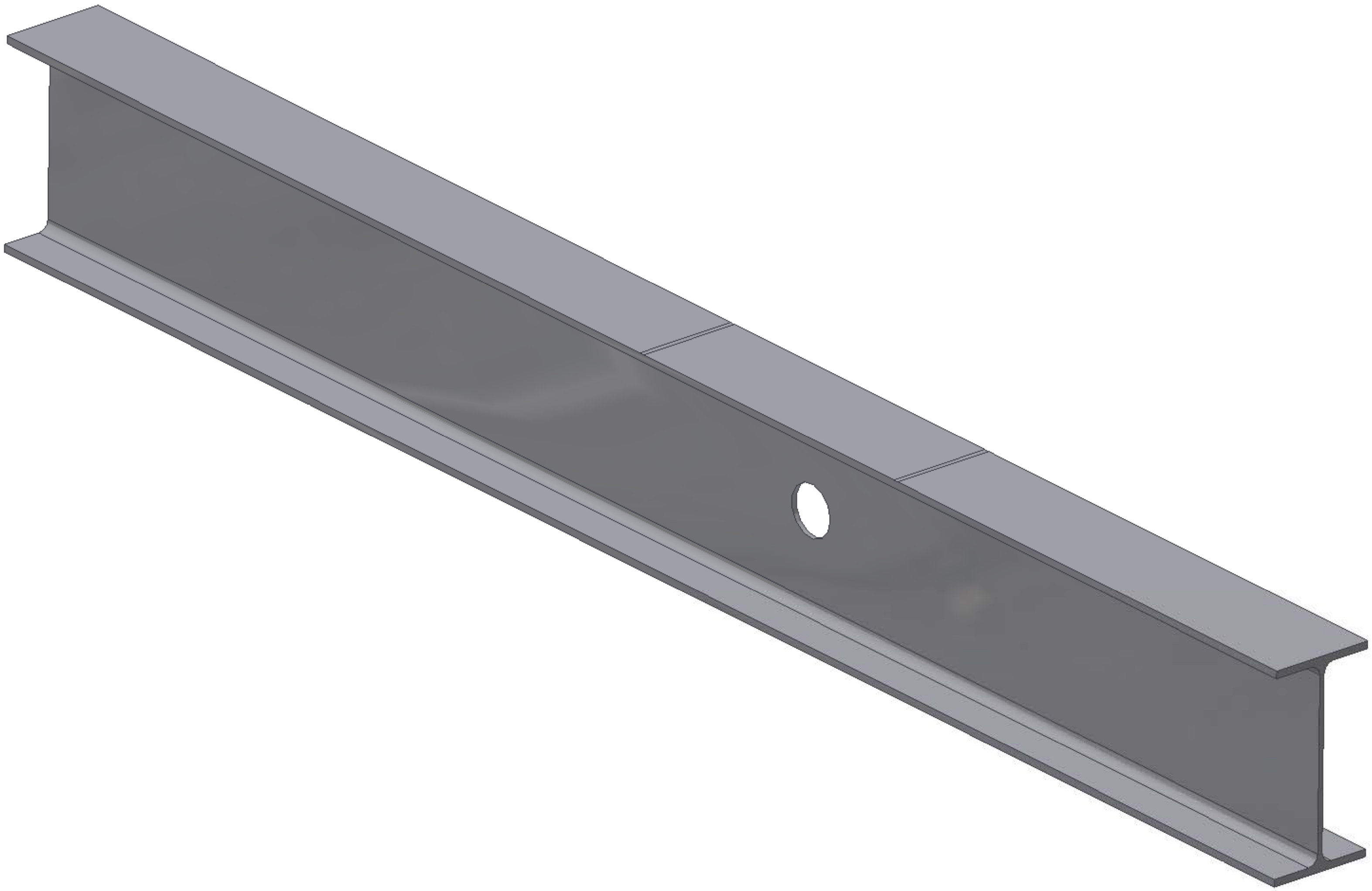
Comments to the design phase



It is still possible to

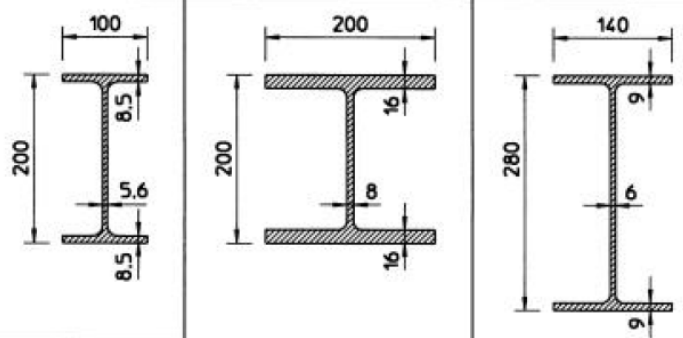
lay down the back seats

Example - simulation



Mechanical Properties

http://www.sasak.dk/



Profiler		Stål IPE 200	Aluminium profiler	
A	mm2	2848	7830	4178
E	N/mm2	2,1 E5	7,0 E4	7,0 E4
I	mm4	1,94 E7	5,80 E7	5,67 E7
W	mm3	1,94 E5	5,80 E5	4,05 E5
E*I	N*mm2	4,07 E12	4,06 E12	3,97 E12
Vægt pr. m	kg/m	22,4	21,1	11,3
Bøjnings spænding	N/mm2	164	55	78
Nedbøjning	mm	29	29	29
1. ordens egenfrekv.	Hz	3,3	5,7	5,6

THANK YOU FOR YOUR ATTENTION