Connections (Part 1.1)

Eurocode 9: Design of aluminium structures

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Contents

Importance of Joining Technology

Design of aluminium structures requires knowledge of:

- **Available joining techniques**
- **Design of connections**

To arrive at optimum performance at low costs.

Joining is a key technology in aluminium structural engineering

Types of joints

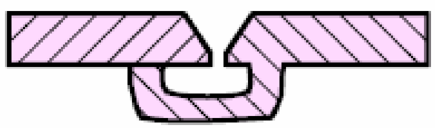
- **Primary structures**
  - Welded connections
  - Bolted connections
  - Riveted connections
  - Adhesive joints

- **Special joints**
  - Solid state welding
  - Joints with cast parts
  - Snap joints, rolled joints etc.

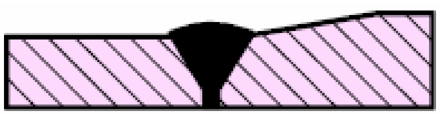
- **Joints in Thin-walled Structures**
  - Thread forming and self-drilling screws
  - Blind rivets
  - Cartridge fired pin
  - Spot welding

Advantage of welded connection

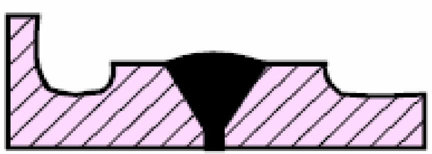
- Saving work and material
- Absence of drilling
- Tight joints
- No crevice corrosion
- Joint preparation by extrusion



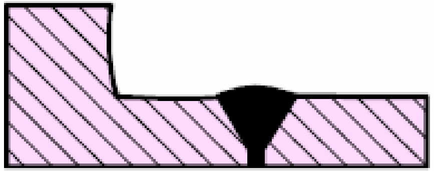
- Groove preparation, backing and support



- Difference in thickness



- Local increase of thickness in strength reduction Zone



- Distance to corners

Requirements of joints

- **Structural requirements**
  - Strength
  - Stiffness
  - Deformation capacity

- **Non-structural requirements**
  - Economic aspects
  - Durability
  - Tightness
  - Aesthetics

Principles of design

F_{Ed}
Force in Joint Caused by Design Load

$\leq$

F_{Rd}
Design Strength of Joint

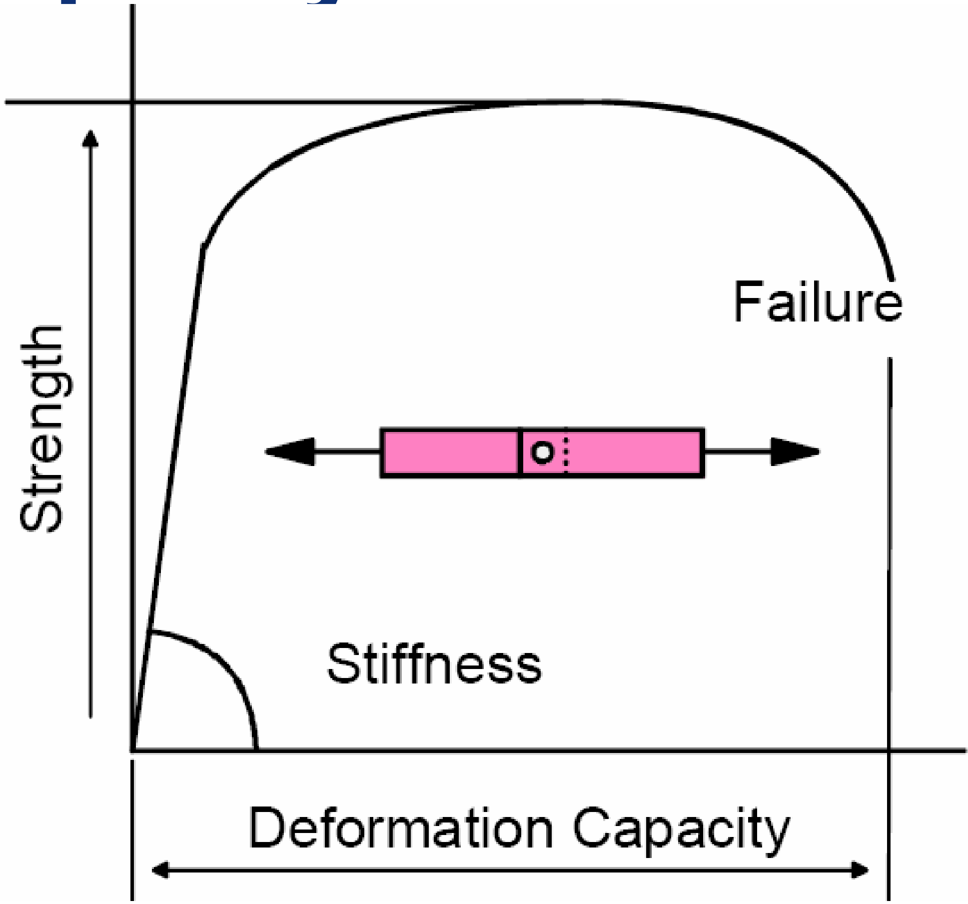
$F_{Ed} \rightarrow \Sigma \gamma_f F_{Ek}$

$F_{Rd} \rightarrow F_{Rk} / \gamma_m$

where
- F_{Ek} = force in connection caused by characteristic load
- F_{Rk} = characteristic strength of connection
- γ_f = appropriate load factor
- γ_m = appropriate material factors

Strength, stiffness and deformation capacity

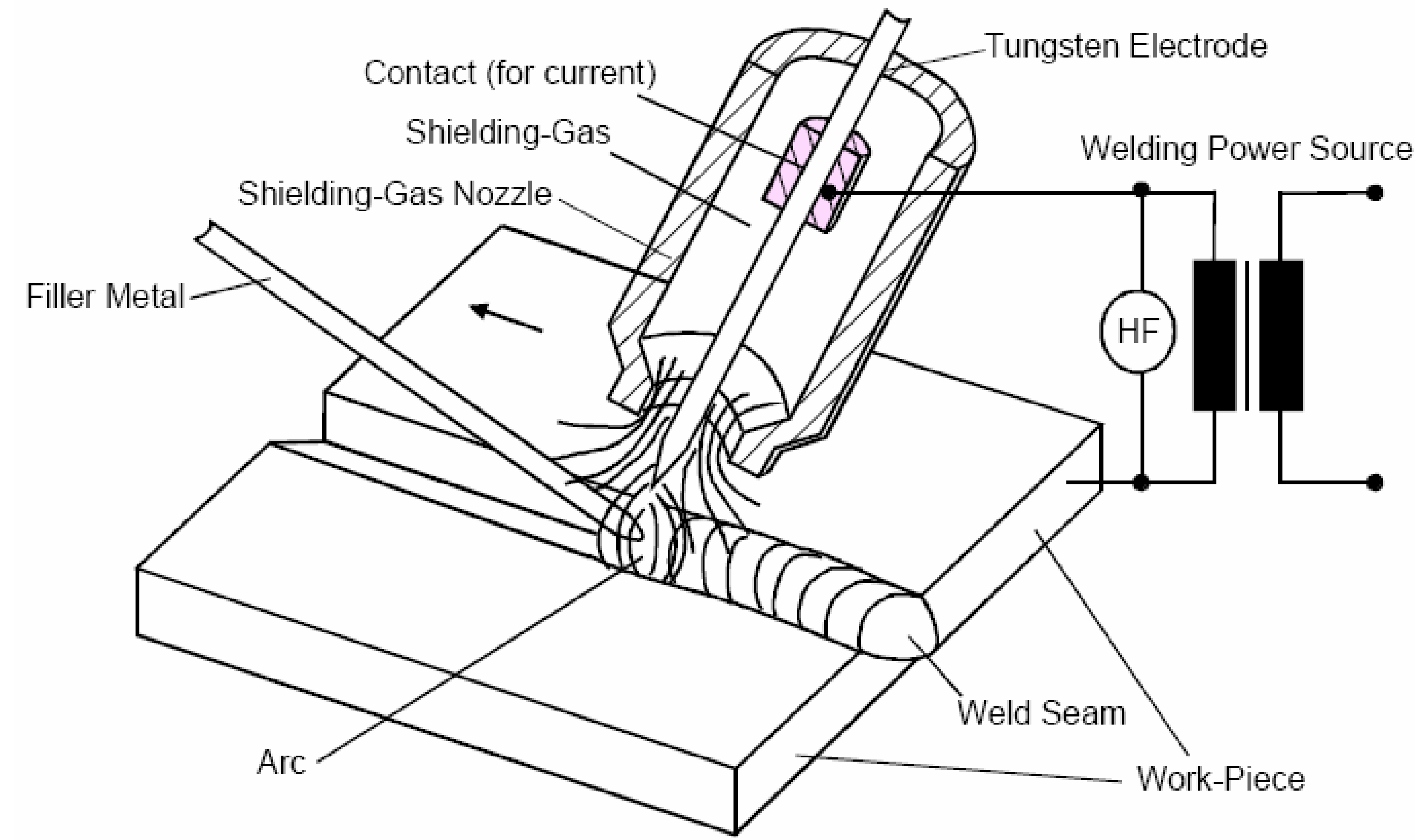
- **Strength:**
  - Analytical determination
  - Determination by tests
- **Stiffness:**
  - Influence on entire structure
  - Influence on force distribution in connections
  - Distribution of loads
- **Deformation capacity:**
  - Prevention of brittle fracture
  - Redistribution of stresses



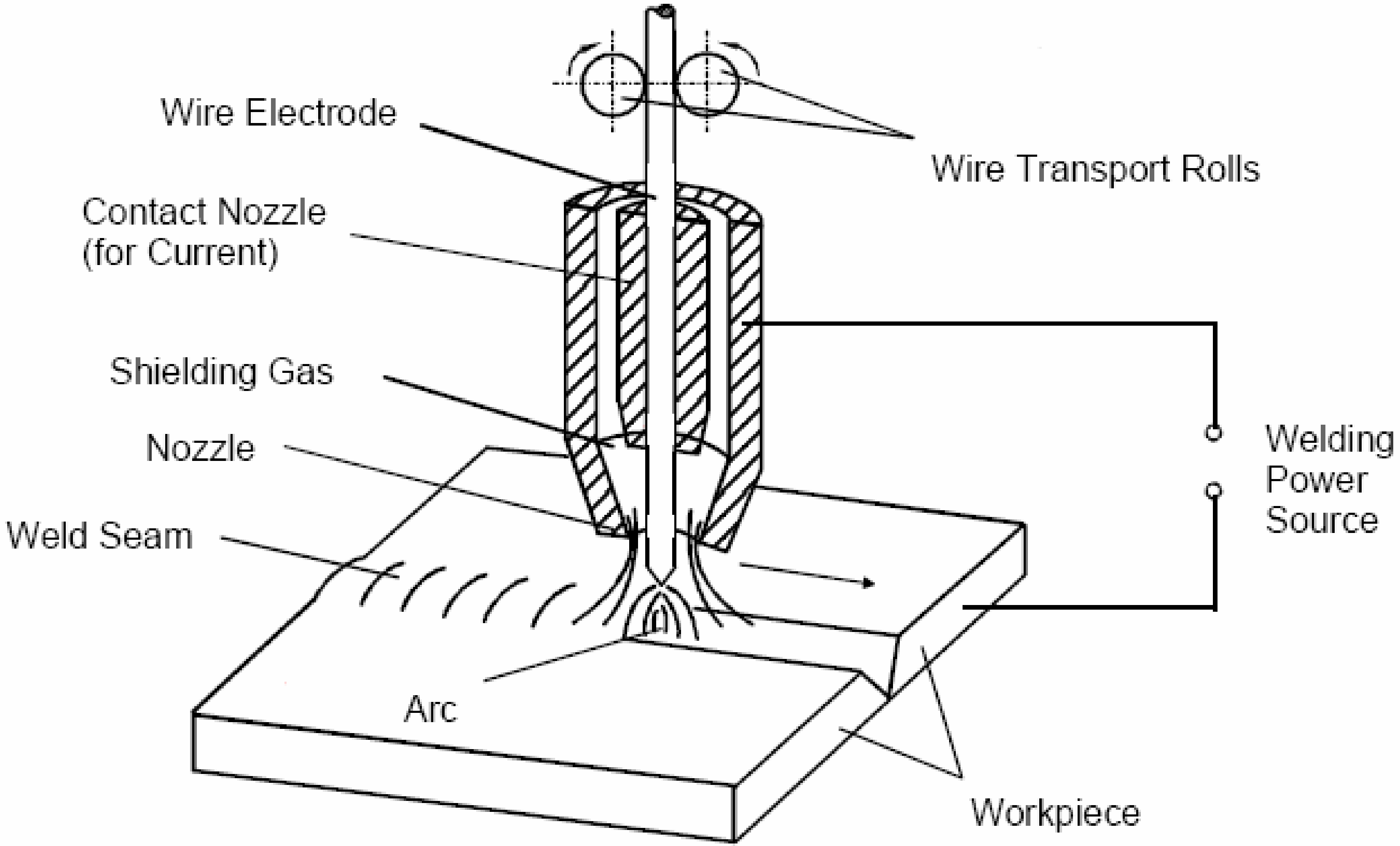
Welding

- **Gas welding**
- **Metal arc welding**
- **TIG**
- **MIG**
- **Electric resistance welding**
  - Spot welding
  - Seam welding
- **Solid state welding**
  - Ultrasonic welding
  - Electron beam welding
  - Friction welding

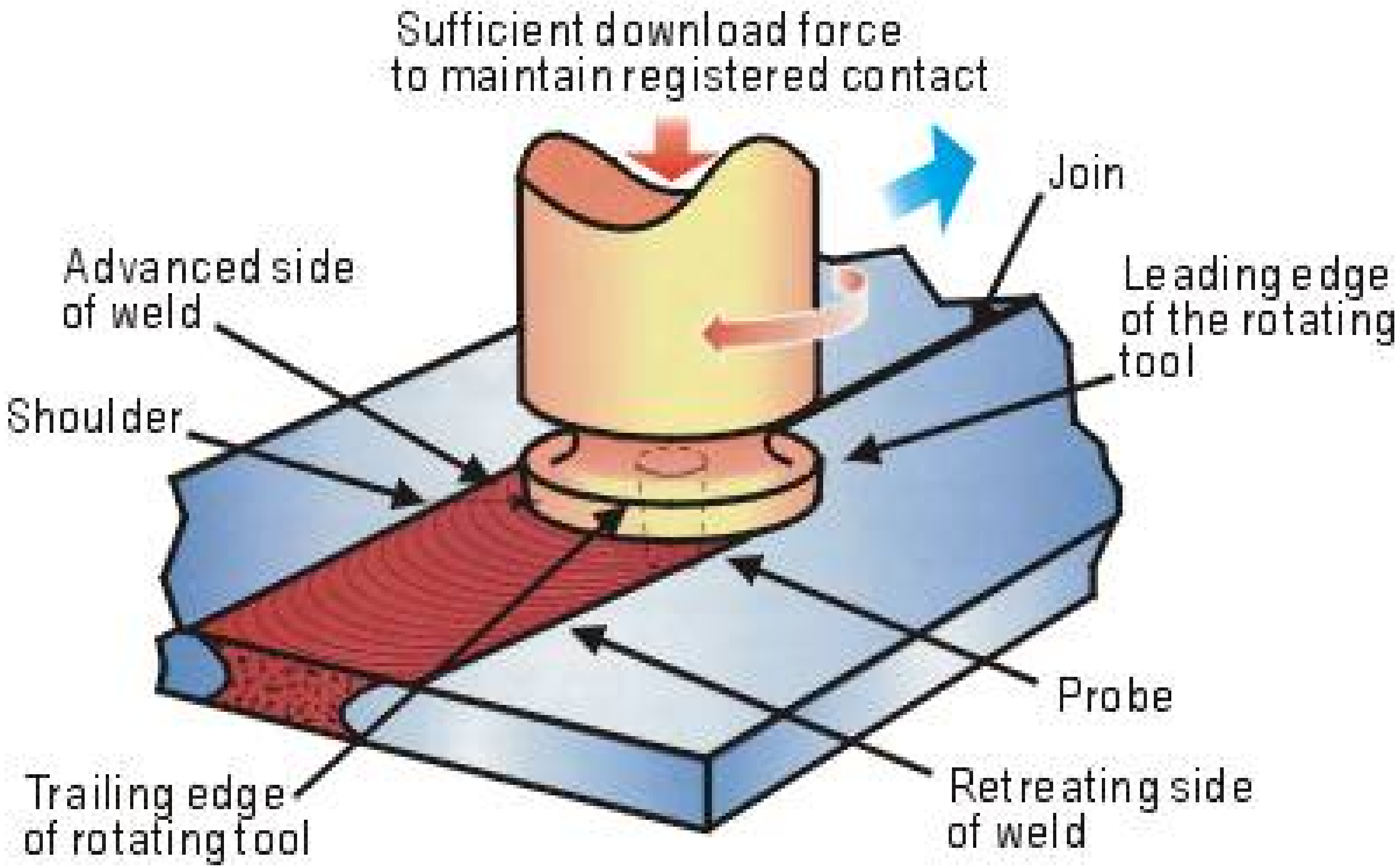
Principle of TIG welding



Principle of MIG welding



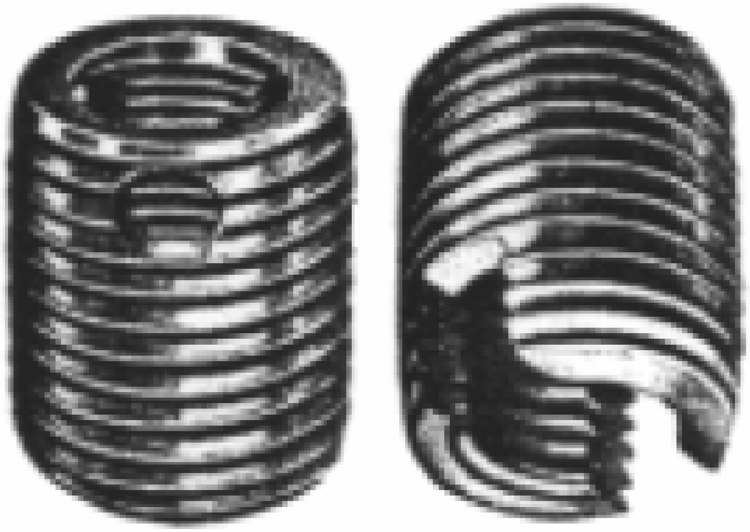
Friction stir welding



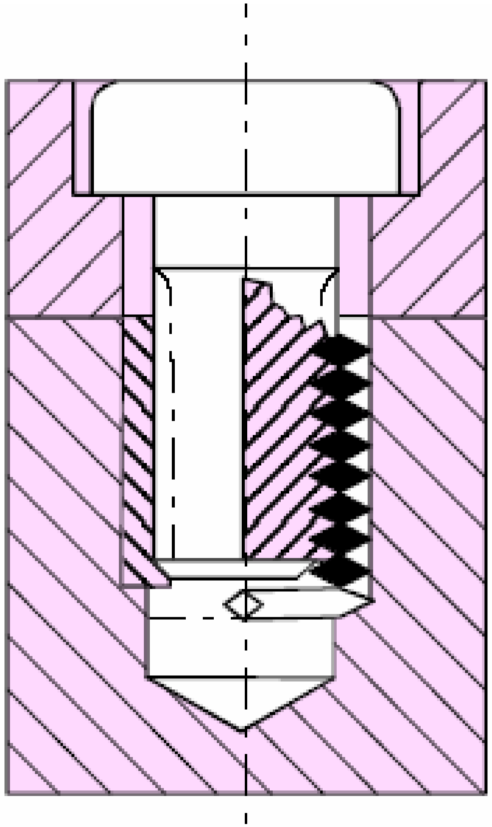
Screws, bolts and rivets

- Aluminium
- Steel
- Thread inserts

Thread inserts

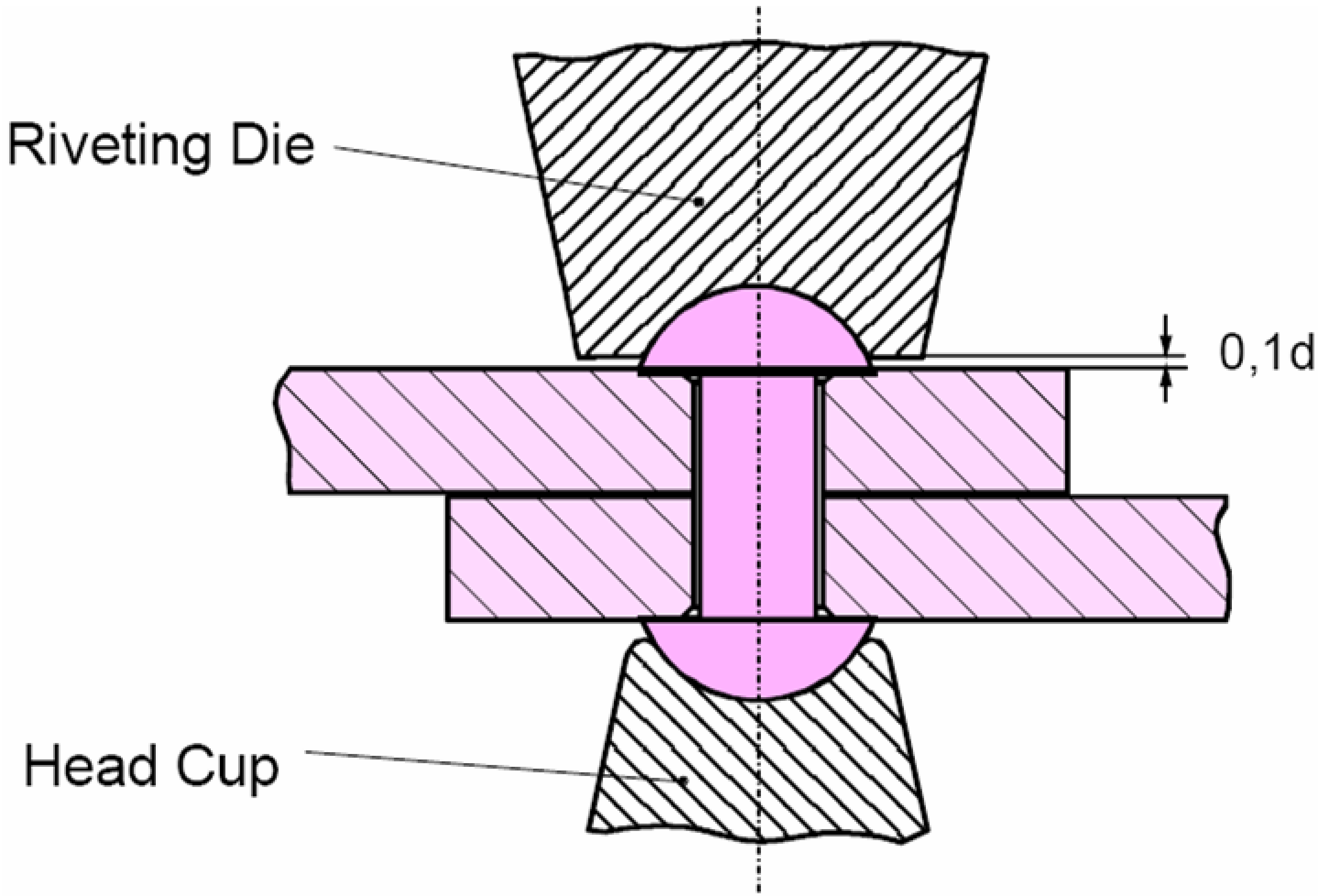


Ensat



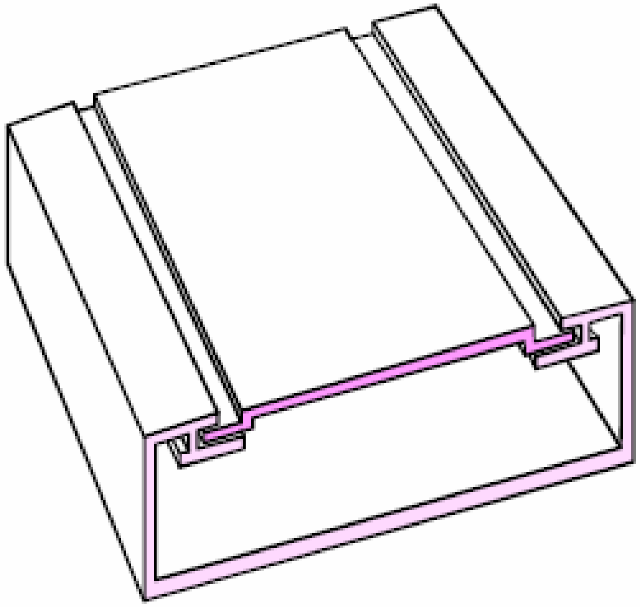
Heli-coil

Solid Rivets

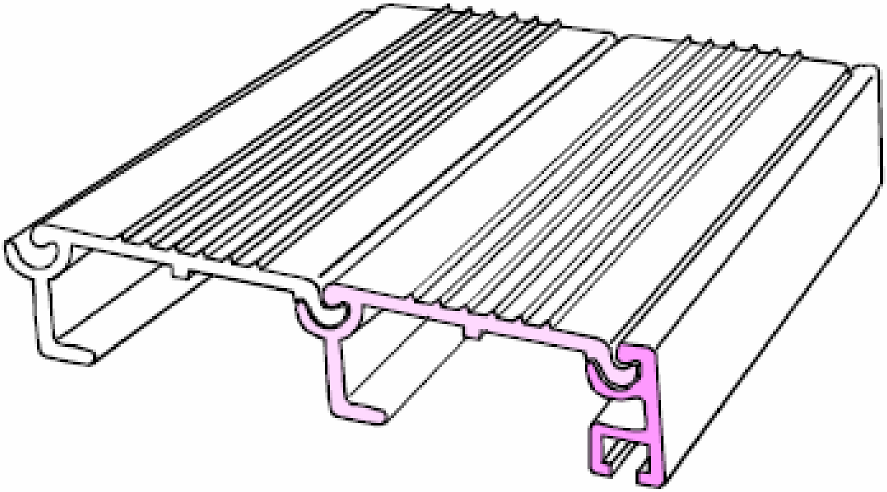


Special joints

Profile to profile joints



Groove and tongue



Hooked connection

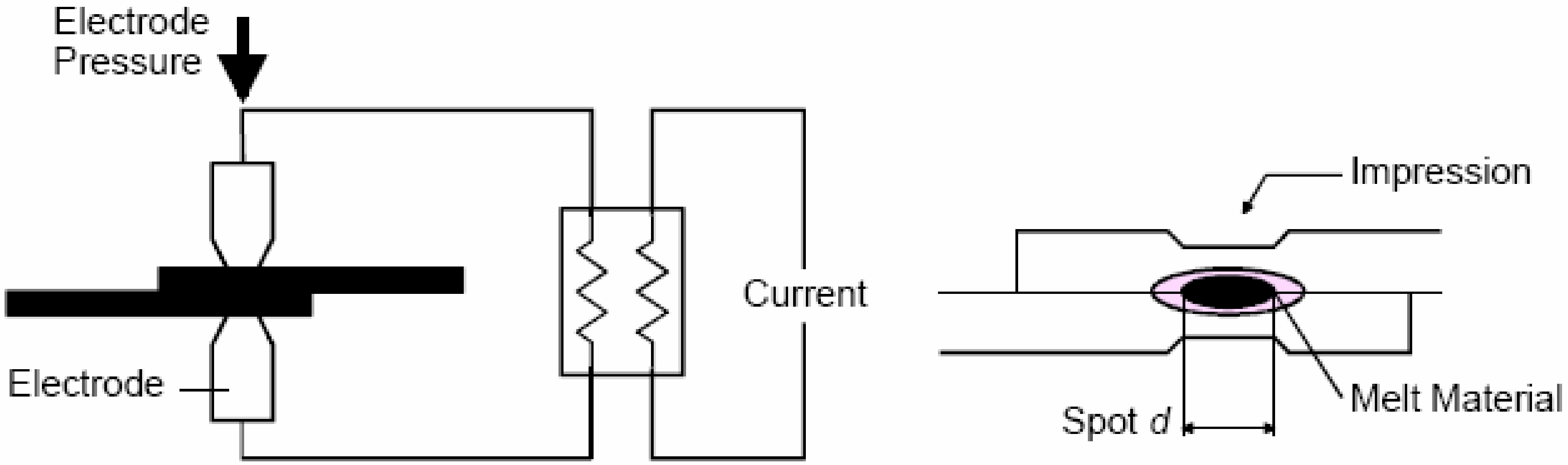
Resistance spot welding

Advantages

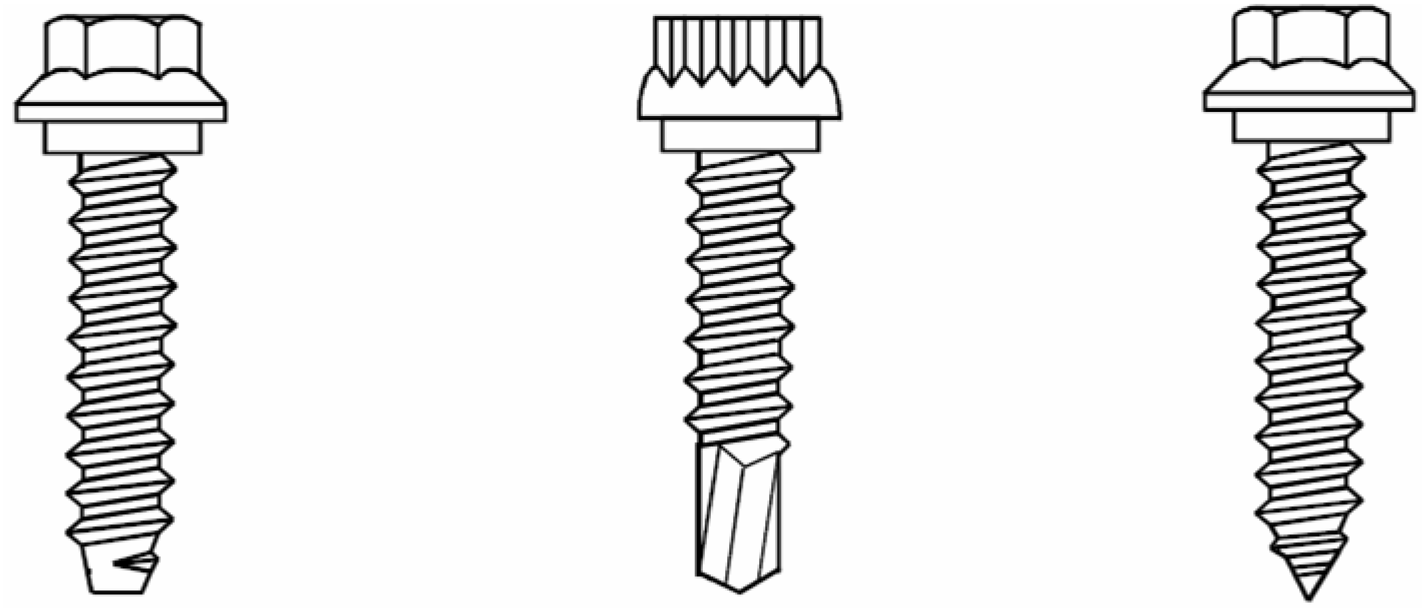
- Fast, automatic
- Small distortion
- Excellent weld strength

Limitations

- Only lap joints
- Max. 3.2 mm thickness
- Access to both sides required
- Expensive equipment



Thread forming and selfdrilling screws



Thread forming screw

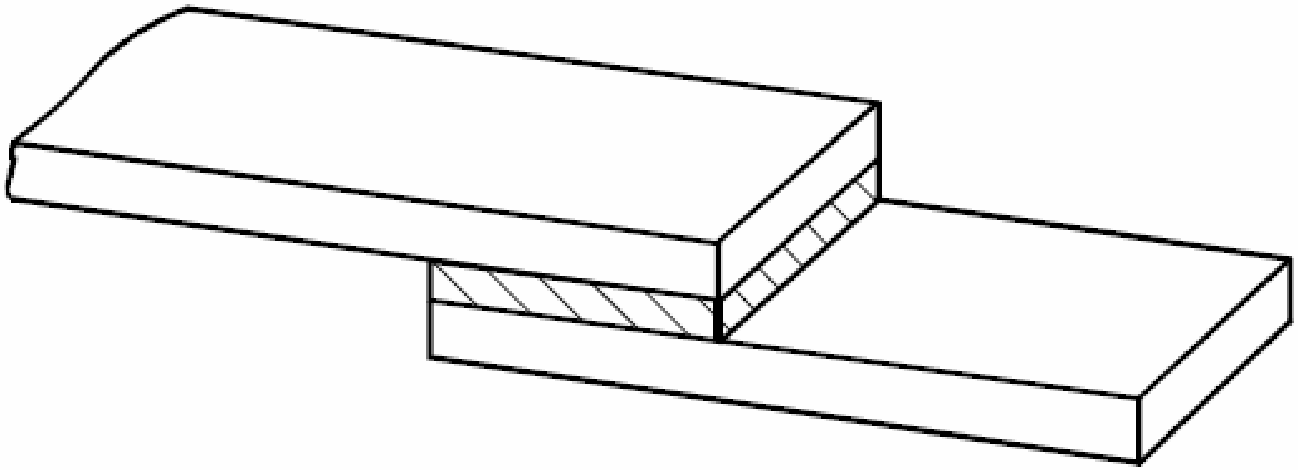
Self drilling and thread forming

Self drilling and thread forming

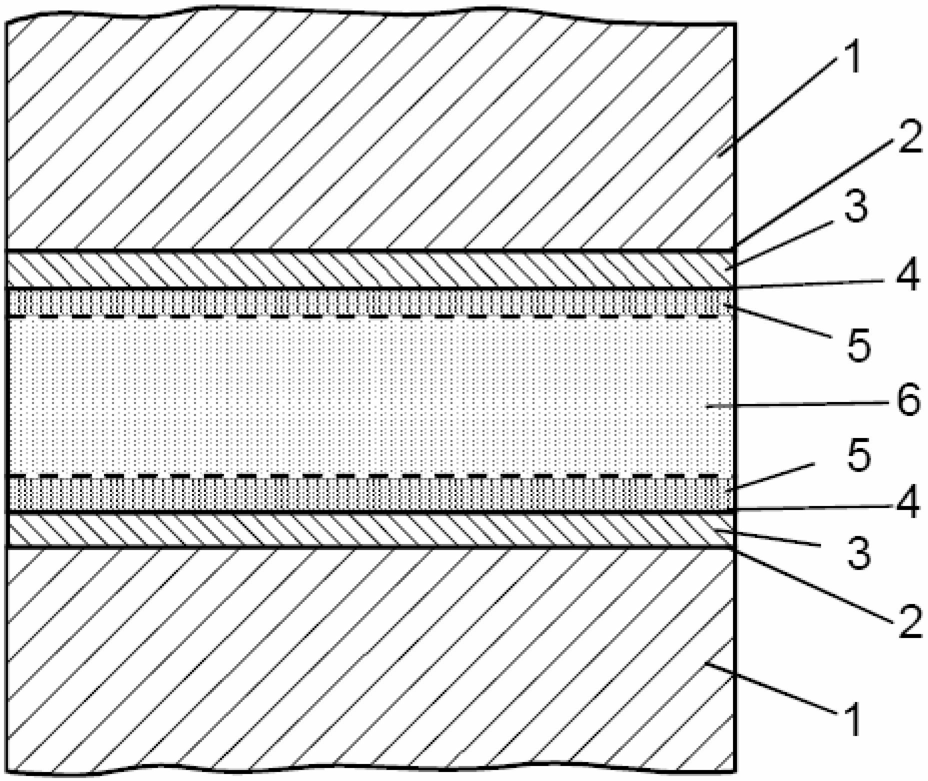
Adhesive bonding

Advantages
- Microstructure unaffected
- Joining of different materials
- Joining of very thin parts
- High fatigue strength
- Good vibration damping

Disadvantages
- Low strength
- Pretreatment of surfaces
- Ageing
- Tolerance of process parameters

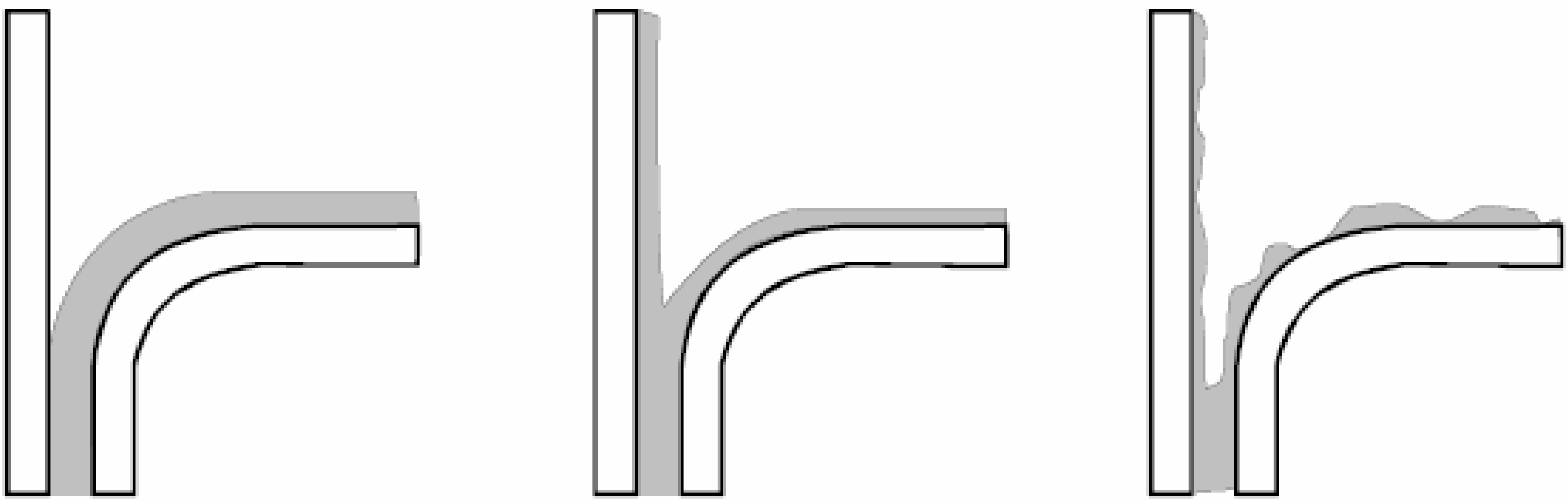


Structure of adhesive joint



1. Strength parent material
2. Adhesive strength oxide layer
3. Strength oxide layer
4. Adhesive strength between oxide layer and interface
5. Adhesive strength between interface and adhesive
6. Cohesion strength of adhesive

Failure of adhesive joints

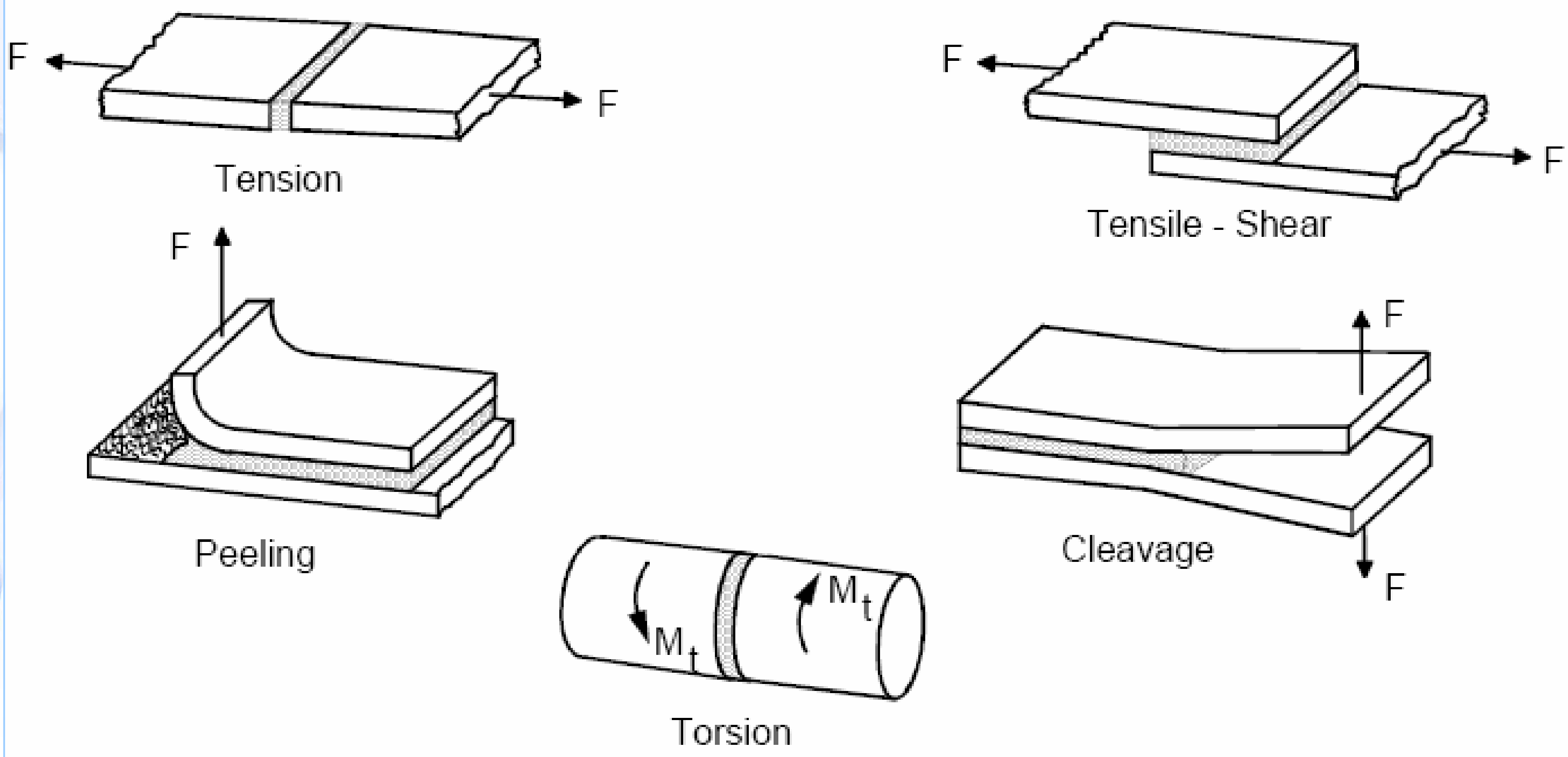


Adhesion failure **Cohesion failure** **Mixed failure**

Properties of adhesives

Adhesive base	Temperature Range ºC
One-component epoxy	110-130
Two-component epoxy	60-90
Phenolic adhesive	80-120
Methylacrylate	80-100
Polyurethane	80-100
Polyamide	120-140
Silicone	180-190

Design of adhesive metal joints



Welded connections

- **Design of welded joints**
  - Strength of the welds
  - Strength of the HAZ
- **Design guidance applicable for**
  - Welding process MIG or TIG (up to t = 6 mm)
  - Approved welder and welding procedure
  - Prescribed combinations of parent and filler metal
  - Statically loaded structures
- **Above conditions not fulfilled**
  - Primary structures → testing
  - Secondary structures or non loaded members → γ_{Mw} = 1,6

Heat-affected zone (HAZ)

- **Heat-treatable alloys Condition T4 or higher (6xxx and 7xxx series)**

  HAZ softening ↓

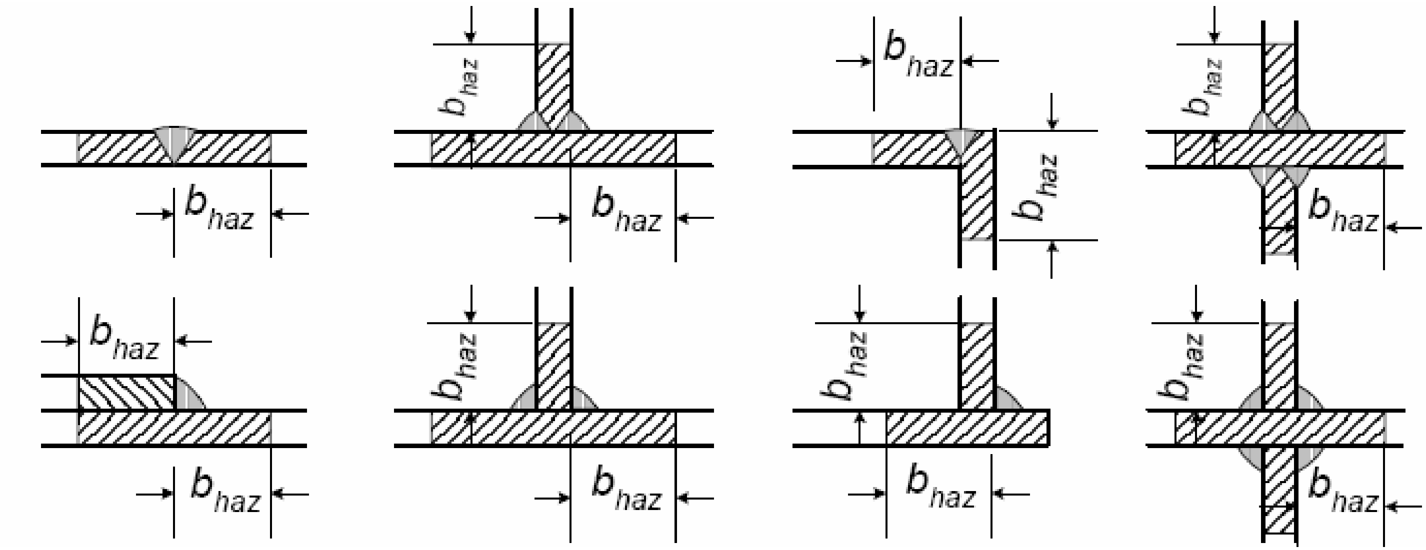
- **Non-heat treatable alloys in work-hardened cond. (3xxx and 5xxx series)**

  TIG welding more severe than MIG welding

HAZ softening factor ρ_{HAZ}

Alloy series	Condition	ρ_{HAZ} (MIG)	ρ_{HAZ} (TIG)
6xxx	T4	1,0	1,0
	T5	0,65	0,60
	T6	0,65	0,50
7xxx	T4	0,90	0,70
	T6	0,80	0,60
5xxx	H22	0,86	0,86
	H24	0,80	0,80
3xxx	H14, H16, H18	0,60	0,60

Extent of HAZ (b_{HAZ})



b_{HAZ} (mm)	MIG	TIG
$0 < t \leq 6$ mm	20	30
$6 < t \leq 12$ mm	30	-
$12 < t \leq 25$ mm	35	-
$t > 25$ mm	40	-

Characteristic strength weld metal (f_w)

- Lower than parent metal strength
- Depending on filler metal used (appropriate 5xxx or 4xxx series)

Characteristic strength values weld metal f_w [N/mm^2]								
Filler metal	Parent metal							
	3003 H12	5083 O	5454 H24	6060 T5	6005 T6	6061 T6	6082 T6	7020 T6
5356	-	240	220	160	160	190	210	260
4043	95	-	-	150	150	170	190	210

Design of butt welds

- Strength members → full penetration butt welds
- Throat thickness equal to thickness *t*
- Effective length equals total weld length when run-on and run-off plates are used

Design stresses

- Normal stress, perpendicular to weld axis

$$\sigma \leq \frac{f_w}{\gamma_{Mw}}$$

- Shear stress

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

- Normal + shear stress

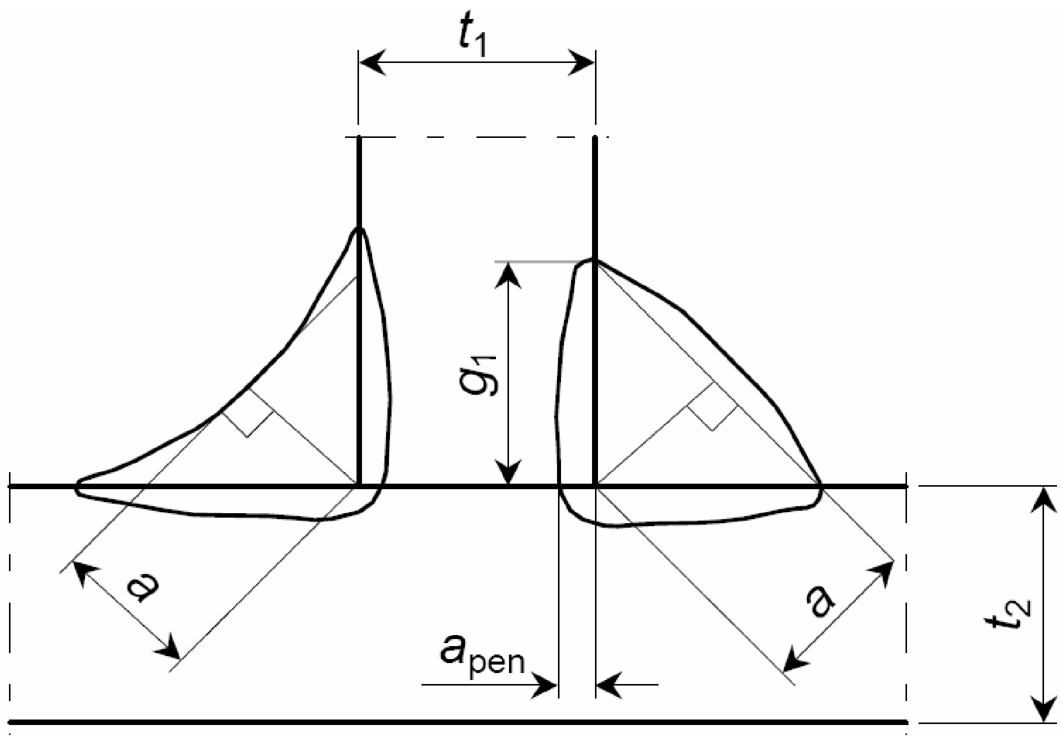
$$\sqrt{\sigma^2 + 3\tau^2} \leq \frac{f_w}{\gamma_{Mw}}$$

Design of fillet welds

- **Strength of fillet welds**
  - Throat section
  - Forces acting on throat section
- **Throat section**
  - Effective throat thickness *a*
  - Effective length
    - Longitudinal fillet weld
    - Length > 100 a
    - Non uniform stresses

} **Reduction of weld length**

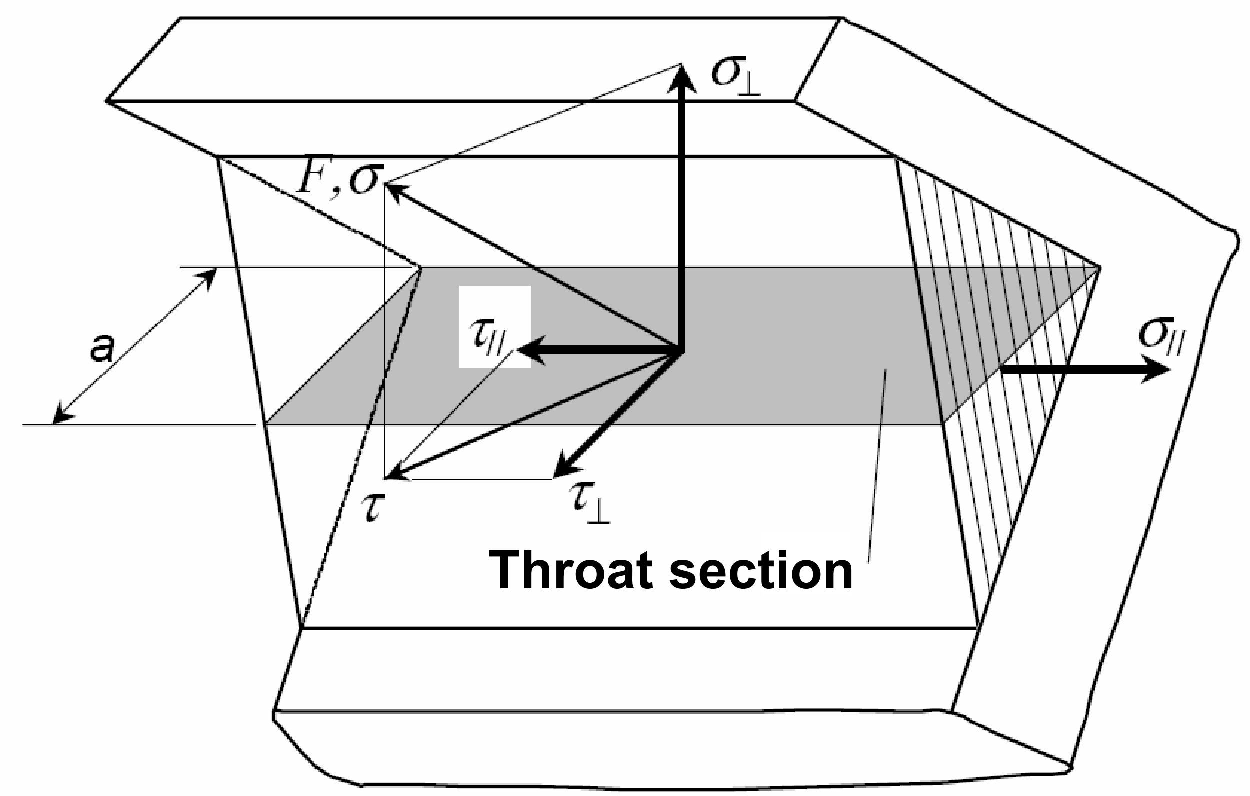
Effective throat thickness



With positive root penetration:

a = 1,2 a or a + 2 mm or a = a + a_{pen} (verified by testing)

Forces acting on a fillet weld



Stresses $\sigma_\perp$, $\tau_\perp$ and $\tau_{//}$, acting on the throat section of a fillet weld

Design strength fillet weld

- Stresses → comparison stress σ_c:

$$\sigma_C = \sqrt{\sigma_\perp{}^2 + 3\left(\tau_\perp{}^2 + \tau_{//}{}^2\right)}$$

- Design stresses:

$$\sigma_C \leq \frac{f_w}{\gamma_{Mw}}$$

Design strength HAZ

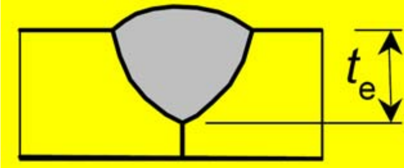
- Tensile force perpendicular to failure plane
- HAZ butt welds

$$\sigma \leq \frac{f_{a,HAZ}}{\gamma_{Mw}}$$

(Full penetration butt welds)

$$\sigma \leq \frac{f_{a,HAZ} \cdot t_e}{\gamma_{Mw} \cdot t}$$

(Partial penetration butt welds)

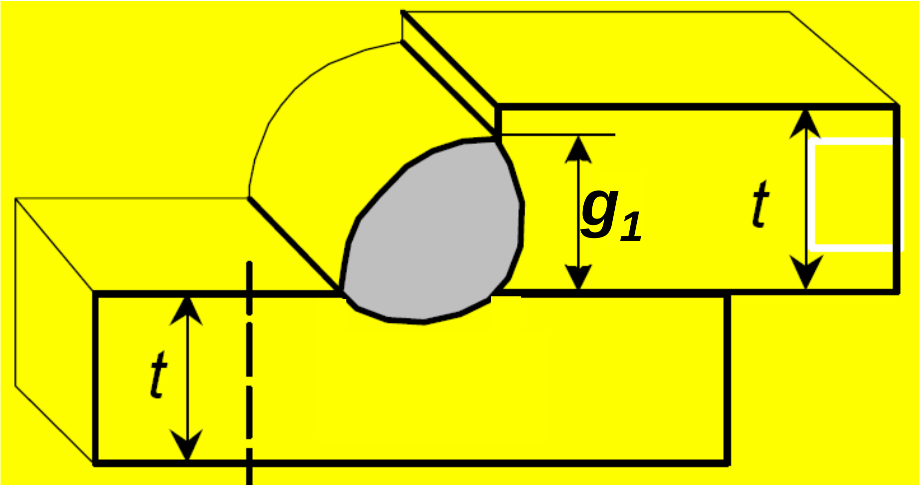


t_e = effective throat thickness
$f_{a,HAZ}$ = Characteristic strength HAZ

HAZ fillet welds

$$\sigma \leq \frac{f_{a,HAZ}}{\gamma_{Mw}}$$ (Toe of the weld, full cross-section)

$$\sigma \leq \frac{f_{a,HAZ}}{\gamma_{Mw}} \frac{g_1}{t}$$ (At the fusion boundary)



For shear forces and combined tensile / shear forces similar rules apply

Design of connections with combined welds

Two approaches

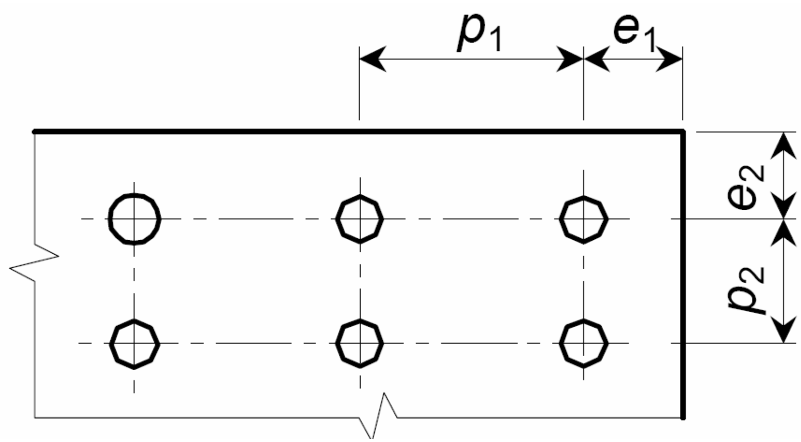
1. Welds designed for stresses in parent metal of the different parts of the joint → Linear Elastic Approach

2. Loads acting on joint are distributed to the welds that are most suited to carry them → Plastic Approach

Bolted and riveted connections

Positioning of holes

Direction of load transfer



End distance e_1: min. 1,2 d

Edge distance e_2: max. 4 t + 40 mm → corrosion environment
12 t + 150 mm → no corrosion

Spacing p_1: min. 2,2 d
Spacing p_2: min. 2,4 d
} max. 14 t or 200 mm

Categories of bolted connections

Shear connections

- **Category A: Bearing type**
  - Shear resistance
  - Bearing resistance
- **Category B: Slip-resistant at serviceability limit state**
  - Add. check at ult. limit state: shear and bearing
- **Category C: Slip-resistant at ultimate limit state**
  - Add. check: shear and bearing

Tension connections

- **Category D: non-preloaded bolts**
  - Tension resistance
- **Category E: Preloaded high strength bolts**
  - Tension resistance

Design resistance of bolts

- Shear resistance per shear plane:

$$F_{v,Rd} = \frac{0{,}6 f_{ub} A}{\gamma_{Mb}}$$ Strength grades lower than 10.9

$$F_{v,Rd} = \frac{0{,}5 f_{ub} A}{\gamma_{Mb}}$$ Strength grade 10.9, stainless steel bolts, aluminium bolts

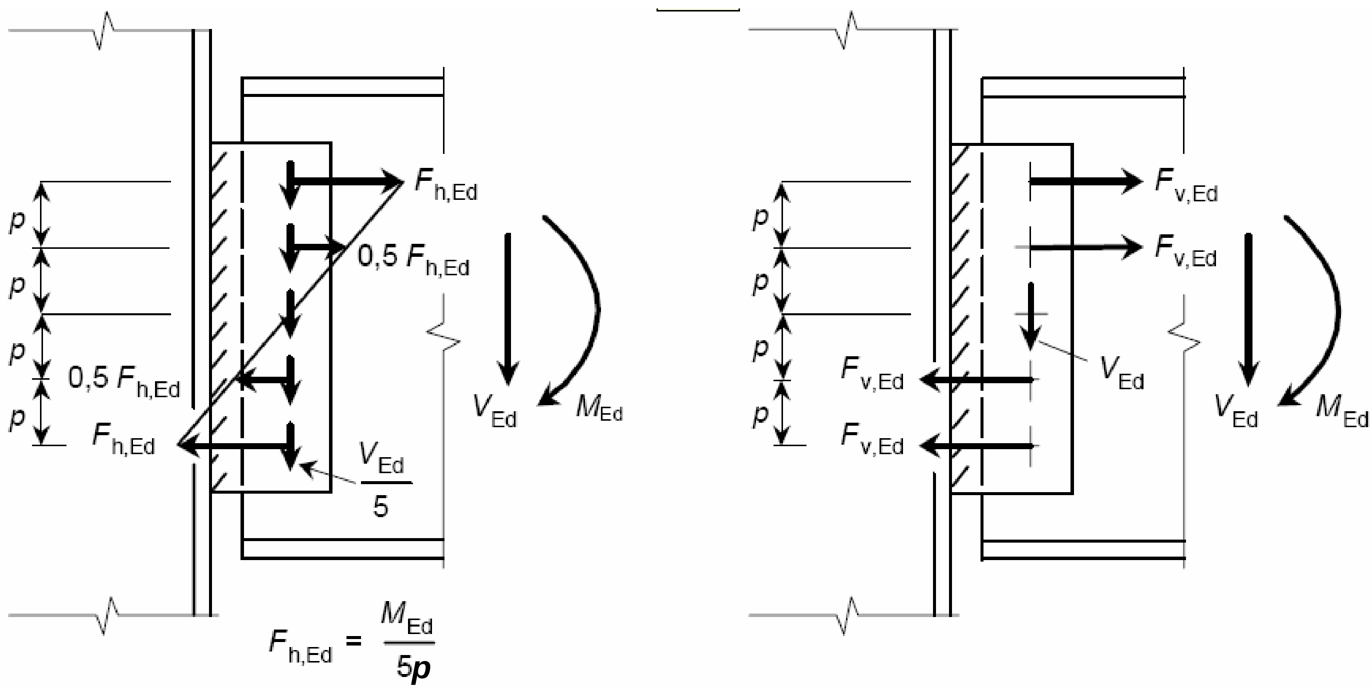
- Bearing resistance

$$F_{b,Rd} = \frac{2{,}5 \alpha f_u d t}{\gamma_{Mb}}$$ α smallest of: $\frac{e_1}{3d_0}; \frac{p_1}{3d_0} - \frac{1}{4}; \frac{f_{ub}}{f_u}$ or 1,0

- Tension resistance

$$F_{t,Rd} = \frac{0{,}9 f_{ub} A_s}{\gamma_{Mb}}$$

Distribution of forces between fasteners



(a) Elastic load distribution

Distribution proportional to distance from centre of rotation

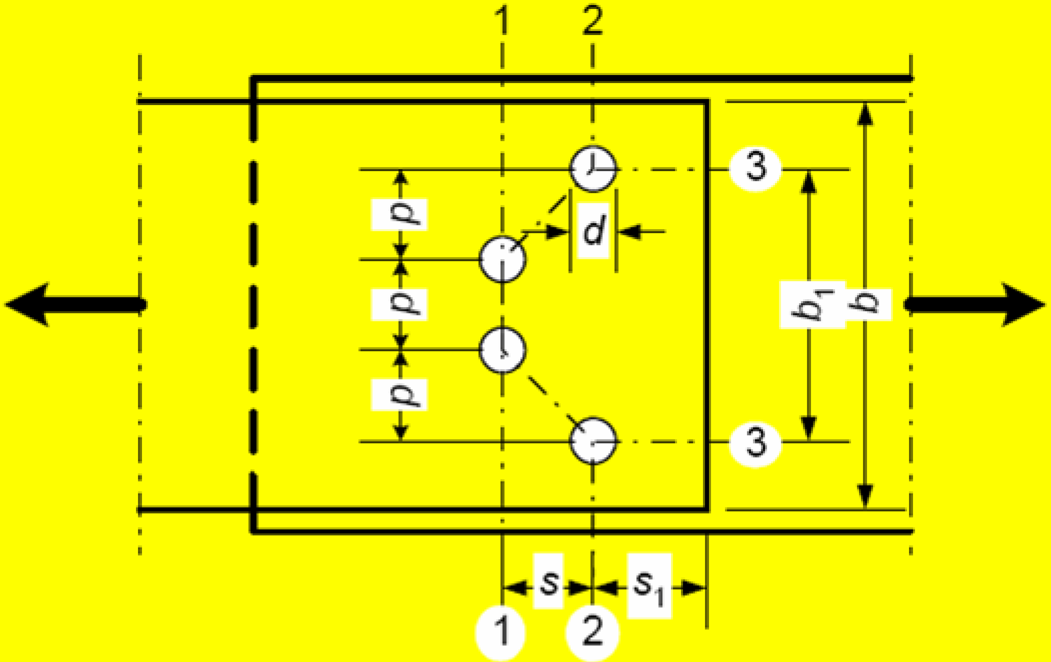
$$F_{\mathrm{v,Ed}} = \sqrt{\left(\frac{M_{\mathrm{Ed}}}{5p}\right)^2 + \left(\frac{V_{\mathrm{Ed}}}{5}\right)^2}$$

(b) Plastic load distribution

Possible plastic distribution with one fastener resisting V_{Ed} and four resisting M_{Ed}

$$F_{\mathrm{v,Ed}} = \frac{M_{\mathrm{Ed}}}{6p}$$

Deductions for fastener holes



A_{net} = min:

$t\,(b - 2d)$	line 1
$t\,(b - 4d + 2s^2/(4p))$	line 2
$t\,(b_1 + 2{\times}0{,}65s_1 - 4d + 2s^2/(4p))$	line 3

For compression members: no deductions for fastener holes

High strength bolts in slip-resistant connections

Preloaded bolts
Surface treatments } **force transfer by friction between clamped surfaces**

↕

friction grip or slip-resistant connections

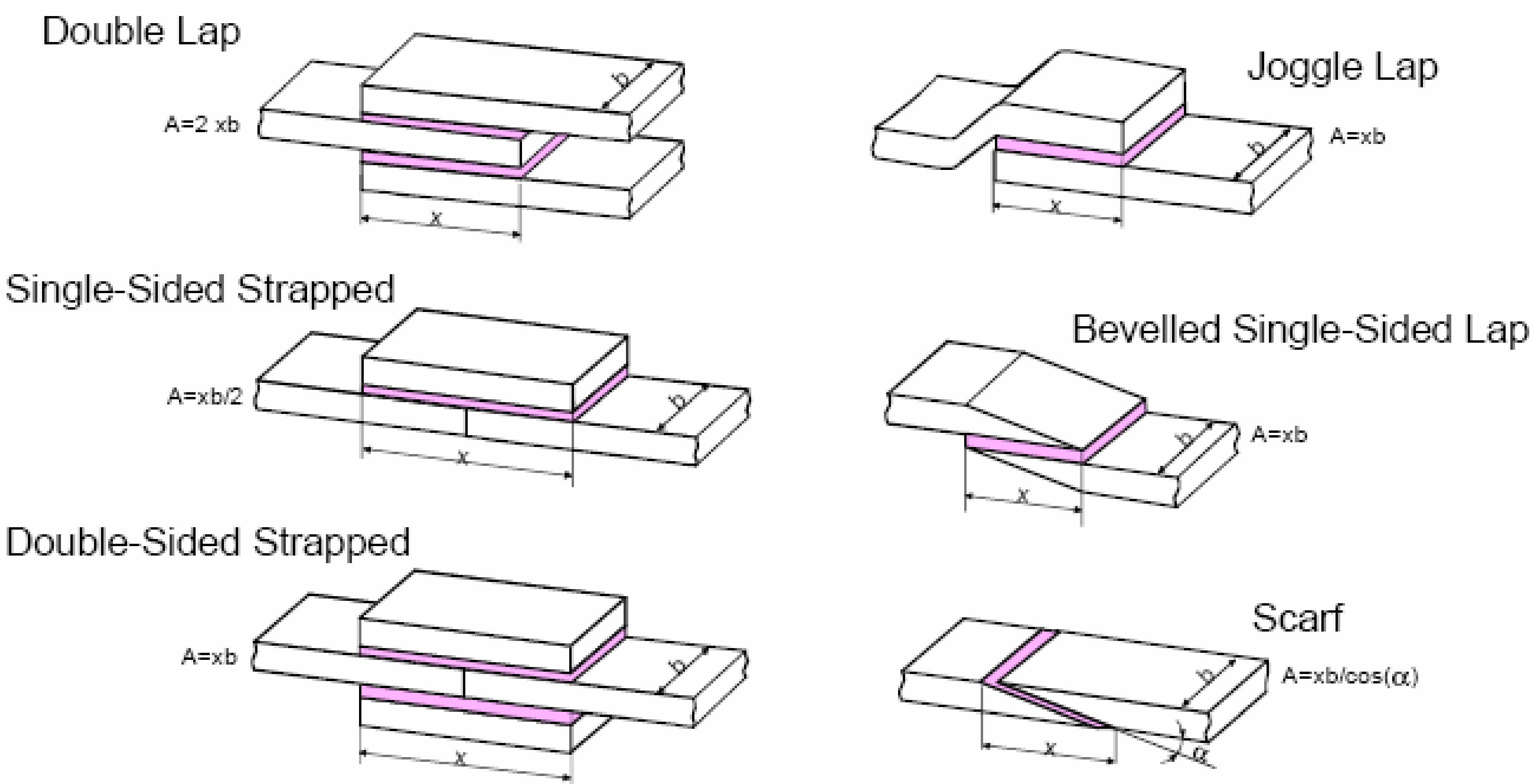
Design slip resistance:

$$F_{s,Rd} = \frac{nm\mu}{\gamma_{Ms}} F_{p,cd}$$

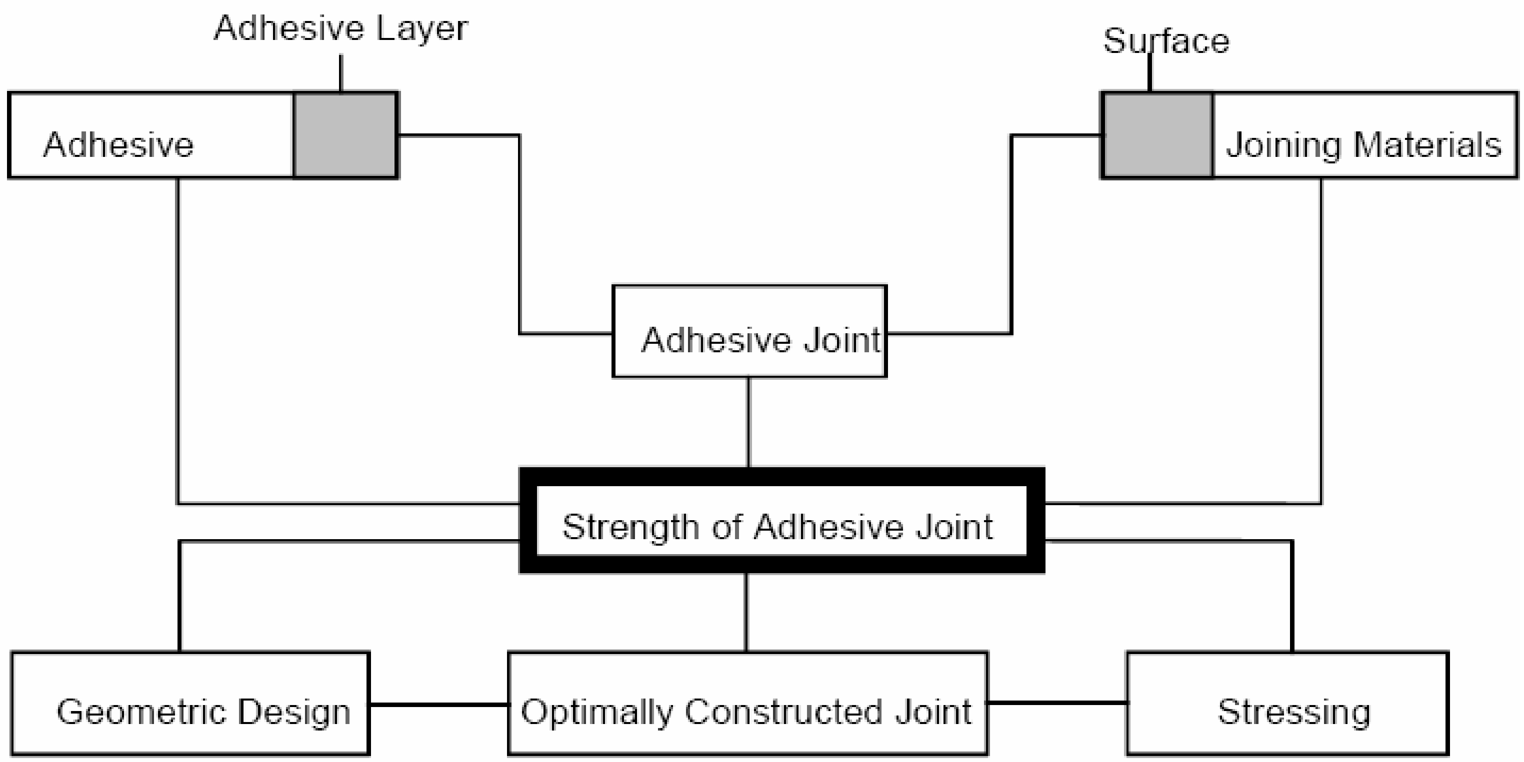
n = number of friction surfaces
m = factor; m = 1,0 for nominal clearance holes
μ = slip factor; μ = 0,27 up to 0,40 → Σt
γ_{Ms} = 1,25 for ultimate limit state
1,10 for serviceability limit state

$$F_{p,cd} = 0{,}7 f_{ub} A_s$$ → **Controlled tightening**

Design of adhesive lap joints



Strength of adhesive joints



Adhesive bonded joints

- **Design guidance applicable for:**
  - Shear forces
  - Appropriate adhesives
  - Specified surface preparation

- **Structural application: characteristic shear strength values f_{vADH}:**

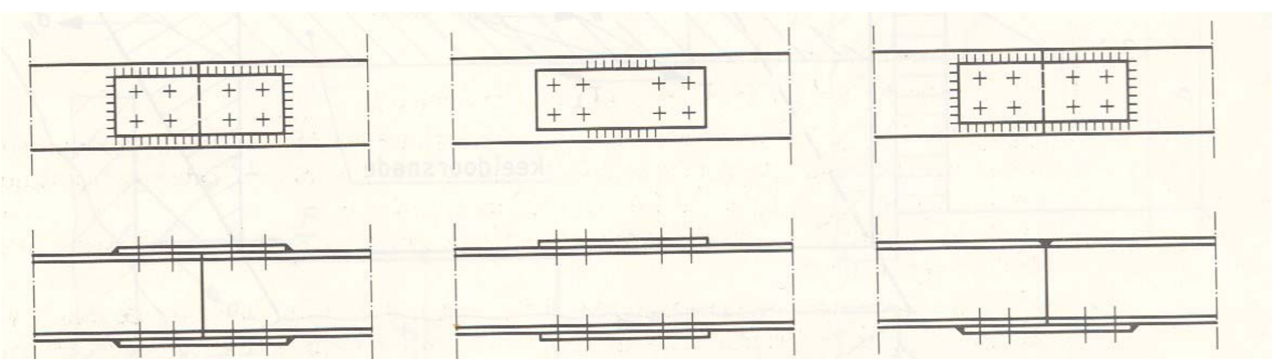
Adhesive types	f_{vADH} [N/mm²]
1-component epoxy	35
2-component epoxy	25
2-component acrylic	20

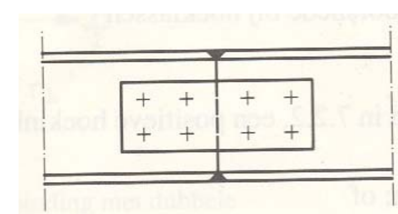
Higher values are allowed when demonstrated by tests

- **Design shear stress:** $\sigma = \dfrac{f_{v,ADH}}{\gamma_{M,adh}}$ **where:** $\gamma_{M,adh} = 3{,}0$

Hybrid connections

- **Different fasteners combined such as bolts and welds**
- **Unequal stiffness of different fasteners:**
  - Only higher stiffness fastener is acting
  - Only design strength of stiffest fastener is taken into account
- **When fasteners act at the same time: design strengths may be summarised**





Final remarks

- Research resulted in up-to-date design rules
- Design rules available for structural connections
  - welds
  - bolts and rivets
  - adhesives
- EC9 important design tool for aluminium structures