University of BRISTOL

StM3. Aircraft manufacture
Part 4

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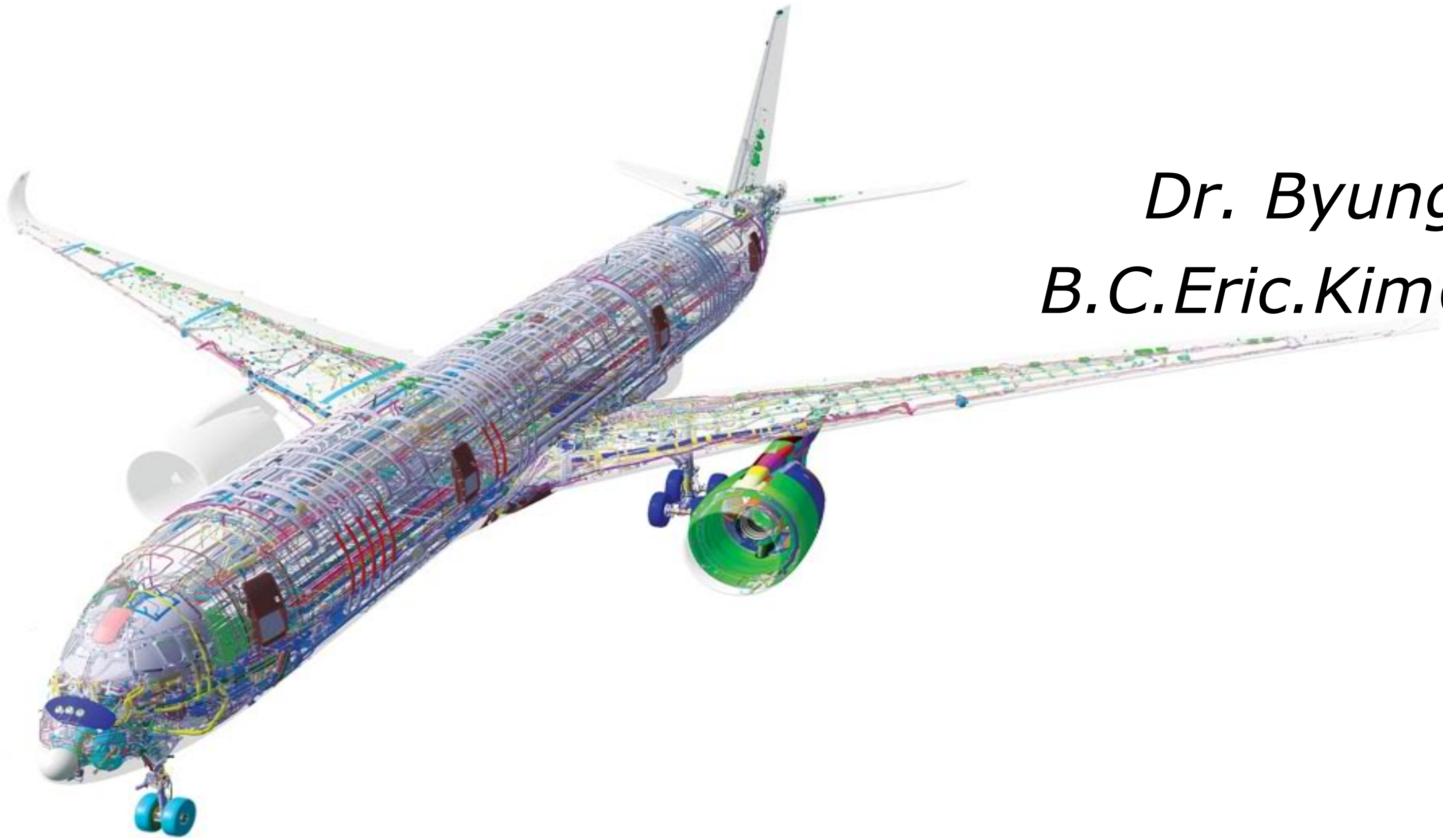


Joining

Part 2

Adhesive joints

Joining method 2: Adhesive joining

- Is it really strong enough?

Is this really amazing?

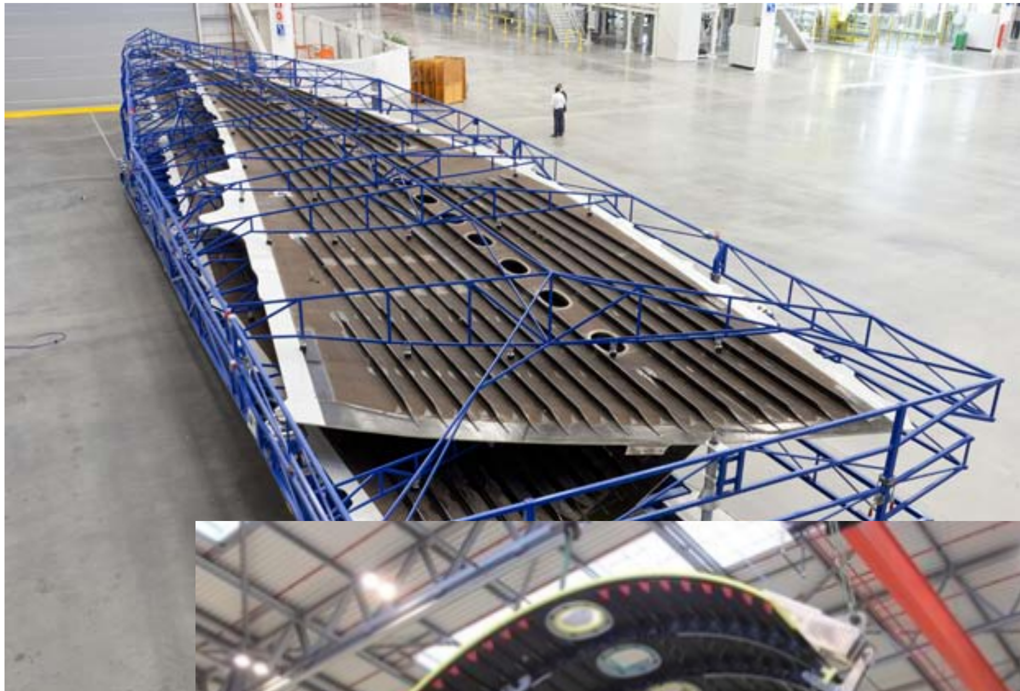
Tensile stress applied to the adhesive layer:

$1{,}200\,kgf \times 9.8\,N/m^3 \,/\, 900\,mm^2$
$= 13\ MPa$

The tensile strength of this epoxy adhesive is about 20 MPa.

Not amazing at all in this case, Strangely they couldn't use the full strength of the epoxy adhesive. Why?

Adhesive joining in aircraft manufacturing



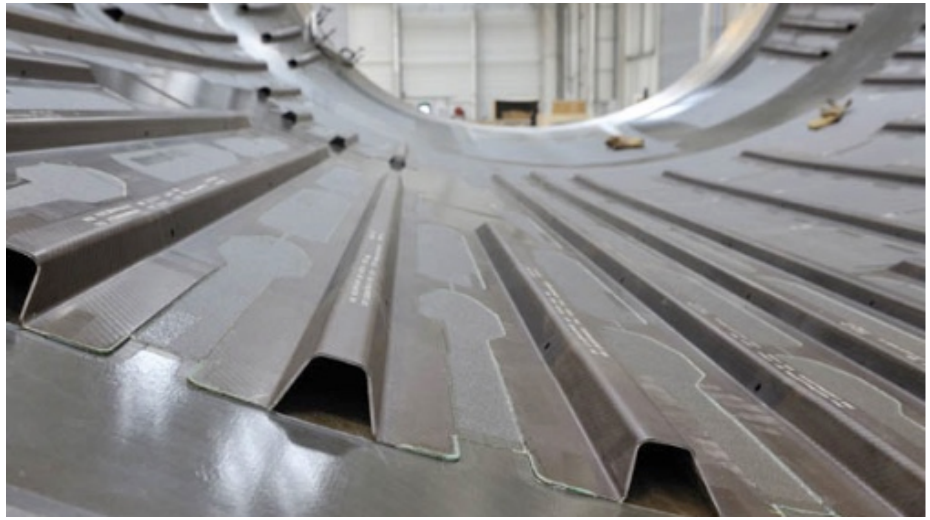
Airbus A350XWB
Composite wing skin & fuselage

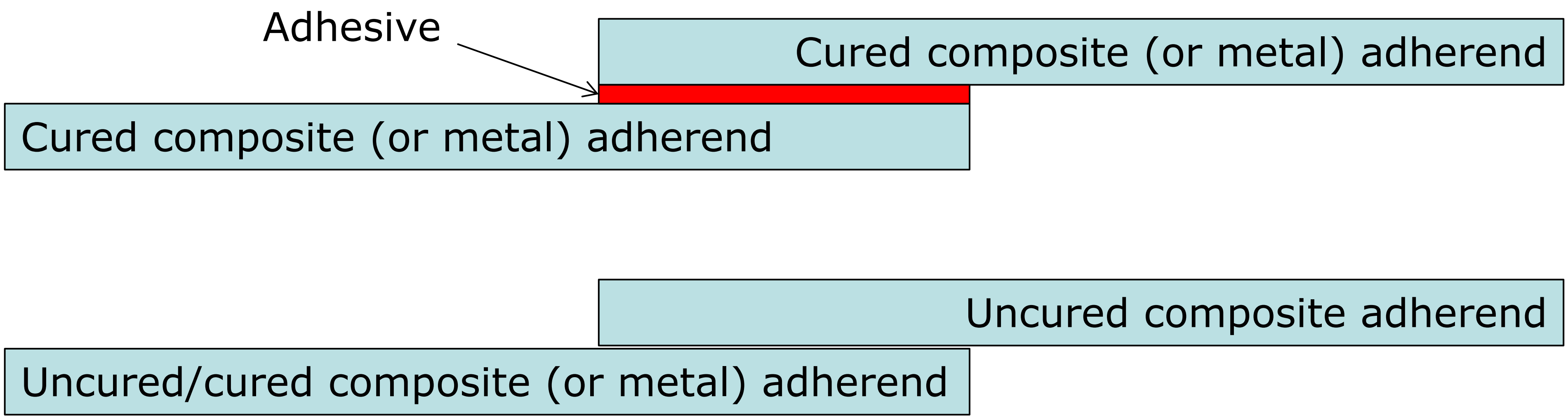
Total bonding length:
~ 5 km

Significant cost reduction by eliminating riveting process
But, more strict quality control and inspection processes are required.

Joining method 2: Adhesive joining

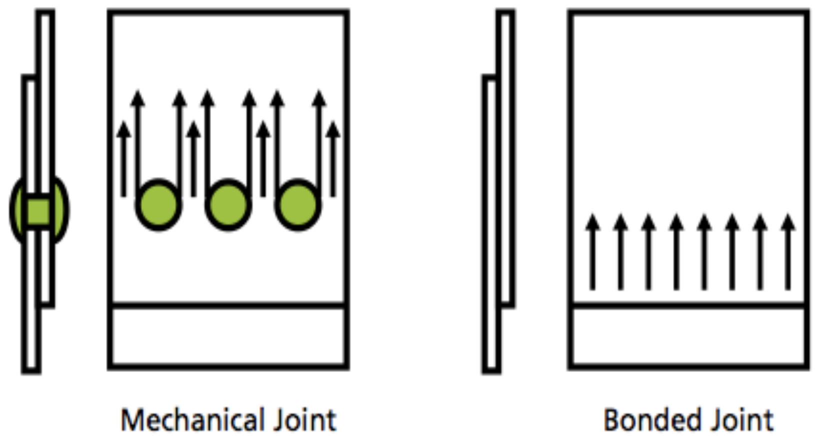
- Adhesive bonding
  - Applying polymeric adhesive on cured composites or metals and curing it at high (or room) temperature
  - Co-curing: Uncured composite plies are cured and bonded simultaneously during curing.

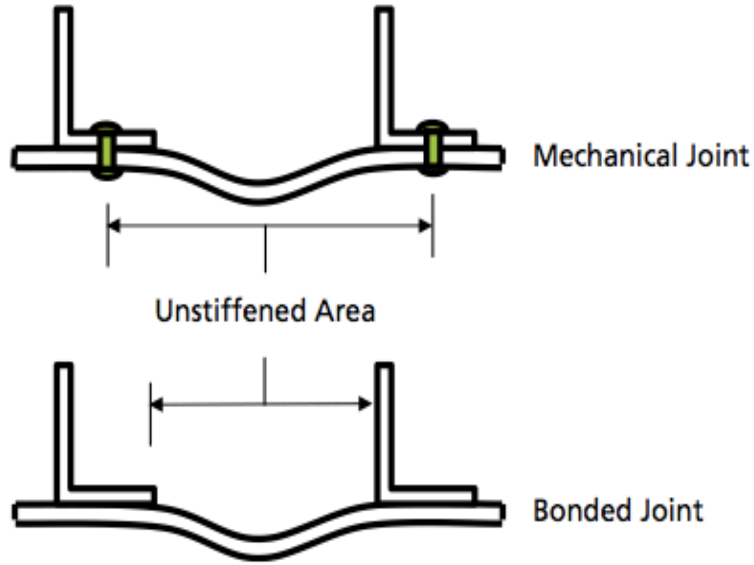




Joining method 2: Adhesive joining

- Advantages
  - More uniform stress distribution
  - Reducing unstiffened areas
  - Joining a large area at once
  - Weight saving
  - Smooth aircraft surface
  - Electrical insulation (No galvanic corrosion)
- Disadvantages
  - Difficult to inspect and repair
  - Unable to disassemble
  - Low environmental resistance
  - Surface pre-treatment required
  - Sensitive to peel stress
  - Weak in fatigue loading

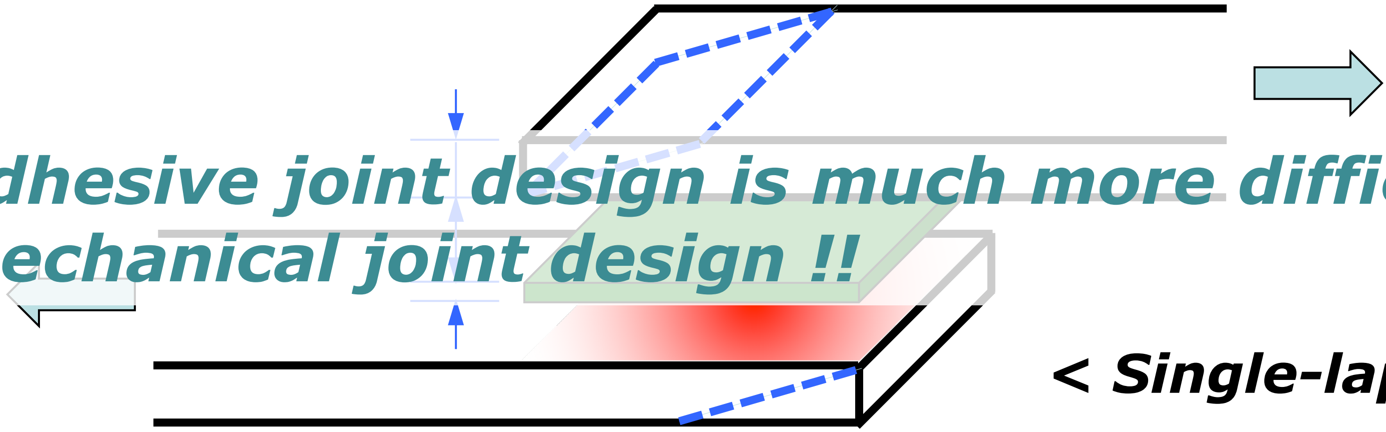




Adhesive joint design

Given:
- Adherend materials
- Loading conditions

Joint configuration
- Joint type (single or double lap, scarf, step)
- Overlap length
- Bonding thickness
- Tensile/flexural stiffness of adherends
- Reduction of stress concentration



Adhesive joint design is much more difficult than mechanical joint design !!

< Single-lap shear joint >

Surface treatment
- Surface cleaning
- Suitable method for adherend materials
- Damage of adherend (surface damage, degradation)
- Cost & speed
- Environmental effect, Health & safety

Type of adhesive
- Curing temp. ➔ Residual stress & joint strength
- Glass transition temp. ➔ Service temp.
- Fracture toughness ➔ Fatigue & Impact
- Viscosity ➔ Application method
- Environmental effect (Humidity, UV)
- Pot life & Cost

1. Adhesive Materials

Adhesive materials

- Non-linear shear behaviour & temperature dependency

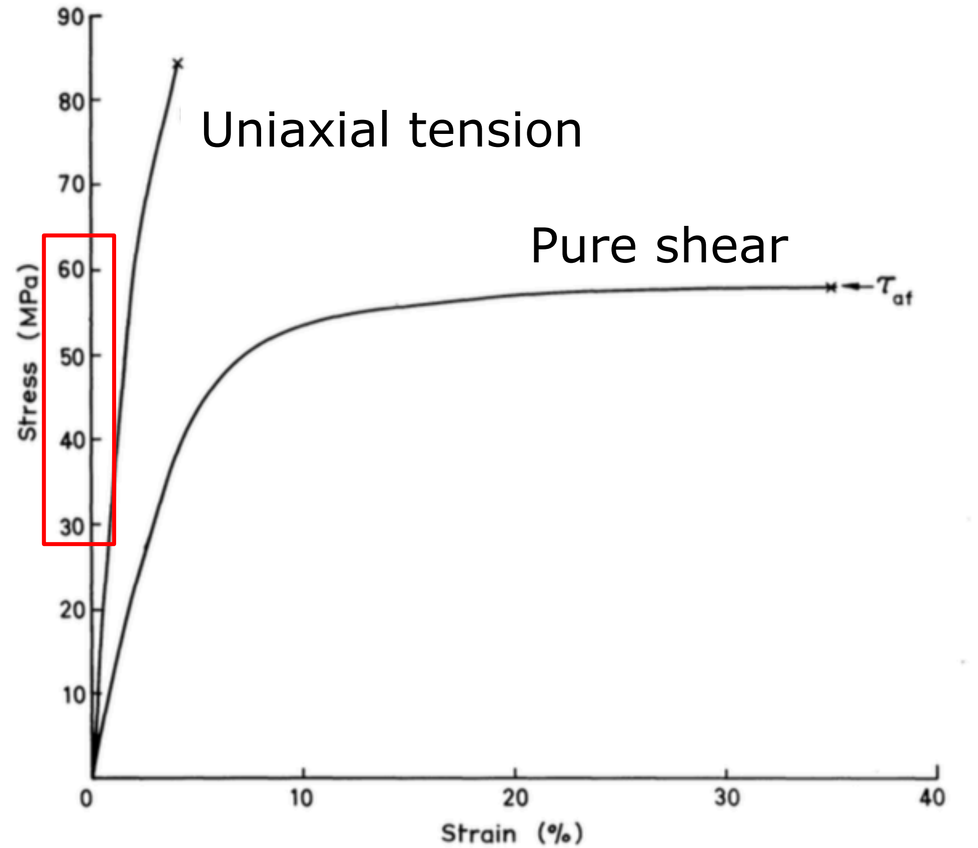


Figure 6.3 Stress versus strain curves for a hot-cured rubber-toughened epoxy adhesive (at 23 °C and an average strain rate of $7.5 \times 10^{-4} s^{-1}$) in uniaxial tension and pure shear [8].

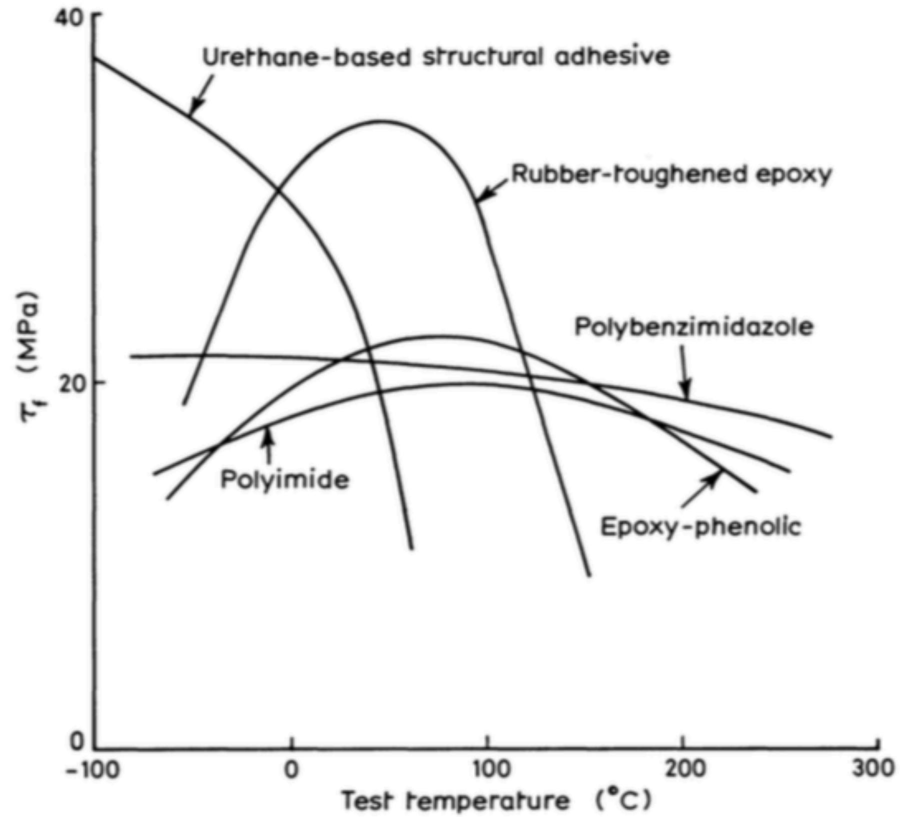


Figure 6.20 Typical strengths of single lap joints loaded in tension using various structural adhesives as a function of test temperature [76,77].

Adhesive materials

Table 9.2 Advantages and limitations of the five most widely used chemically reactive structural adhesives

Advantages

Epoxy	Polyurethane	Modified acrylic	Cyanoacrylate	Anaerobic
High strength Good solvent resistance Good gap-filling capabilities Good elevated-temperature resistance Wide range of formulations Relatively low cost	Varying cure times Tough Excellent flexibility even at low temperatures One or two components, room- or elevated-temperature cure Moderate cost	Good flexibility Good peel and shear strengths No mixing required Will bond dirty (oily) surfaces Room-temperature cure Moderate cost	Rapid room-temperature cure One component High tensile strengths Long pot life Good adhesion to metal Dispenses easily from package	Rapid room-temperature cure Good solvent resistance Good elevated-temperature resistance No mixing Indefinite pot life Nontoxic High strength on some substrates Moderate cost

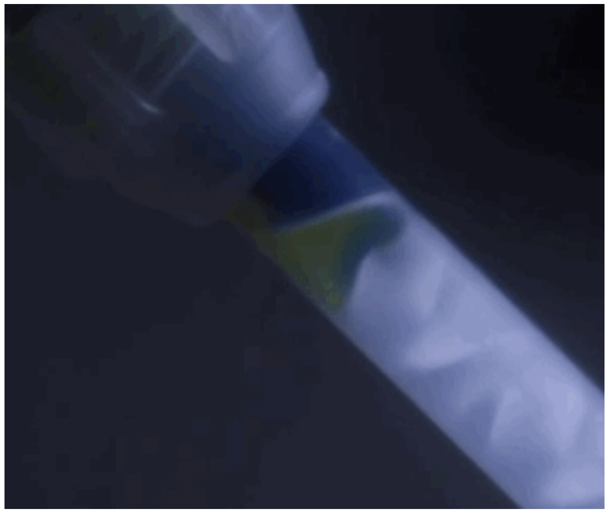
Limitations

Epoxy	Polyurethane	Modified acrylic	Cyanoacrylate	Anaerobic
Exothermic reaction Exact proportions needed for optimum properties Two-component formulations require exact measuring and mixing One-component formulations often require refrigerated storage and an elevated-temperature cure Short pot life (more waste)	Both uncured and cured are moisture sensitive Poor elevated-temperature resistance May revert with heat and moisture Short pot life Special mixing and dispensing equipment required	Low hot-temperature strength Slower cure than with anaerobics or cyanoacrylates Toxic Flammable Odor Limited open time Dispensing equipment required	High cost Poor durability on some surfaces Limited solvent resistance Limited elevated-temperature resistance Bonds skin	Not recommended for permeable surfaces Will not cure in air as a wet fillet Limited gap cure

Ref. Adhesives, Engineered Materials Handbook, ASM international, 1995.

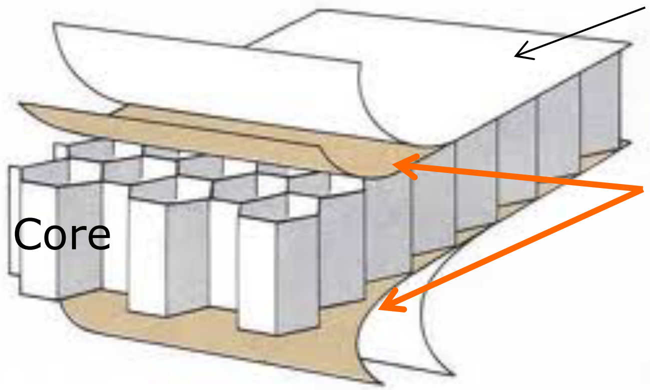
Epoxy adhesives

- Liquid type adhesives
  - Toughened epoxy is the most popular.
  - Application: Resin + Hardener > Mixing > Degassing > Pasting > Pressing with adherends > Curing
  - Good penetration, but difficult to control the bonding thickness
  - Difficult to apply
  - Wide curing temperature range, various grades
  - Considerations: Viscosity, pot-life, service temperature.




Epoxy adhesives

- Film (Hot-melt) adhesives
  - B-stage epoxy resin film (partially cured, so sticky)
  - Application: Cutting > Attaching to adherends > Pressing > Curing at high-temperature
  - Easy to handle and clean
  - Easy to control the bonding thickness
  - But, expensive. High-temperature curing only. Short shelf-life
  - Limited adhesive types available, low temperature storage
  - Considerations: Tackiness, areal weight, shelf-life



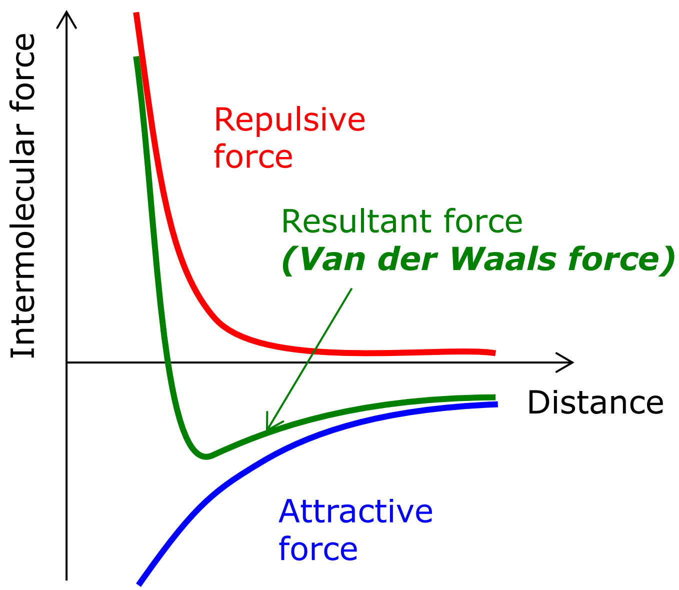
Adhesive bonding in automotive industry

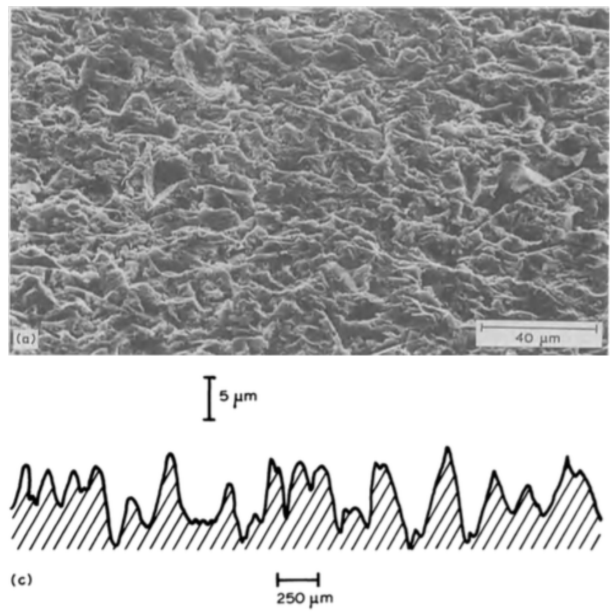
2. Surface Treatment

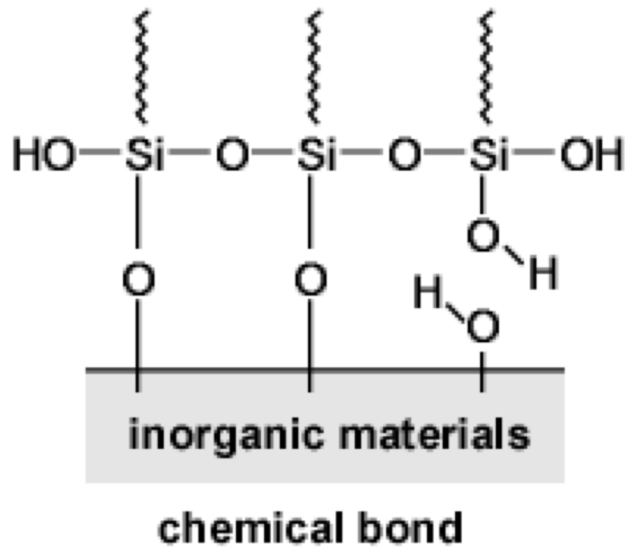
Mechanism of adhesion

Adhesion by
- Physical absorption
- Mechanical interlocking
- Chemical bonding
- Diffusion
- Electrostatic

Surface treatment is crucial to make the adhesion mechanism work properly.



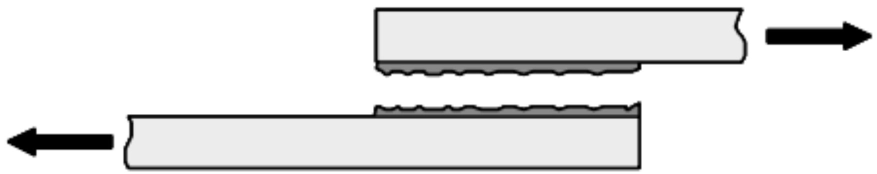


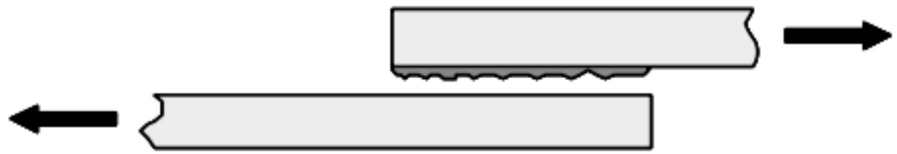


Surface treatment

- Purpose of surface treatment
  - Removing surface contamination (e.g. oil contamination during machining or rolling)
  - Surface activation (increasing surface free energy & wettability)
  - Creating surface roughness
  - Surface chemistry modification

- Impact on joint failure mode





Cohesive failure
Full use of adhesive strength

Bonding strength
>>

Interfacial failure
Weak bonding

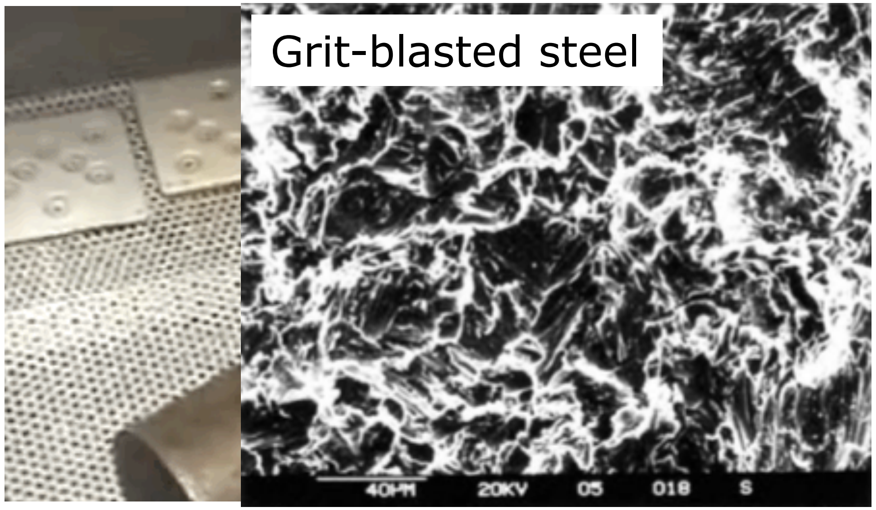
Surface treatment methods

- Types
  - Mechanical abrading (e.g. grid-blasting, grinding, manual abrading)
  - Chemical etching (e.g. phosphoric acid anodising)
  - Plasma treatment (Corona)
  - UV treatment
  - Flame treatment
  - Primer coating (e.g. silane coupling agent)

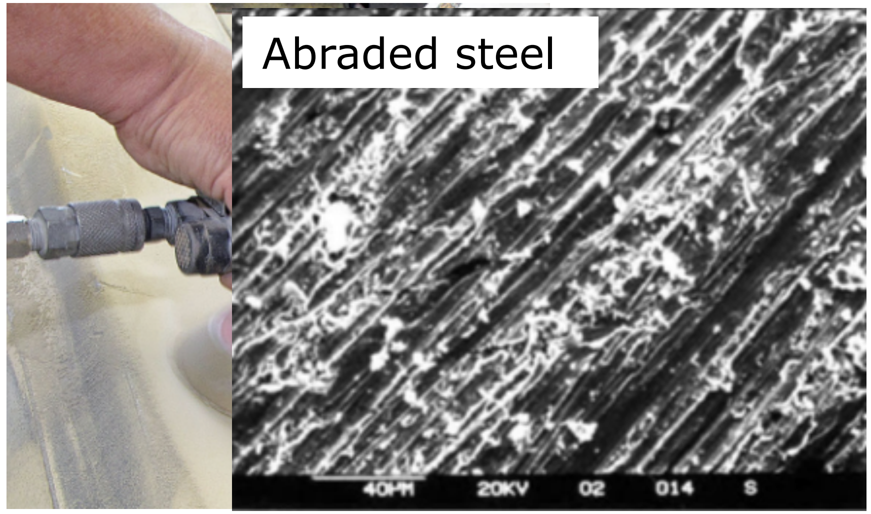
- *Thermoplastic adherends cannot be bonded with thermoset adhesives without changing surface chemistry (surface functionalisation) due to their low surface energy. Even if bonded, the interfacial failure causes a very low joint strength.*
  - *e.g. Teflon (PTFE), PEEK: Very low surface energy*

Surface treatment methods

- Grit-blasting

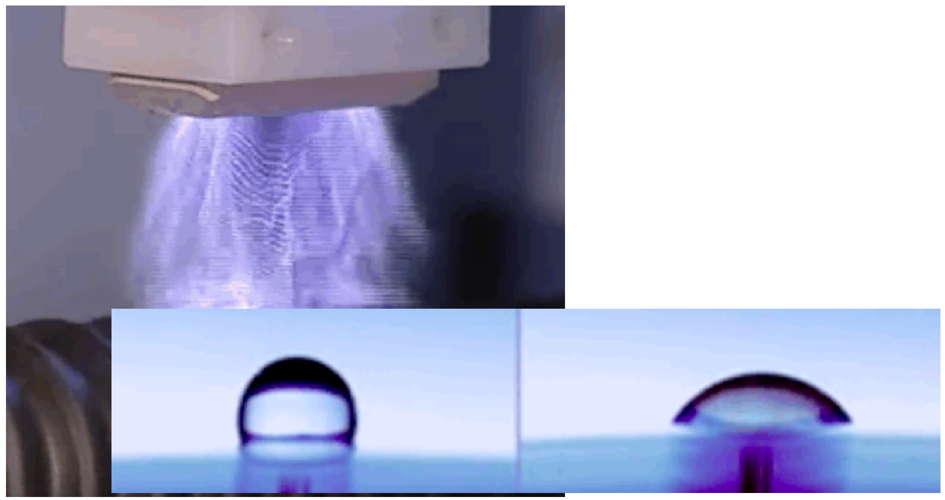


- Manual abrading



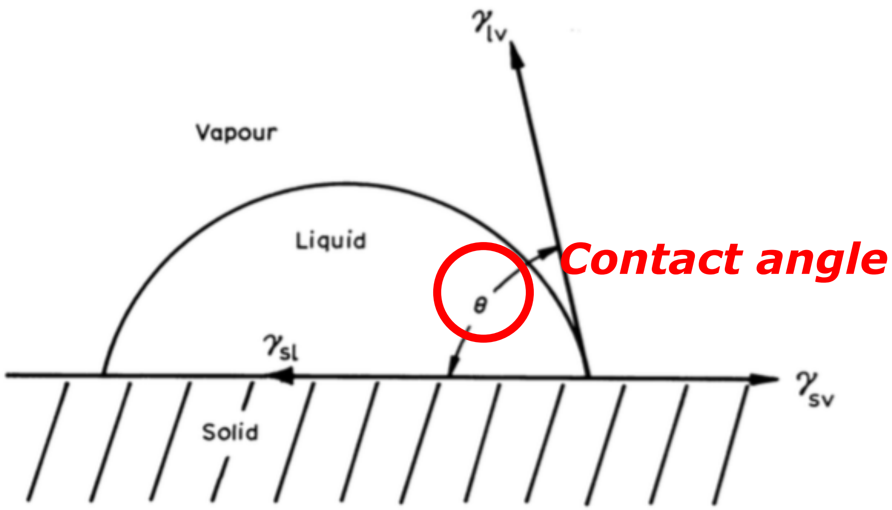
- Chemical etching

- Plasma treatment



Surface free energy (Physical Absorption)

- ***Wettability***
  - Wetting: intimate molecular contact between two substances



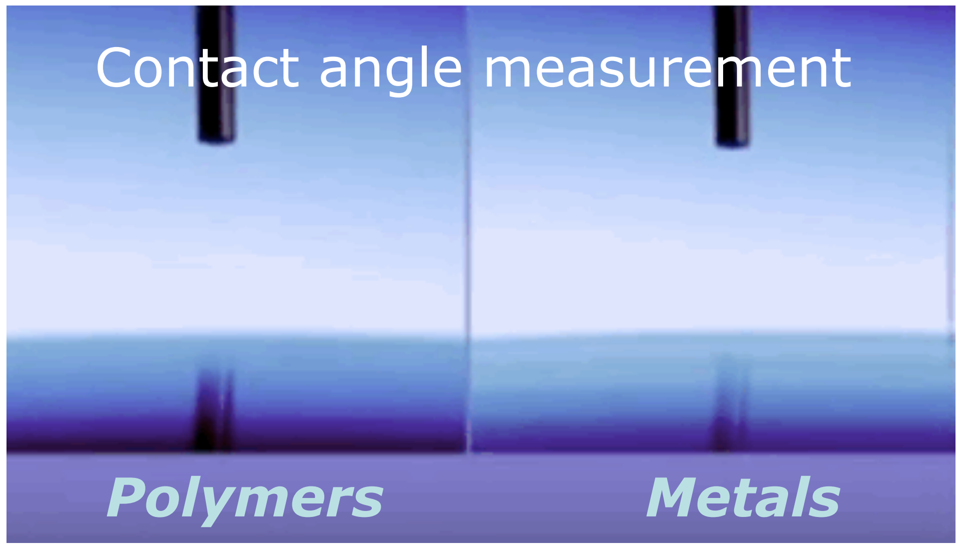
Spontaneous wetting condition

$$\gamma_{sv} \geq \gamma_{sl} + \gamma_{lv}$$

Equilibrium spreading coefficient

$$S = \gamma_{sv} - \gamma_{sl} - \gamma_{lv}$$

$$\gamma_{sv} = \gamma_{sl} + \gamma_{lv}\cos\theta$$ ***(Young's equation)***



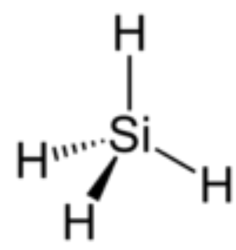
γ_{sv} *Surface free energy of the solid substrate*

γ_{sl} *Interfacial free energy b/w solid and liquid*

γ_{lv} *Surface free energy of the liquid (= Surface tension)*

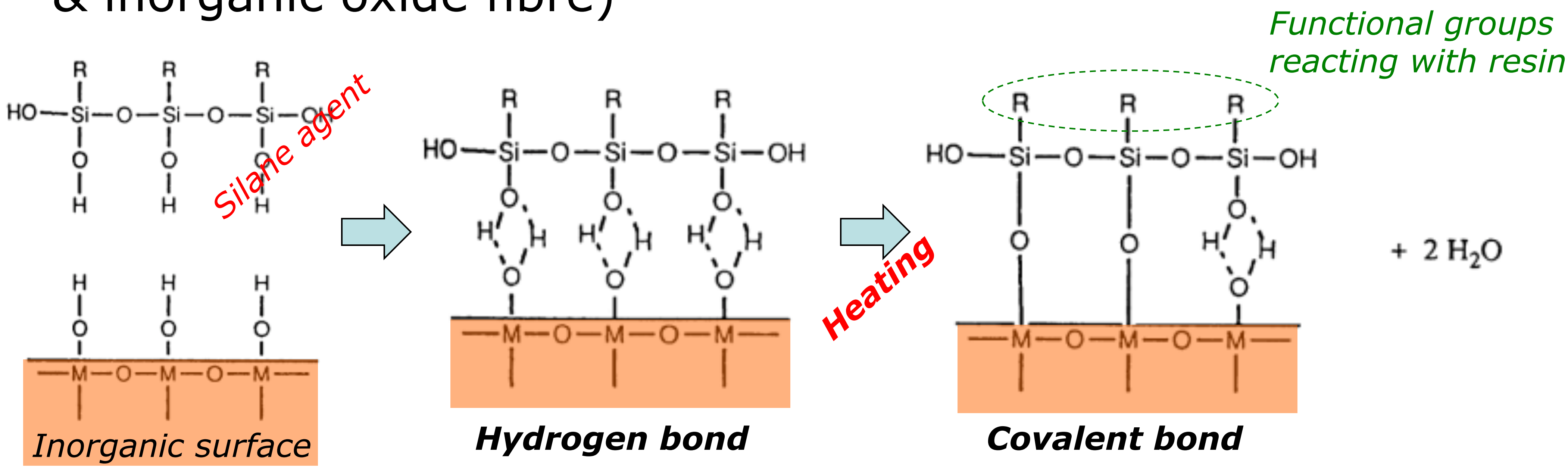
Silane coupling agent (Chemical bonding)

- Silane coupling agents have the ability to form a durable bond between organic and inorganic materials.



Silane: Inorganic compound with chemical formula, SiH_4

- The most popular application is the surface treatment of glass fibres for glass composites. (Organic polymer resin & inorganic oxide fibre)

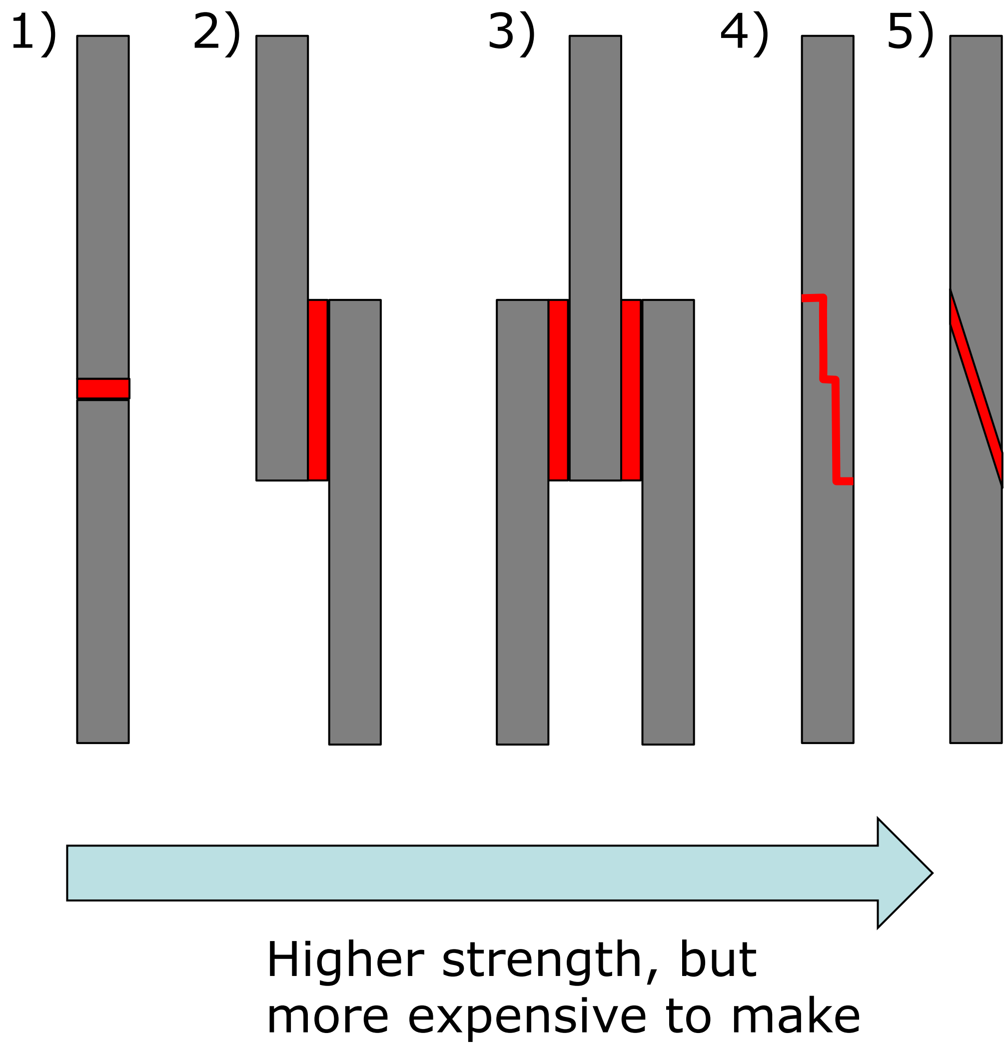


3. Joint Configuration

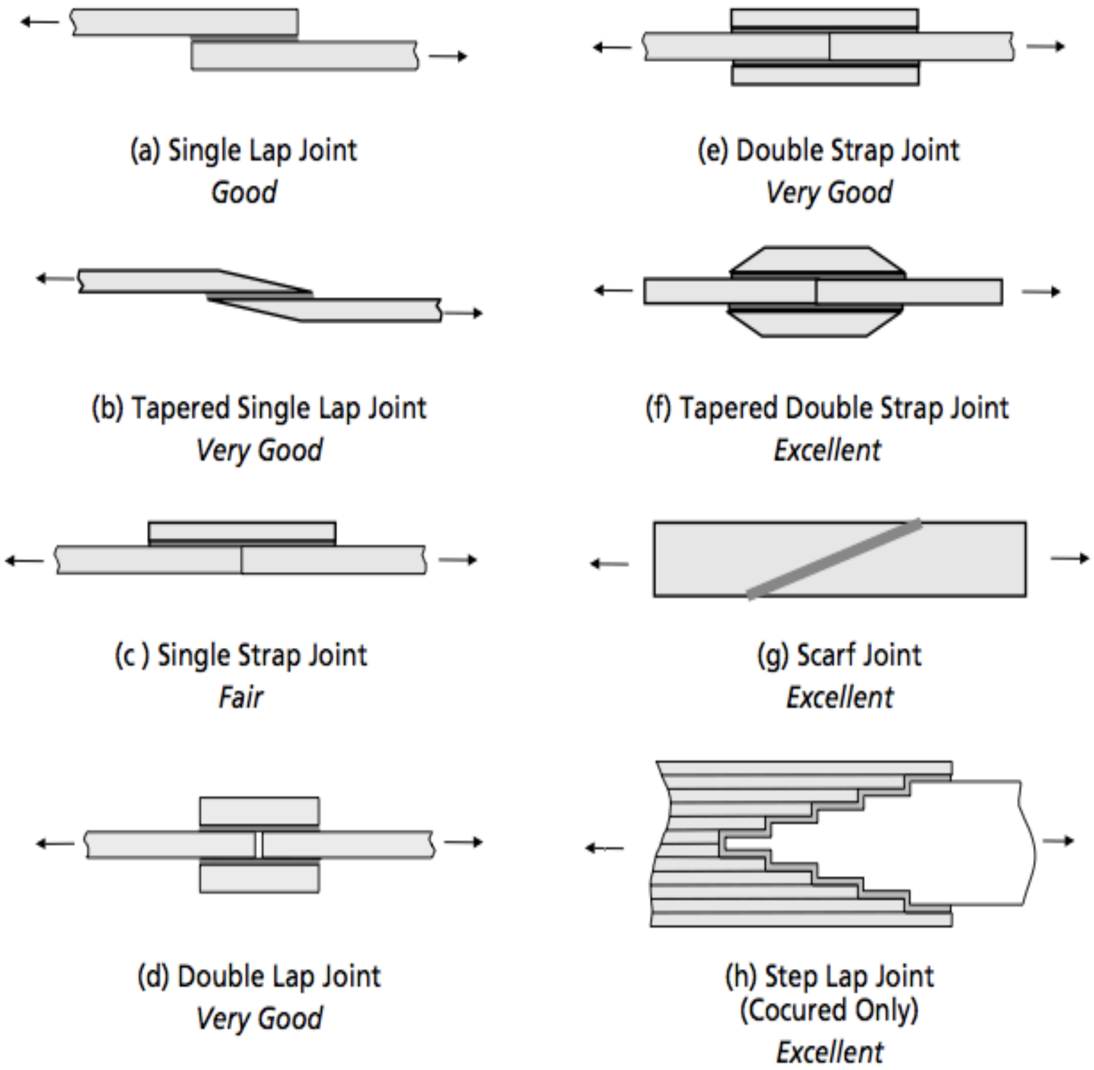
Adhesive joint design

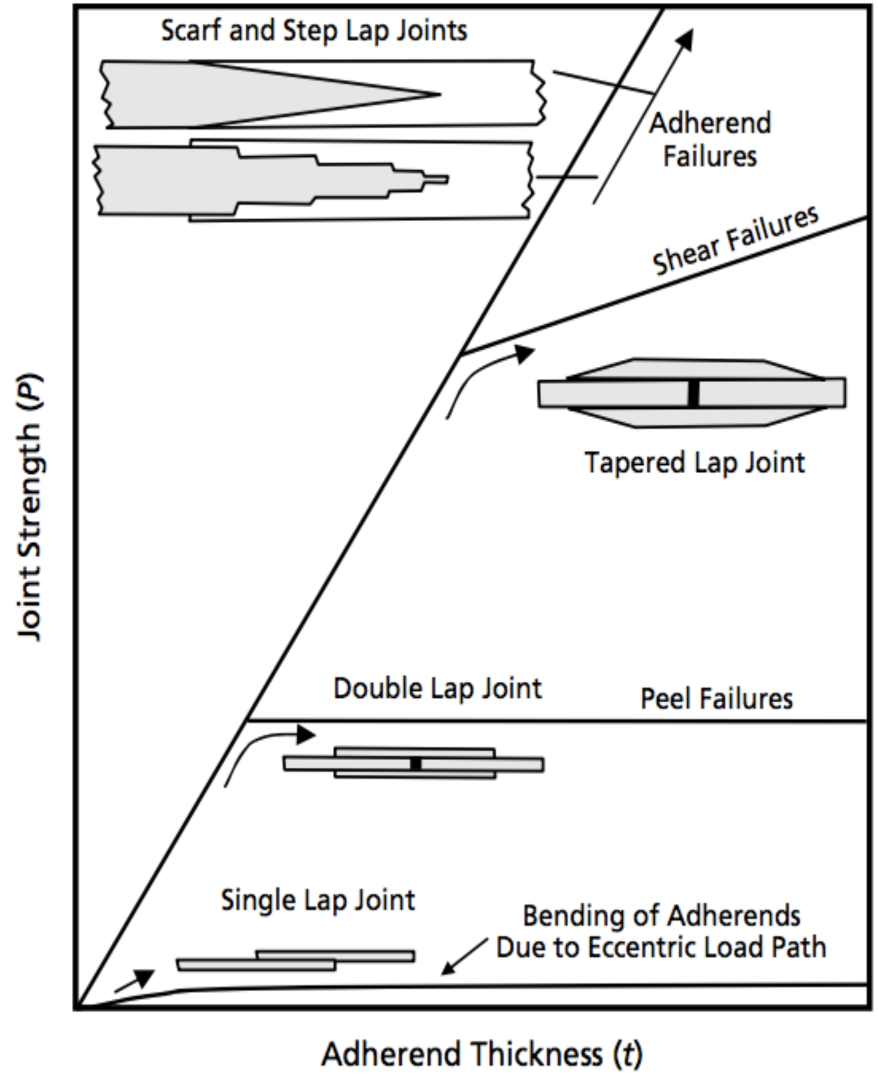
Joint configuration

1) Butt joint
2) Single lap joint
3) Double lap joint
4) Step joint
5) Scarf joint
6) Tubular joint

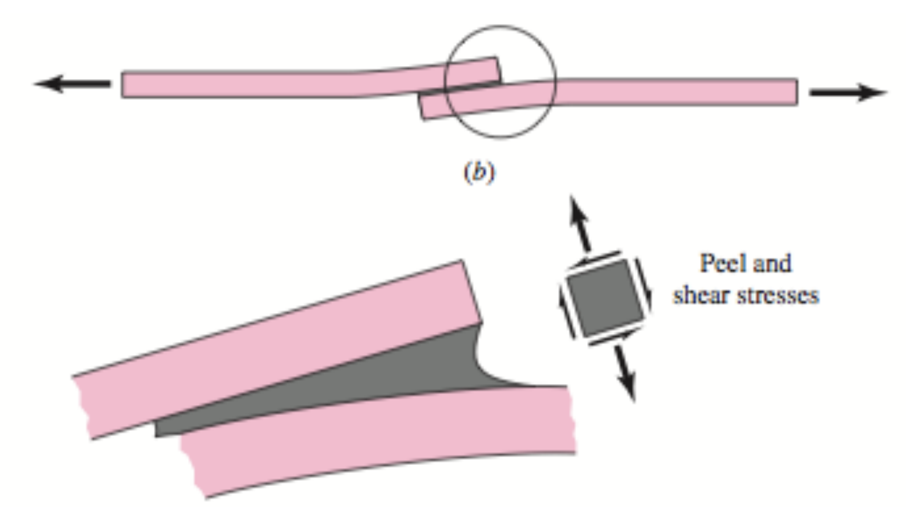


Adhesive joint design





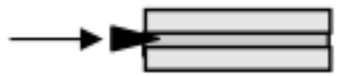
Adhesive joint design



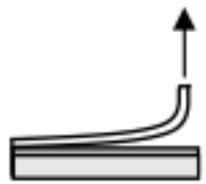
Adhesive is very strong to shear loadings, but very weak to peel stress.

How to minimise peel stress on the edge is critical.

Tension
(Butt Joints in Thin Sheet)

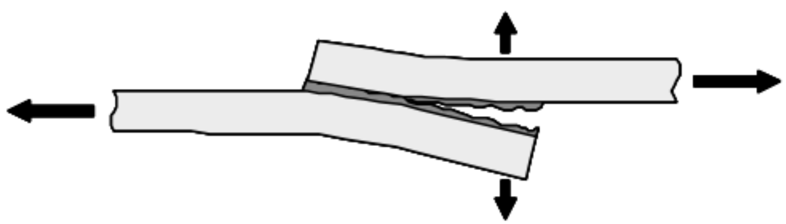


Cleavage



Peel

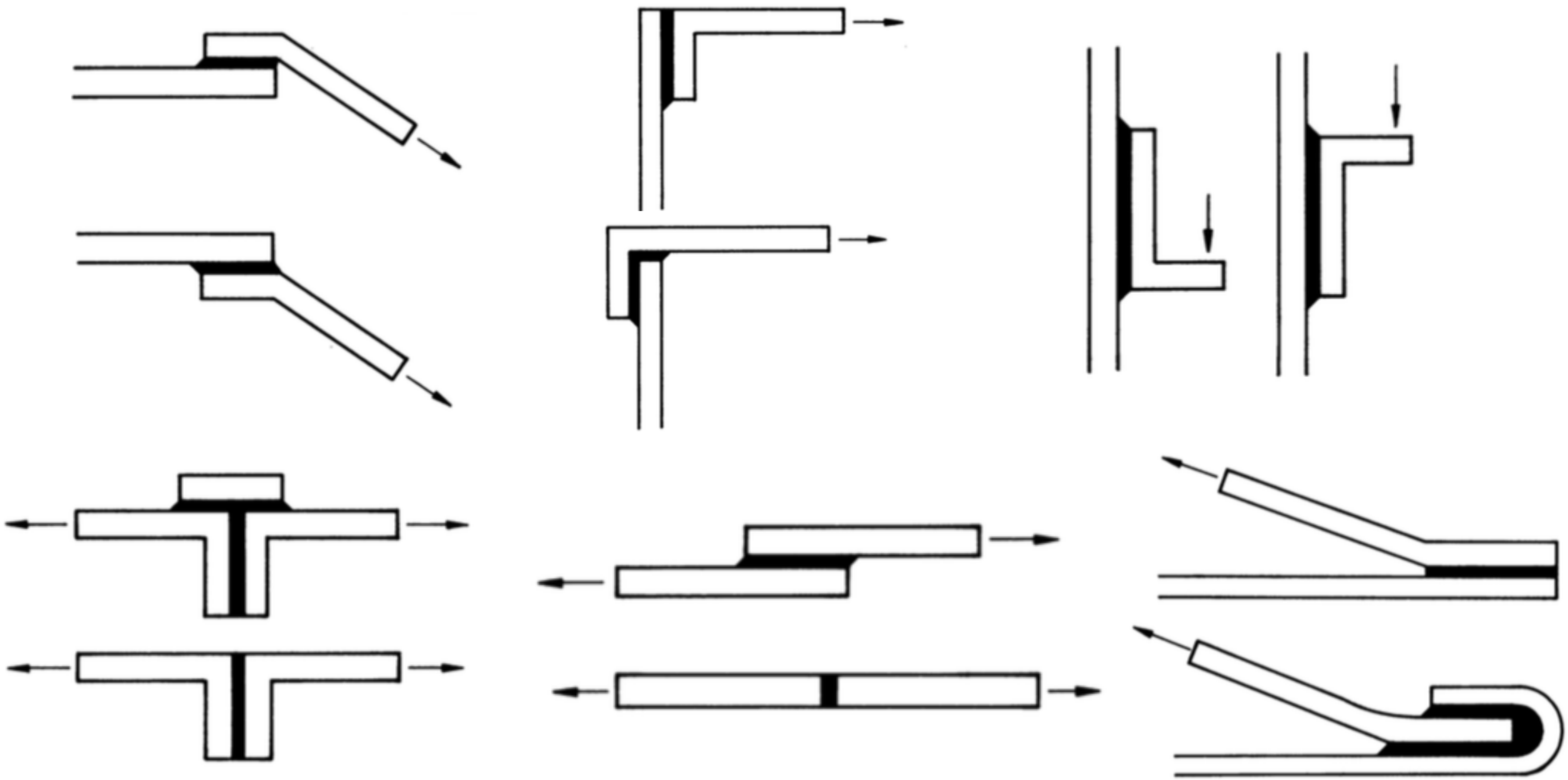
Wrong joint designs !



Adhesive Peel
(Excessive Out-of-Plane Loads)

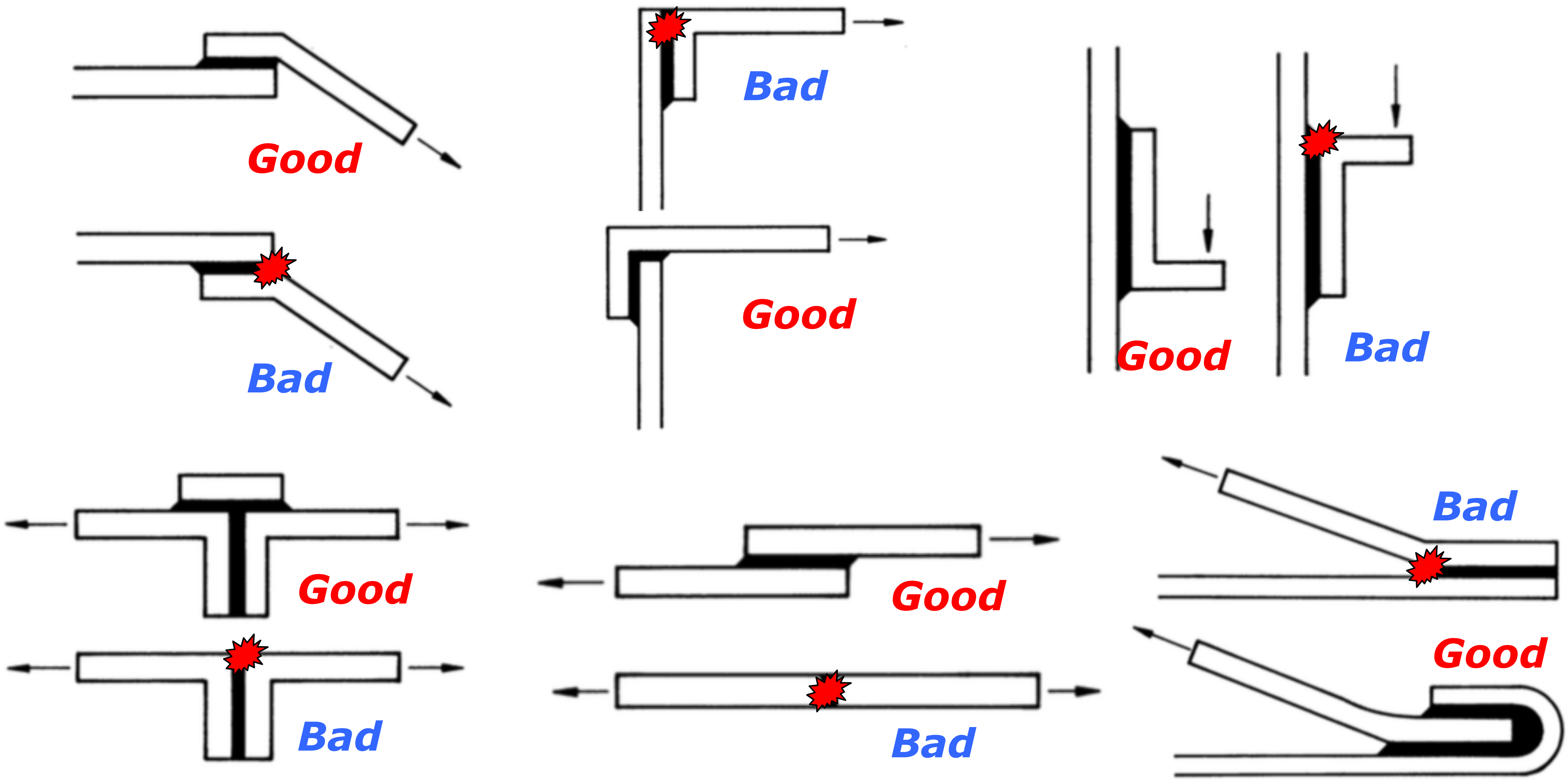
Quizzes

- Which one is a good adhesive joint design?



Quizzes

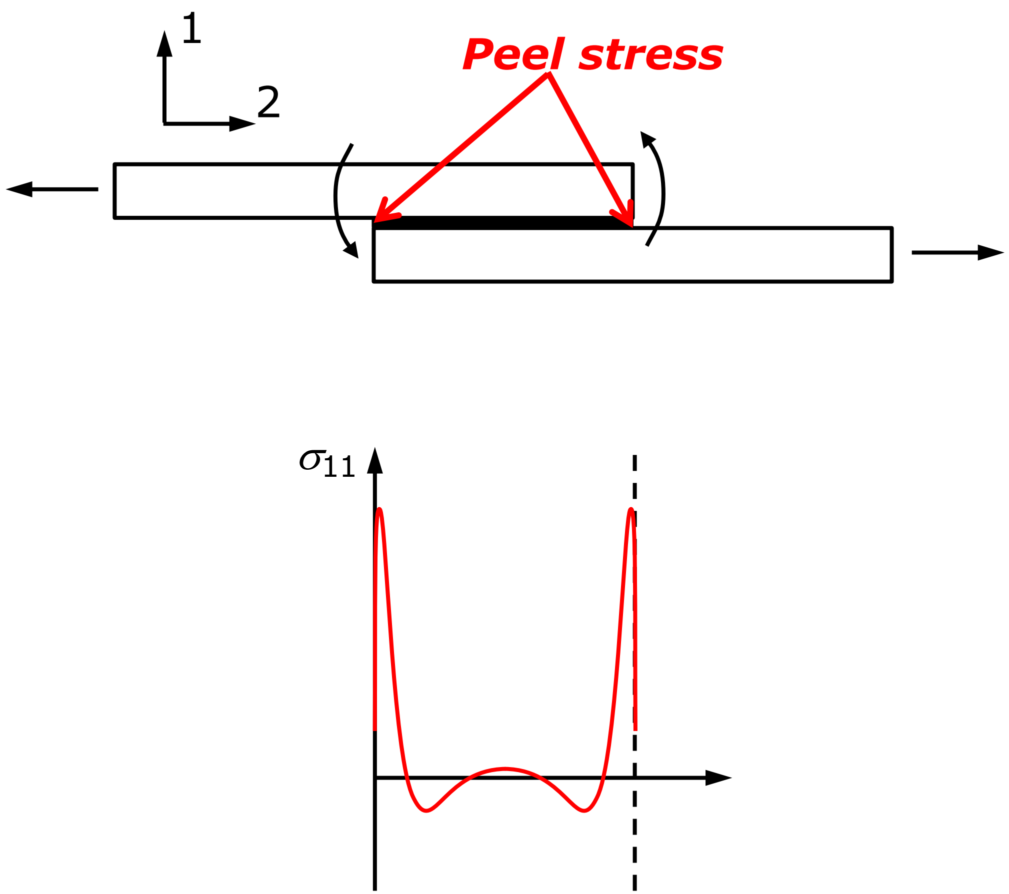
- Which one is a good adhesive joint design?



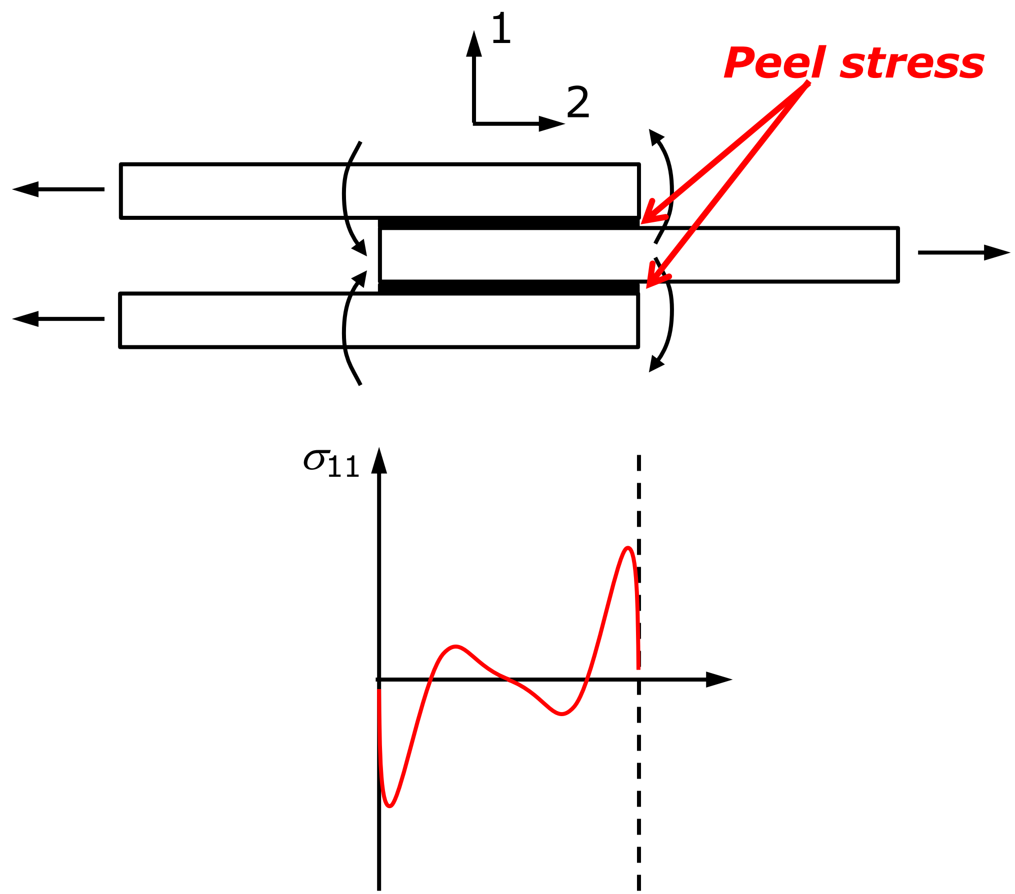
Adhesive joint design

- **Peel stress** distribution

< Single-lap joint >

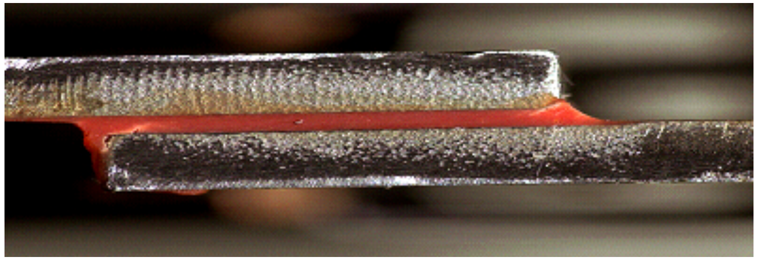


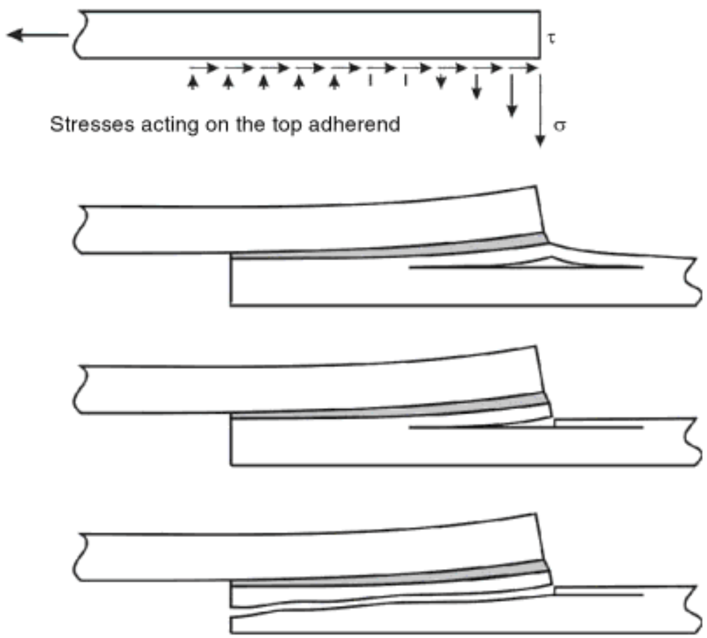
< Double-lap joint >



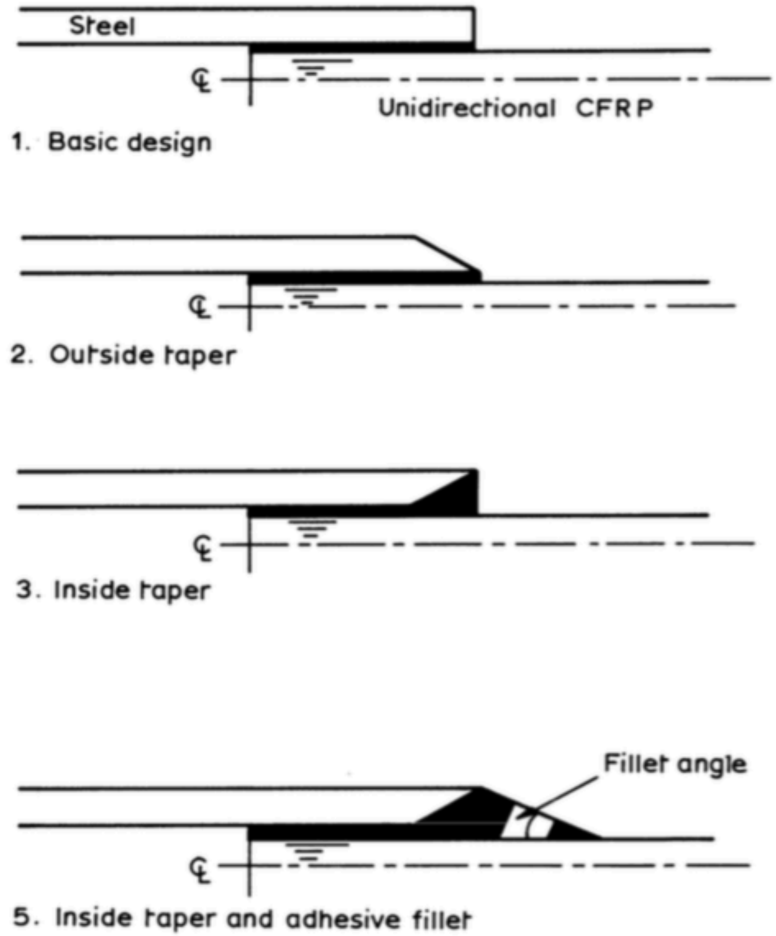
Adhesive joint design

- Reduction of peel stress concentration





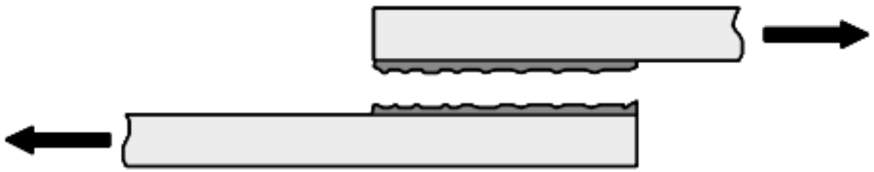
< Interlaminar failure of composite adherend due to the peel stress concentration >



< Design modification reducing stress concentration >

Failure modes

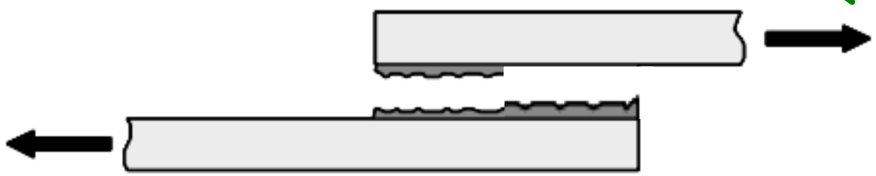
- Cohesive failure



- Interfacial failure

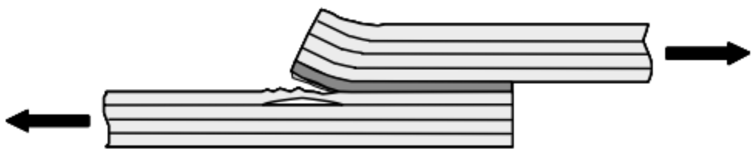
The selected surface treatment is not good enough.

- Mixed failure



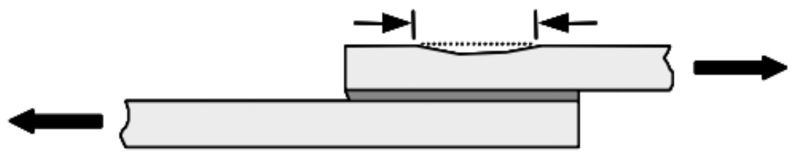
It matters how to make full use of adhesive strength minimising the weight!

- Adherend failure



Surface ply delamination
(Composite Adherends)

Adherend failure



Adherend yielding

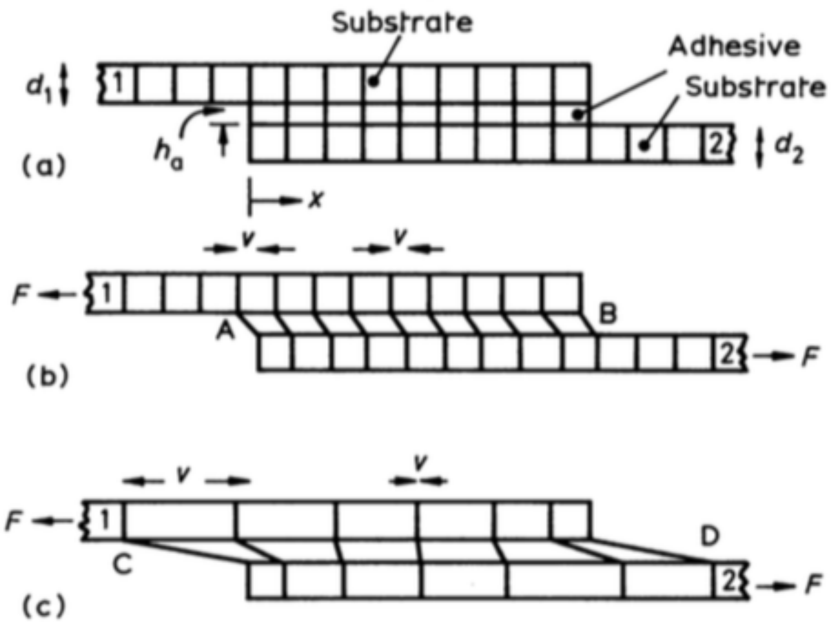
Adhesive joint design

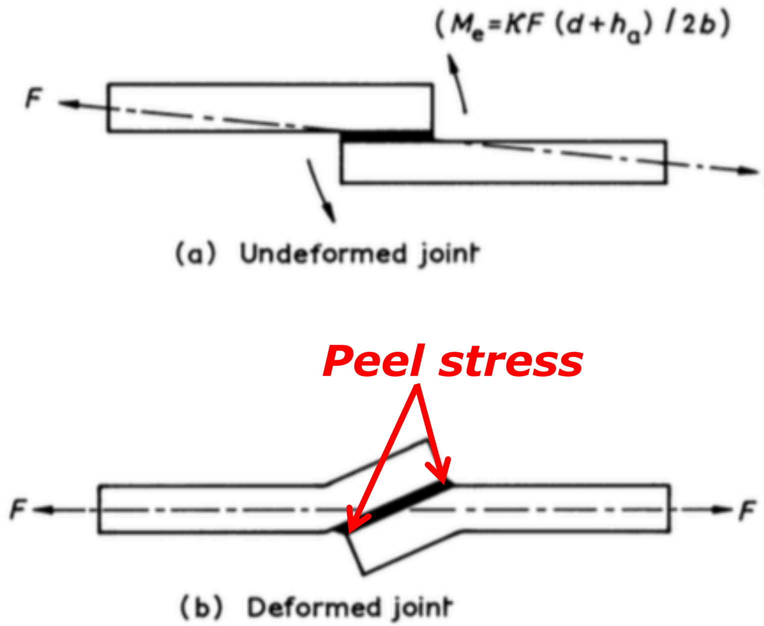
- **Shear stress** distribution

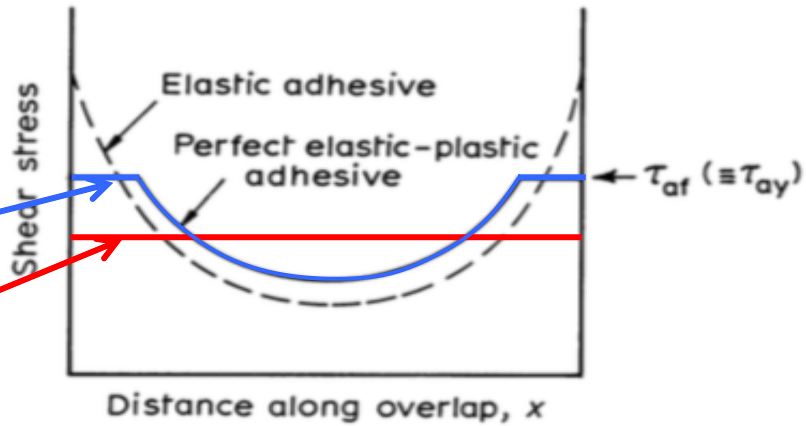
Unloaded

Inextensible adherends

Extensible adherends







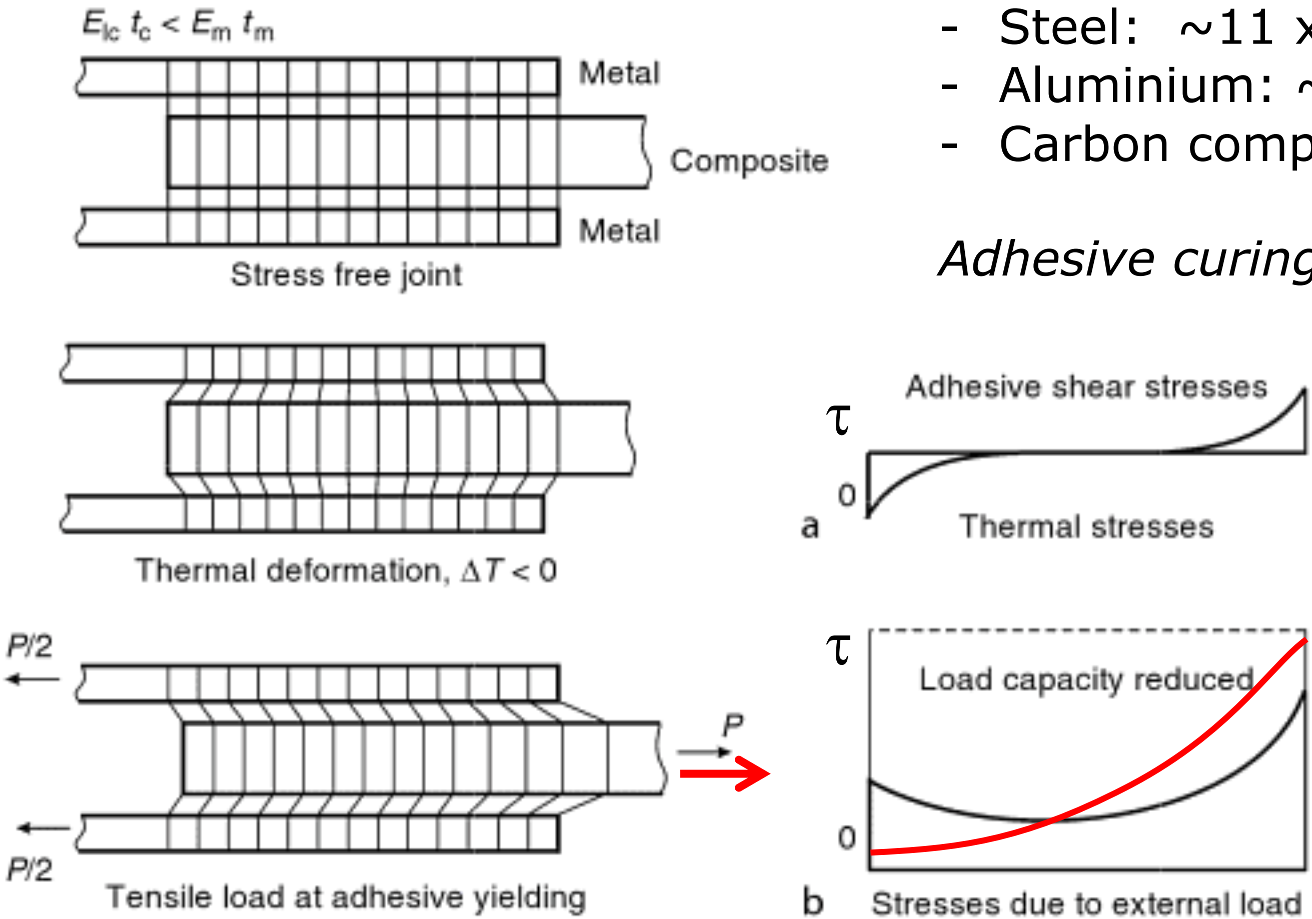
We often use the average shear stress for the joint strength, but should bear in mind that <u>the actual shear stress is not uniform.</u>

Adhesive joint design

- Thermal residual stress

CTE (Coefficient of Thermal Expansion)
- Adhesive (Polymer): 30-60 x 10^{-6} m/m°C
- Steel: ~11 x 10^{-6} m/m°C
- Aluminium: ~24 x 10^{-6} m/m°C
- Carbon composite: ~0 m/m°C

Adhesive curing temp.: 80~180°C



Factors affecting the thermal residual stress
- Adherends stiffness
- Curing temperature
- CTEs of adherends & adhesive
- ***Bonding thickness***

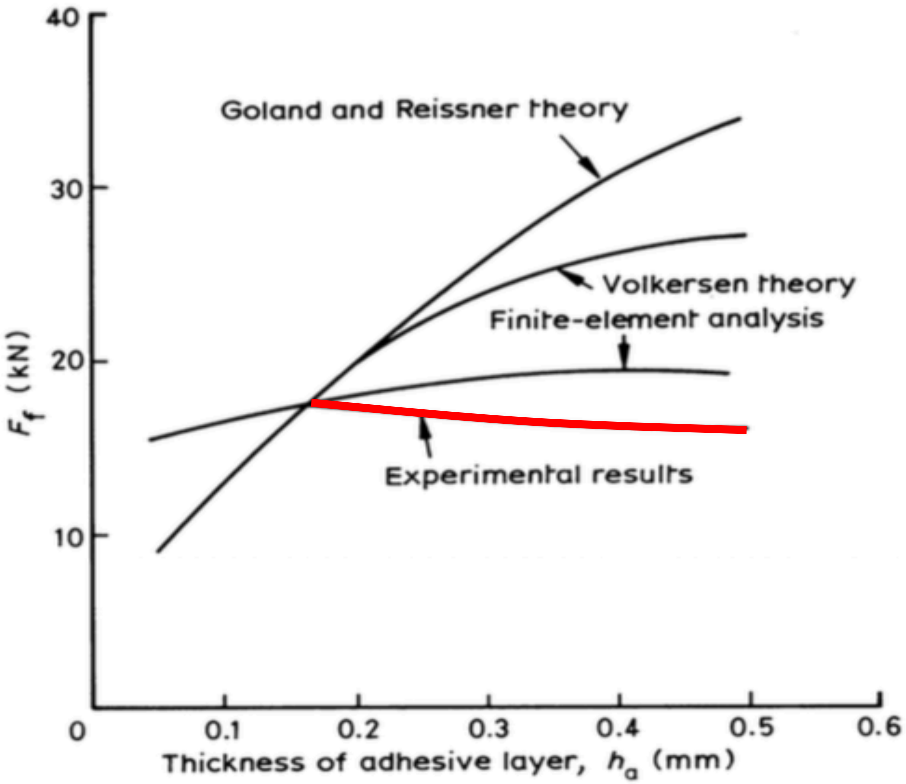
Adhesive joint design

- Importance of the bonding thickness
  - The bonding thickness significantly affects the joint strength.
  - For brittle adhesive, a thinner adhesive layer causes less stress concentration as well as less thermal residual stress.
  - Generally, 0.1~0.2 mm thickness is recommended.

However, analytical models predict the opposite trend. (Thermal residual stress is not taken into account.)

For ductile adhesive cured at room temperature (e.g. polyurethane), a thicker adhesive layer may exhibit higher strength.

Many conflicting experimental results exist ➔ Generalisation is very difficult.



Adhesive joint design

Correct prediction of the stress distribution within the adhesive layer is important to predict the joint failure. When you choose a analytical model, you should check its limitation.

Analytical models

- Elastic analysis
  - Volkersen (1938)
  - Goland & Reissner (1944)
  - Ojalvo & Eidinoff (1978)
  - …
- Elastic-plastic analysis
  - Hart Smith (1973)
  - Adams (1997)
  - …

- Can it consider the material non-linearity of the adhesive and adherends?
- Can it consider dissimilar adherends?
- Can it predict both peel and shear stresses?
- Is it a closed-form or a numerical solution?

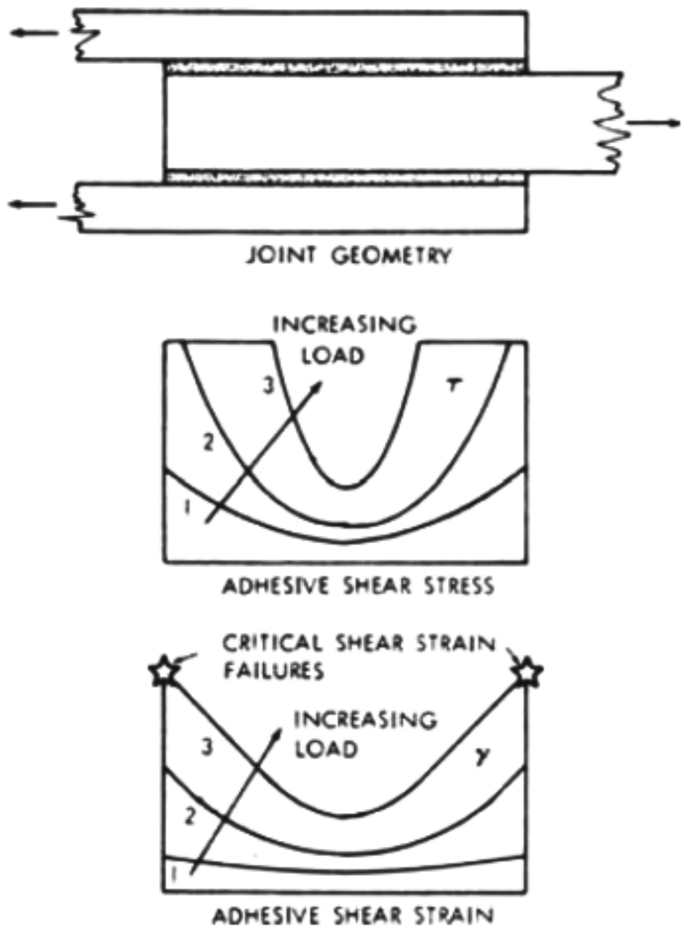
For complex geometry and loading conditions (e.g. thermal), FEA is used. But, singularity issues exist.

Adhesive joint design

One should choose an appropriate failure criterion.

- Based on Continuum Mechanics
  - Maximum stress/strain criterion
  - Von Mises stress/strain criterion
- Based on Fracture Mechanics
  - Stress intensity factor
  - Energy release rate
  - Damage model
- For Fatigue loading
- For Impact loading

** Unfortunately, there is no golden rule due to the complexity, and people still highly rely on experimental methods.*

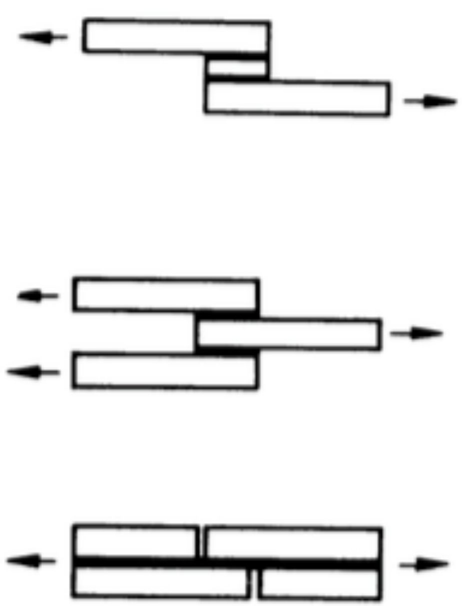


Failure prediction based on max. shear strain (Hart-Smith model)

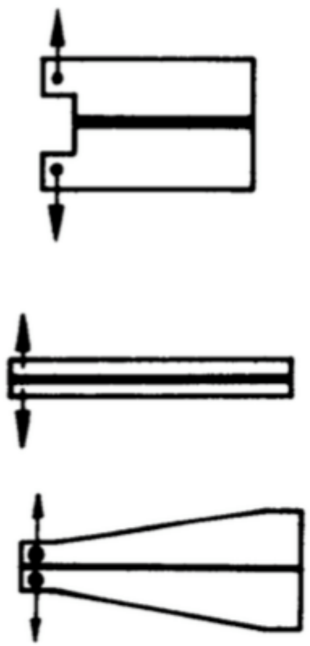
Adhesion strength tests

Testing is crucial since the analytical models and failure predictions are not perfect !!

- Structural testing

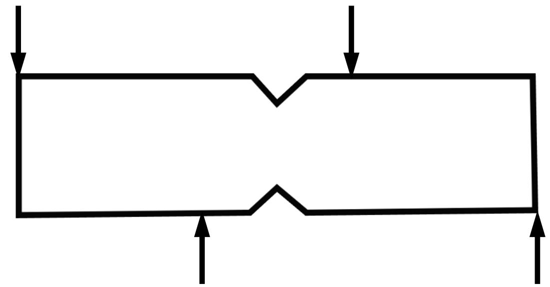


Lap shear test

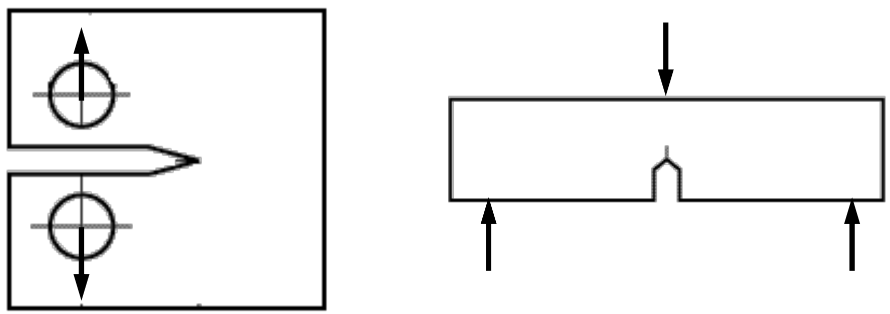


Cleavage test

- Material testing
  - Tensile and shear test



  - Fracture toughness test



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