

## Welcome! About Socrative student response system

Dear students

I look forward meeting you next Tuesday on the lecture on load introductions

We will be using the Socrative student response system for some small quizzes

To participate use the following link on your laptop or smartphone

<https://b.socrative.com/login/student/>

As Room Name use **brauner**

(alternatively you may use the socrative student app

<https://www.socrative.com/apps.html> )



Student Login

Room Name

JOIN

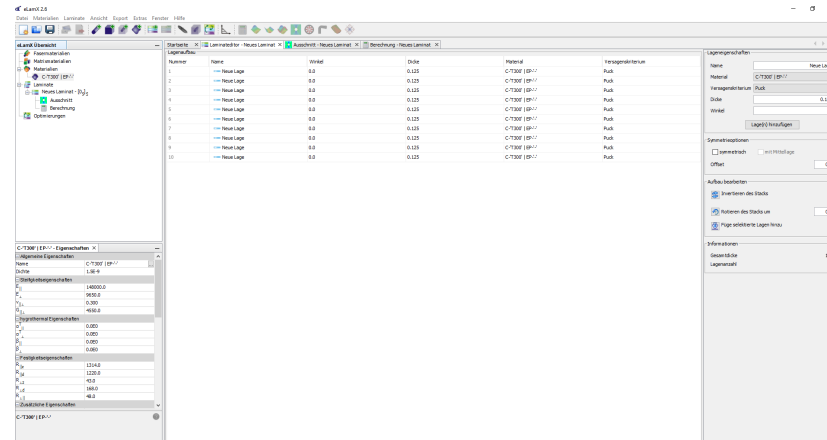
English ▾

# Welcome!

Second please install elamx from:

<https://tu-dresden.de/ing/maschinenwesen/ilr/lft/elamx2/elamx>

We will use it as a small tool to show the design workflow and to solve some small examples



# Composites Technology

## Load Introductions in Preliminary Design



**Prof. Christian Brauner, Institute of Polymer Engineering**

## About myself

**FH Bielefeld**

Mechanical Engineering



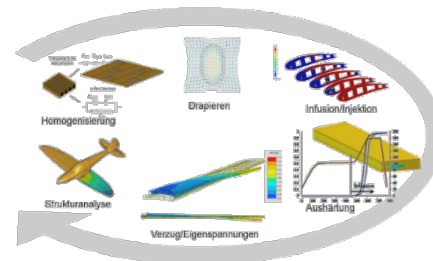
Manufacturing and design



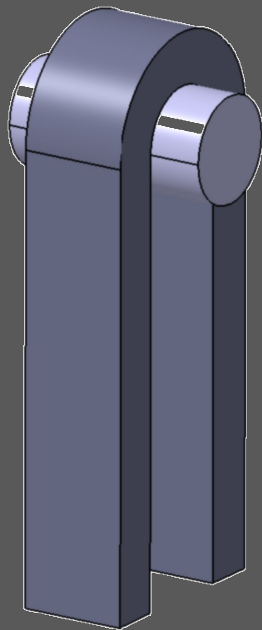
Software Engineering



Since 2016  
Institute of Polymer Engineering



## PIN LOADED STRAP



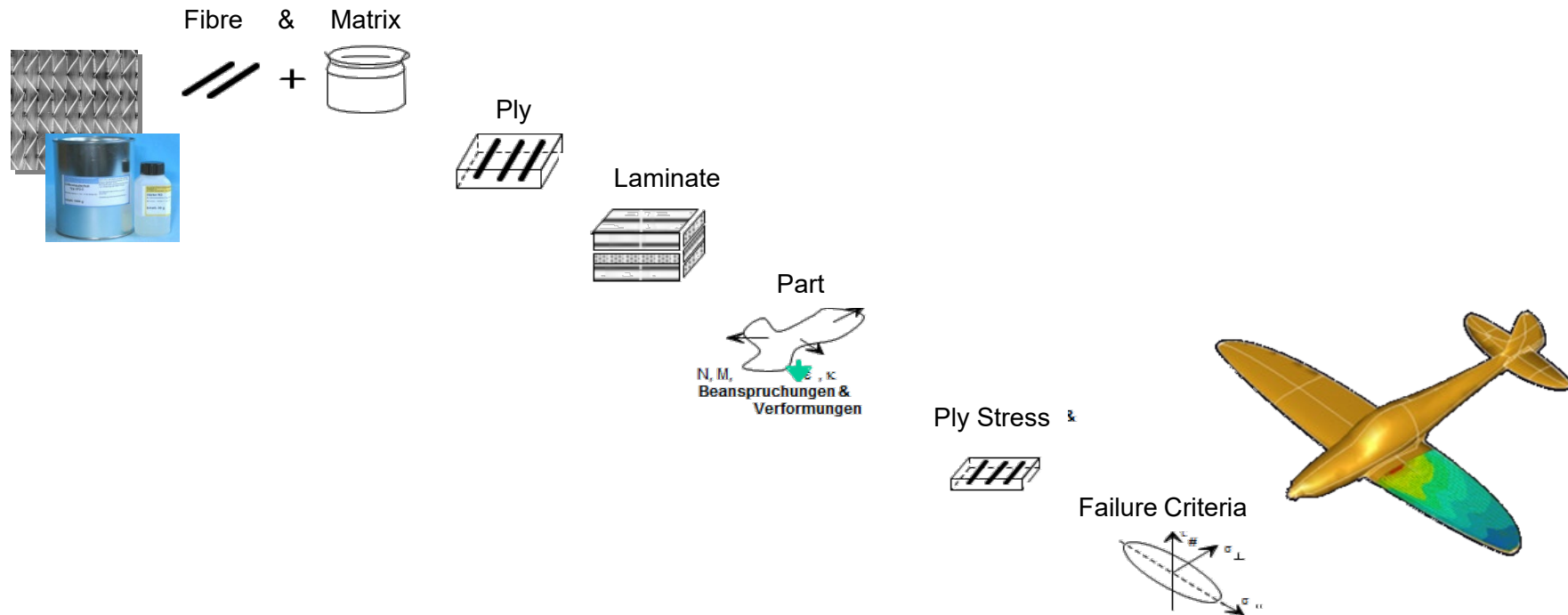
## BOLTED JOINT



## BONDED JOINT



## General introduction into stress analysis of composite



## Active unit : short introduction to elamx:

Please open elamx

Start with database material like T300

Add 10 layers,  $t=0.125$

Add a “Berechnung” to check ABD matrix

Check “Polardiagram”

Check “Ingenieurskonstanten”

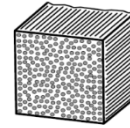
Check “Versagenskörper”

# Process of stress analysis in a composite laminate: 12 steps

1. Basic material properties

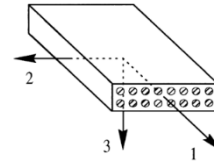
Fibre, Matrix

$$E_F, \nu_F, E_M, \nu_M, \nu_F$$



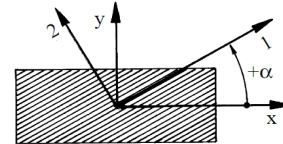
$$E_1, \nu_{12}, \nu_{21}, E_2, G_{12}$$

2. Elastic constants of the UD ply



$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{Bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix} \begin{Bmatrix} \epsilon_1 \\ \epsilon_2 \\ \gamma_{12} \end{Bmatrix}$$

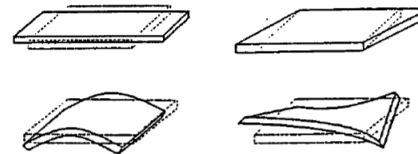
3. Stiffness of the UD plies related to the local ply coordinate system



$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} = \begin{bmatrix} \bar{Q}_{11} & \bar{Q}_{12} & \bar{Q}_{16} \\ \bar{Q}_{12} & \bar{Q}_{22} & \bar{Q}_{26} \\ \bar{Q}_{16} & \bar{Q}_{26} & \bar{Q}_{66} \end{bmatrix} \begin{Bmatrix} \epsilon_x \\ \epsilon_y \\ \gamma_{xy} \end{Bmatrix}$$

4. Transformed stiffness of the UD plies related to the global xy coordinate system

5. Calculate A, B and D terms per ply and summation



$$A_{ij} = \sum_{k=1}^n \bar{Q}_{ij,k} \cdot t_k$$

$$B_{ij} = \sum_{k=1}^n \bar{Q}_{ij,k} \cdot t_k \cdot \left( z_k - \frac{t_k}{2} \right)$$

$$D_{ij} = \sum_{k=1}^n \bar{Q}_{ij,k} \cdot \left( \frac{t_k^3}{12} + t_k \cdot \left( z_k - \frac{t_k}{2} \right)^2 \right)$$

## Process of stress analysis in a composite laminate: 12 steps

6. Assembly of the ABD Matrix,

$$\begin{Bmatrix} N \\ - \\ M \end{Bmatrix}_{xy} = \begin{bmatrix} A & | & B \\ - & | & - \\ B & | & D \end{bmatrix} \begin{Bmatrix} \epsilon^o \\ - \\ \kappa \end{Bmatrix}_{xy}$$

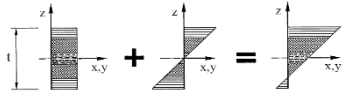
7. Analyse load case and calculate force and moment flux

$$N_x = \int_{-h/2}^{h/2} \sigma_x dz ; N_y = \int_{-h/2}^{h/2} \sigma_y dz ; N_{xy} = \int_{-h/2}^{h/2} \tau_{xy} dz$$

8. If loads known compute the inverse ABD tensor = compliance tensor of the laminate

$$M_x = \int_{-h/2}^{h/2} \sigma_x z dz ; M_y = \int_{-h/2}^{h/2} \sigma_y z dz ; M_{xy} = \int_{-h/2}^{h/2} \tau_{xy} z dz$$

9. Calculate strain and curvature of the laminate and thereby of all UD plies related to the global xy coordinate system

$$\begin{Bmatrix} \epsilon_x \\ \epsilon_y \\ \gamma_{xy} \end{Bmatrix}_k = \begin{Bmatrix} \epsilon_x \\ \epsilon_y \\ \gamma_{xy} \end{Bmatrix}_0 + z_k \begin{Bmatrix} \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{Bmatrix}_0$$


10. Transform lamina strain back into ply coordinate system

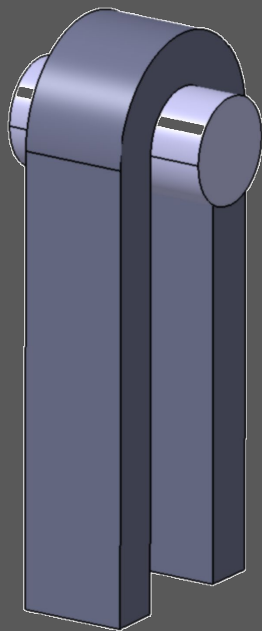
$$\begin{Bmatrix} \epsilon_1 \\ \epsilon_2 \\ \gamma_{12} \end{Bmatrix} = [T]^T \cdot \begin{Bmatrix} \epsilon_x \\ \epsilon_y \\ \gamma_{xy} \end{Bmatrix} = \begin{bmatrix} \cos^2 \psi & \sin^2 \psi & \sin \psi \cos \psi \\ \sin^2 \psi & \cos^2 \psi & -\sin \psi \cos \psi \\ -2 \sin \psi \cos \psi & 2 \sin \psi \cos \psi & \cos^2 \psi - \sin^2 \psi \end{bmatrix} \cdot \begin{Bmatrix} \epsilon_x \\ \epsilon_y \\ \gamma_{xy} \end{Bmatrix}$$

11. Stress in the single UD plies related to the local ply coordinate system

$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{Bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix} \begin{Bmatrix} \epsilon_1 \\ \epsilon_2 \\ \gamma_{12} \end{Bmatrix}$$

12. Use failure criteria to evaluate failure (not shown here)

## PIN LOADED STRAP



## BOLTED JOINT



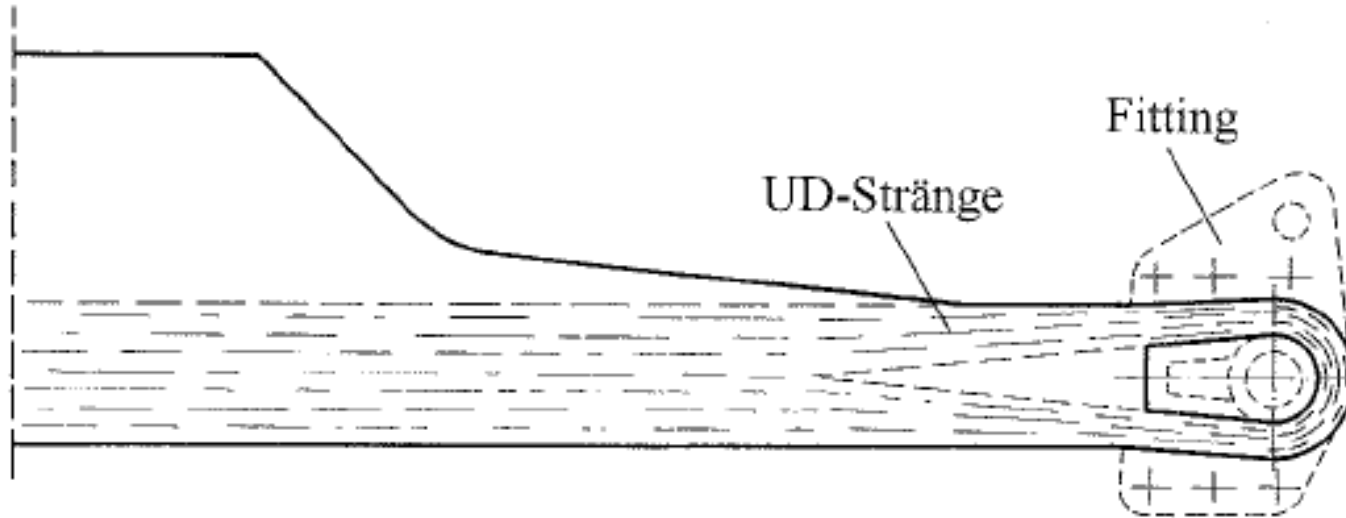
## BONDED JOINT



# Objective – to understand

- **Concept**
- **Manufacturing challenges**
- **Sizing**
- **Design integration**

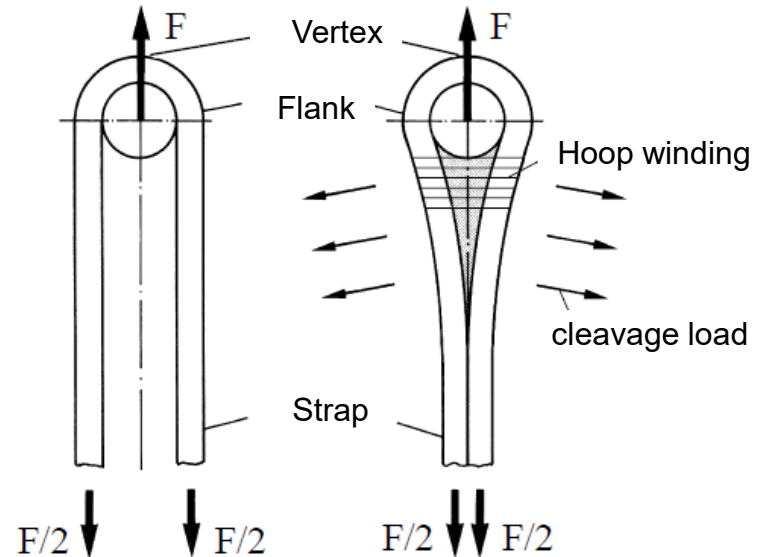
## Pin loaded strap



# A composite pin loaded strap in a nutshell

- Uses unidirectional carbon fibres in a polymer matrix
- Fibres are aligned along the load path

	Unidirectional CFRP	Steel
Strength [MPa]	2000	600
Density [kg/m <sup>3</sup> ]	1560	7850
Spec. strength [kNm/kg]	1282	76



[Schürmann]

# Applications

## CFRP holdings bars

- **Lightweight: easy to assemble**
- **Lightweight: up to 50% higher lifting loads with longer reach**
- **non-corrosive**



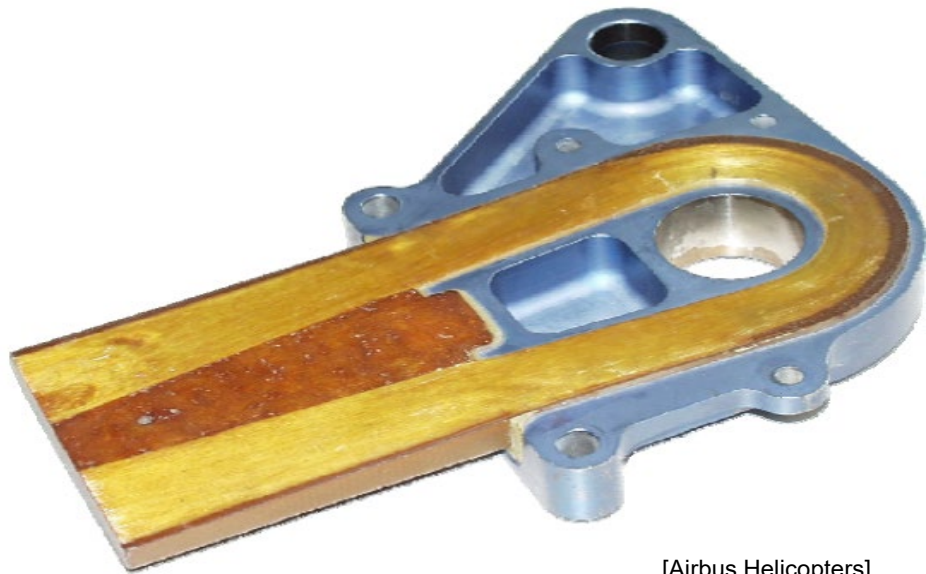
## CFRP holding bars

- Connected by pin loaded straps and coupling plates
- Suppression of vortex shedding vibration by helical strakes



# Applications

## BO105 Rotorcraft blade attachment



[Airbus Helicopters]



[flyingbulls.at]



[flyingbulls.at]

# Applications

## Composite Connecting Rod

- Axial load transfer by pre-stressed structure
- Reduced oscillating mass

Jaguar 4.2L straight six cylinder engine



[Dransfeld 1990]

# Applications

## Bike wheel

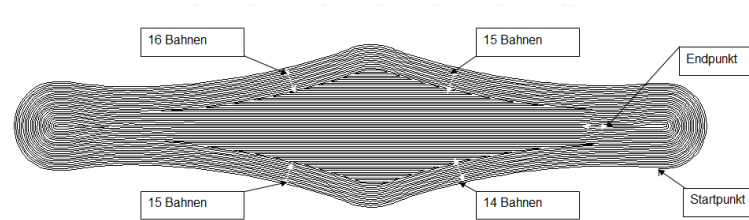
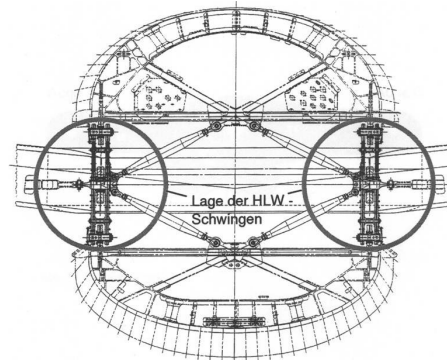
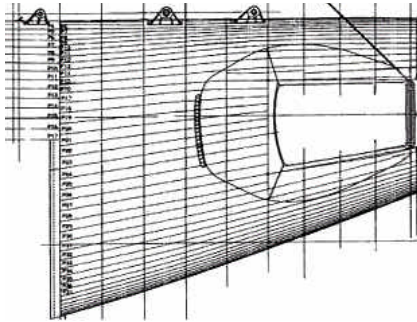


**Radiate Engineering**

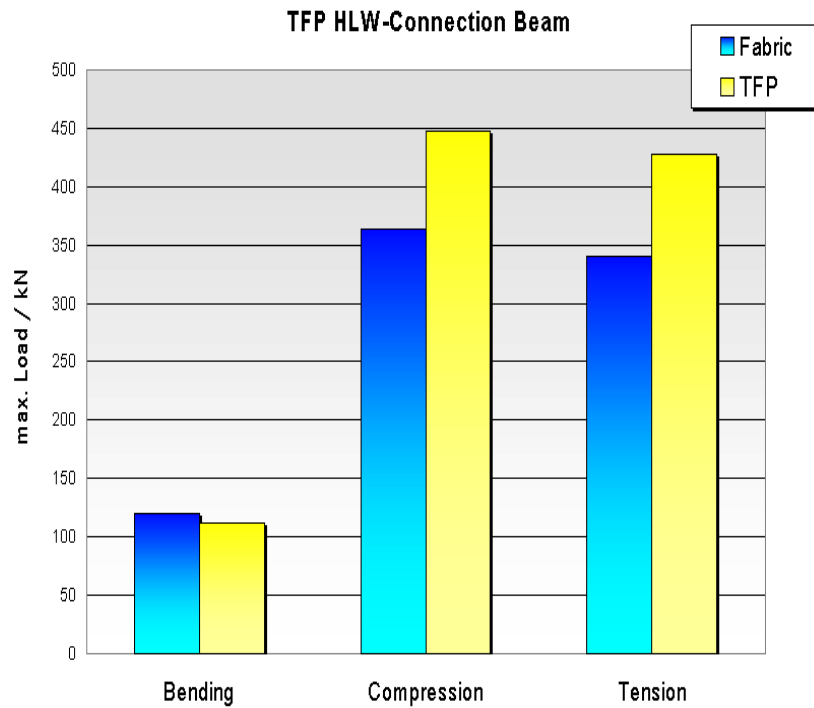


**Lightweight - CarbonSports GmbH**

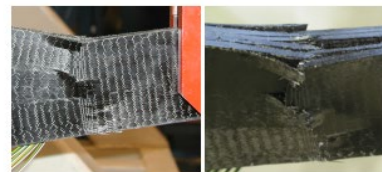
# Applications



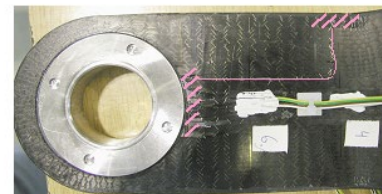
# Applications



Statically load test



Bending

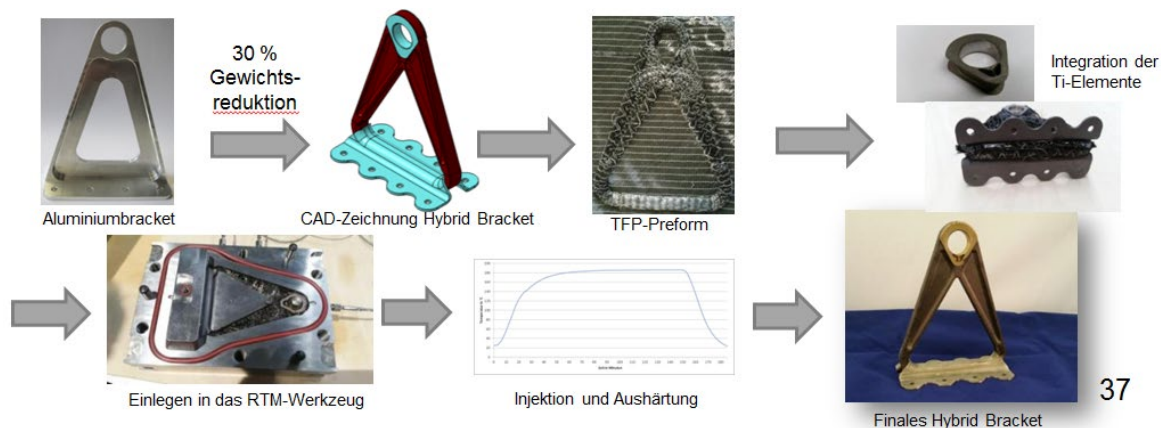
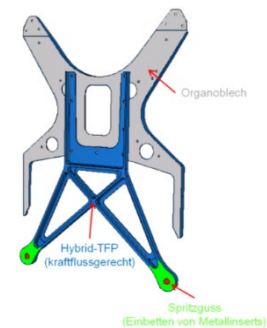
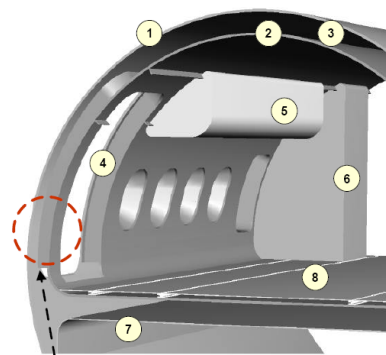


Compression



Tension

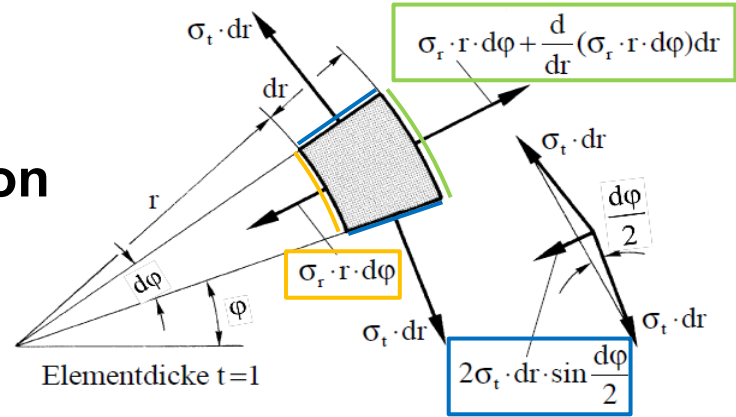
# Applications



37

# Equilibrium of forces in radial direction

## Tangential stresses create radial compression on pin



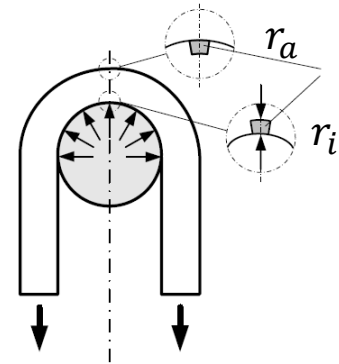
$$-\sigma_r(r \cdot d\phi) + \left[ \sigma_r(r \cdot d\phi) + \frac{d}{dr}(\sigma_r \cdot r \cdot d\phi) \cdot dr \right] - 2\sigma_t \cdot dr \cdot d\phi = 0$$

Index r = radial; Index t = tangential

$$\sigma_r(r_i) = -p_i \quad \sigma_r(r_a) = 0$$

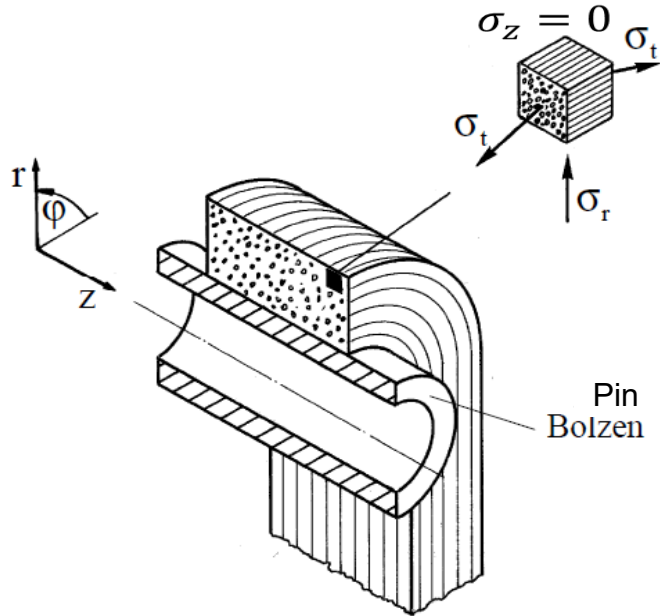
$$p_i = \frac{F}{2r_i \cdot b}$$

Radial pressure on pin corresponds to bearing stress



[Schürmann]

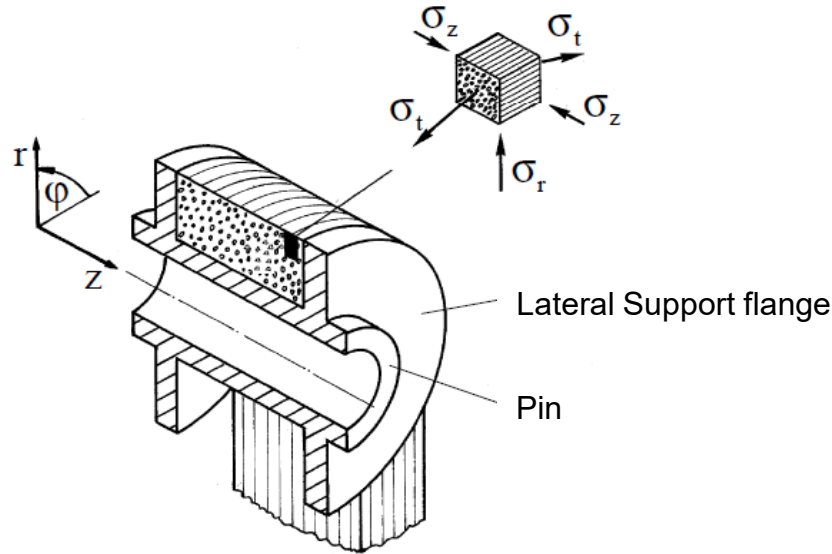
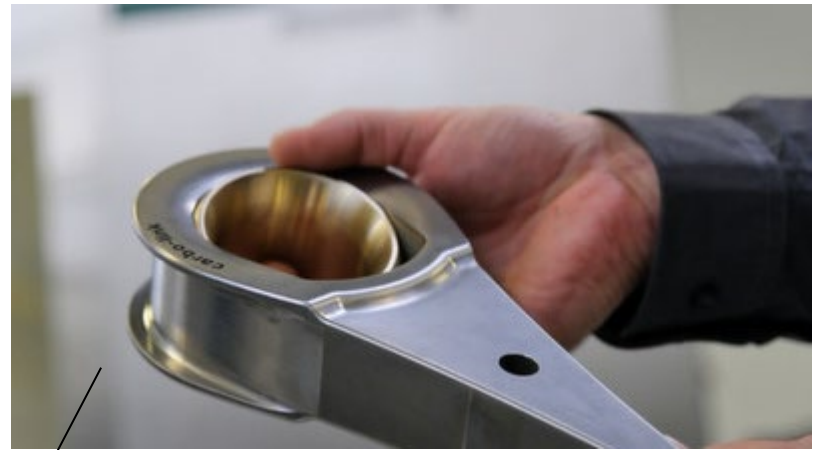
## Strains in unsupported pin loaded strap



$$\begin{aligned}\varepsilon_r &= \frac{\sigma_r}{E_{\perp}} - \nu_{\perp\parallel} \frac{\sigma_t}{E_{\parallel}} \\ \varepsilon_t &= \frac{\sigma_t}{E_{\parallel}} - \nu_{\parallel\perp} \frac{\sigma_r}{E_{\perp}} \\ \varepsilon_z &= -\nu_{\perp\perp} \frac{\sigma_r}{E_{\perp}} - \nu_{\perp\parallel} \frac{\sigma_t}{E_{\parallel}}\end{aligned}$$

[Schürmann]

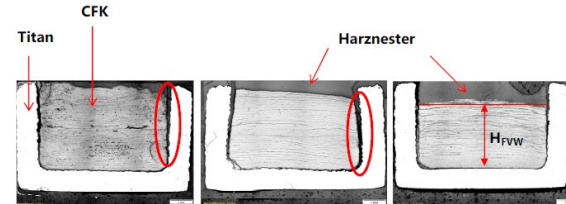
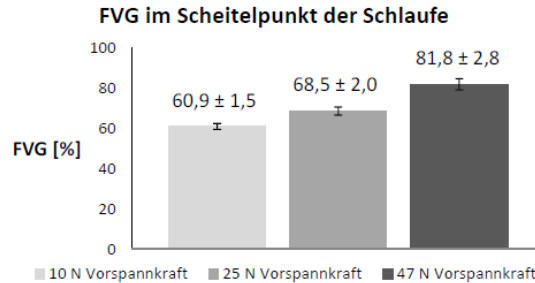
## Strains in supported pin loaded strap



$$\begin{aligned}\varepsilon_r &= \frac{\sigma_r}{E_{\perp}} - \nu_{\perp\parallel} \frac{\sigma_t}{E_{\parallel}} - \nu_{\perp\perp} \frac{\sigma_z}{E_{\perp}} \\ \varepsilon_t &= \frac{\sigma_t}{E_{\parallel}} - \nu_{\parallel\perp} \frac{\sigma_z}{E_{\perp}} - \nu_{\parallel\perp} \frac{\sigma_r}{E_{\perp}} \\ 0 &= \frac{\sigma_z}{E_{\perp}} - \nu_{\perp\parallel} \frac{\sigma_r}{E_{\perp}} - \nu_{\perp\parallel} \frac{\sigma_t}{E_{\parallel}}\end{aligned}$$

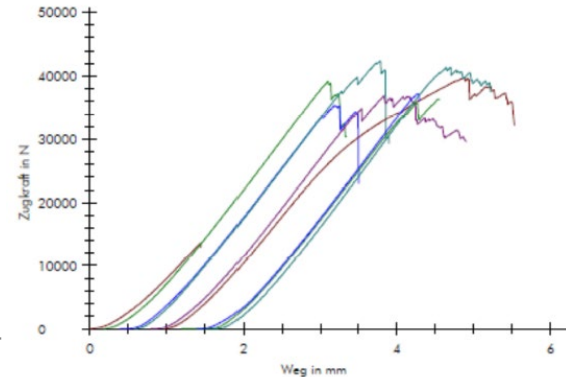
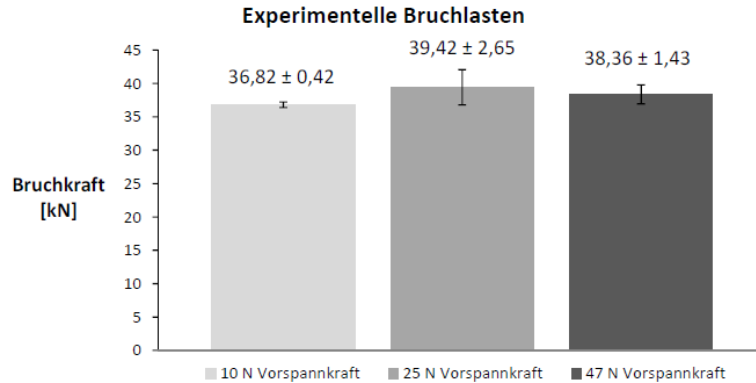
[Schürmann]

## Strap example



**Fibre volume content variation based on different pre load configurations**

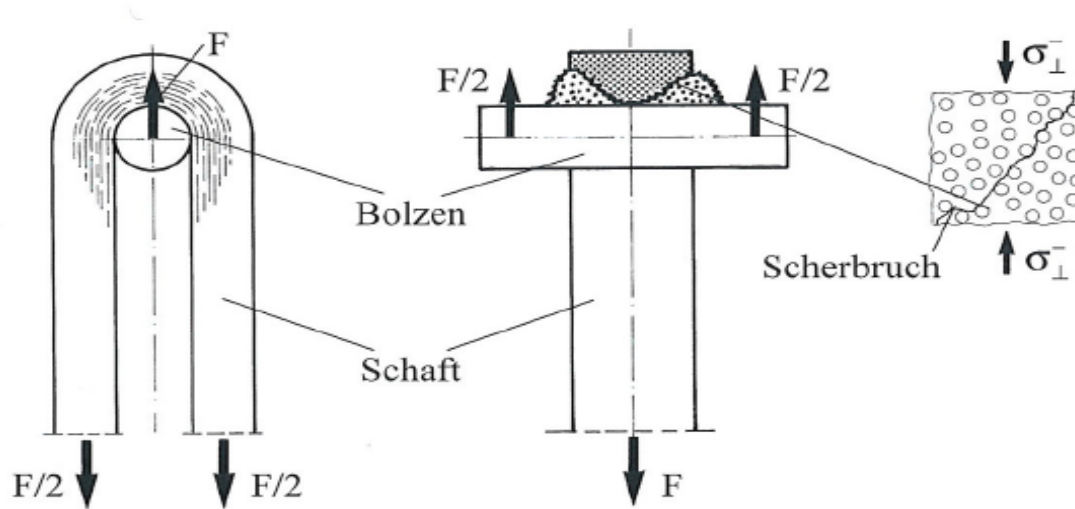
## Strap example



**Failure load variation based on different pre load configurations**

## Failure of pin loaded straps

Failure dominated by radial stresses  
(and shear stresses – not part of analytical solution)



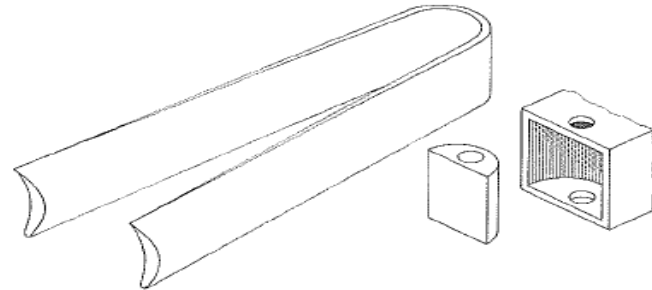
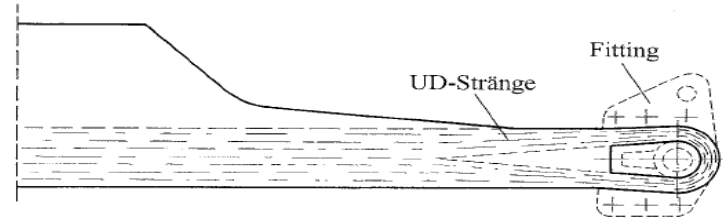
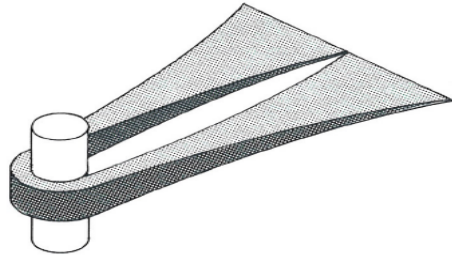
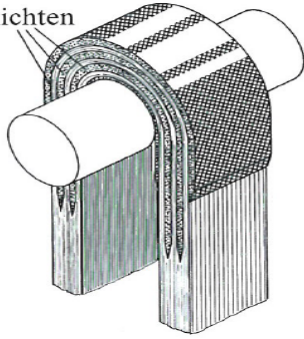
Puck mode C

[Schürmann]

[Schürmann]

## Design integration

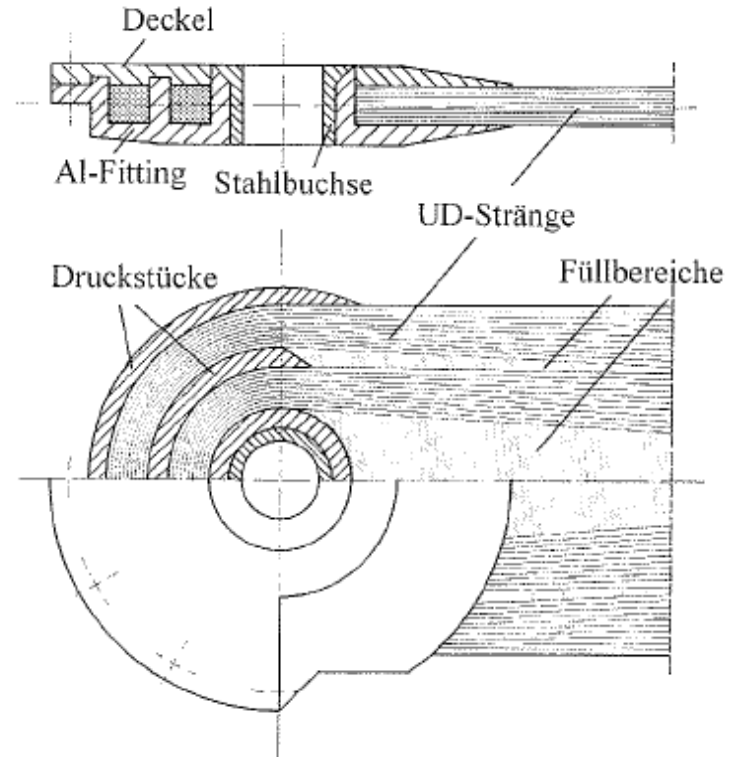
Eingefütterte  
Gewebeschichten



[Schürmann]

## Design variations

- Reduces  $r_a/r_i$  by subdivision
- Also transmits compression
- Suitable for wing root attachments



[Schürmann]

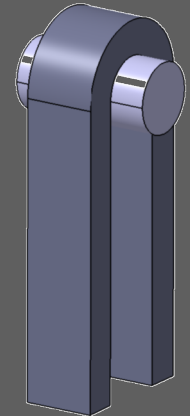
## Questions on pin loaded strap

What is the primary failure mode of a pin loaded strap?

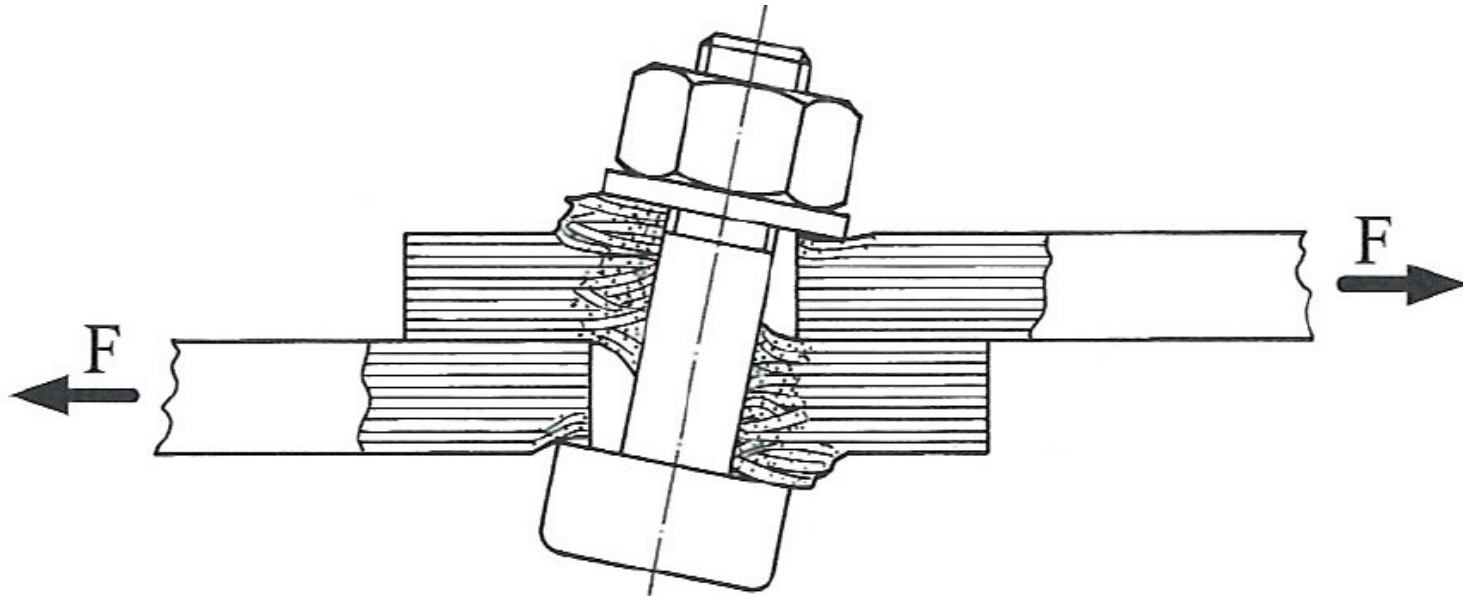
- a. Coaxial bifurcation
- b. Bearing failure due to radial compressive stresses
- c. Fiber tensile failure

In a unsupported pin loaded strap

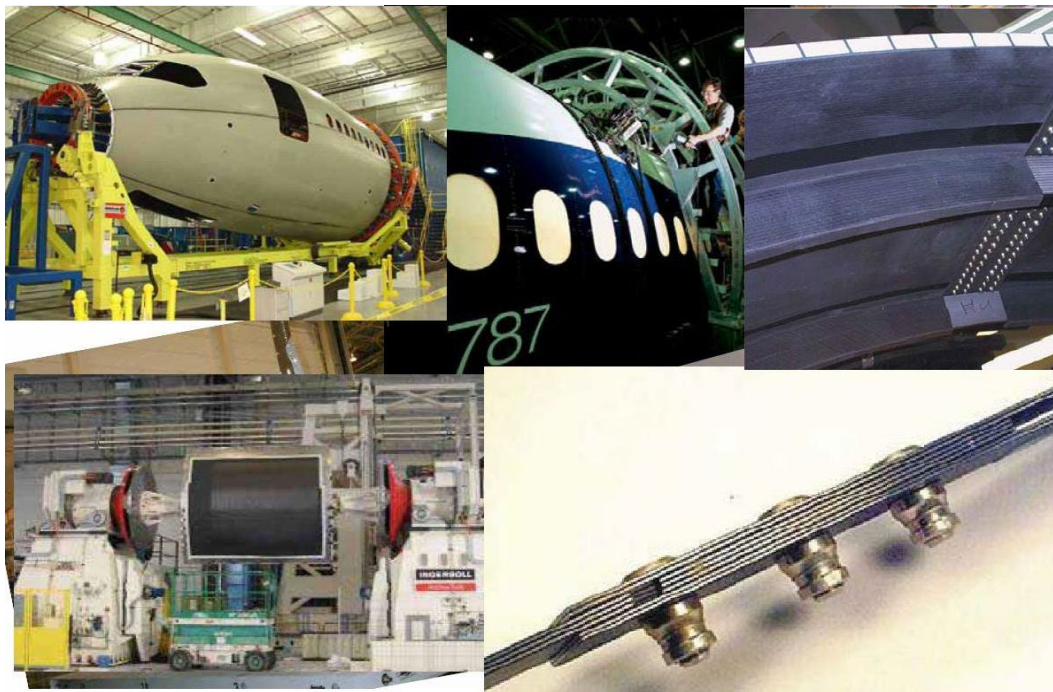
- a. Stresses in bolt axis  $\neq 0$
- b. Stresses in bolt axis  $= 0$
- c. Failure load is higher than in a supported configuration



## Bolted joints



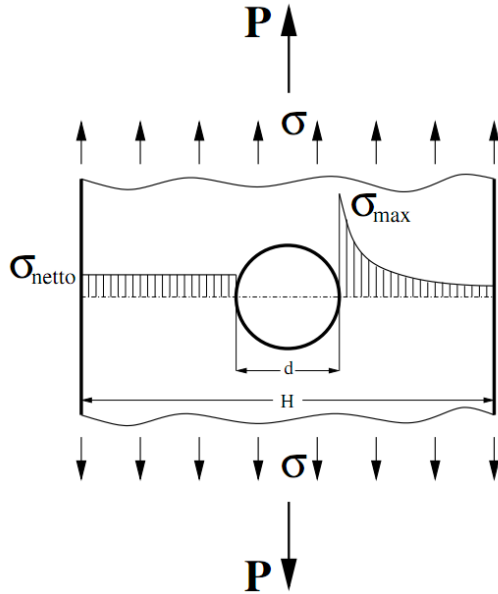
## Bolted joints in aviation



## Why bolted joint

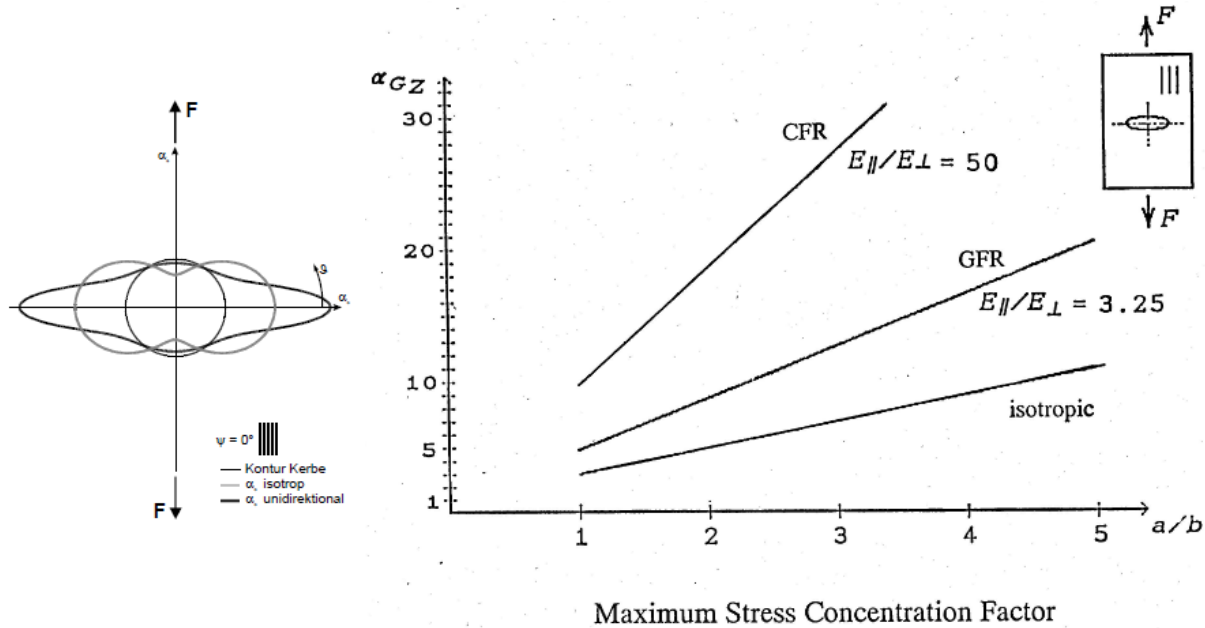
- Strap: localised oriented loads.
- **Bolts: high distributed loads.**
- Bonded joints: low distributed loads.

## Principles of stress distribution around holes in composites

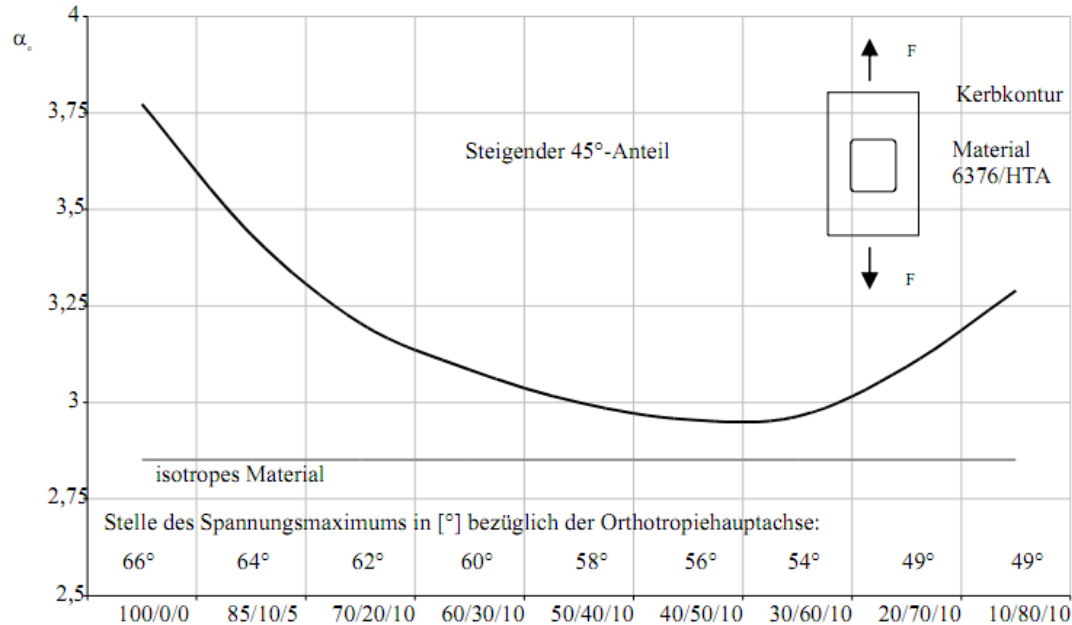


**Difference from isotropic materials to composites?**

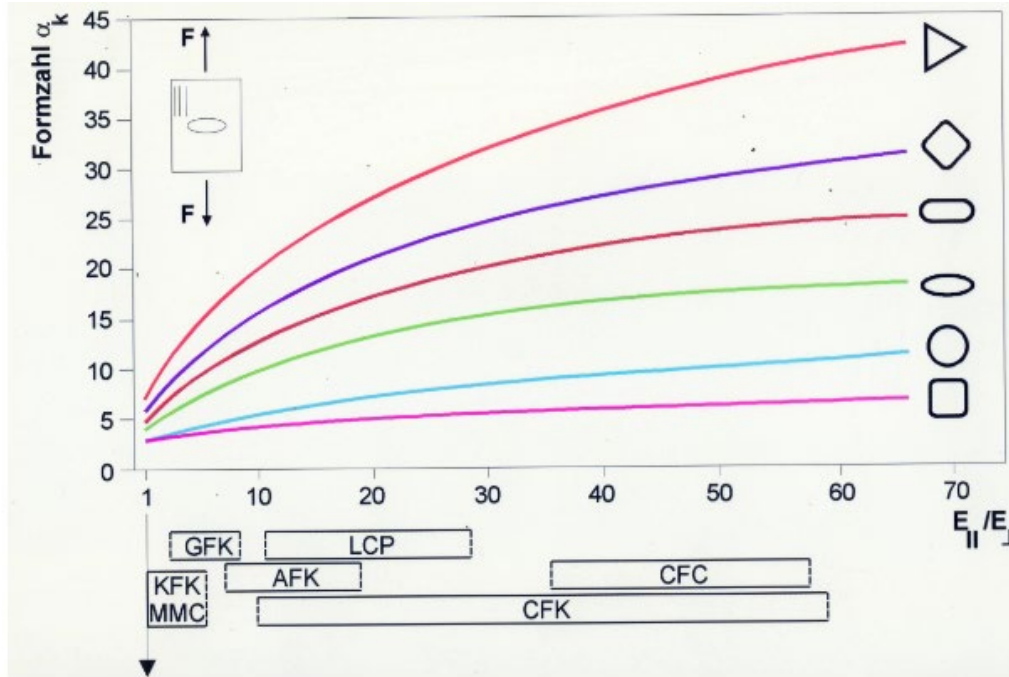
# Principles of stress distribution around holes in composites



## Principles of stress distribution around holes in composites

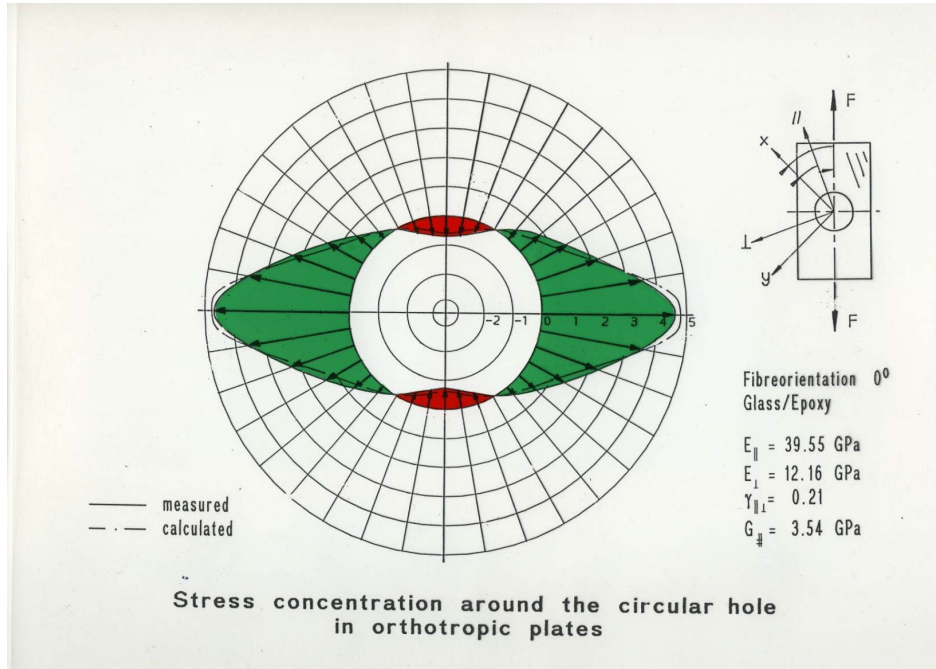


## Principles of stress distribution around holes in composites



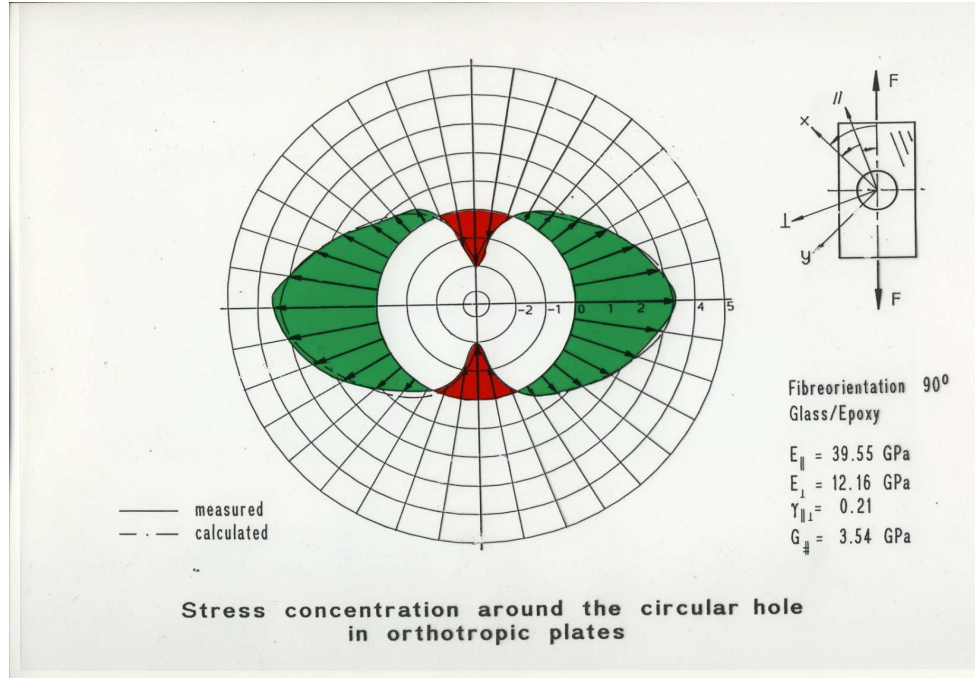
Tensile Force – Fibre direction (0°)

## Principles of stress distribution around holes in composites



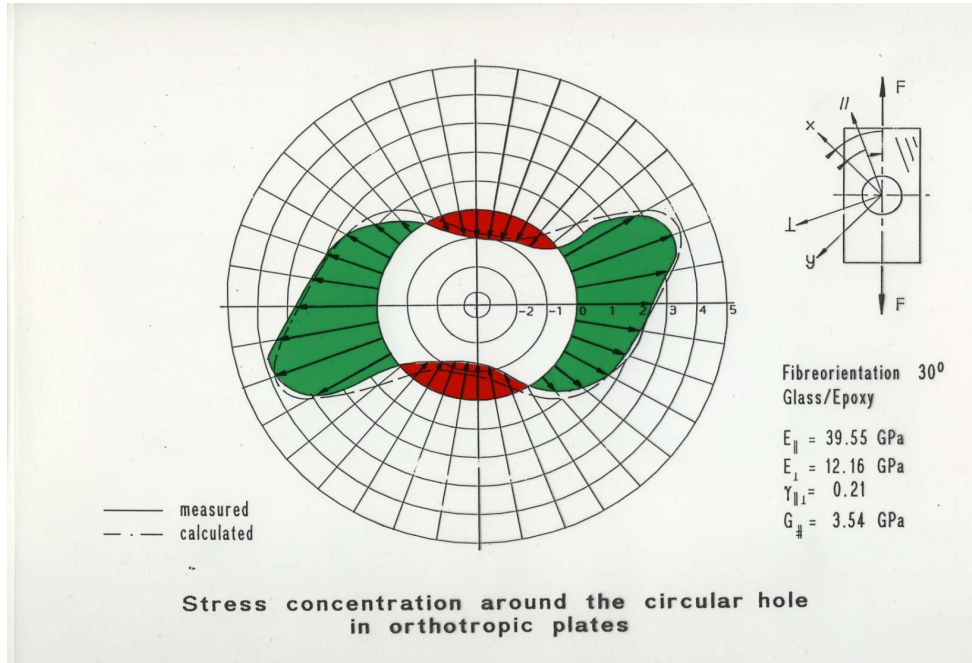
### Glas/Epoxy – Load direction( $0^\circ$ )

## Principles of stress distribution around holes in composites



### Glas/Epoxy – Load direction( $30^\circ$ )

## Principles of stress distribution around holes in composites



### Glas/Epoxy – Load direction(30°)

## Active unit stress around a holes:

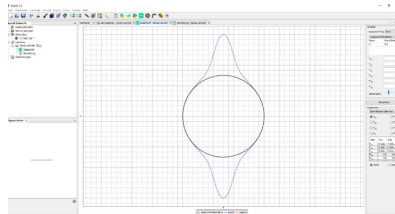
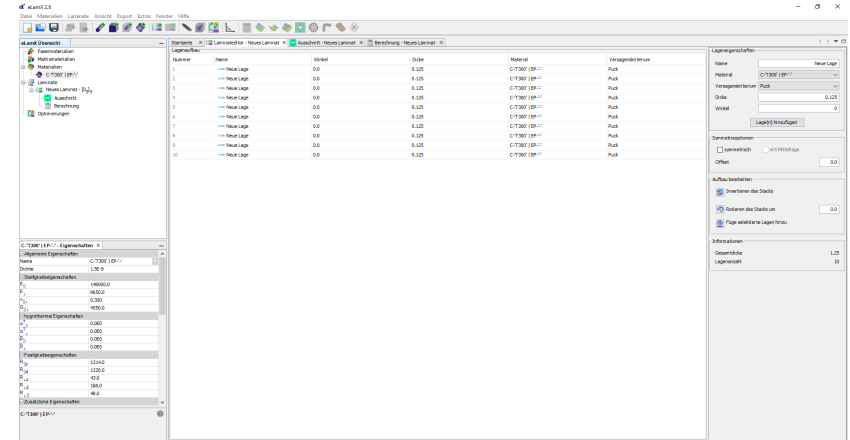
Please open elamx

Start with database material like T300

Add 10 layers,  $t=0.125$

Analyse stress around a hole,  $d=8$

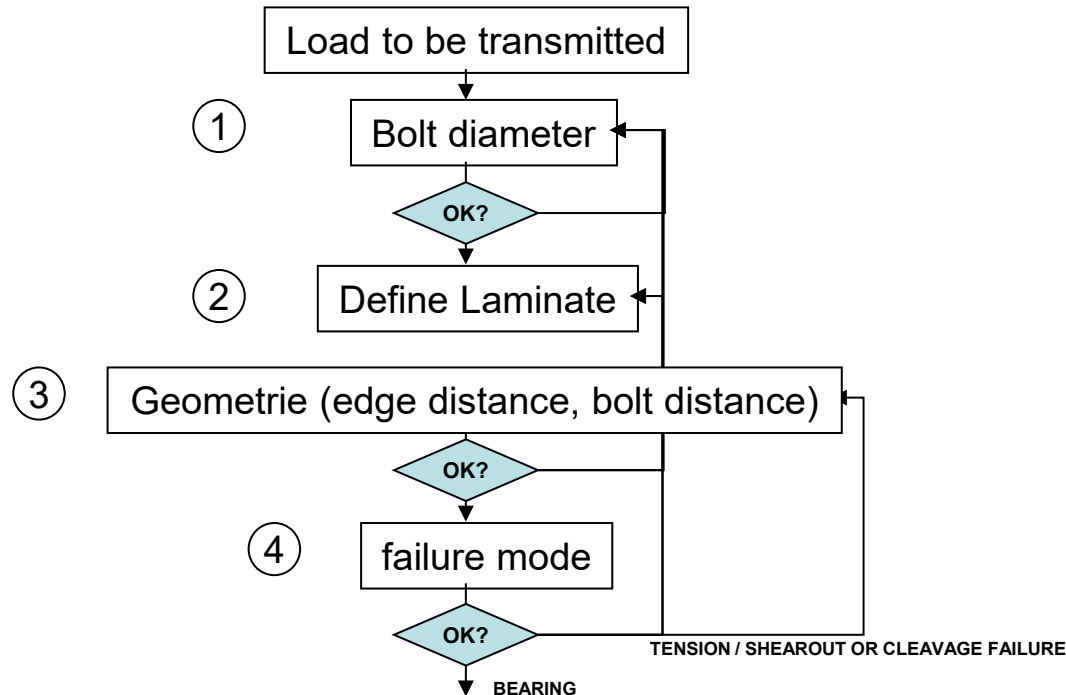
Define a load case and post your solution in  
the chat



## Advantages of bolted joints

- Joining of dissimilar materials.
- Reversible joints.
- Simple quality survey (vs. bond)
- High energy absorption possible (if designed accordingly)

## Methodology for preliminary design of bolted joint

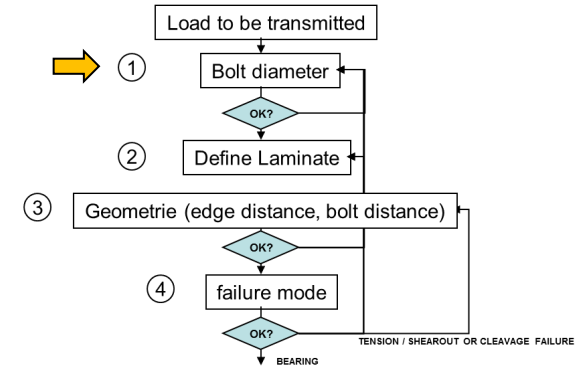


## 1 Definition of bolt diameter

- Shearing of bolt

$$F_{ult} = R_s \cdot \frac{d^2 \cdot \pi}{4} \cdot i$$

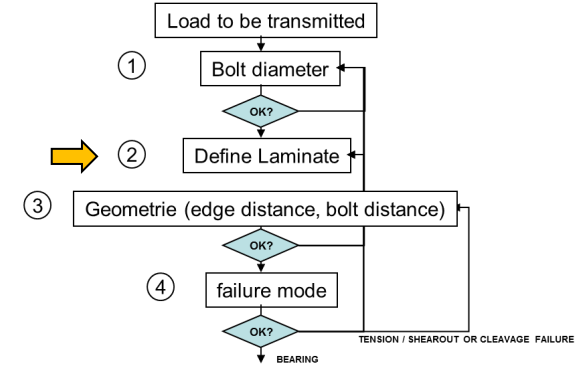
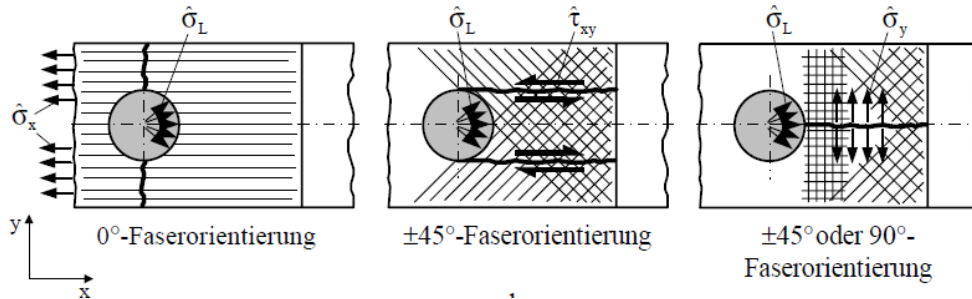
- Usually not critical as metals have higher strength than composites



## 2 Definition of laminate

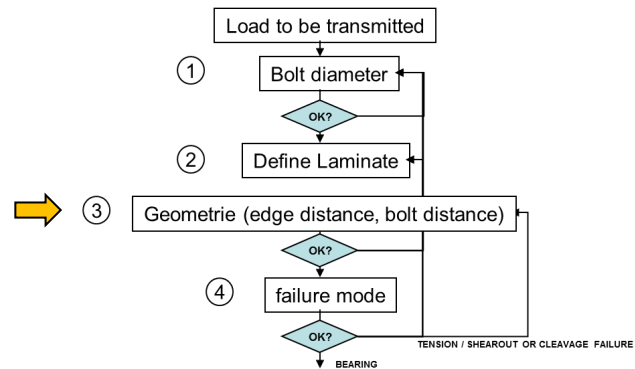
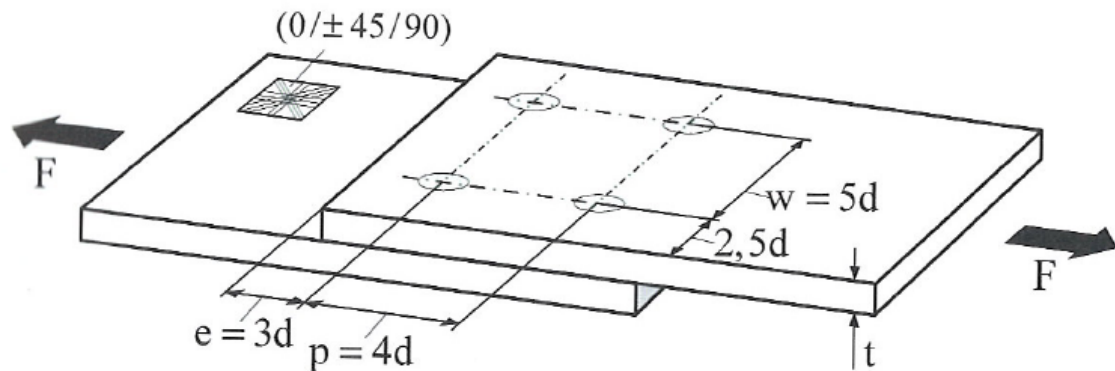
Ideal laminate in respect o load direction  $0^\circ$

- 50% in  $0^\circ$
- 40% in  $\pm 45^\circ$
- 10% in  $90^\circ$



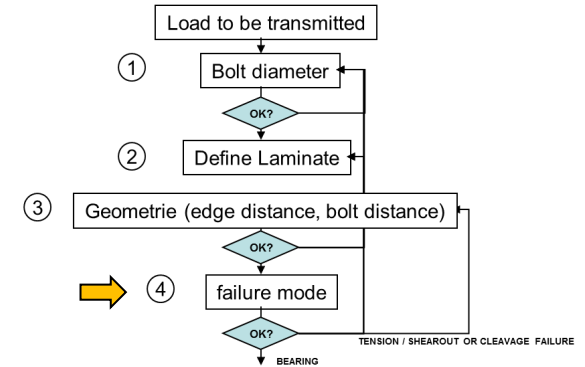
If base laminate does not fullfill this additional layer have to be interstacked

### 3 Design rules



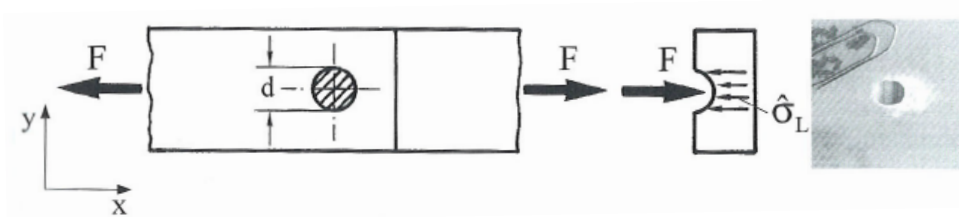
## 4 Failure modes (Schü 22.2.3 bis 22.2.7)

- Bearing failure: **tolerant failure by opening of hole**
- Tension failure: **catastrophic failure mode**
- shearout failure: **catastrophic failure mode**
- Cleavage failure: **catastrophic failure mode**
- Cleavage tension failure: **catastrophic failure mode**

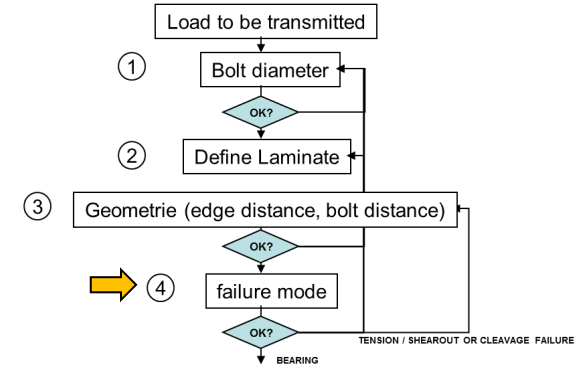
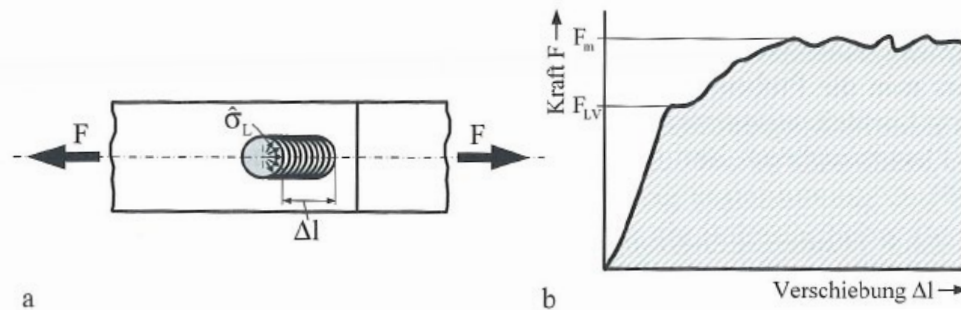


The objective is to have bearing as the dominant failure mode. All other failure modes have to be excluded.

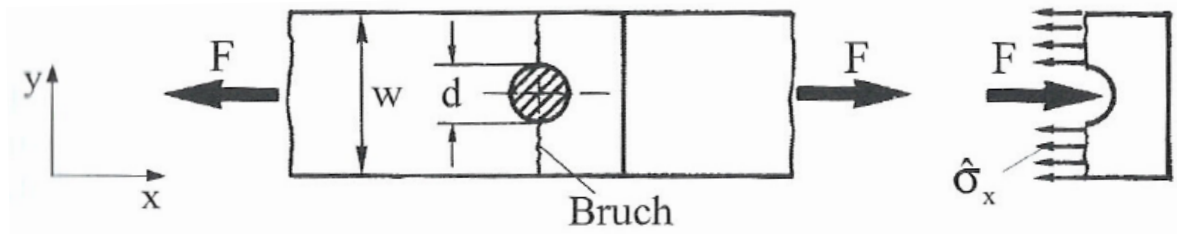
## 4 Bearing failure



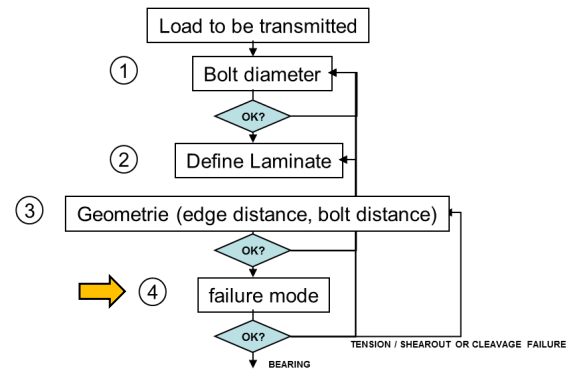
$$F_{\text{ult}} = \hat{R}_L \cdot d \cdot t$$



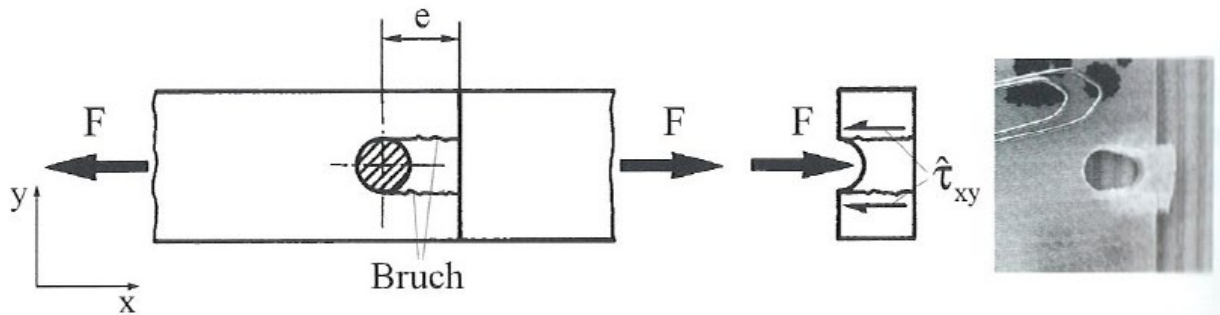
## 4 Tension failure



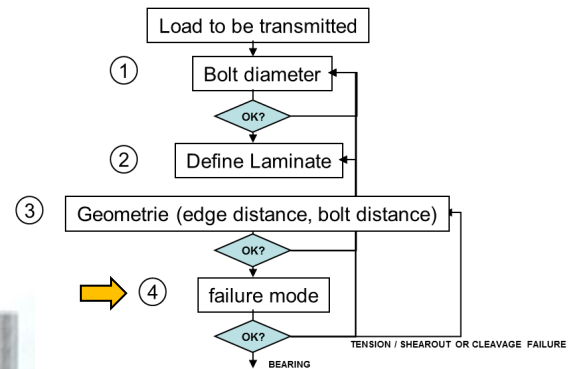
$$F_{ult} = \hat{R}_x^+ \cdot (w - d) \cdot t$$



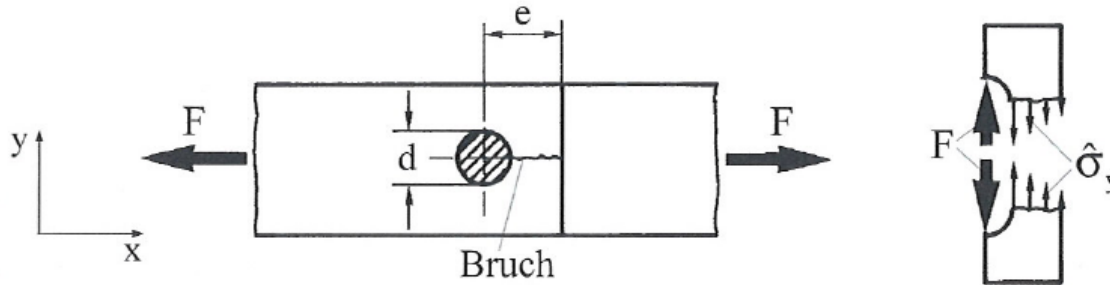
## 4 Shearout failure



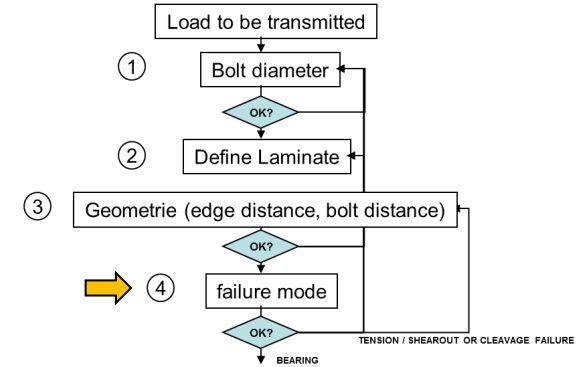
$$F_{ult} = \hat{R}_{xy} \cdot 2e \cdot t$$



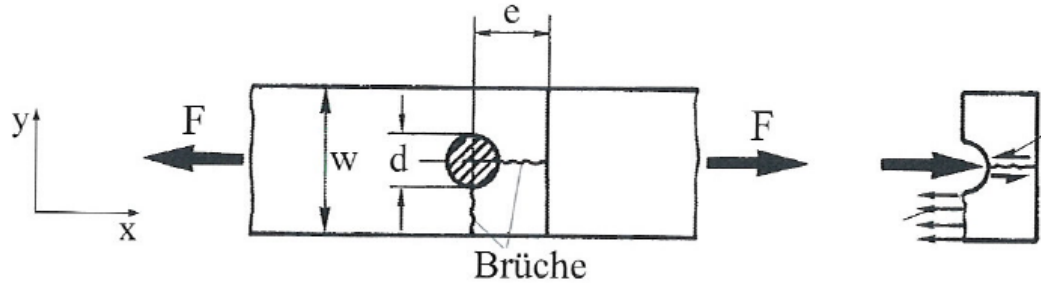
## 4 Cleavage Failure



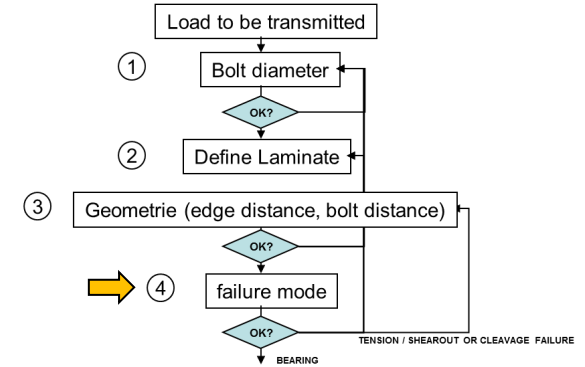
$$F_{ult} = \hat{R}_y^+ \cdot \left(e - \frac{d}{2}\right) \cdot t$$



## 4 Cleavage tension failure



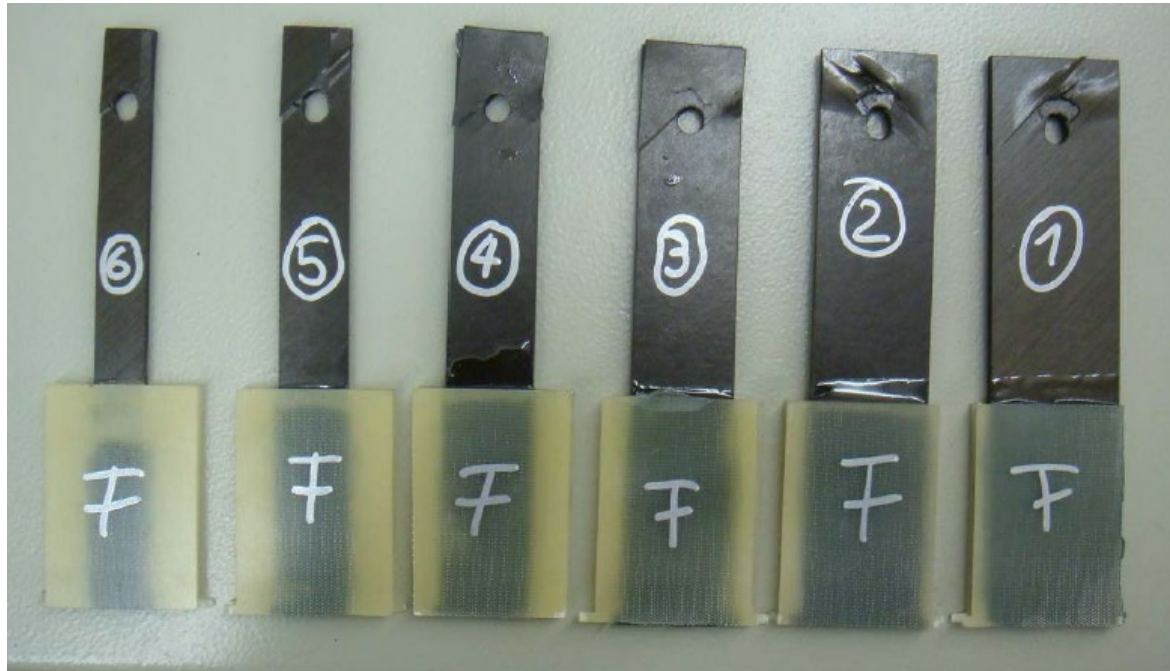
$$F_{ult} = \hat{R}_x^+ \cdot \frac{1}{2} (w - d) \cdot t + \hat{R}_{xy} \cdot \left( e - \frac{d}{2} \right) \cdot t$$



## Test series cleavage vs. bearing

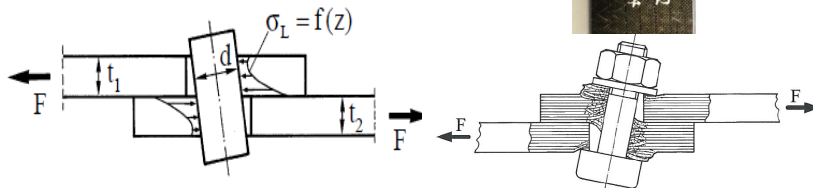


## Test series tensile vs. bearing

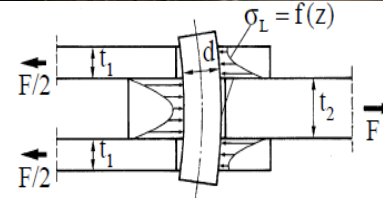


## Determination of load bearing strength: ASTM Standard D 5961M – 08

Single lap



Double lap

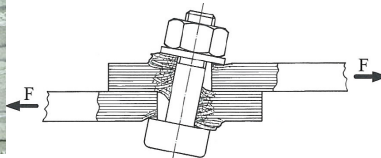


# Determination of load bearing strength: ASTM Standard D 5961M – 08

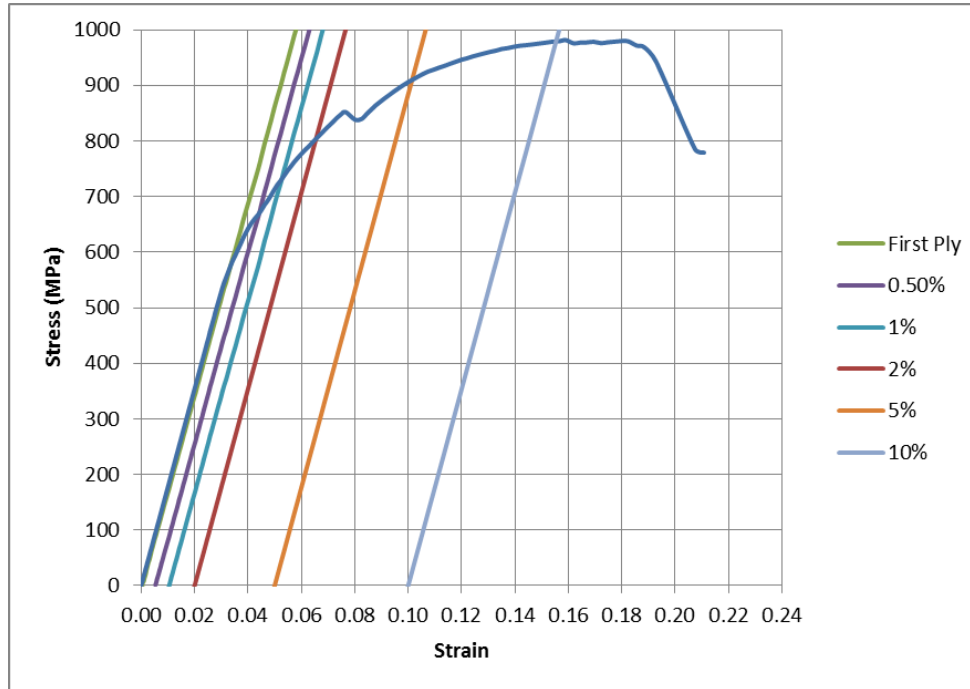
single lap



double lap



## Load displacement curves – relevant design limits



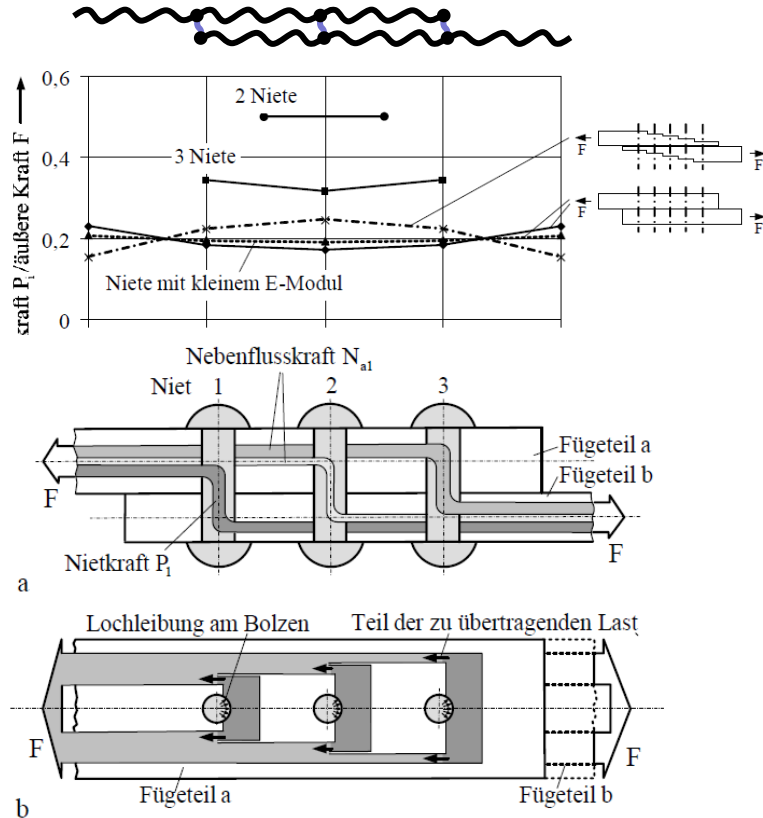
$$\hat{R}_l = \frac{F}{i * d * t}$$

## Analysis of bolts

- Two bolts: both bolts equally share load
- N bolts > 2: outer bolt carry more load
- Stepping specimen thickness may inverse this trend
- Bolt loads allow the determination of tensile load  $N_{aj}$  on bolt whole

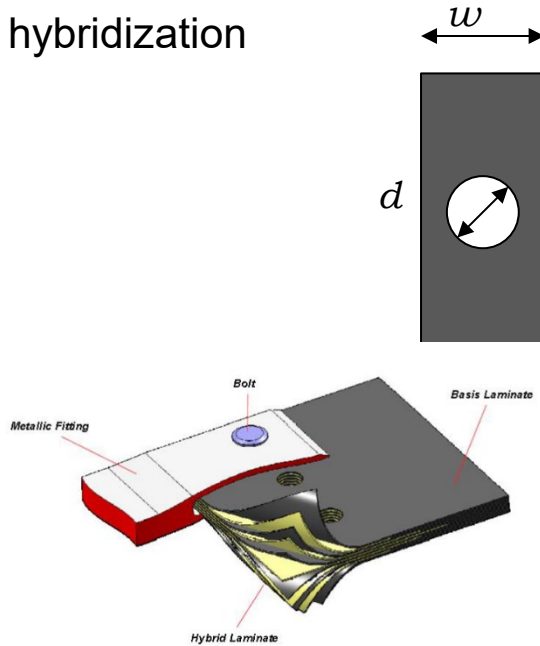
$$F = N_{aj} + \sum_{i=1}^j P_i$$

- Bolt hole is loaded in tensile load + bearing load

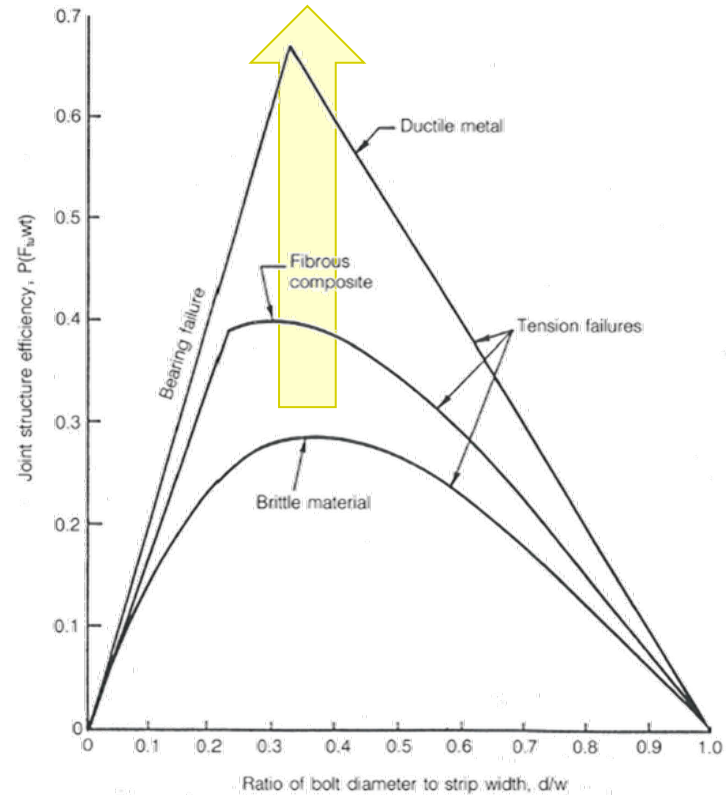


## The joint efficiency challenge

### Metal foil hybridization

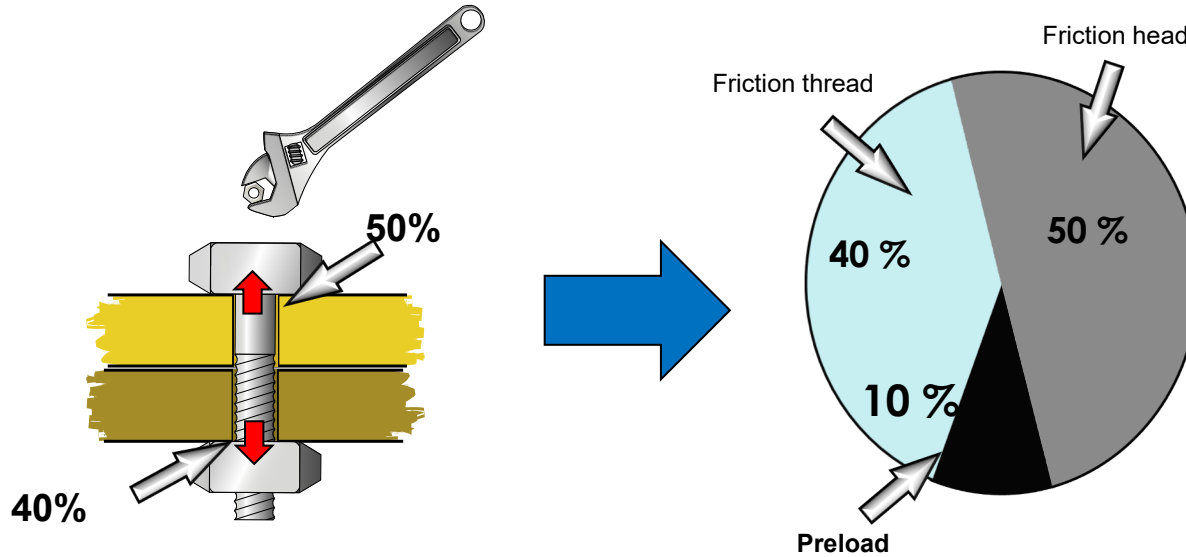


Source: DLR



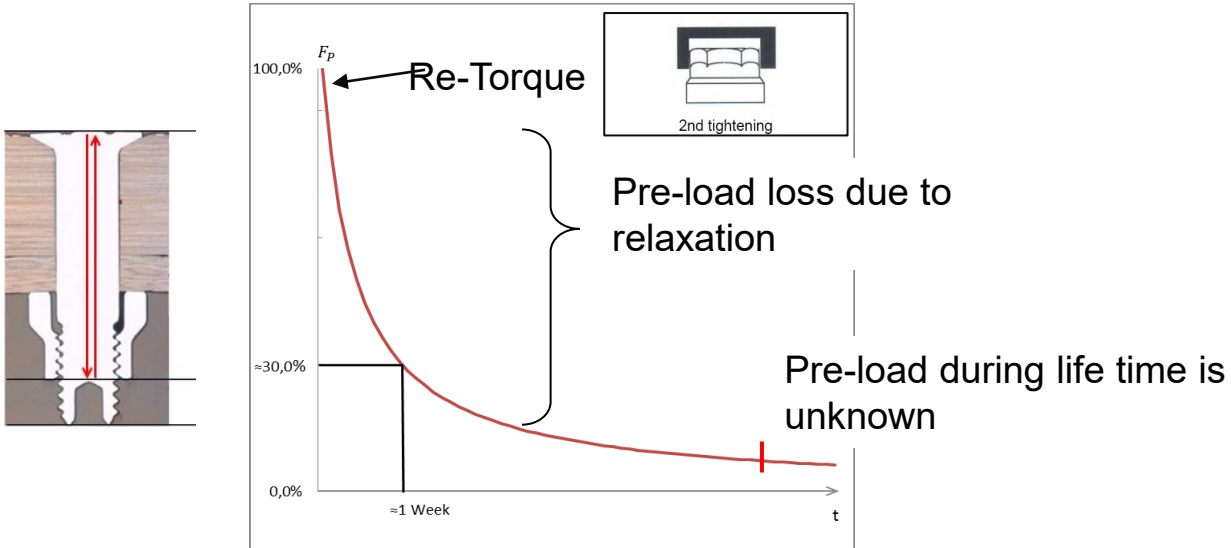
Source: Niu

## Preload in bolted joints



Source: DLR

## Preload in bolted joints

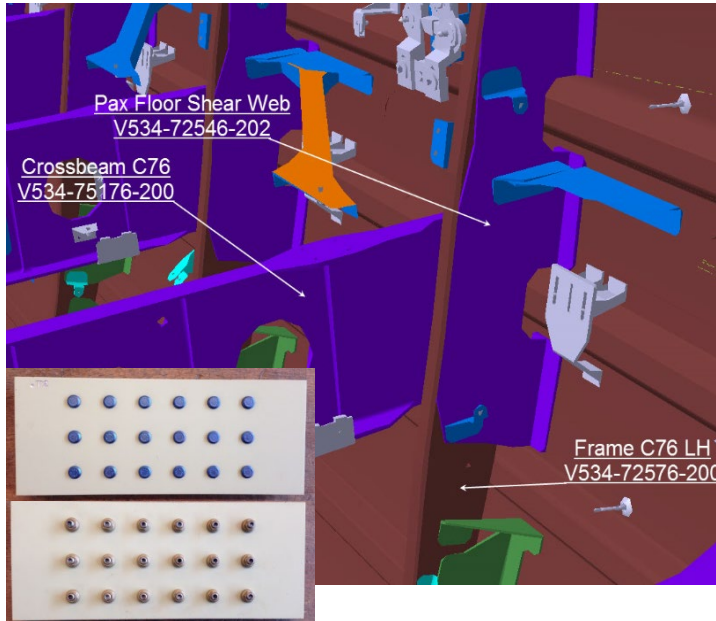


Source: Unkenbold, Prof. Dr.-Ing. Wilm. Hybrid Structures (HYS) Part 1 Adhesive Joints and Boltings. 2014.

Source: DLR

## Preload in bolted joints

### A350XWB Querträger/ Spant Verbindung



### Materialien

#### **Metall Frame:**

Aluminium Legierung 2099/2196  
Zustand: T83 and T8511

#### **Composite Frame:**

IMA-M21e  
Matrix: M21e (Duroplast)  
Faser: IMA carbon fiber  
Faserflächengewicht: 134g/m<sup>2</sup>  
Faserhalbzeug: UD-Tape (Prepreg)  
Harzgehalt (% Gewicht): 34 %

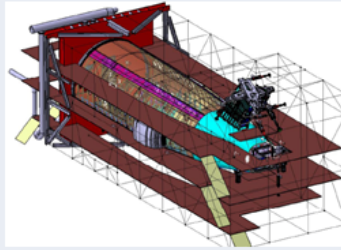

#### **PAX Shear Web**

Aluminium Legierung 7010/7050  
Zustand: T7451

#### **Bolted Joint:**

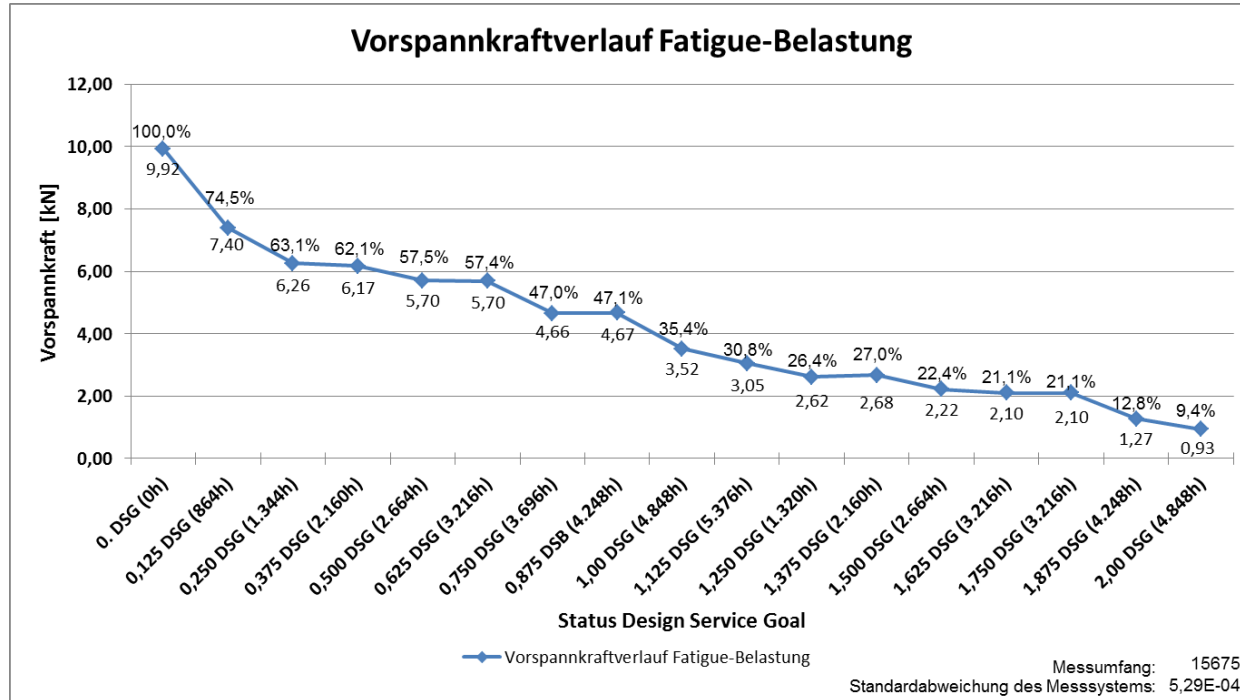
Niet: EN6115B4E08 Collar: ABS1738K  
Ti6Al4V

## Preload in bolted joints

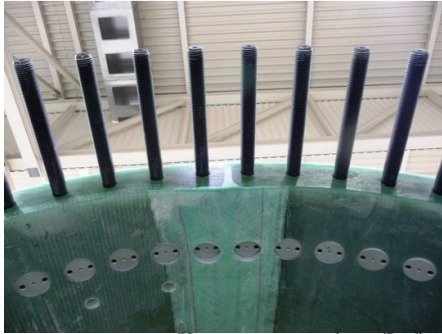
	1	2
Umgebung	A350XWB Full Scale Fatigue Test – EF3	A350XWB Strukturmontage Hamburg
Darstellung		
Ziel:	Messungen in 0,125 DS <sup>G</sup> * Schritten → Einfluss der Fatigue Belastung auf die Vorspannkraft	Messungen nach der Installation → erzielte Vorspannkraft (Retorque-Einfluss)

\*DSG = Design Service Goal = Flugzeugleben (28800 Flüge)

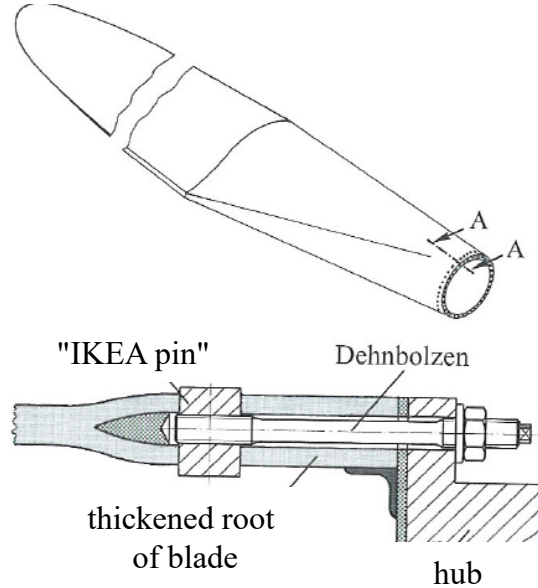
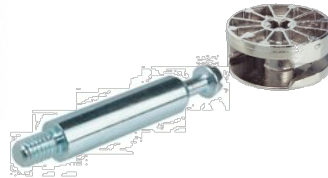
## Preload in bolted joints



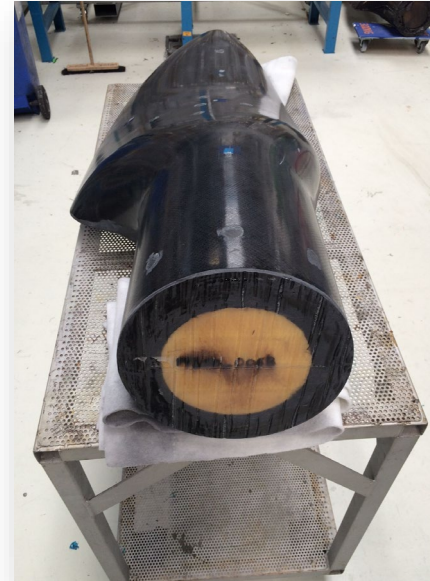
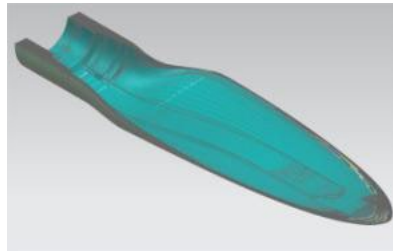
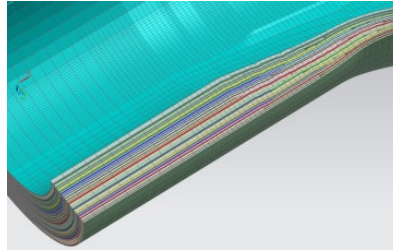
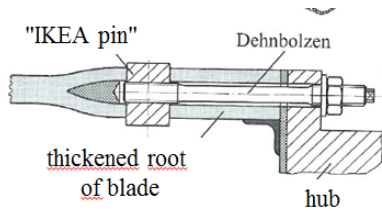
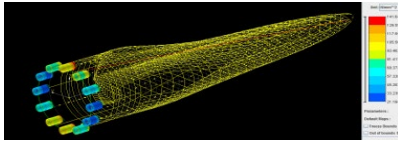
## Bolted joints in highly loaded structures



IKEA Billy



## Bolted joints in highly loaded structures



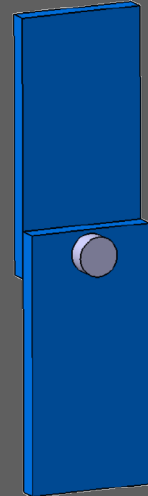
## Questions on bolted joints

**Why is bearing the preferred failure mode?**

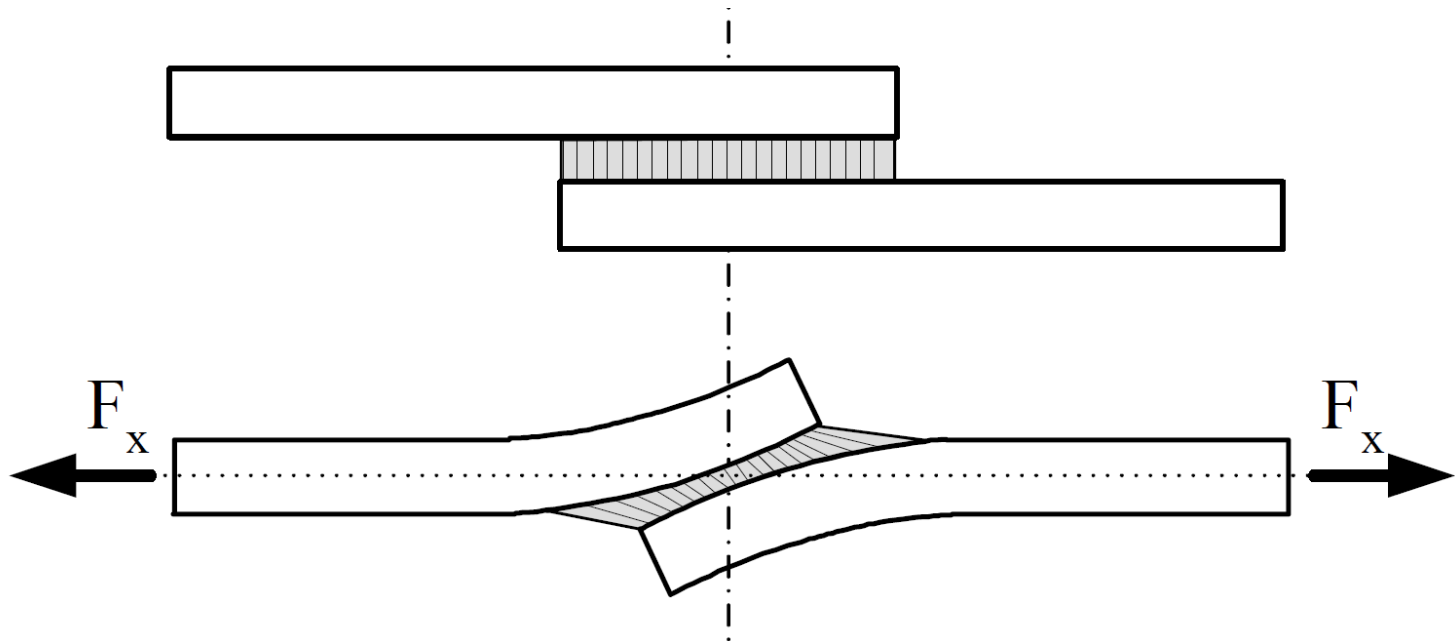
- a. It is the strongest
- b. It is damage tolerant
- c. It is easier to design

**Which failure mode is most likely here?**

- a. Bearing failure
- b. Cleavage failure
- c. Tensile failure



# Bonded joints

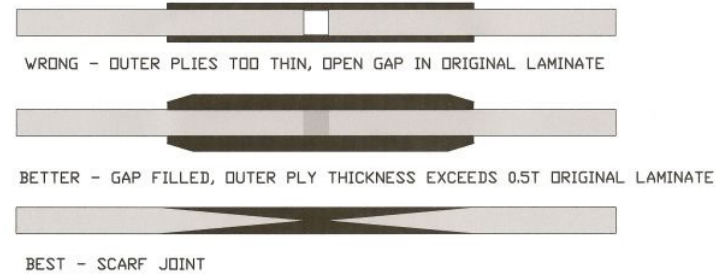


## Why bonded joints

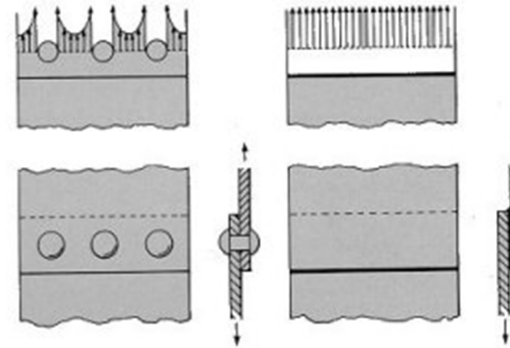
- Strap: localised oriented loads.
- Bolts: high distributed loads.
- **Bonded joints: low distributed loads.**

## Advantage versus bolted joints

- No reduction of load bearing section
- Adapting to tolerances
- No gap corrosion
- Moderate stresses over large area



<http://www.vansairforce.com>

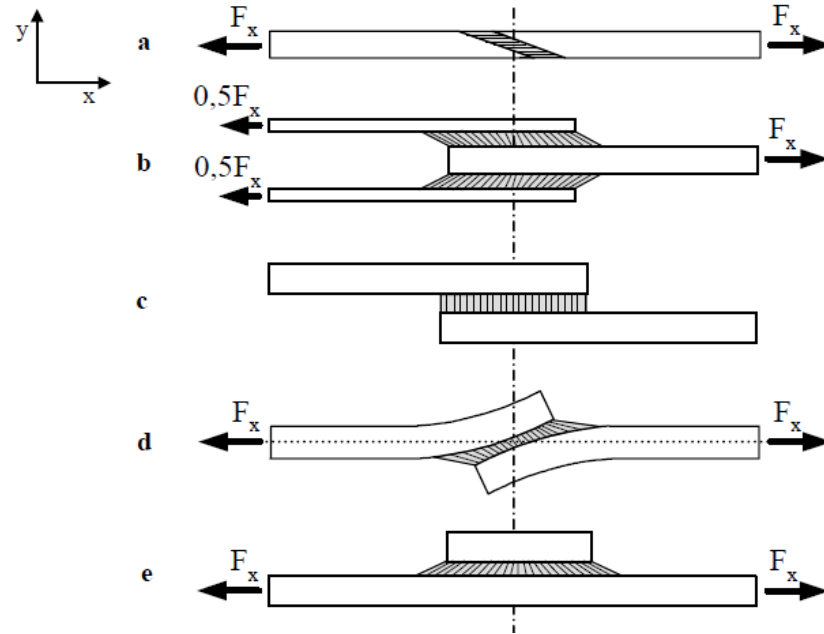


## Drawbacks vs bolted joints

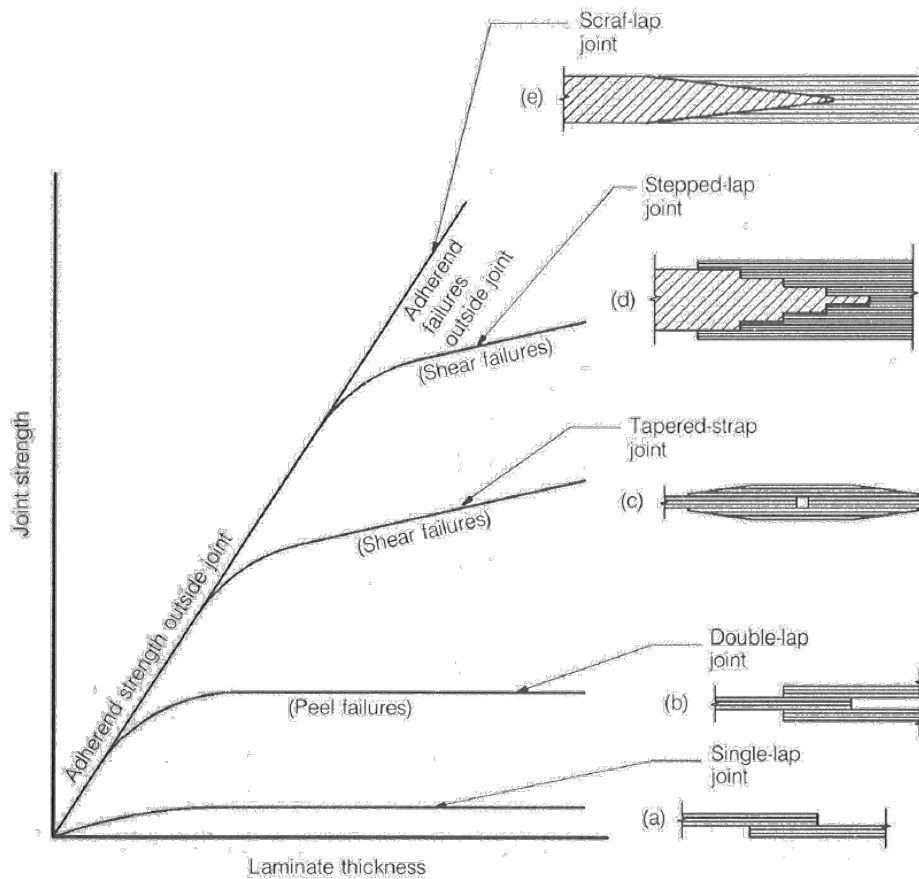
- Connection not detachable
- Sensitive to peel stresses
- Stress peaks
- Catastrophic failure
- Sensitive to moisture and humidity
- Preparation of bonding partners, surface and geometry
- Chemical reaction: temperature, pressure and time have influence on quality
- Quality control

## Bond types

- Scarf joint
- Double lap
- Single lap
- Local patch



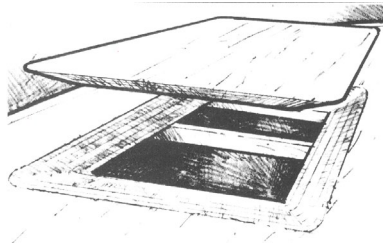
## Bond types



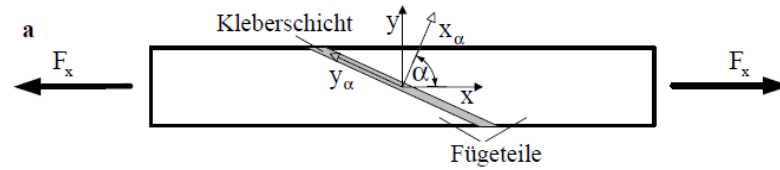
Source: Niu

## Scarf joint

- No stress peak
- No added weight
- May be expensive to realize
- Efficient repair technique



Reparatur eines Holzschiffes durch Schäftung  
[http://www.sailingbreezes.com/sailing\\_breezes\\_current/articles/sept99/repair.htm](http://www.sailingbreezes.com/sailing_breezes_current/articles/sept99/repair.htm)



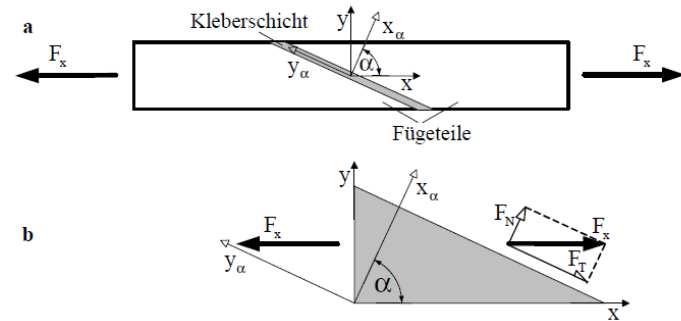
## Design of a scarf joint

• Load vector:  $F_N = F_x \cdot \cos \alpha$ ;  $F_T = F_x \cdot \sin \alpha$

• Bond area:  $A_\alpha = b \cdot \frac{t}{\cos \alpha} = \frac{A}{\cos \alpha}$

• Normal stress:  $\sigma_\alpha = \frac{F_N}{A_\alpha} = \frac{F_x \cdot \cos \alpha}{A / \cos \alpha} = \sigma_x \cdot \cos^2 \alpha$

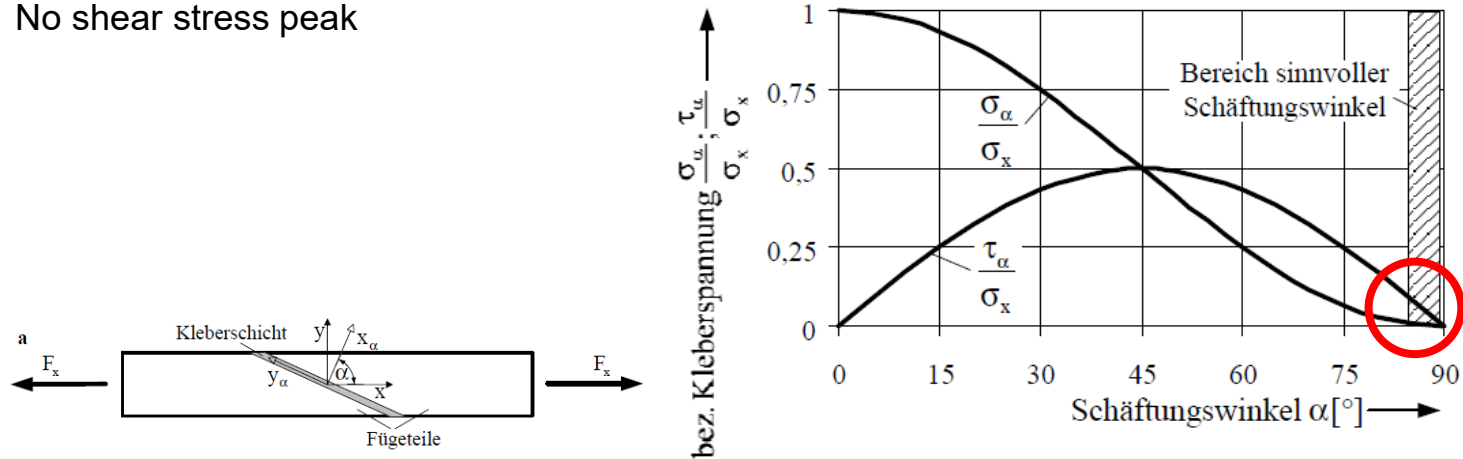
• Shear stress:  $\tau_\alpha = \frac{F_T}{A_\alpha} = \frac{F_x \cdot \sin \alpha}{A / \cos \alpha} = \sigma_x \cdot \sin \alpha \cdot \cos \alpha = \frac{1}{2} \sigma_x \cdot \sin 2\alpha$



## Scarf joint

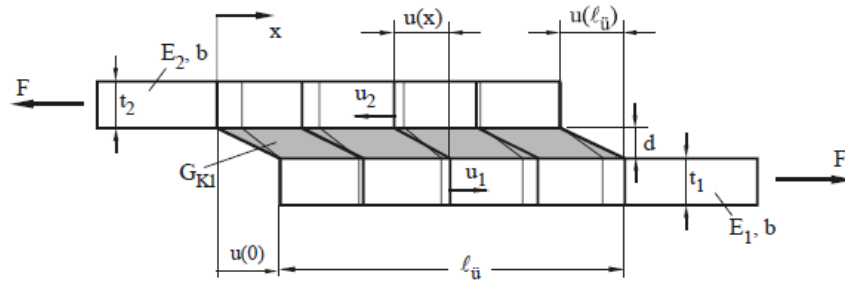
### Large scarf angle

- Larger bond area > reduction in stresses
- Normal stress vanishes
- Pure shear loading
- No shear stress peak



## Single lap joint

- High shear stress peaks
- Limited influence of overlap length on shear stress peak
- High stiffness ratio between partners and adhesive reduces shear stress peaks



— Verschiebungen der elastischen Fügeteile  
— reine Schubverformung des Klebers

[Klein]

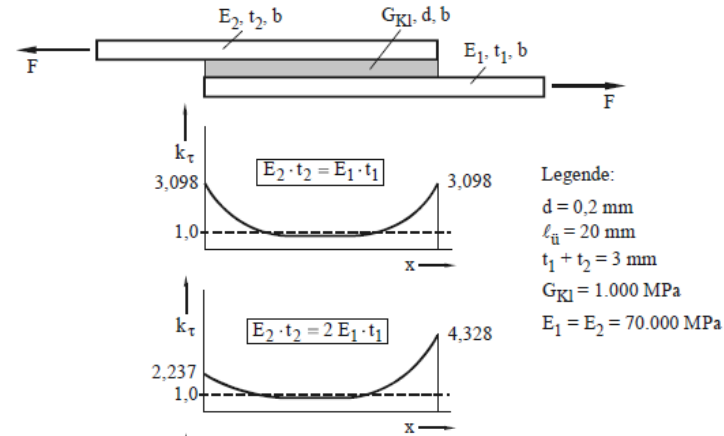
## Single lap joint

Analytical approach for shear stress distribution (constant sections, no bending)

$$\tau(x) = \frac{\omega \cdot \tau_m}{(\beta + 2) \cdot (\cosh \omega - 1)} \left[ \sinh \left( \omega \left( 1 - \frac{x}{\ell_{\ddot{u}}} \right) \right) + (\beta + 1) \sinh \left( \omega \frac{x}{\ell_{\ddot{u}}} \right) \right]$$

$$\omega = \lambda \cdot \ell_{\ddot{u}} = \sqrt{\frac{G_{KI} (E_1 \cdot t_1 + E_2 \cdot t_2) \ell_{\ddot{u}}^2}{E_1 \cdot t_1 \cdot E_2 \cdot t_2 \cdot d}}$$

$$\beta = \frac{(E_2 \cdot t_2 - E_1 \cdot t_1) G_{KI} \cdot \ell_{\ddot{u}}^2}{E_1 \cdot t_1 (G_{KI} \cdot \ell_{\ddot{u}}^2 + E_2 \cdot t_2 \cdot d)}$$



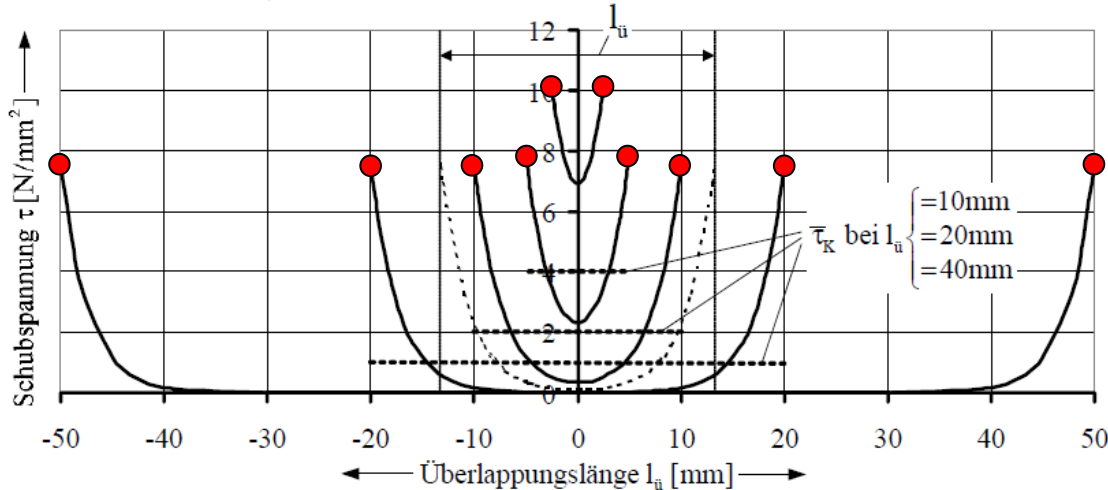
[Klein]

## Single lap joint

Aproximation by Volkersen for  $\tau_{\max}$

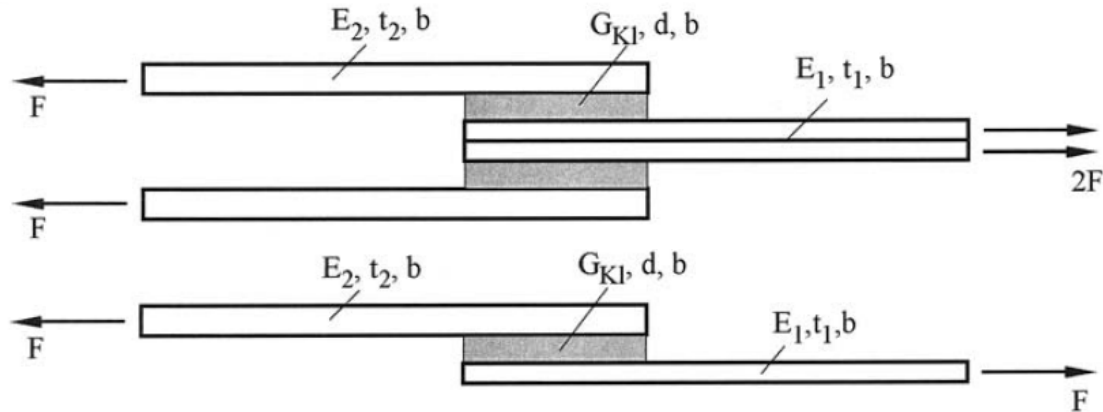
$$\tau_{K\max} = \frac{F_{10}}{b} \sqrt{\frac{1}{2} \cdot \frac{1}{Et} \cdot \frac{G_K}{t_K}}$$

$\tau_{K\max}$  = Schubspannungsspitze  
 $F_{10}$  = äussere Kraft an den Fügeteilen  
 $b$  = Fügeteilbreite  
 $E$  = E-Modul Fügeteile  
 $t$  = Fügeteildicke  
 $G_K$  = Schubmodul des Klebers  
 $t_K$  = Klebefugendicke

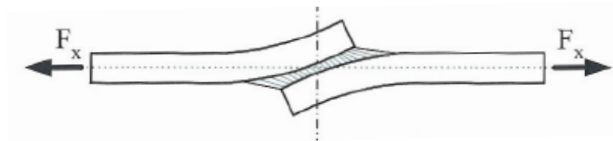


## Double lap joint

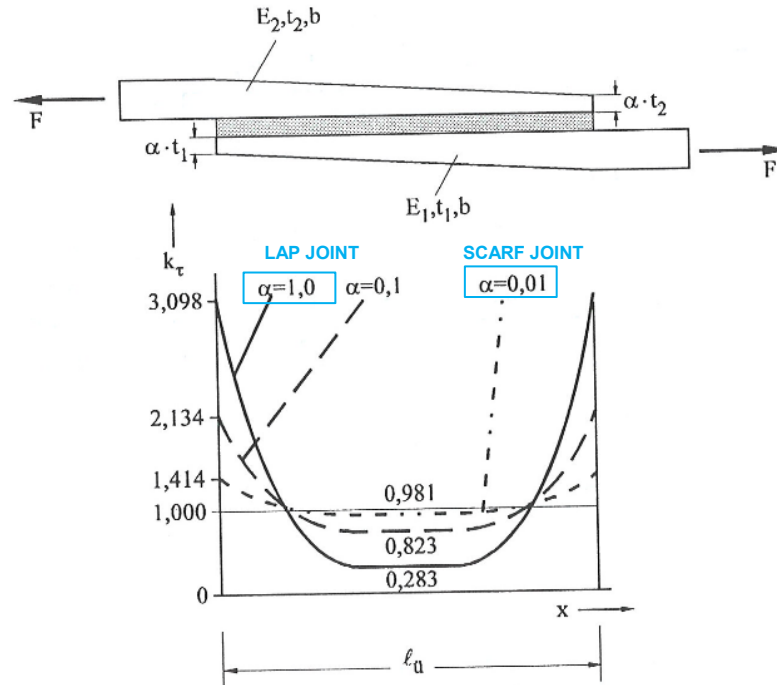
Symmetry of single lap joint



No secondary bending



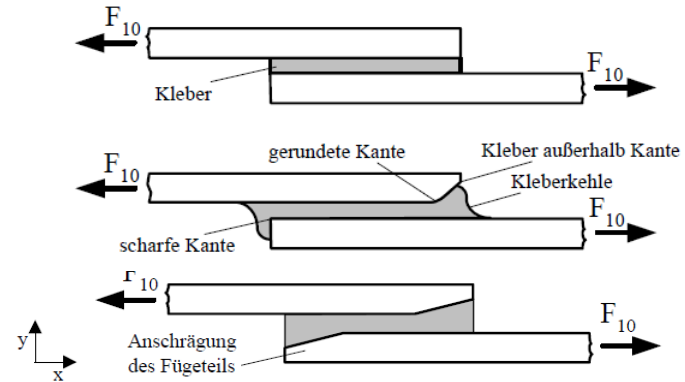
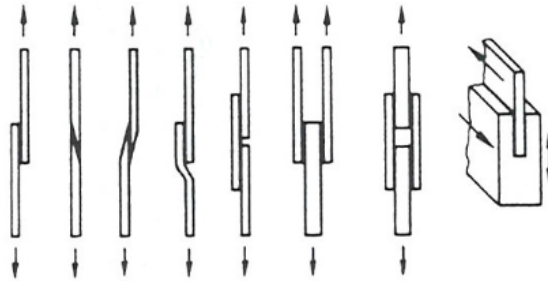
## Lap vs scarf joint



Quelle: Klein

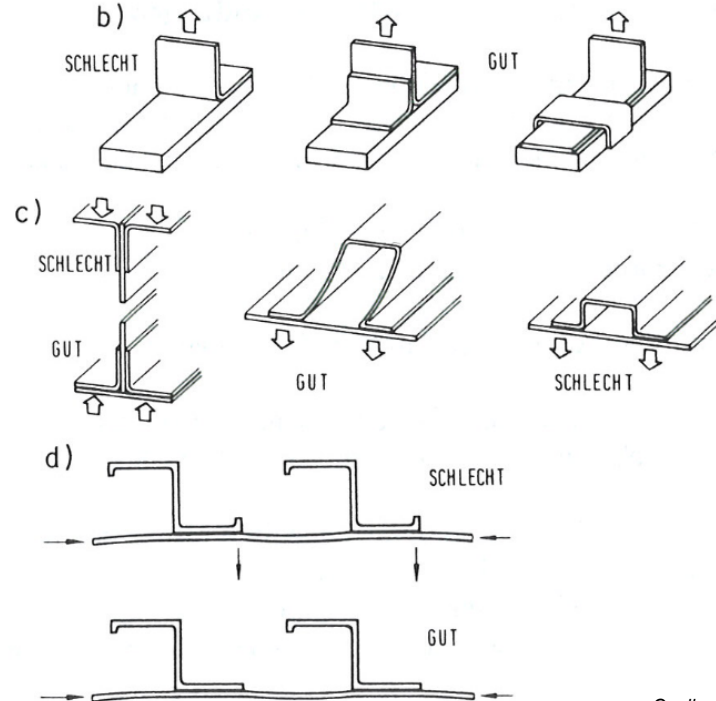
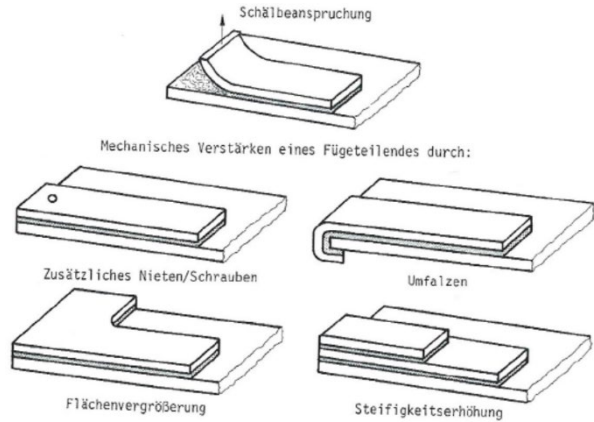
## Design recommendations for joints

- Optimize for shear loading
- Wedged bond gap
- Fillet joint



Quelle: Klein/Schürmann

## Design recommendations for joints – avoiding peel stresses



Quelle: Klein

## Surface treatment of adhesives

Good wetting = good adhesion

Increase surface

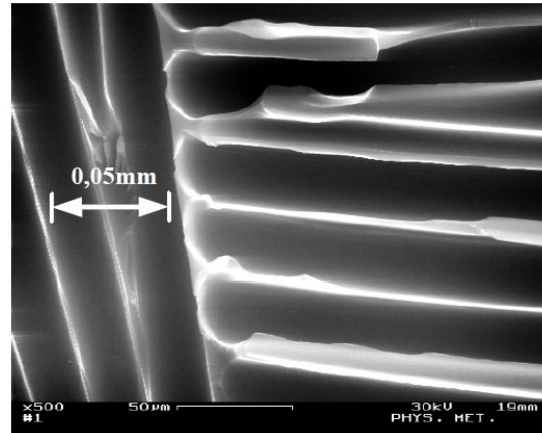
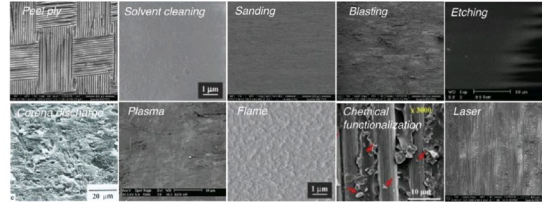
- peel ply (CFK)
- sanding (120er grit)
- sand blasting

Degrease

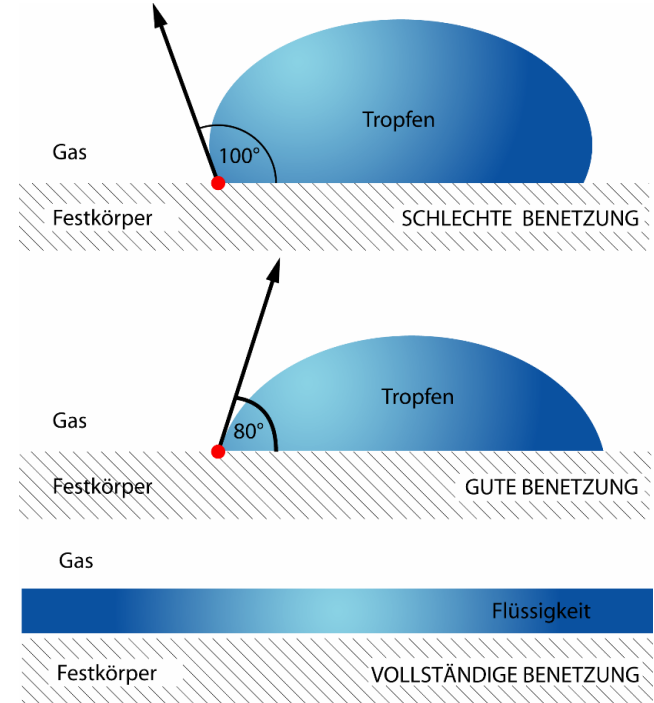
- organic solvent
- bases
- acids

Option

- plasma / flame treatment
- etching
- primers
- laser

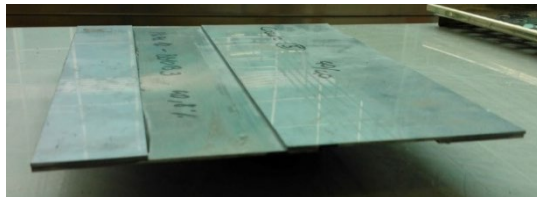
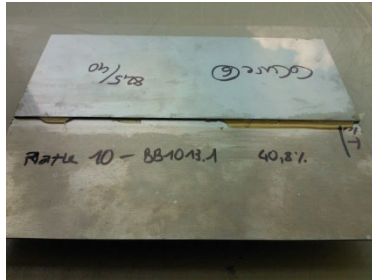


Structure from peel ply



## How to determine lap shear strength

Preparation:

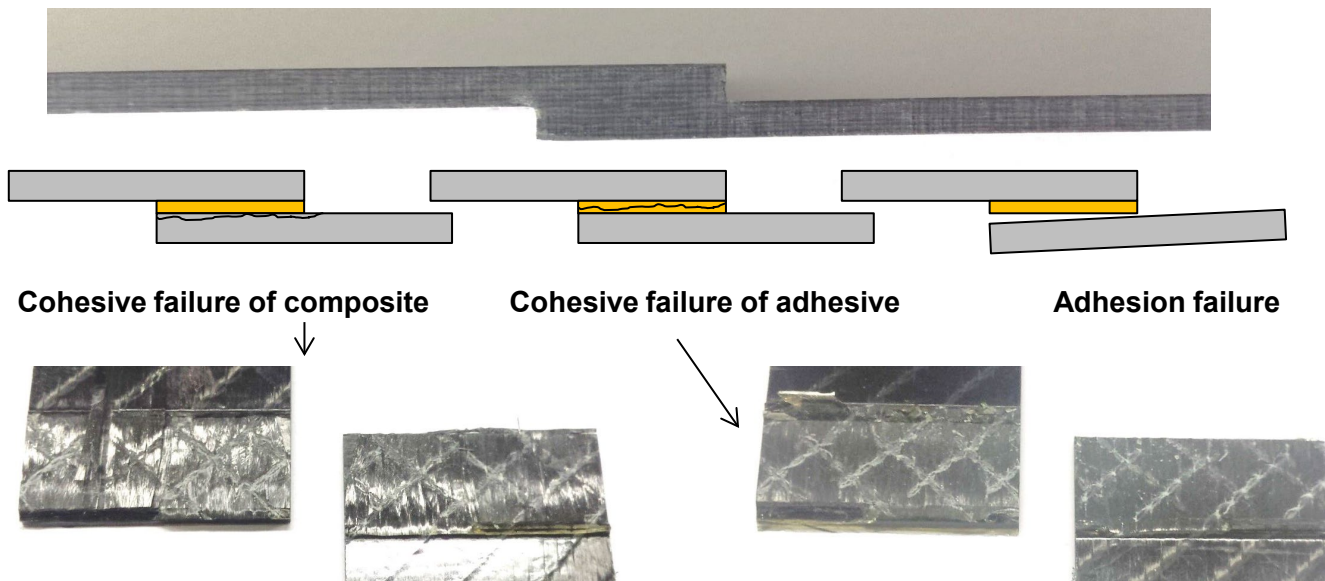


Test:



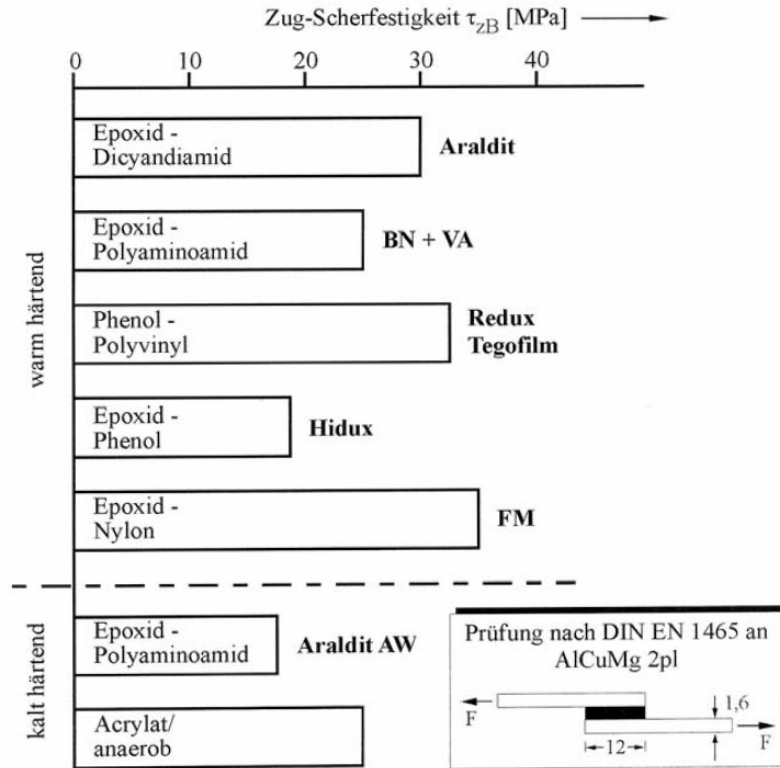
## How to determine lap shear strength

Preparation of specimen, remove fillet joint



## Choice of adhesive

- cold / hot curing
- Strength depending on adhesive part
- Reduced strength
  - Wrong curing cycle
  - Aging and creep up to 40%



Klebstoffe	$\nu_{KI}$	$E_{KI}$ [MPa]	$G_{KI}$ [MPa]	$\tau_{zB}$ [MPa]
warm abbindende Klebstoffe	0,38-0,40	3.000-4.200	900-1.520	20-35
kalt abbindende Klebstoffe	0,38-0,44	1.500-2.500	1.500-2.500	18-25

Quelle: Klein

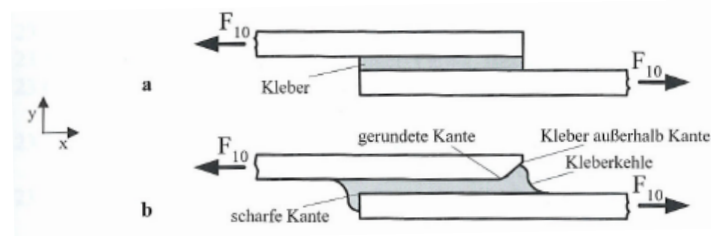
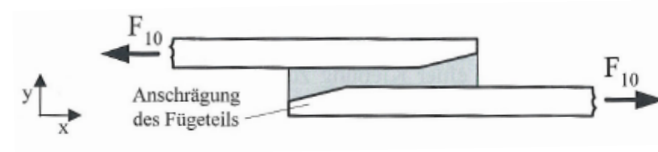
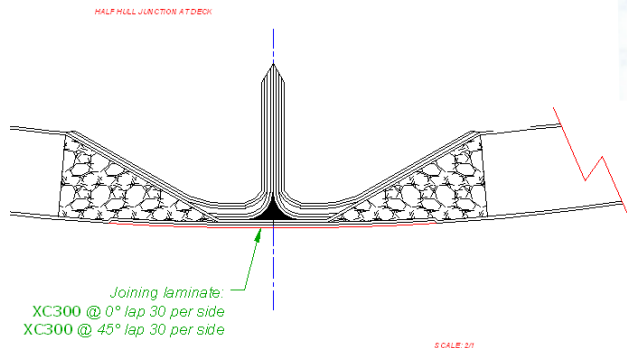
## Design aspects of bonded joints

Avoid peel stresses

Favor shear stresses

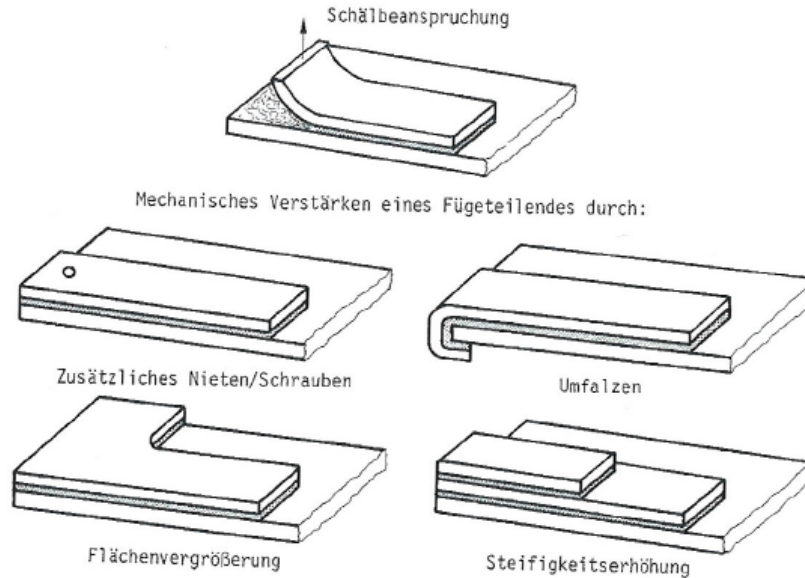
conical bond gap

bond fillets at ends



## Design aspects of bonded joints

### Avoiding peel stresses

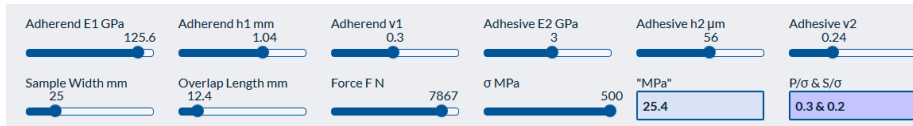


## Active unit on lap joints:

Please go to

<https://www.stevenabbott.co.uk/practical-adhesion/g-rlap.php>

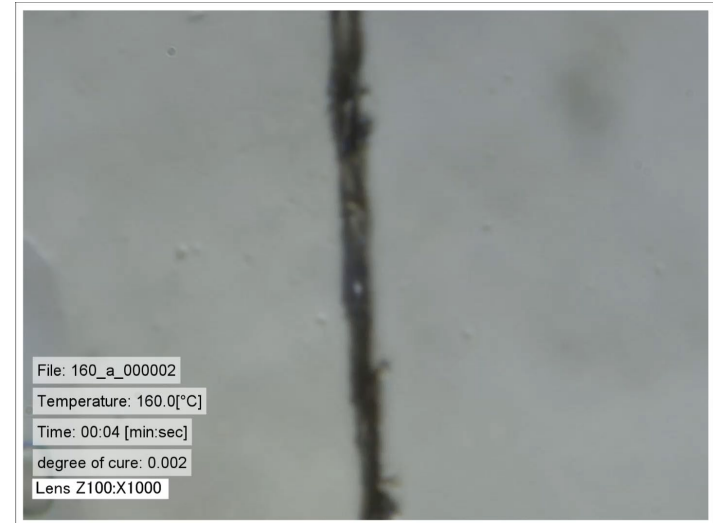
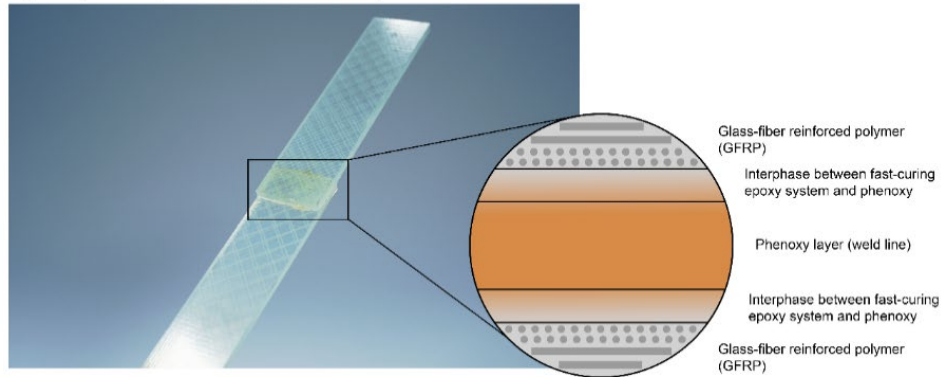
Use the sliders to optimise the following lap joint,  
start with this values:



How can the stress reduced, please post your result  
in the chat as a screen shot

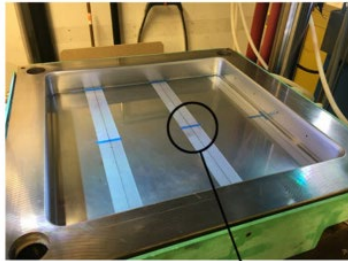
## Advanced concepts applying welding to thermosets

Hybrid phenoxy/GFRP lap shear samples



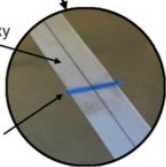
## Advanced concepts applying welding to thermosets

Placement of phenoxy film in tooling at room temperature:

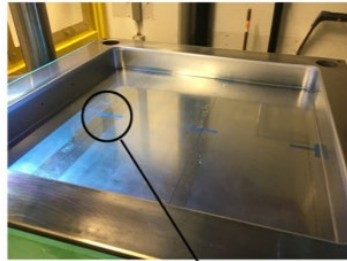


Placement of phenoxy film in joining area

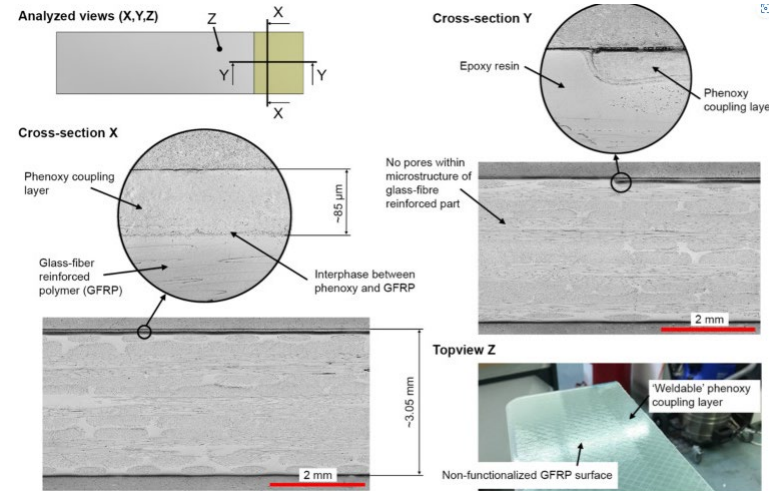
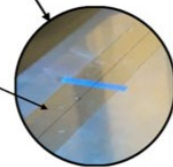
Fixation with blue tape



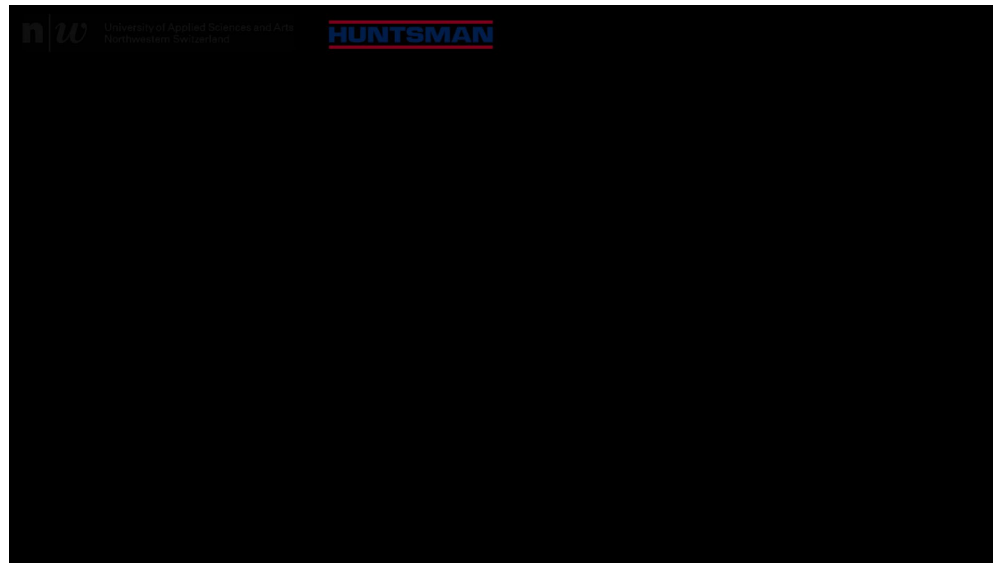
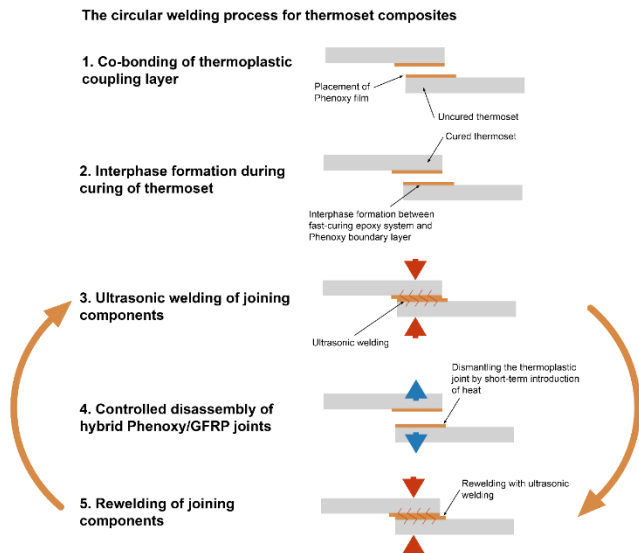
Preheating of tooling to defined curing temperature at 140 °C:



No movement or shrinkage during preheating phase



## Advanced concepts applying welding to thermosets



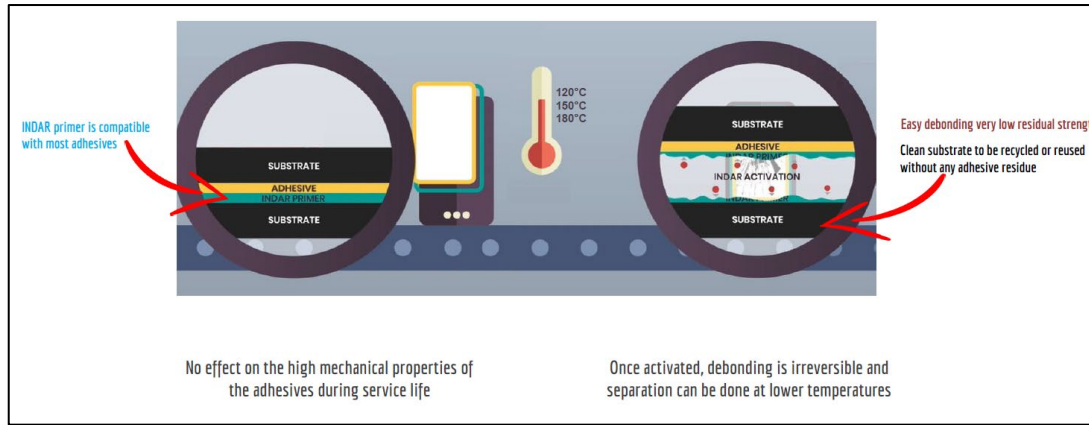
Zweifel, Lucian & Ritter, Klaus & Brauner, Christian. (2022). The Mechanical Characterization of Welded Hybrid Joints Based on a Fast-Curing Epoxy Composite with an Integrated Phenoxy Coupling Layer. *Materials*. 15. 1264. 10.3390/ma15031264.

## Repurpose - Debonding on Demand

### Rescoll INDAR

#### Primer system, activated by temperature

#### Compatible with the majority of available adhesives



- Temperature activation selectable in the range of 100°-200°C
- The primer loses its strength after one-time activation
- Adhesive residues can be removed

## Repurpose - Debonding on Demand

### Thermoplastic adhesive film

Nolax films

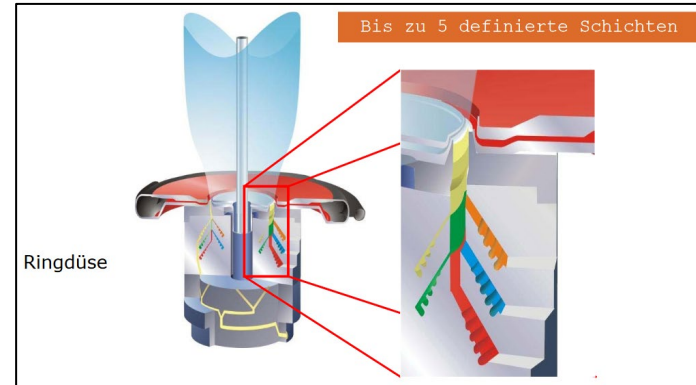
Thermoplastic adhesive film

Single-layer or multi-layer film for optimum adhesion depending on the material

Technically a high strength hotmelt

Flexible in application

- Production with press
- Lamination processes
- Vacuum bag



❖ Production process of the adhesive film, source: <https://nolax.com>

## Repurpose - Debonding on Demand

### Life bonding

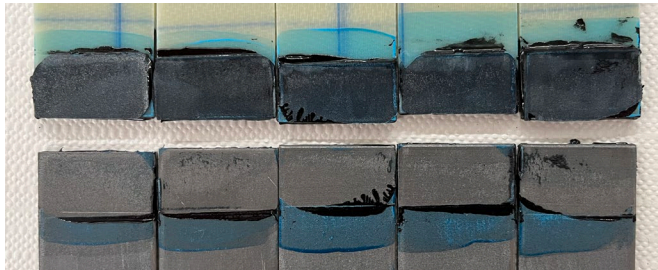
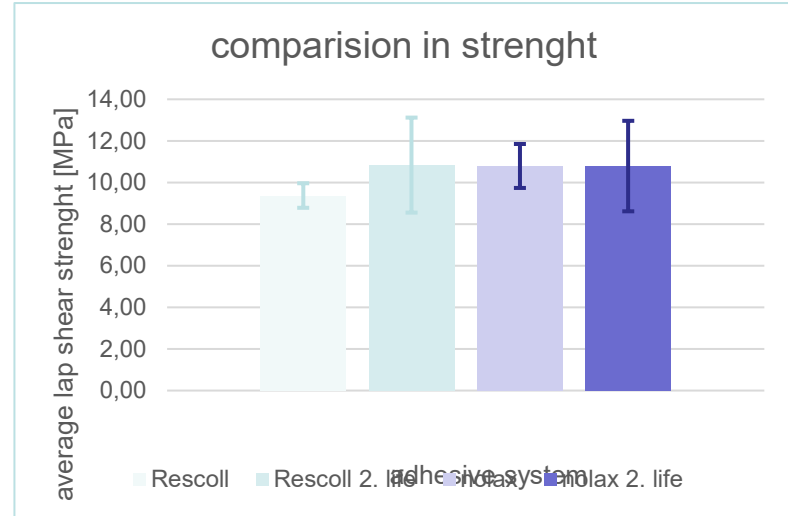
Reused the two batches from the debonding test

Removal of the adhesive according to the video

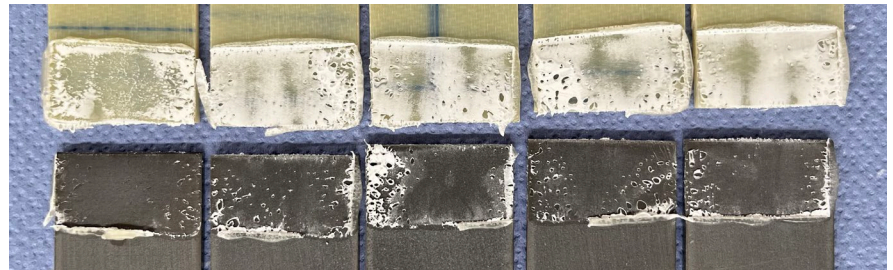
- Rescoll can be easily removed
- Nolax is not completely removed but because of the thin layer there is almost no material built up which allows a second bonding

Tendency to even higher strength with the second bonding

- With a bit more variation
- Presumption: rougher surface leads to better adhesion

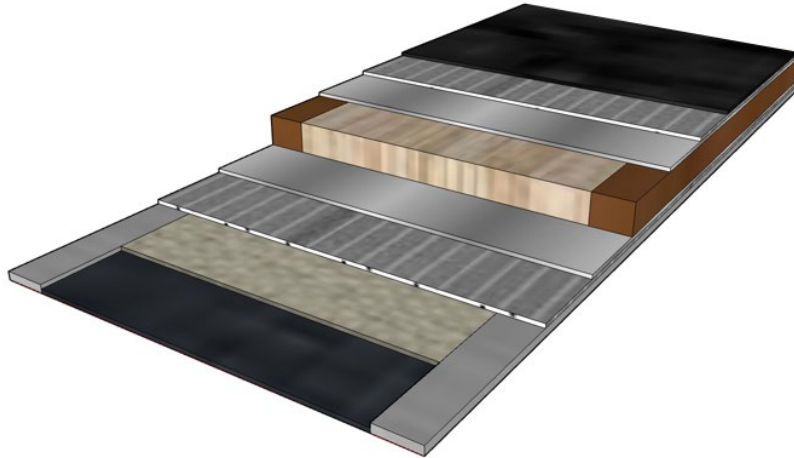


❖ Fracture analysis 2. life Rescoll system



❖ Fracture analysis 2. life nolax system

## Ski – A multimaterial Composite



**Topsheet: PA11, PA12, ABS/TPU**

**Top skin: Fiber reinforcements, Titanal**

**Side wall: ABS**

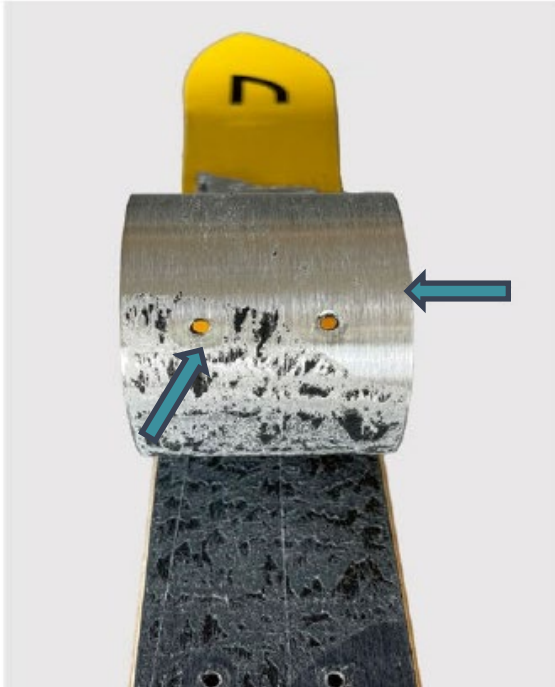
**Core: Wood, PU foam**

**Bottom skin: Rubber, Titanal, Fiber reinforcements**

**Edge: Steel**

**Base: UHMW-PE**

## Metal-Polymer hybrids



### State of the art:

- Weak bonding of Epoxy and untreated Titanal
- Phosphor anodization
- Grinding of Titanal
- Short shelf life of activated Titanal

## Metal-Polymer Hybrids



### Pontacol's solution:

- Laminating a multilayer adhesive film
- Good bonding on Titanal and Aluminium
- Get an accessible surface for epoxy resins
- Use directly as adhesive
- Extend the shelf life

## Pre-trials: Experimental design

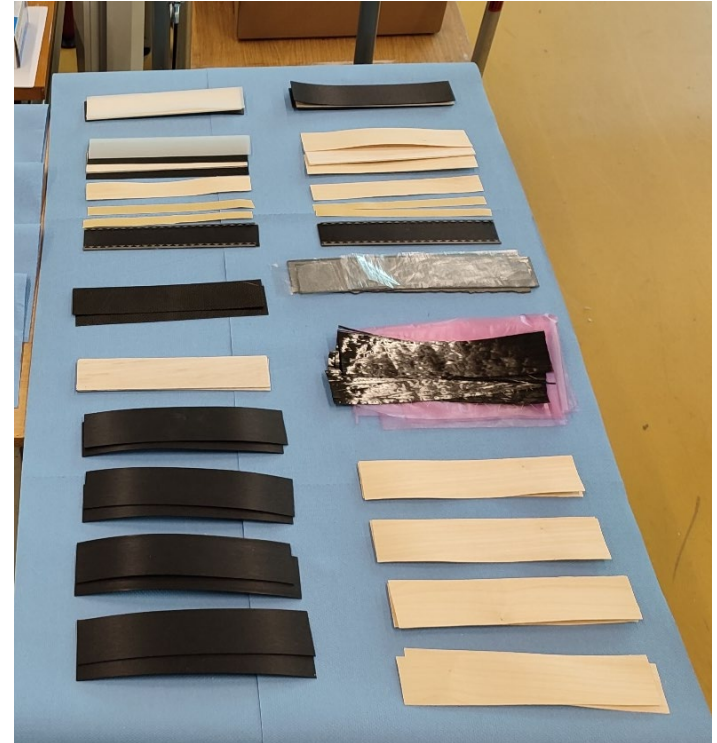
### Different Thermoplastic Adhesive Films

#### Adherends

- Wood core (asch, poplar)
- Wood veneer (birch)
- Carbon fibre laminate
- UHMW-PE base

#### Vogt laboratory press

- Press size: 250 mm x 250 mm, 100 bar
- Temperature: ca. 30 °C above melting point
- Per material 3 samples, L = 200 mm / W = 40 mm
- Release foil vs. caul plate on top and bottom



[www.fhnw.ch/htu](http://www.fhnw.ch/htu)

## Tested Thermoplastic Adhesive Films

→ It was decided to choose 120 °C processing temperature for all adhesives

Code	Material	T <sub>m</sub> [°C]	Processing [°C]	Areal weight [g/m <sup>2</sup> ]
Adh-1 (PE/CoPA)	Polyolefin / Copolyamid	70 – 80	100 – 150	50
Adh-2 (TPU)	TPU	65 – 85	90 – 140	25
Adh-3 (PE)	Modified Polyolefin	85 – 105	105 – 150	40
Adh-4 (TPU/CoPA)	TPU / Copolyamid	100 – 110	120 – 170	25



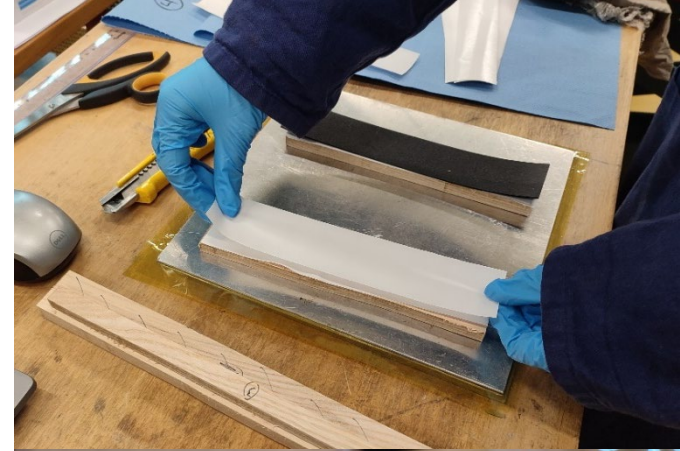
[www.fhnw.ch/htu](http://www.fhnw.ch/htu)

## Stacking and pressing

2 specimen:

Asch wood + PE/CoPA + UHMW-PE base

- Hold: 120 °C / 100 bar / 5 min
- Ramp-down:  $\Delta T = 100 \text{ K} / 1 \text{ min}$
- Surface preparation with Isopropanol
- 2 mm Alu caul plates + PI release foil



[www.fhnw.ch/htu](http://www.fhnw.ch/htu)

## Stacking and pressing

### General

- Hold: 120 °C / 100 bar / 5 min
- Ramp-down:  $\Delta T = 100 \text{ K} / 1 \text{ min}$

### Pine wood veneer + PE/CoPA | TPU | PE | TPU/CoPA

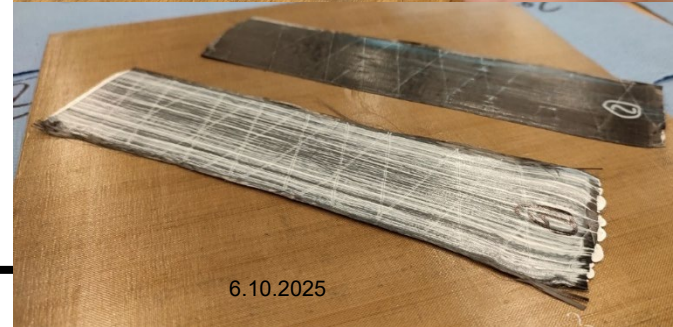
- Surface preparation with Isopropanol
- 2 mm Alu caul plates with Teflon cover (no extra release foil)

### Consolidated CFRP woven fabric

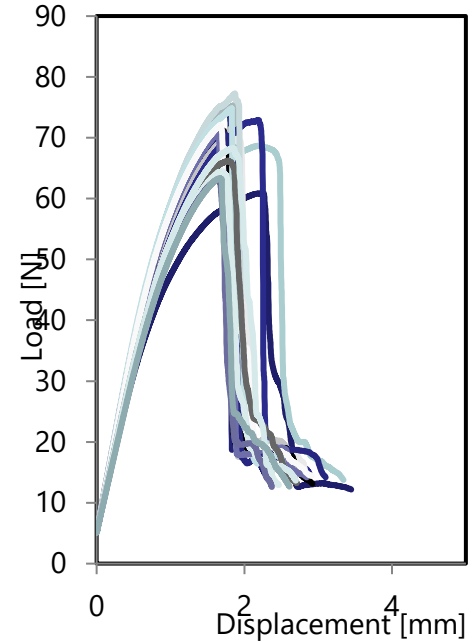
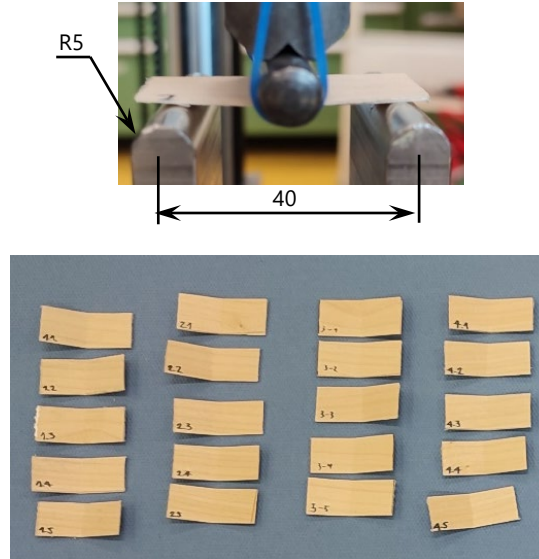
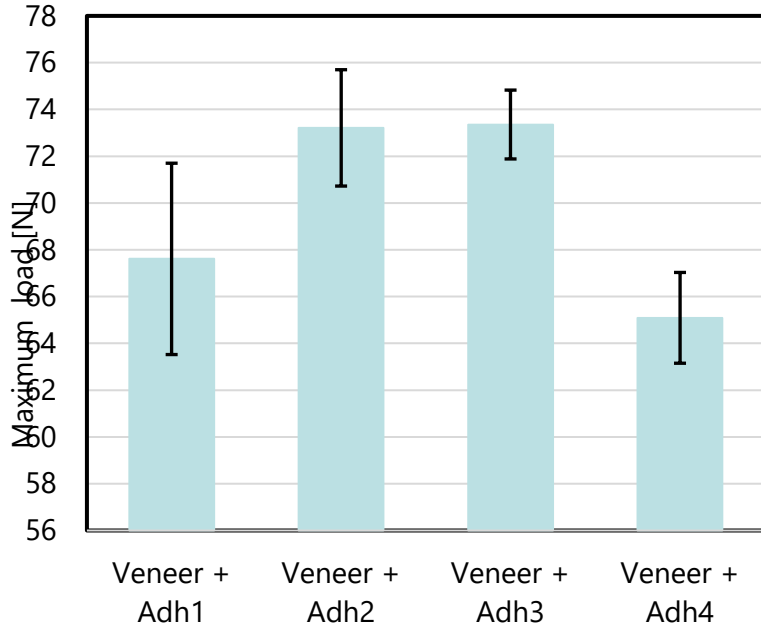
- No surface preparation possible

### Dry carbon fibre unidirectional

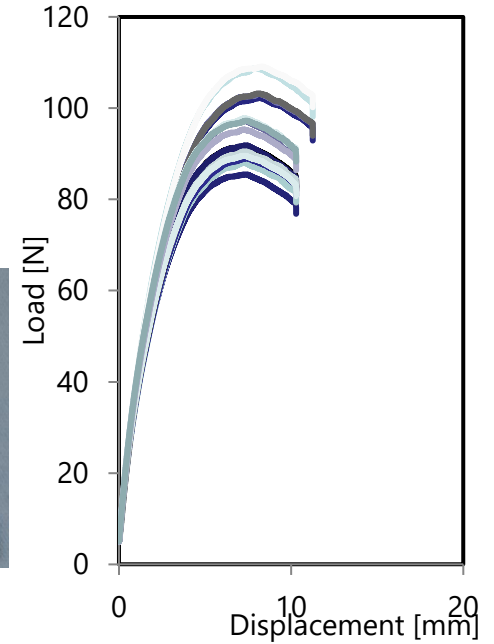
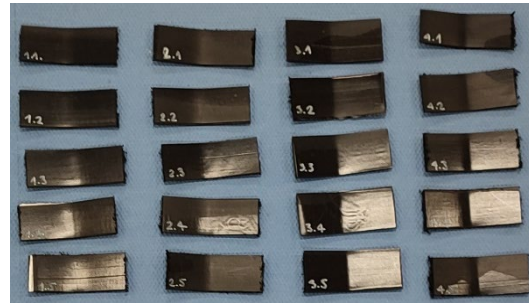
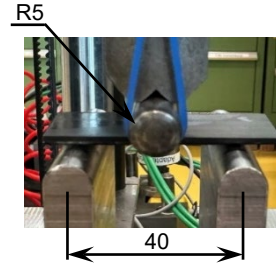
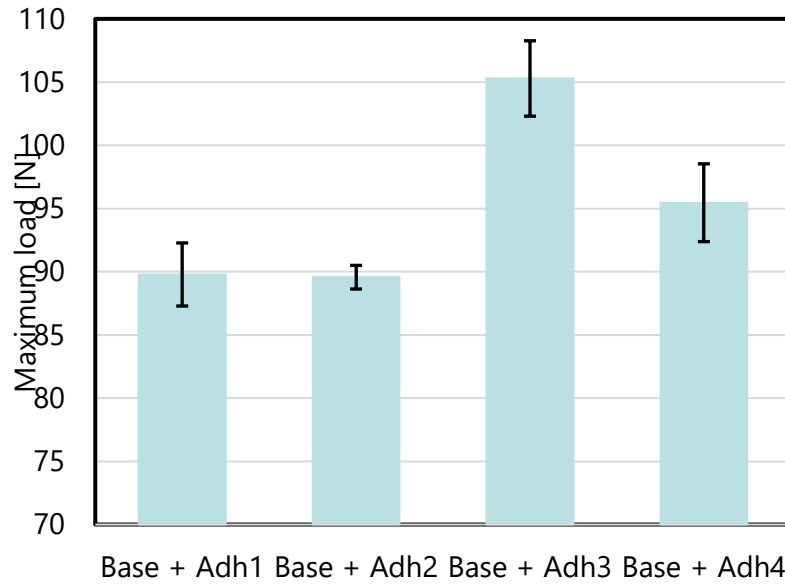
- No surface preparation possible



### Pine wood veneer



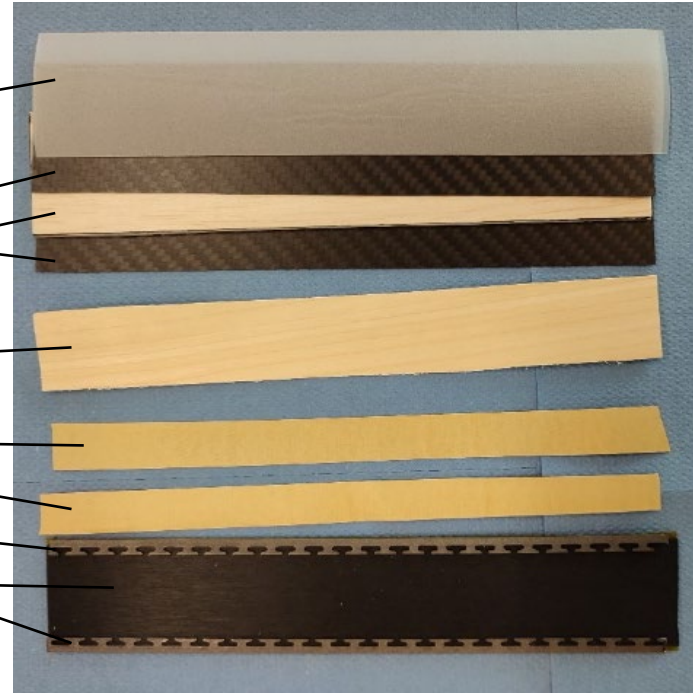
## UHMW-PE sintered base



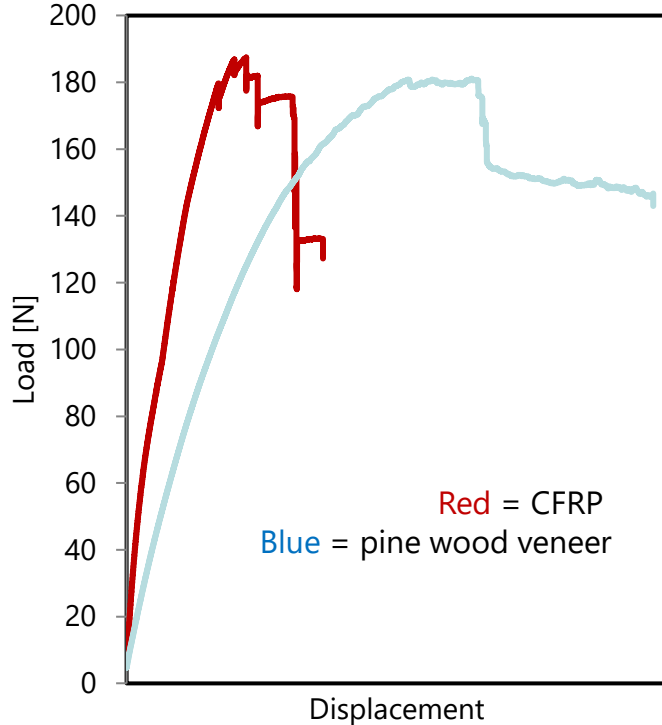
### 3PB: Ski laminates - CFRP vs. pine wood veneer

#### Ski laminate 1 + PE

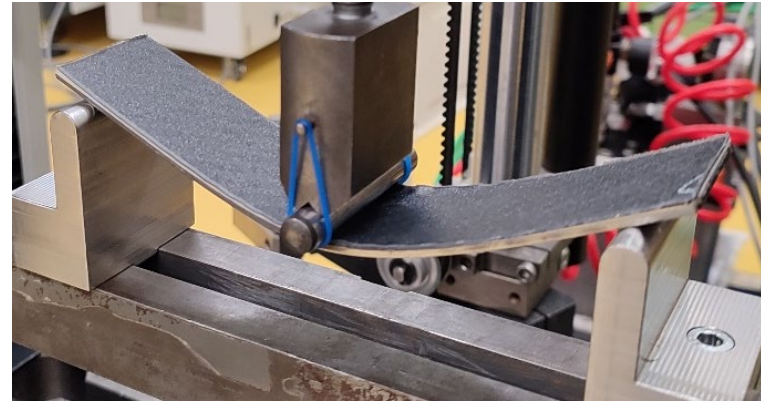
- PA11 topsheet, 0.3 mm
- CFRP/twill weave/epoxy, 0.2 mm
- Balsa wood veneer, 1 mm
- Pine wood veneer, 0.6 mm
- VDS rubber band, 0.2 mm
- Steel edge - light, 1.7 mm
- UHMW-PE base, 1.3 mm



### 3PB: Ski laminates - CFRP vs. pine wood veneer



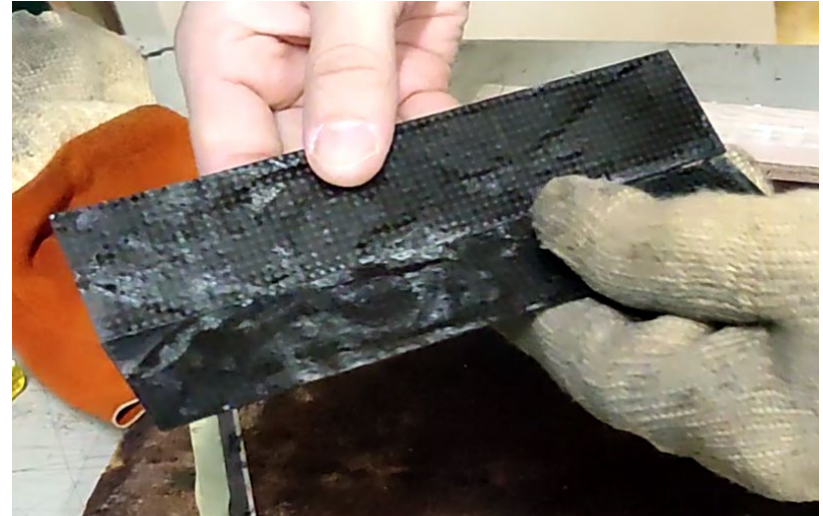
Zwick Allround 100 kN  
Small load cell > 1 kN  
150 mm between supporting points



**Debonding trial (heating in oven for 5 min)**



10 mm asch wood +  
1.3 mm UHMW-PE +  
PE/CoPA  
at 70 °C → good  
debonding



2x 1 mm CFRP + TPU  
at 100 °C → no damage of CFRP

## Summary debonding on demand

### Manufacturing

- All adhesive processed at 120 °C, 100 bar, 5 min consolidation
- No excessive polymer flow
- Bond to all adherend types: soft wood, hard wood, steel, UHMW-PE, CFRP, rubber band

### Testing

- 3PB test on Zwick result into expected failure modes
- For (stiff) pine wood veneer: TPU and PE appear most promising for maximum 3PB-strength
- For (soft) UHMW-PE base: PE and TPU/CoPA appear most promising for maximum 3PB-strength
- 3PB of full ski laminate stack does not reveal bonding issues to any of the adherends for PE and TPU/CoPA
- Debonding feasible

## Questions on bonded joints

**Which bond type bears more load (with same basic geometry and bond area)?**

- a. Single lap stronger than scarf**
- b. Scarf stronger than single lap**
- c. Same bond area, same strength**

**In a single lap joint, lower adhesive modulus leads to ...?**

- a. Higher peak shear stress**
- b. Lower peak shear stress**
- c. Higher average shear stress**

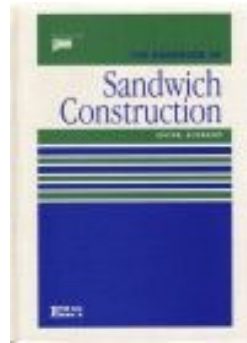
## Recommended design related textbooks



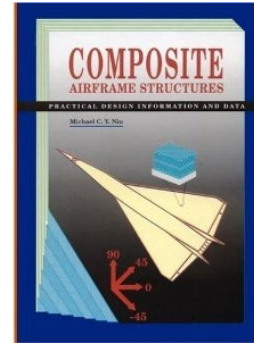
Helmut Schürmann:  
Konstruieren mit  
Faser-Kunststoff-  
Verbunden  
ISBN 978-3-540-  
72190-1  
*All non referenced  
pictures from here*



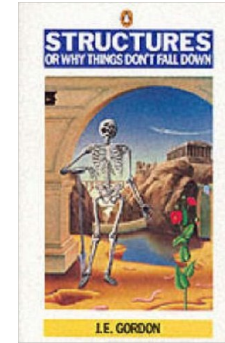
Bernd Klein:  
Leichtbau-  
Konstruktion  
ISBN 978-3-  
658-02272-3



Dan Zerkert:  
Handbook of  
Sandwich  
Construction  
Department of  
Lightweight  
Structures,  
Royal Institute  
of Technology,  
1993



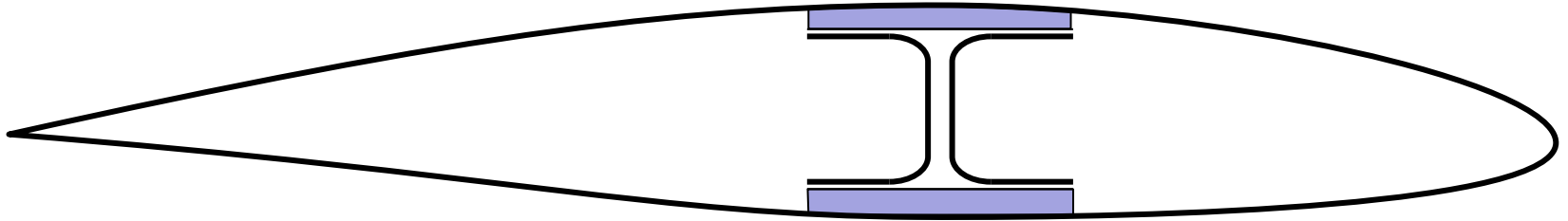
Michael Chun-Yu Niu:  
Composite Airframe  
Structures  
ISBN 978-9627128069



J. E. Gordon:  
Structures or or why  
things don't fall down,  
2003 by Da Capo  
Press (first published  
1978), ISBN  
0306812835

## Exam Questions

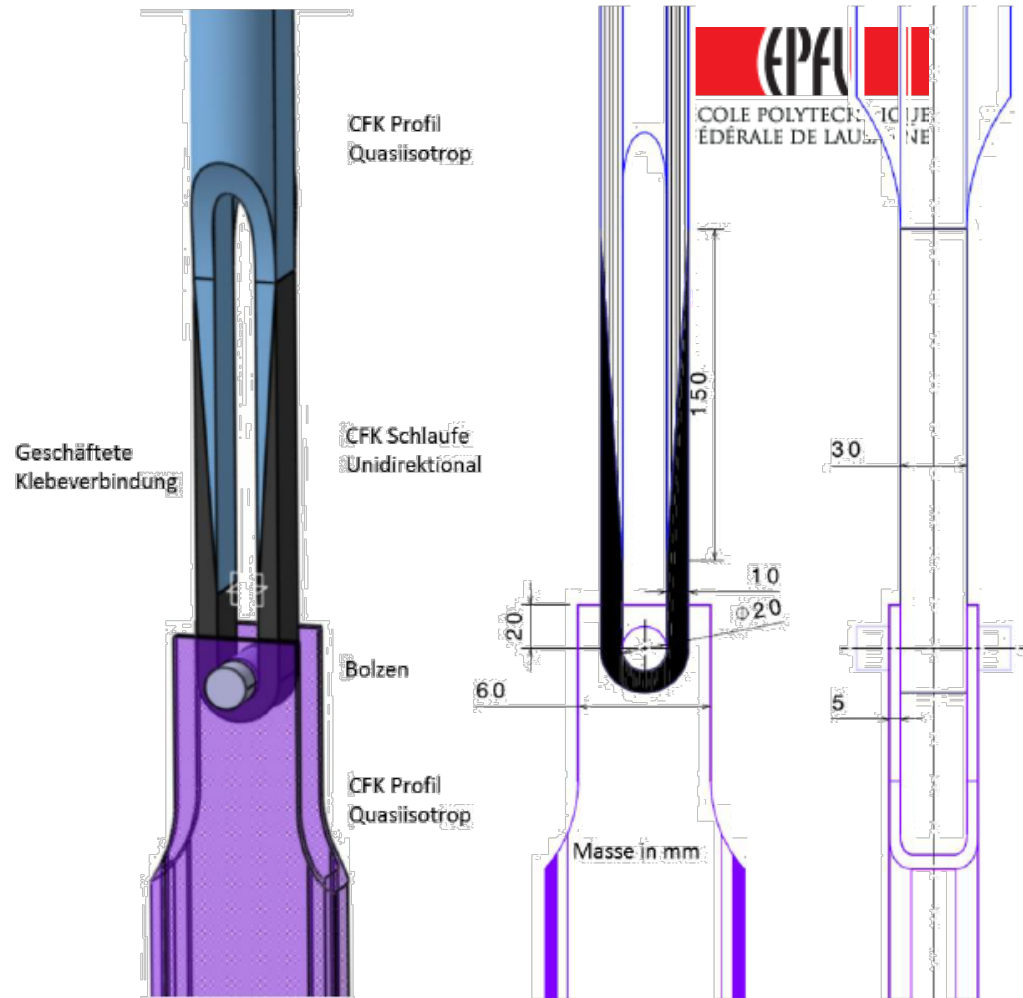
- How would you use pin loaded straps to attach a composite wing spar to the fuselage of an glider airplane?
- Illustrate by sketches



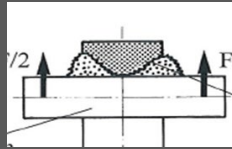
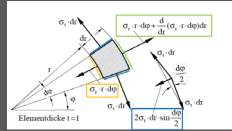
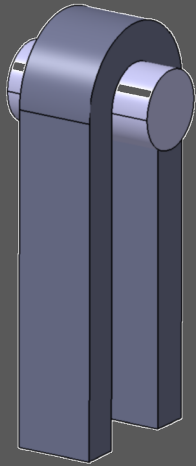
## Exam Questions

Preliminary sizing of given design

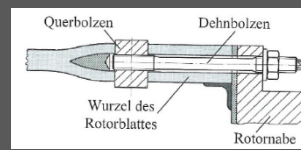
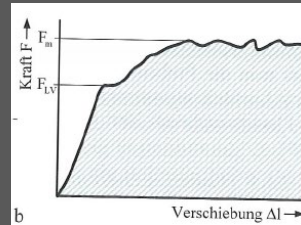
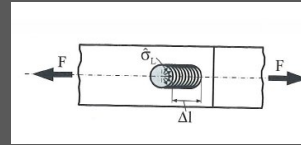
- Which load introductions do we have?
- How to you calculate the failure load?



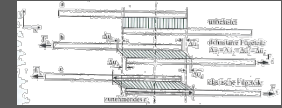
## PIN LOADED STRAP



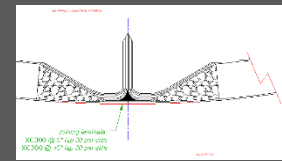
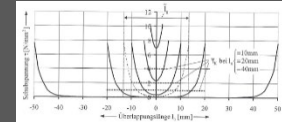
## BOLTED JOINT



## BONDED JOINT



$$\tau_{K \max} = \frac{F_{I0}}{b} \sqrt{\frac{1}{2} \cdot \frac{1}{Et} \cdot \frac{G_K}{t_K}}$$



**Concept, manufacturing, sizing, design integration**

## Contact

Institute of Polymer Engineering



Prof. Dr. Christian Brauner

Klosterzelgstrasse 2

5210 Windisch

T +41 56 202 7475

F +41 56 202 7574

[christian.brauner@fhnw.ch](mailto:christian.brauner@fhnw.ch)

[www.fhnw.ch/technik/ikt/](http://www.fhnw.ch/technik/ikt/)