DELAMINATION OF COMPOSITE STRUCTURES AND FAILURE MODES OF BONDED ELEMENTS

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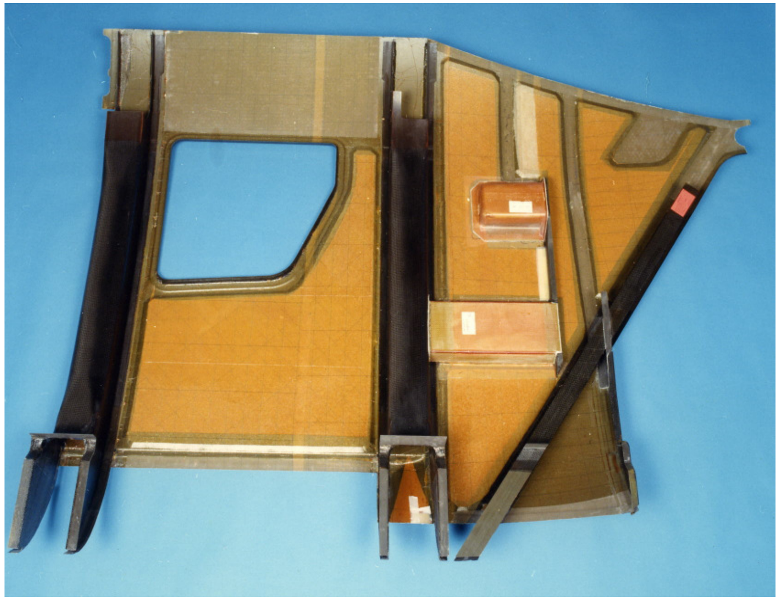
Table of Contents

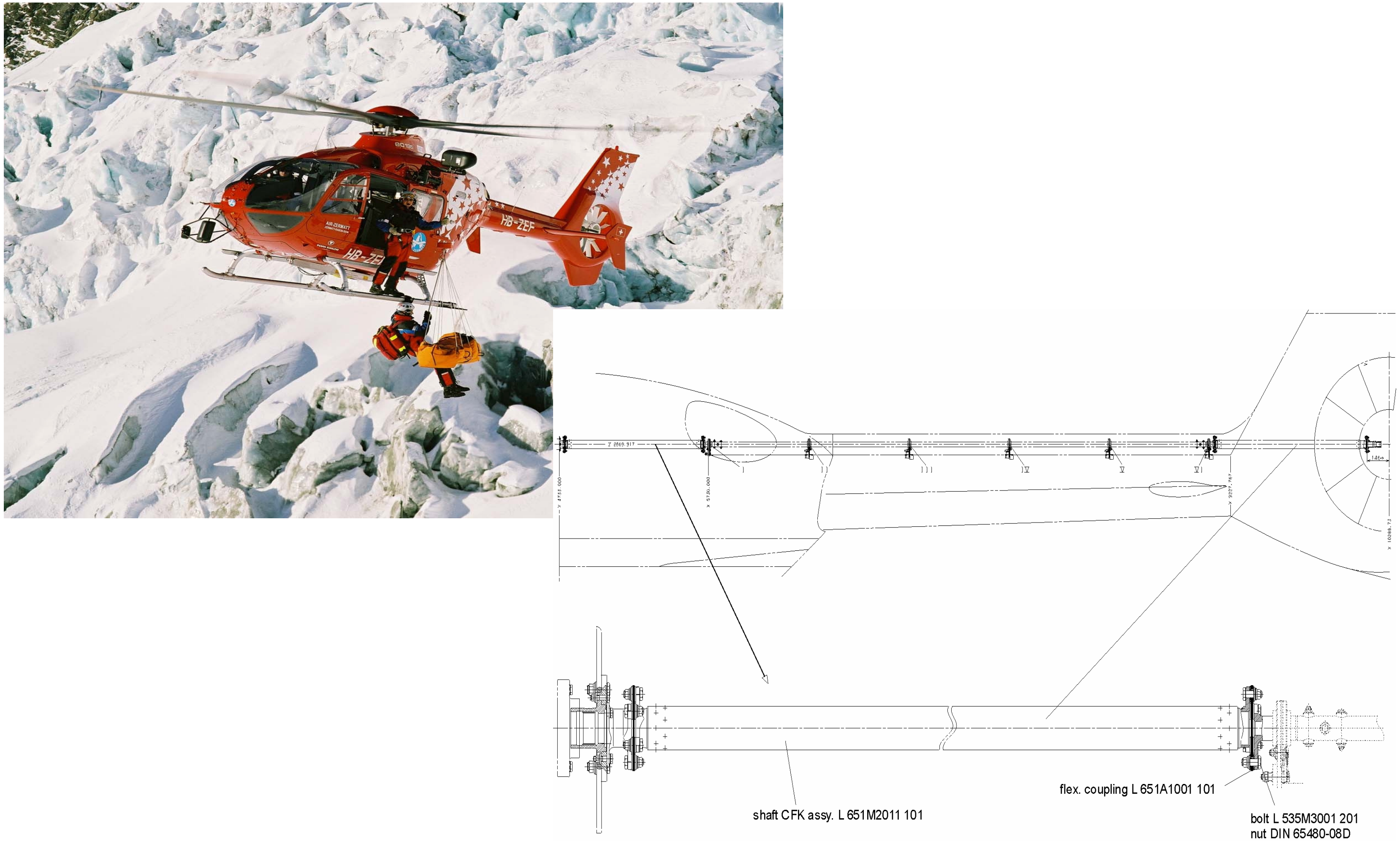
- Introduction
- Examples for Bonded Helicopter Structures
- Stress Analysis According to the “Transfer-Matrix” Method
- The “Three-Beam-Structure” with Different Loading Situations
- Tension and Torsion Loaded Tapered and Bonded Laminates

The Commercial Helicopter BK 117 with the Rotor Blade Attachment Fitting and Metallic Erosion Protection

The BK 117 with Composite Fuselage and Side Shell with Bonded Elements



The EC 135 with „Fenestron“ Drive Shafts

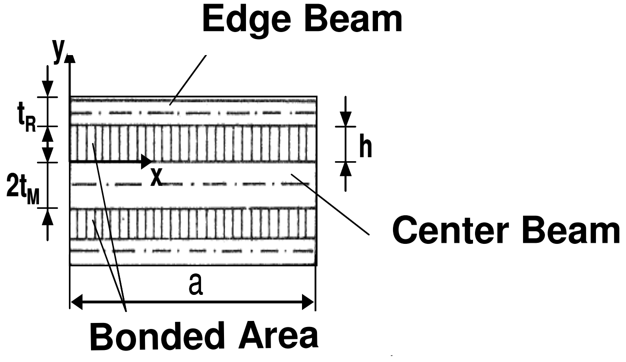


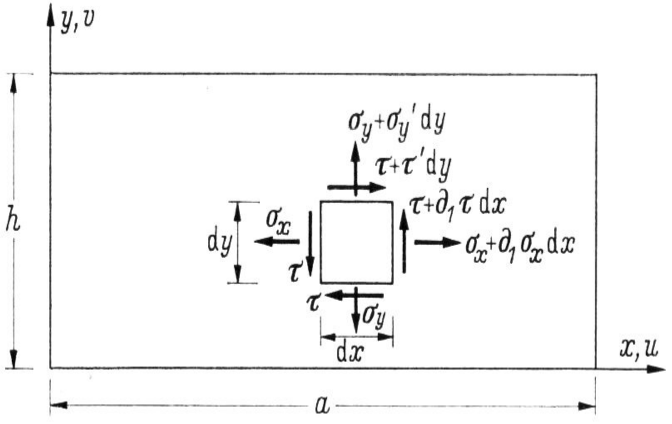
The EC 135 in Life Saving Action with the Impacted Drive Shaft after Static Residual Strength Test

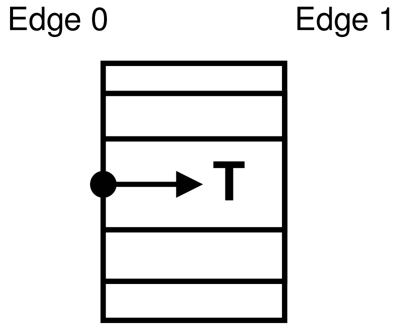
The EC 135 helicopter and the “Fenestron” carbon composite drive shaft

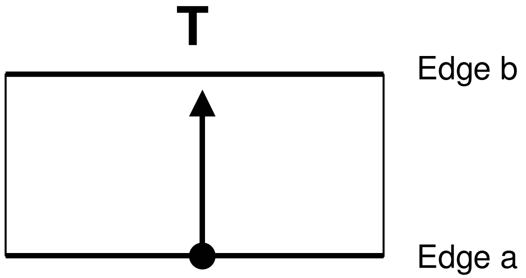
Stress Analysis According to the “Transfer-Matrix” Method

The „Three-Beam-Structure“, the Stress Situation in the Bonded Area, the Transfer Directions and the Solution of the Differential Equation









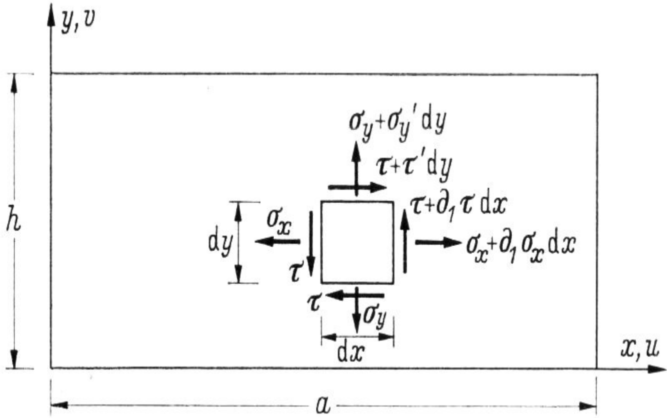
Differential-Equation-System:

$$\partial_1 \boldsymbol{w} = \boldsymbol{A}\,\boldsymbol{w}\,,$$

Transfer-Matrix T:

$$\boldsymbol{T} = \mathrm{e}^{\boldsymbol{A}} = \boldsymbol{E} + \boldsymbol{A} + \boldsymbol{A}^2/2! + \boldsymbol{A}^3/3! + \cdots$$

The Relation between the Stresses, Deformations and Strains in the Bonded Area



a) The Conditions of Equilibrium:

$$\partial_1 \sigma_x + \tau' = 0 \qquad \sigma_y' + \partial_1 \tau = 0$$

σ_x, σ_y are the Normal Stresses, τ is the Shear Stress

b) The Conditions of Deformations

$$\varepsilon_x = \partial_1 \mathrm{u}, \;\; \varepsilon_y = \mathrm{v}', \;\; \gamma = \mathrm{u}' + \partial_1 \mathrm{v}$$

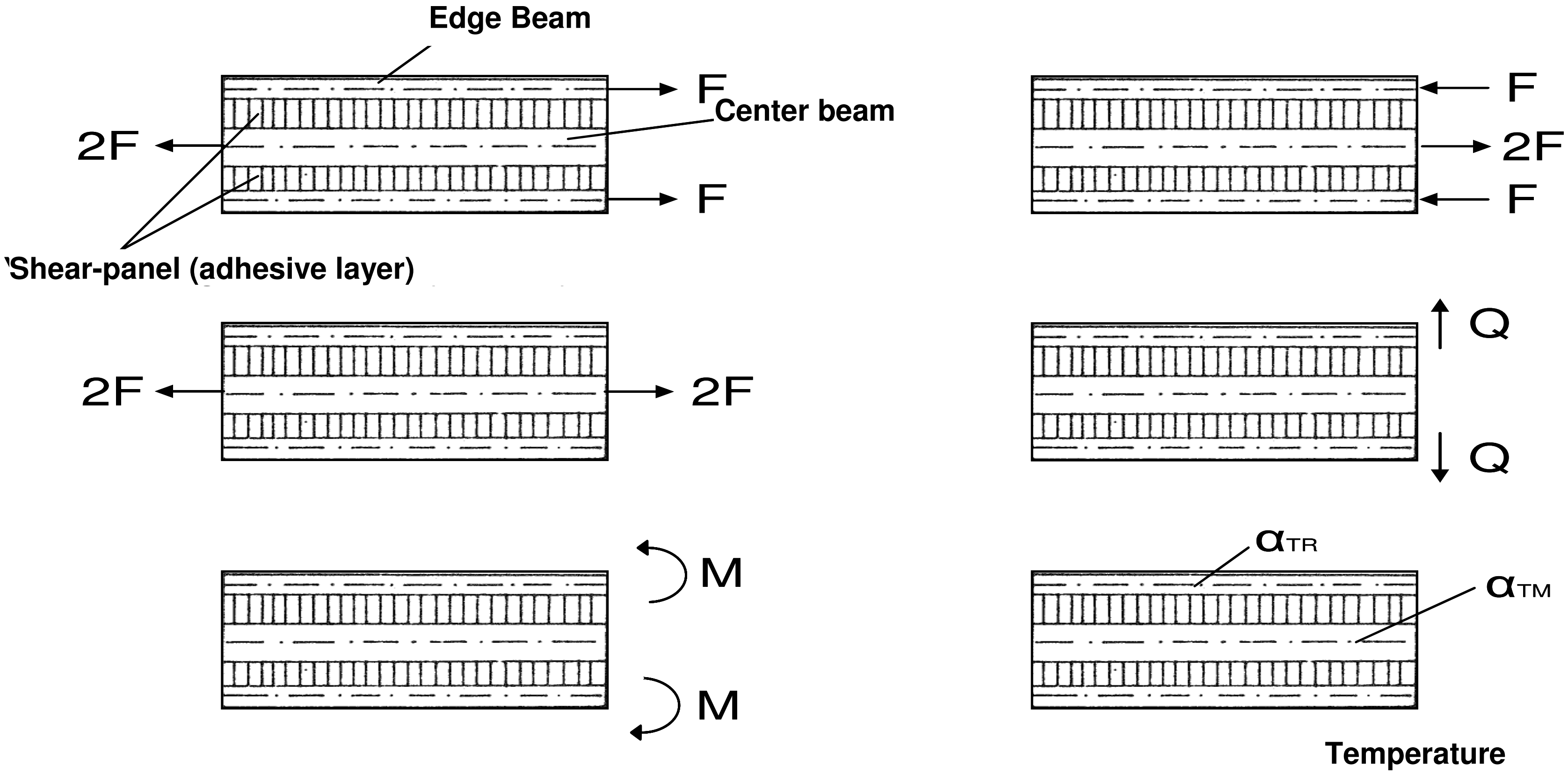
u, v are the Deformations, ε_x, ε_y are the Strains and γ the Shear Angle

c) The Relation between a) and b) can be established with the help of the Elasticity-Law with ν =0, E_x=0 :

$$\sigma_x = 0, \;\; \sigma_y = \mathrm{E}_y \varepsilon_y, \;\; \tau = \mathrm{G}\gamma$$

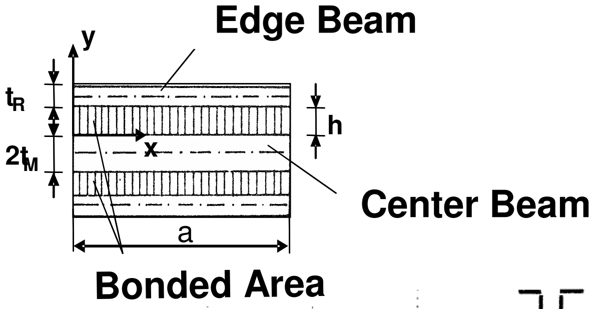
$$\begin{pmatrix} u \\ v \\ \sigma_y \\ \tau \end{pmatrix}' = \begin{pmatrix} 0 & -\partial_1 & 0 & 1/G \\ 0 & 0 & 1/E_y & 0 \\ 0 & 0 & 0 & -\partial_1 \\ 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} u \\ v \\ \sigma_y \\ \tau \end{pmatrix} \qquad (1)$$

Different Basic Loading Conditions



The “Three-Beam-Structure” with different loading situations

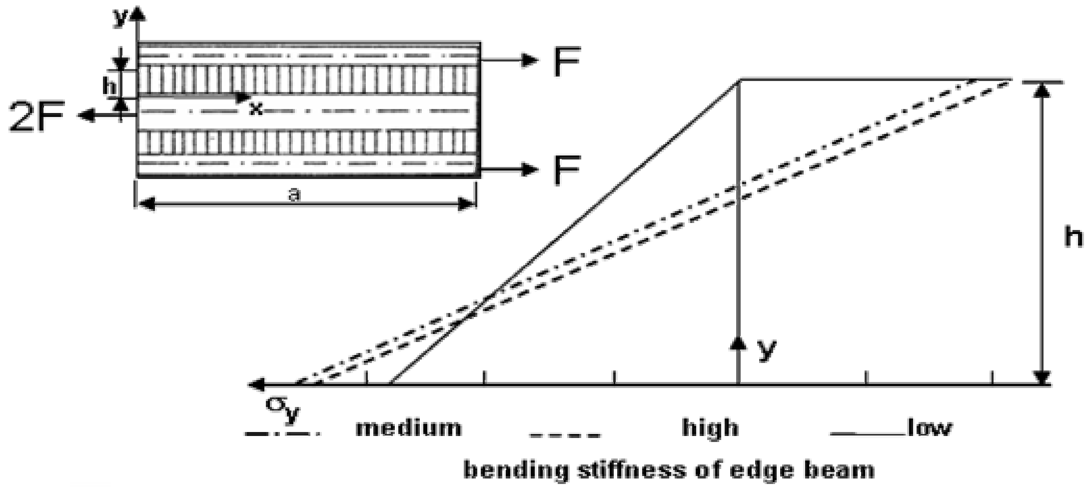
The Differential-Equation-System of the 1. Order for the „Three-Beam-Structure“

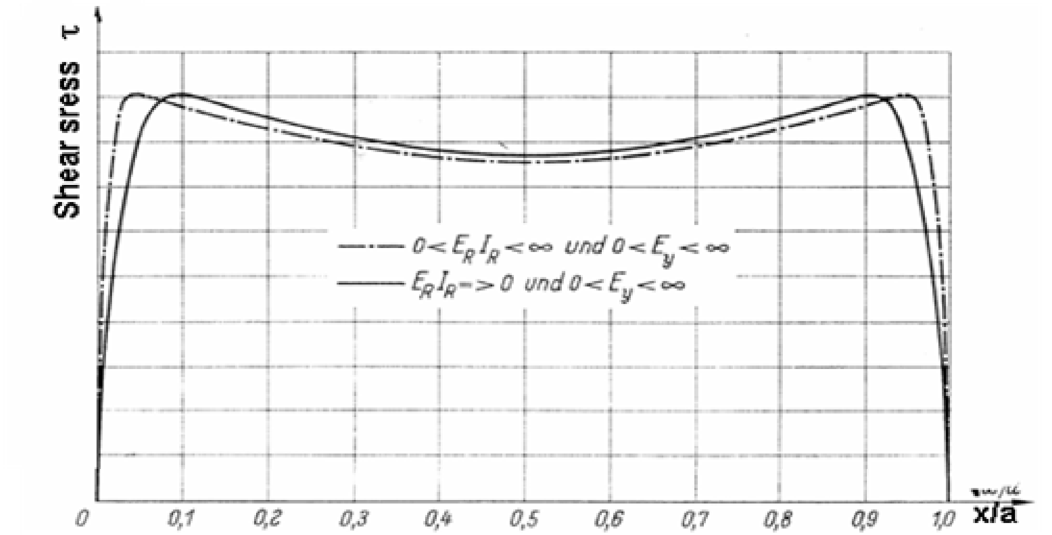


with $k = -6a(t_R/2 + h/3)/h^2$

$$\bar{\partial}_1 \begin{bmatrix} \bar{v}_R \\ \bar{\psi}_R \\ \bar{M}_R \\ \bar{Q}_R \\ \bar{u}_R \\ \bar{N}_{x,R} \\ \bar{\tau}_0 \\ \bar{\sigma}_{y0} \\ \bar{u}_M \\ \bar{N}_{x,M} \end{bmatrix} = \begin{bmatrix} & 1 & & & & & & & & \\ & & 1 & & & & & & & \\ & & & 1 & & & \frac{G\,t_R\,a^2}{2E_R I_R} & & & \\ -\frac{2a^4 E_y}{hE_R I_R} & & & & & & & \frac{a^3 E_y}{E_R I_R} & & \\ & & & & & 1 & & & & \\ & & & & & & \frac{aG}{t_R E_R} & & & \\ -\frac{2a^2 E_y}{h^2 G} & & & & & & & \frac{2aE_y}{hG} & & \\ & k & & & -6\frac{a^2}{h^2} & & 6\frac{a}{h} & & 6\frac{a^2}{h^2} & \\ & & & & & & & & & 1 \\ & & & & & & -\frac{aG}{E_M t_M} & & & \end{bmatrix} \begin{bmatrix} \bar{v}_R \\ \bar{\psi}_R \\ \bar{M}_R \\ \bar{Q}_R \\ \bar{u}_R \\ \bar{N}_{x,R} \\ \bar{\tau}_0 \\ \bar{\sigma}_{y0} \\ \bar{u}_M \\ \bar{N}_{x,M} \end{bmatrix}$$

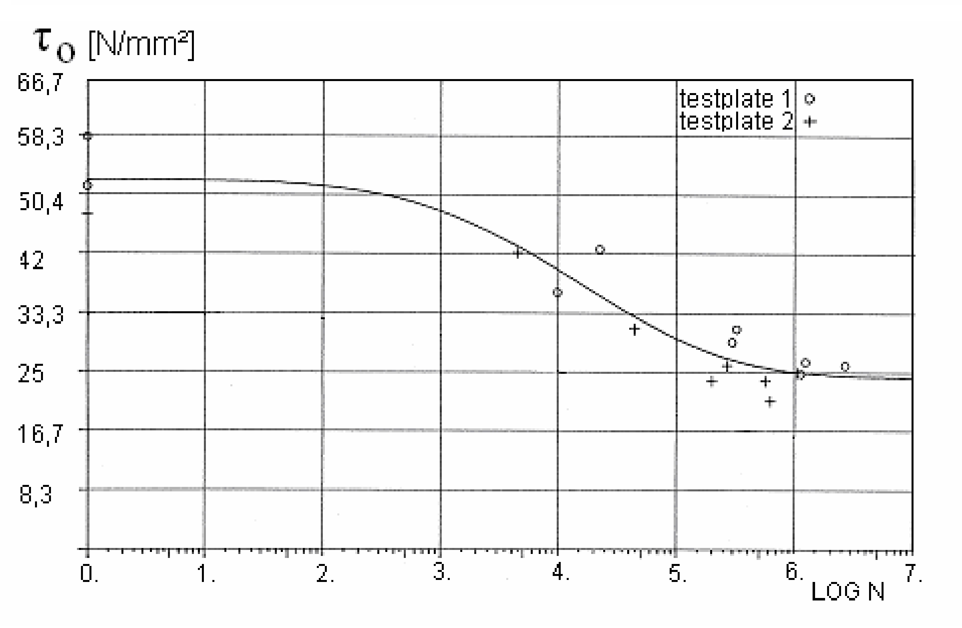
The Shear Stress Distribution for a Double Lap Joint Including the Transverse Stresses for Different Bending Stiffnesses of the Upper Beam

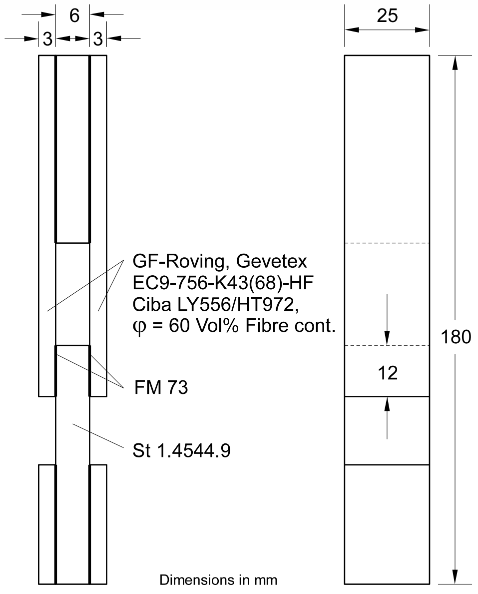




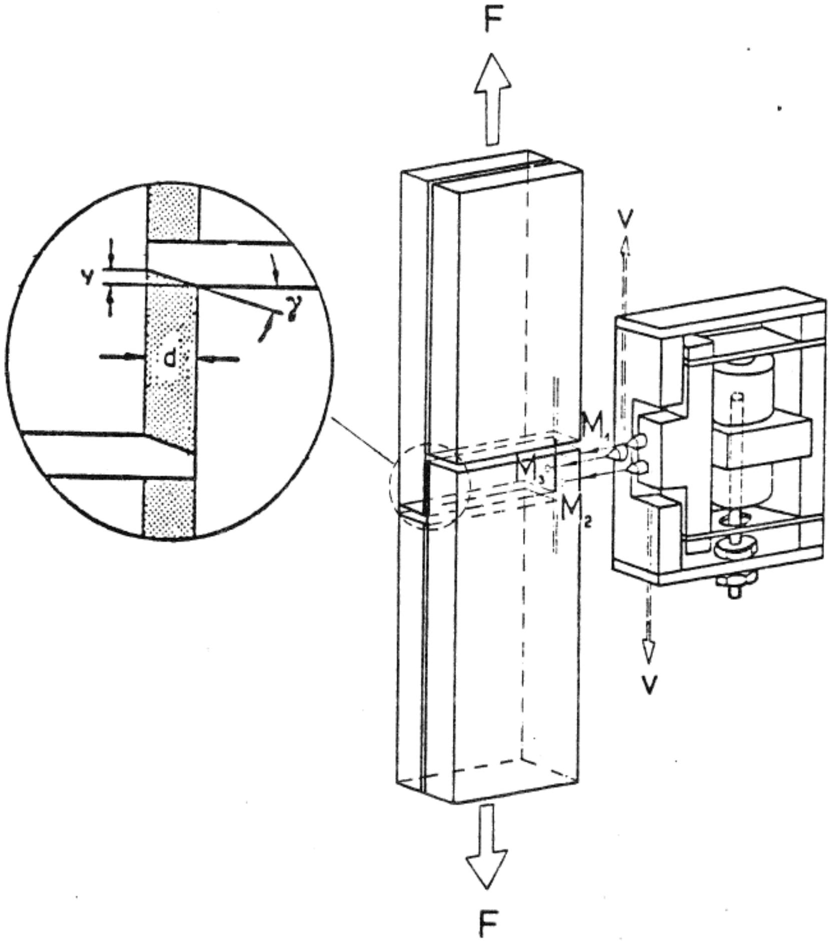
Stress Results of Double-Lap-Joints Loaded by Dynamic Tension for Different Material Combinations and the Adhesive FM 73

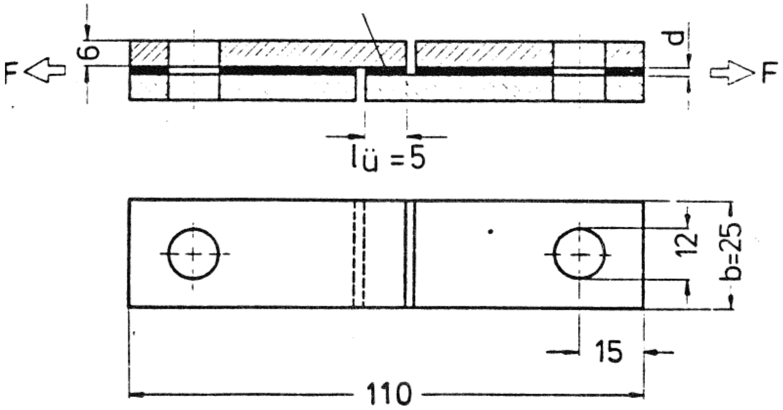
Material Combination	thickness of adhesive layer [mm]	factor for max. shear stress j [-]	max. static shear strength [N/mm²]	G_{cII} (static) [N/mm]	max. dyn. shear strength (10^7 cycles) [N/mm²]	G_{cII} (dynamic) [N/mm]
Ti/GFC	0,2	1,7	52,9	0,40	24,8	0,09
St/GFC	0,13	2,3	67,3	0,42	37,9	0,14
Al/Al	0,19	1,4	48,3	0,33	25,7	0,09



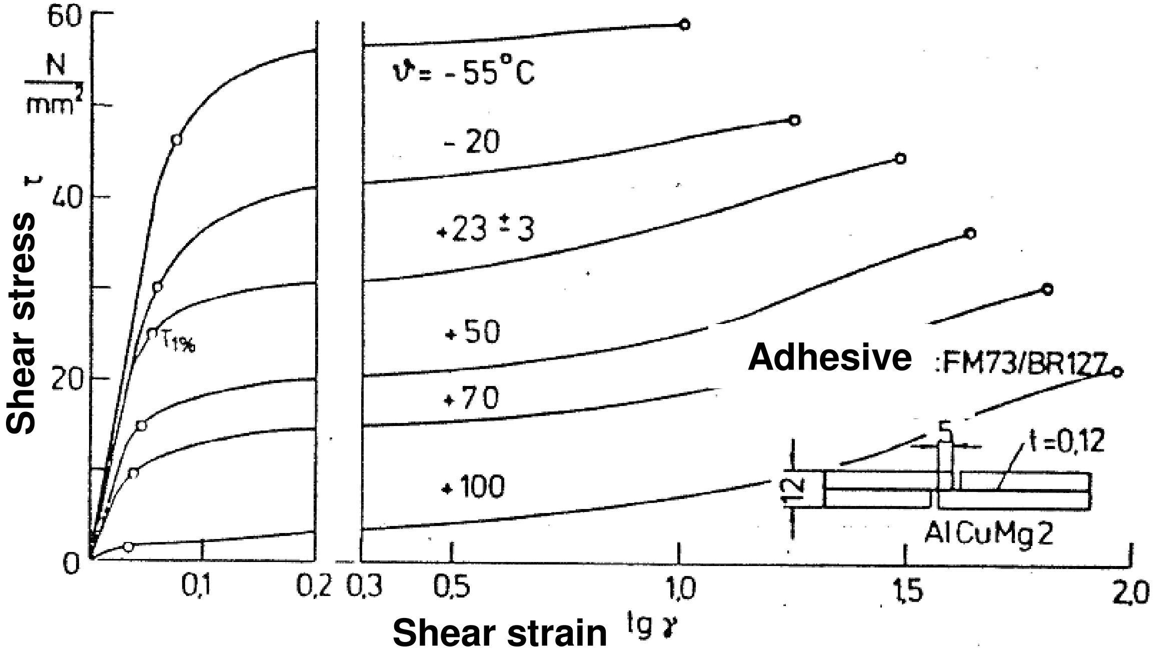


Test Equipment and Set-up for the Determination of the Shear-Strength and Shear-Strain Curves with the Help of Single-Lap Specimens

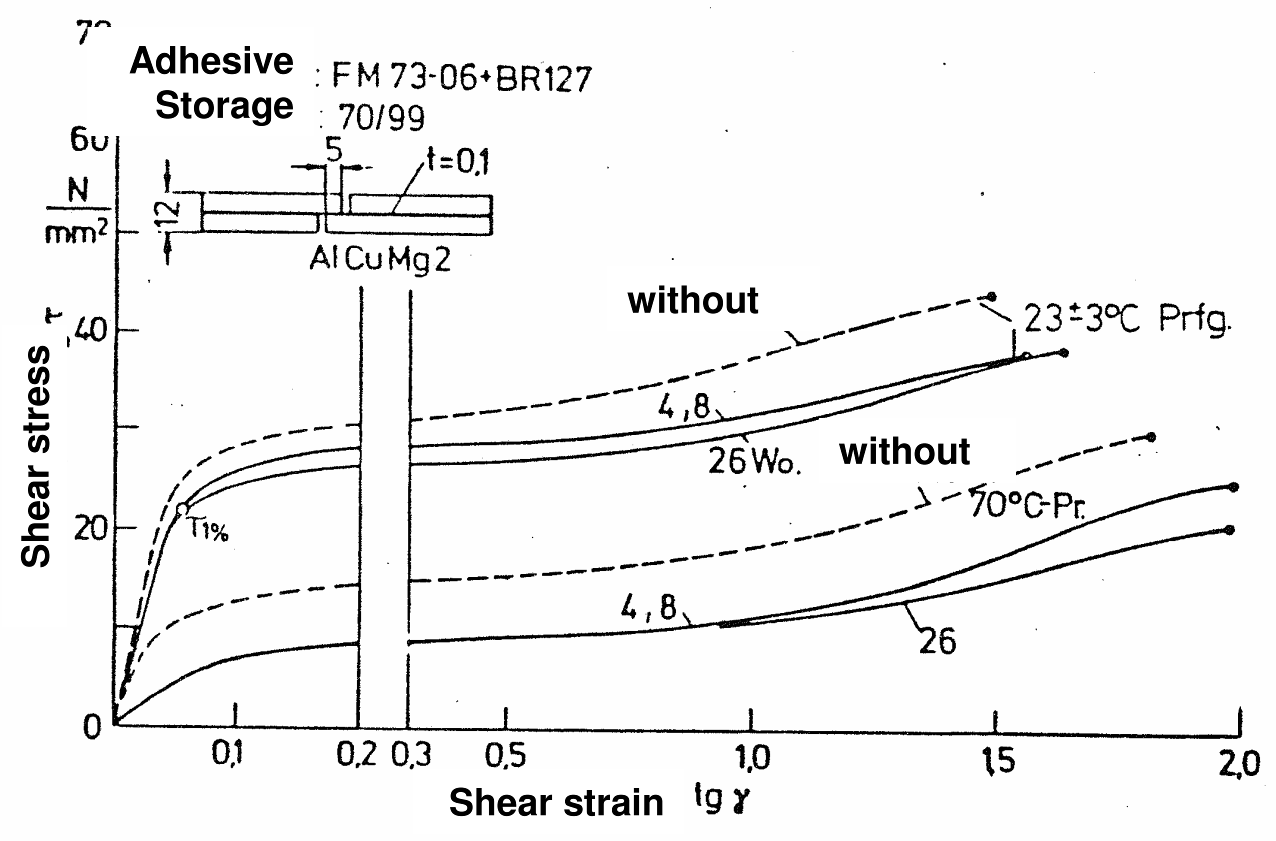



Bonded area

Shear-Strength and Shear-Strain Curves at different Temperatures (Adhesive: FM 73)



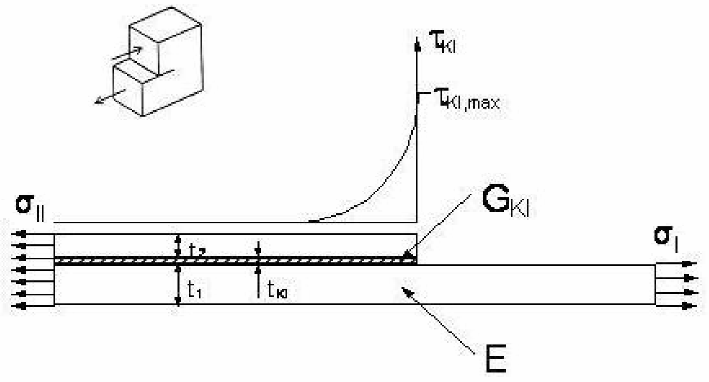
Shear-Strength and Shear-Strain Curves with and without Longtime Storage at hot/wet Conditions 70/99 (Kleber: FM 73)



Tension and Torsion Loaded Tapered and Bonded Laminates

The Commercial Helicopter EC 135 with the „Flex-Beam“ Attachment Area of the Blade

Bonded Erosion Strip, analized with the help of the „Shear-Lag“ Theory and the „Strain Energy Release Rate“



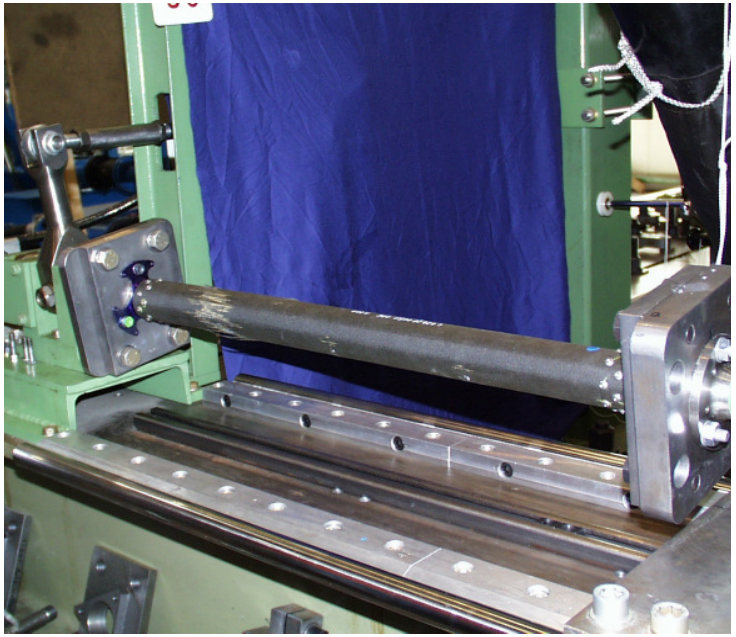
$$\tau_{Kl,max} = \sigma_{II} \cdot \sqrt{\frac{G_{Kl}}{t_{Kl}}} \cdot \sqrt{\frac{t_2 \cdot (t_1 + t_2)}{E \cdot t_1}}$$

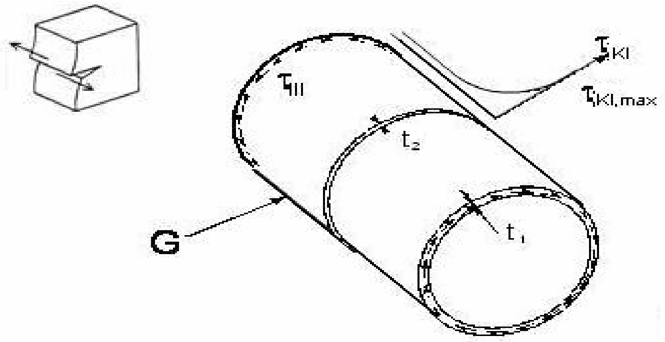
$$\sigma_{II} = \tau_{Kl,max} \sqrt{\frac{t_{Kl}}{G_{Kl}}} \cdot \sqrt{\frac{E \cdot t_1}{t_2 \cdot (t_1 + t_2)}}$$

$$\sigma_{II} = \sqrt{2 \cdot G_{C,II}} \cdot \sqrt{\frac{E \cdot t_1}{t_2 \cdot (t_1 + t_2)}}$$

$$G_{C,II} = \frac{1}{2} \cdot \tau^2_{Kl,max} \cdot \frac{t_{Kl}}{G_{Kl}}$$

Bonded and Riveted Drive Shaft, analized with the help of the „Shear-Lag“ Theorie and the „Strain Energy Release Rate“





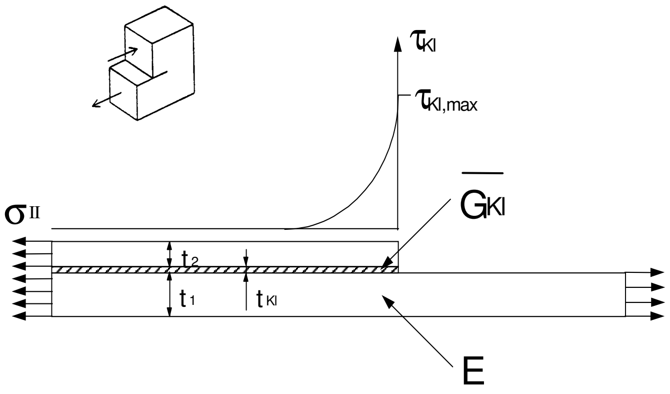
$$\tau_{KI,max} = \tau_{III} \cdot \sqrt{\frac{G_{KI}}{t_{KI}}} \cdot \sqrt{\frac{t_2 \cdot (t_1 + t_2)}{G \cdot t_1}}$$

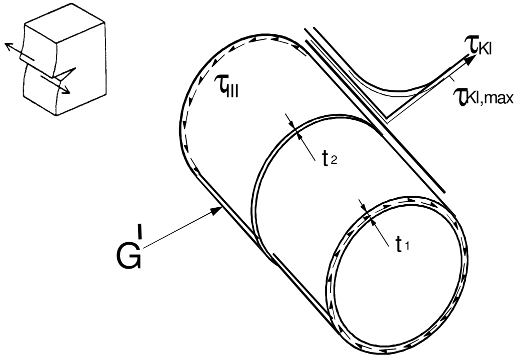
$$\tau_{III} = \tau_{KI,max} \sqrt{\frac{t_{KI}}{G_{KI}}} \cdot \sqrt{\frac{G \cdot t_1}{t_2 \cdot (t_1 + t_2)}}$$

$$\tau_{III} = \sqrt{2 \cdot G_{C,III}} \cdot \sqrt{\frac{G \cdot t_1}{t_2 \cdot (t_1 + t_2)}}$$

$$G_{C,III} = \frac{1}{2} \cdot \tau_{KI,max}^2 \cdot \frac{t_{KI}}{G_{KI}}$$

Tapered/Bonded Structure Loaded in Tension and in Torsion





$\sigma_{II} = \tau_{KI,max} \cdot \sqrt{\frac{t_{KI}}{\overline{G_{KI}}}} \cdot \sqrt{\frac{E \cdot t_1}{t_2 \cdot (t_1 + t_2)}}$	$\tau_{III} = \tau_{KI,max} \cdot \sqrt{\frac{t_{KI}}{\overline{G_{KI}}}} \cdot \sqrt{\frac{G' \cdot t_1}{t_2 \cdot (t_1 + t_2)}}$
$\sigma_{II} = \sqrt{2 \cdot G_{C,II}} \cdot \sqrt{\frac{E \cdot t_1}{t_2 \cdot (t_1 + t_2)}}$	$\tau_{III} = \sqrt{2 \cdot G_{C,III}} \cdot \sqrt{\frac{G' \cdot t_1}{t_2 \cdot (t_1 + t_2)}}$
$G_{C,II} = \frac{1}{2} \cdot (\tau_{KI,max})^2 \cdot \frac{t_{KI}}{\overline{G_{KI}}}$	$G_{C,III} = \frac{1}{2} \cdot (\tau_{KI,max})^2 \cdot \frac{t_{KI}}{\overline{G_{KI}}}$

Summary

- **Bonded structures are widely used for highly loaded helicopter elements**
- **Examples for bonded helicopter elements are e.g. the metallic erosion strips bonded to the composite rotor blades**
- **Stress analysis according to the "Transfer-Matrix" method is a important analytical tool for calculating shear stresses**
- **Tension and torsion loaded tapered and bonded laminates can also be analyzed by energy methods (Strain-Energy-Release-Rate)**
- **Stress-strain curves are important for the calculation of shear stresses in an inelastic range**

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