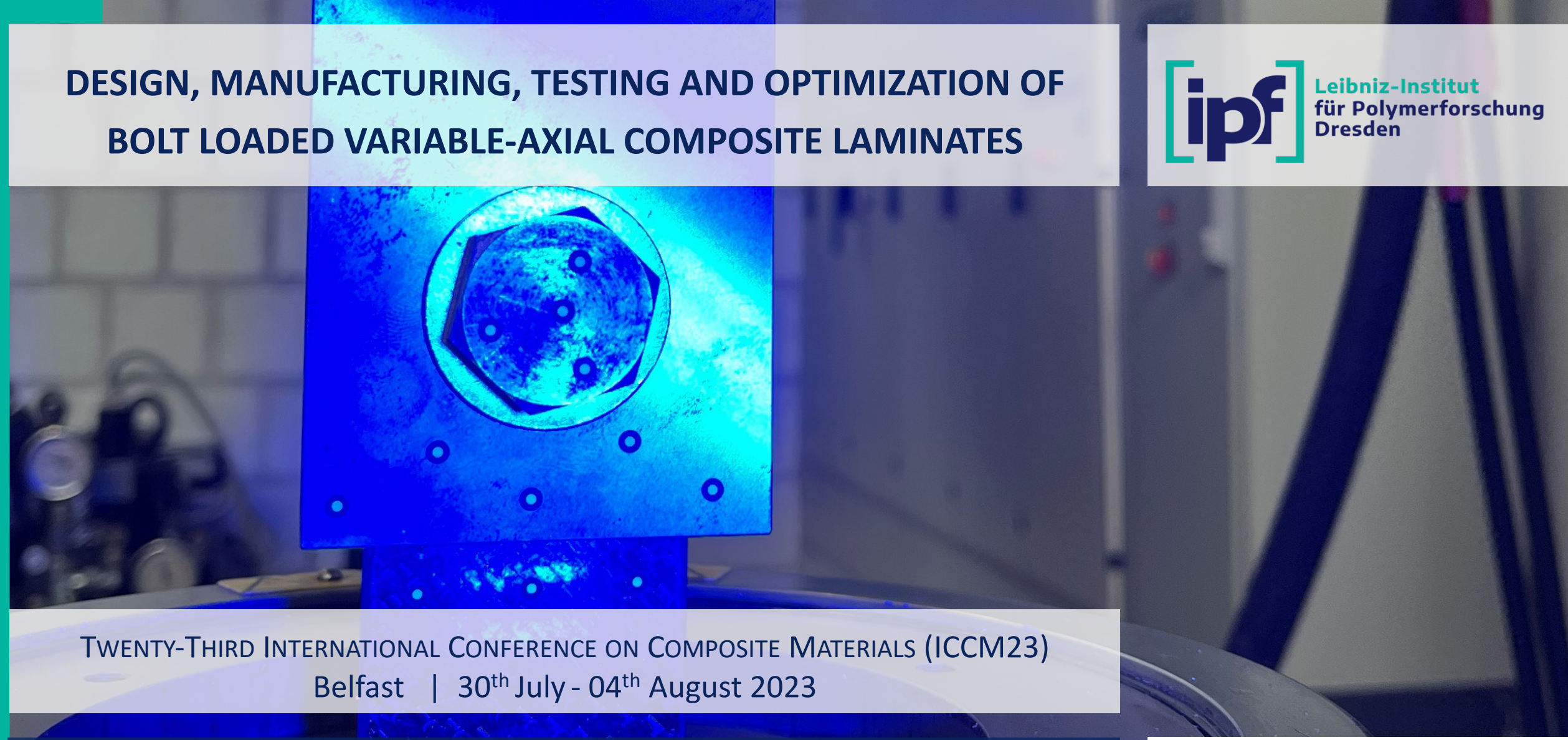
DESIGN, MANUFACTURING, TESTING AND OPTIMIZATION OF BOLT LOADED VARIABLE-AXIAL COMPOSITE LAMINATES



TWENTY-THIRD INTERNATIONAL CONFERENCE ON COMPOSITE MATERIALS (ICCM23)
Belfast | 30th July - 04th August 2023

Axel Spickenheuer[1,*], Tales V. Lisbôa[1], E.A.W. de Menezes[1], Markus Stommel[1,2], Kai Uhlig[1], Lars Bittrich[1], Andreas Freund[3]

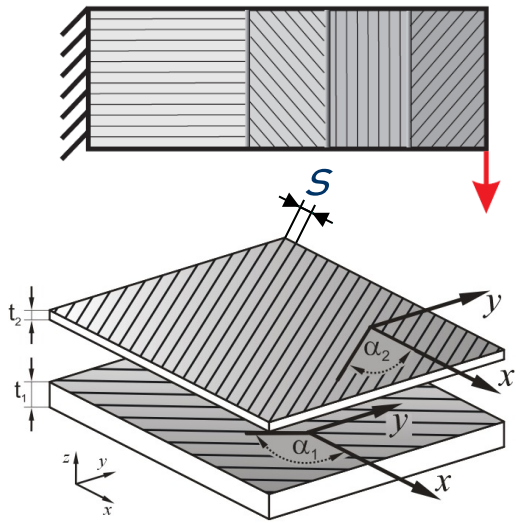
1 Leibniz-Institute für Polymerforschung Dresden e. V.; 2 TU Dresden, Institute of Material Science; 3 Realize Engineering Dresden GmbH

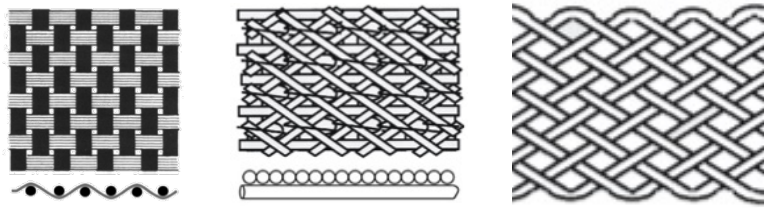
Fiber-reinforced plastics (FRP)

Multi-axial vs. variable-axial

Composite design 1.0

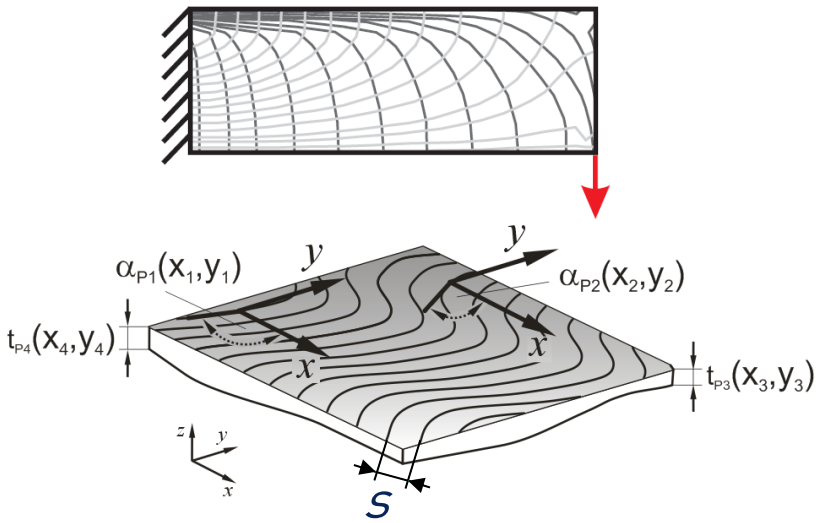
multi-axial





Composite design 2.0

variable-axial

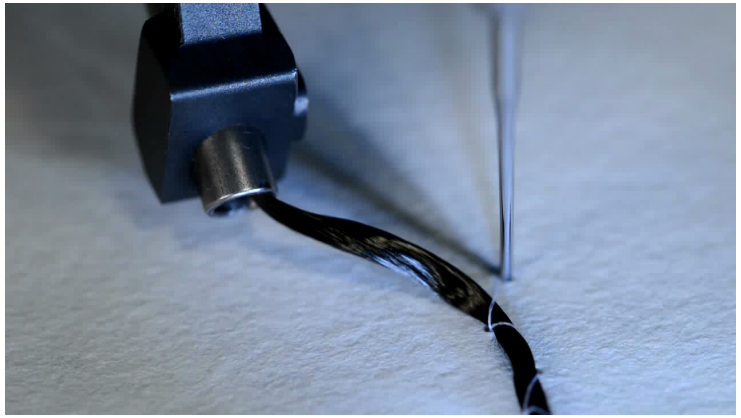


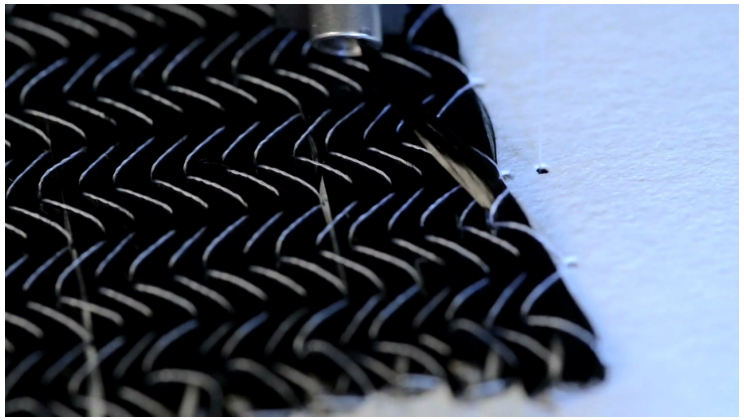
α ≠ const.

s ≠ const.
t = f(s)

Fiber-reinforced plastics (FRP)

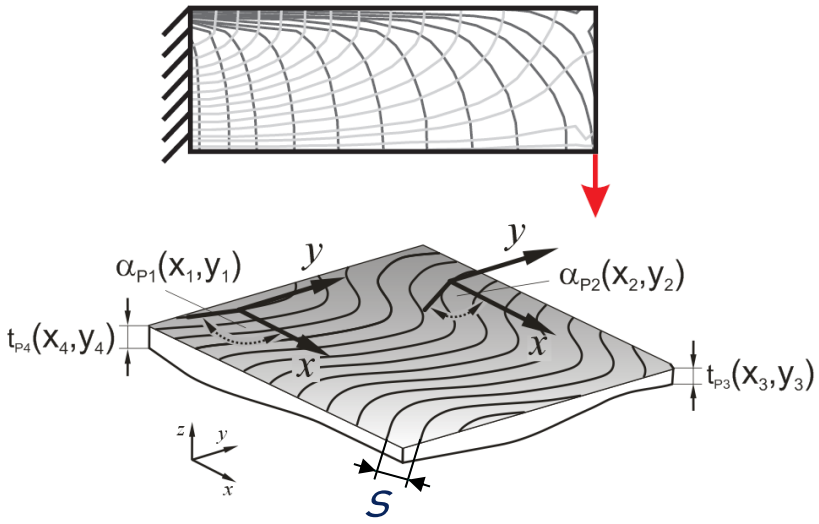
Variable-axial FRP by Tailored Fiber Placement (TFP)





Composite design 2.0

variable-axial

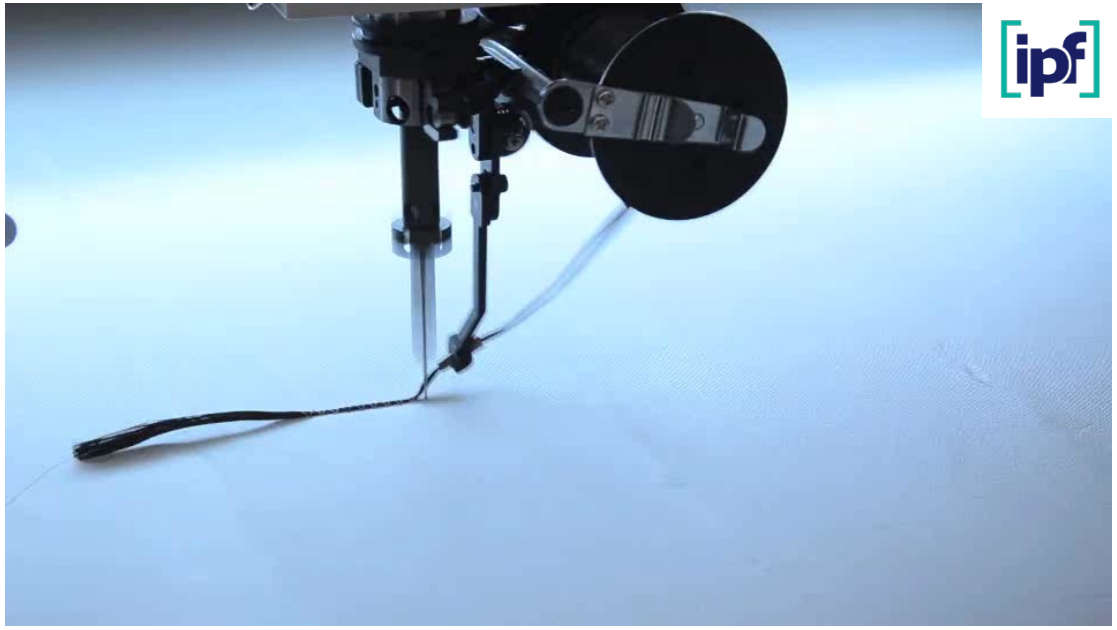


α ≠ const.

s ≠ const.
t = f(s)

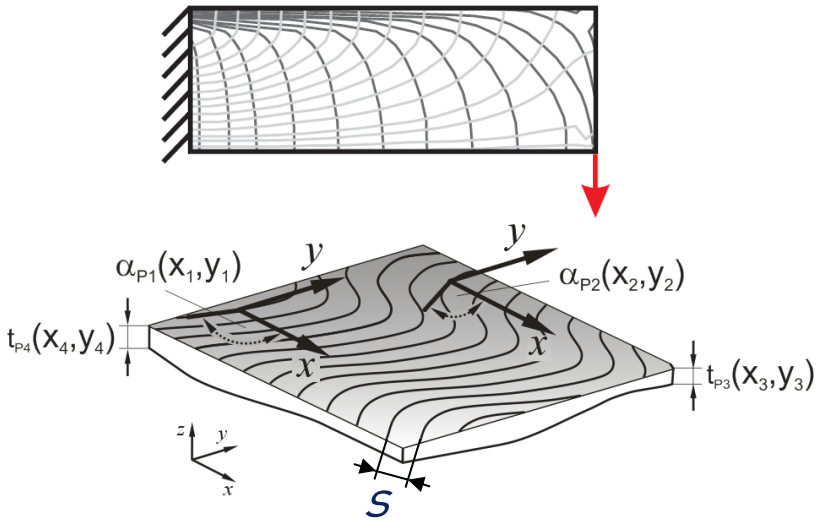
Fiber-reinforced plastics (FRP)

Variable-axial FRP by Tailored Fiber Placement (TFP)



Composite design 2.0

variable-axial

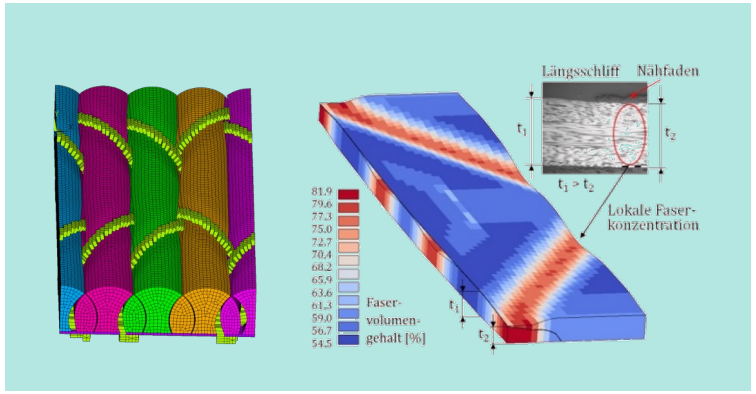


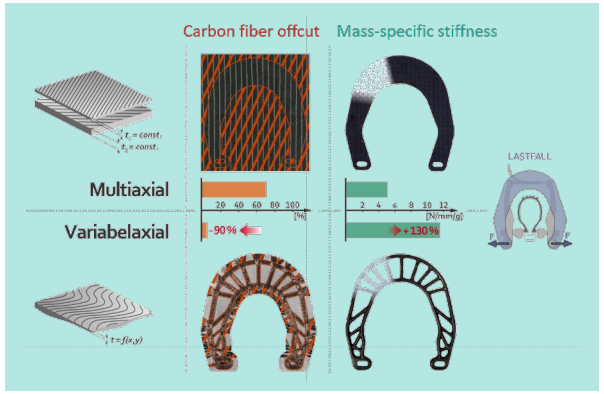
α ≠ const.

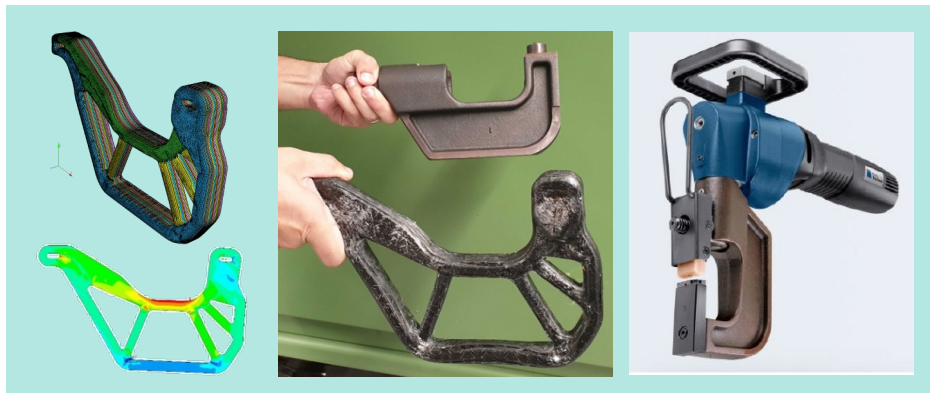
s ≠ const.
t = f(s)

Variable-axial composites made by Tailored Fiber Placement

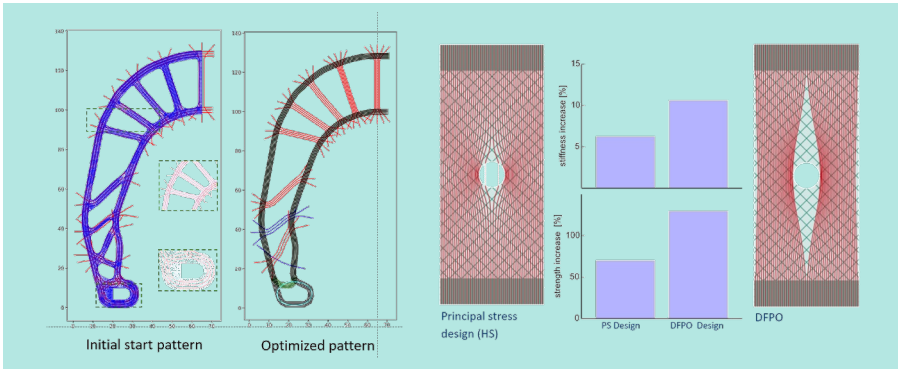
From basic research to industrial deployment

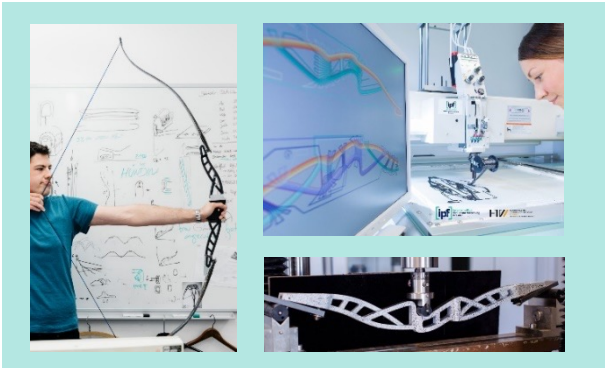


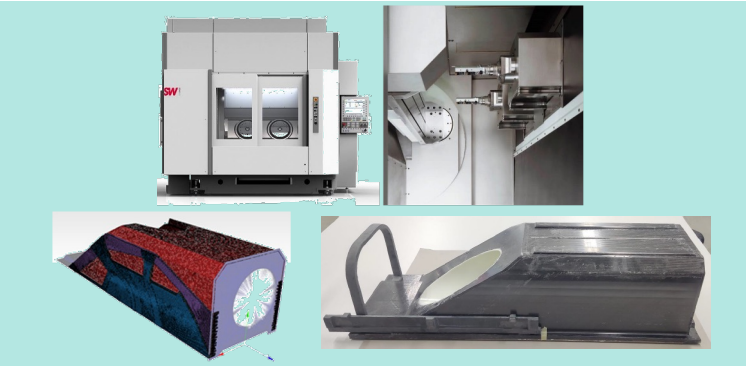




TRL1 TRL4 TRL7





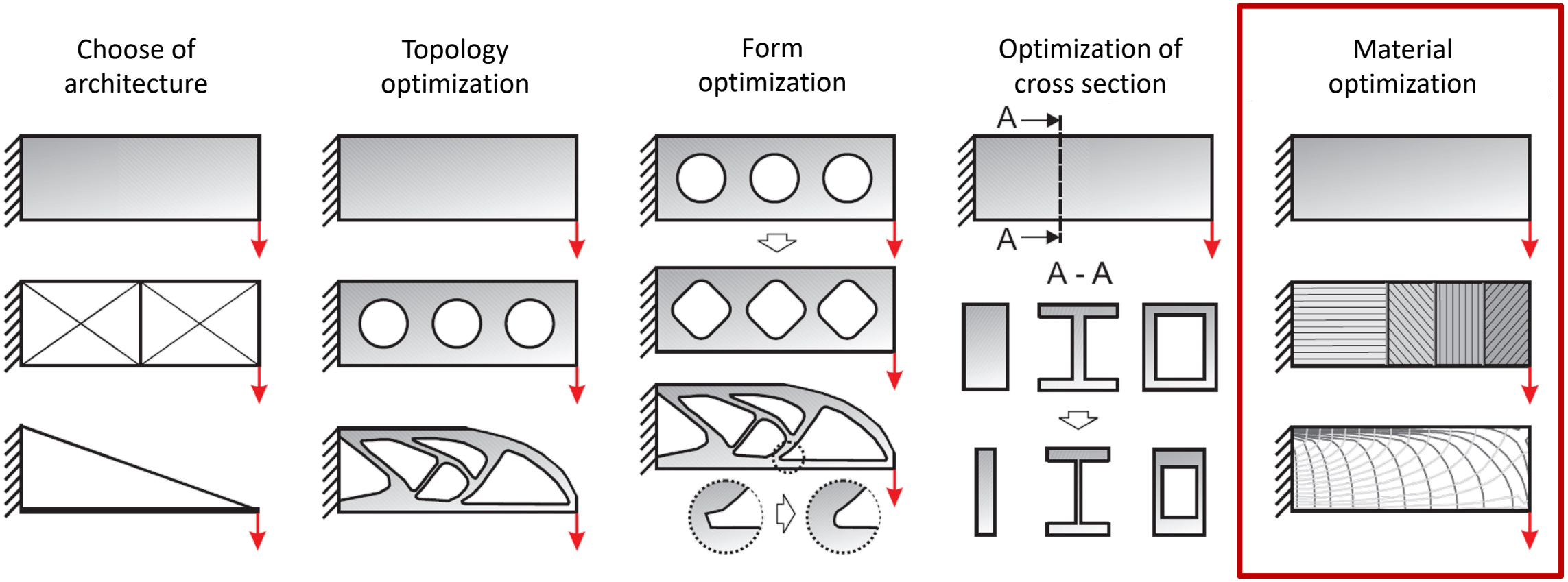


Multi-scale modelling and optimization methods

Process chain for variable-axial composites

Development of industrial components

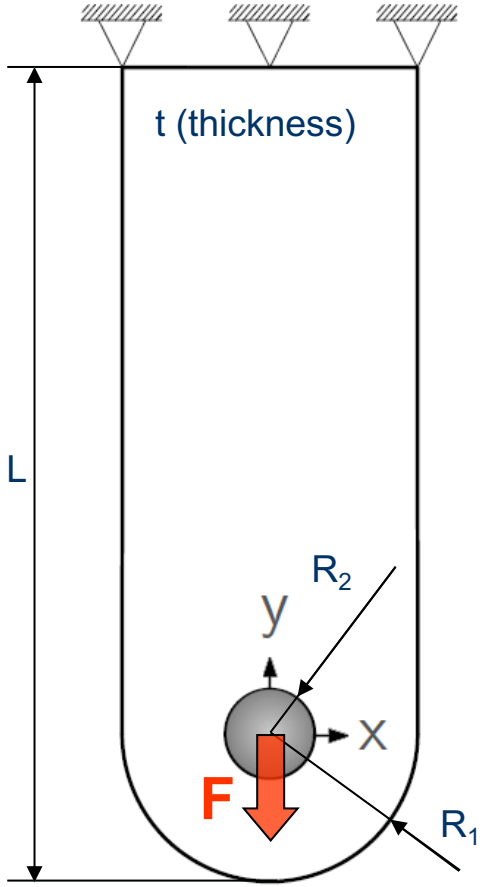
How to design variable-axial composite structures?



Analysis and optimization of bolted joints made by variable-axial laminates

What in-plane fiber orientation strategy shows advantageous mechanical performance?

- Calibration of progressive damage simulation for structural optimization by experimental research
- No consideration of out-of-plane reinforcements



Dimensions of specimen

R_1 = 25 mm, R_2 = 7,5 mm,

L = 170 mm, t ≈ 5 mm

Bolted joints with tailored fiber orientation in literature

1997

Composites Part A 28A (1997) 619–625
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PII:S1359-835X(97)00022-5
1359-835X/97/$17.00

Tailored fibre placement to minimise stress concentrations

P. J. Crothers[a,*], K. Drechsler[b], D. Feltin[c], I. Herszberg[d] and T. Kruckenberg[d]
[a]The Sir Lawrence Wackett Centre for Aerospace Design Technology, Royal Melbourne Institute of Technology, P.O. Box 2476V, Melbourne, Vic. 300, Australia
[b]Daimler Benz AG, Research and Technology, P.O.Box 80 04 65, 81663 Munich, Germany
[c]Institute for Polymer Research Dresden (IPF-Dresden), Hohe Straße 6, D-01069 Dresden, Germany
[d]Cooperative Research Centre for Advanced Composite Structures (CRC-ACS) Ltd, 506 Lorimer St., Fishermens Bend, Vic. 3207, Australia
(Received 16 February 1996; accepted 8 November 1996)

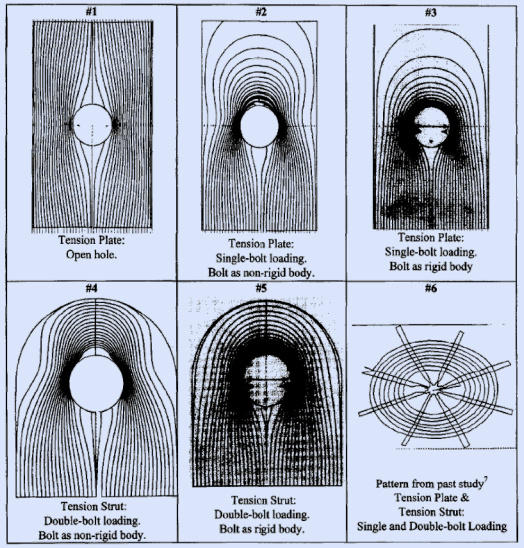


Figure 5 Patterns for TFP reinforcement of test components

1999

Interpreting load paths and stress trajectories in elasticity

D.W. Kelly and M.W. Tosh
School of Mechanical and Manufacturing Engineering, University of New South Wales, Sydney, Australia

Received March 1999
Revised November 1999
Accepted December 1999

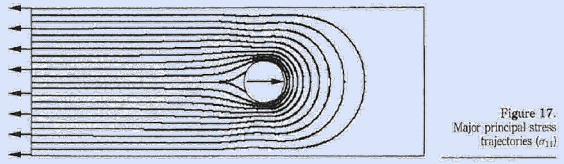


Figure 17. Major principal stress trajectories (σ_{11})

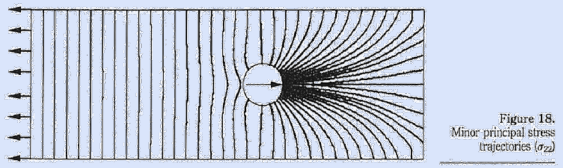


Figure 18. Minor principal stress trajectories (σ_{22})

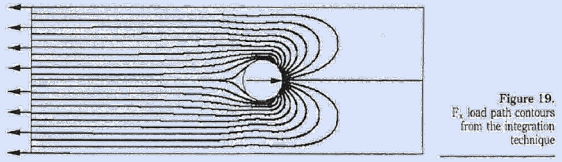
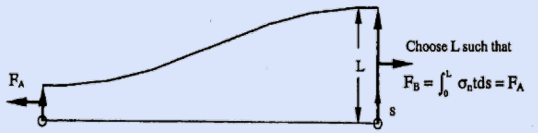


Figure 19. F_x load path contours from the integration technique



2000

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Composites: Part A 31 (2000) 1047–1060
composites
Part A: applied science and manufacturing
www.elsevier.com/locate/compositesa

On the design, manufacture and testing of trajectorial fibre steering for carbon fibre composite laminates☆

M.W. Tosh, D.W. Kelly*
School of Mechanical and Manufacturing Engineering, University of New South Wales, Sydney 2052, Australia
Received 7 May 1999; revised 15 March 2000; accepted 23 March 2000

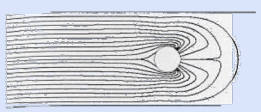


Fig. 15. Contours of dominant principal stress.

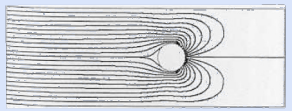


Fig. 16. Dominant or X-direction load paths for an isotropic material

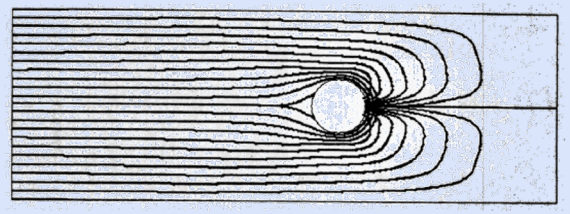
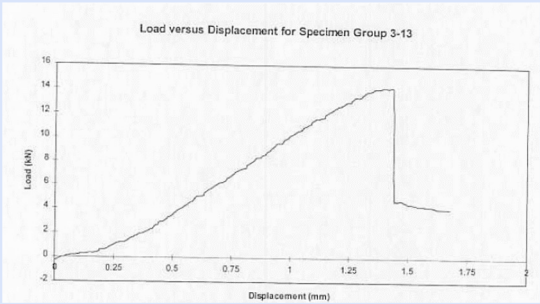


Fig. 21. Hybrid combination of anisotropic load path and tensile principal stress trajectories.



2002

ELSEVIER
Composite Structures 57 (2002) 377–383
COMPOSITE STRUCTURES
www.elsevier.com/locate/compstruct

Strength improvement by fibre steering around a pin loaded hole ☆

R. Li [a], D. Kelly [a,*], A. Crosky [b]
[a] School of Mechanical and Manufacturing Engineering, University of New South Wales, Sydney NSW 2052, Australia
[b] School of Materials Science and Engineering, University of New South Wales, Sydney NSW 2052, Australia

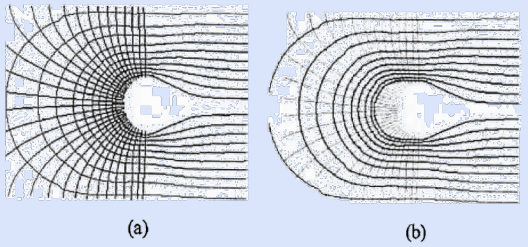


Fig. 9. Reduction of fibre over stacking: (a) FEA pattern; (b) modified pattern.

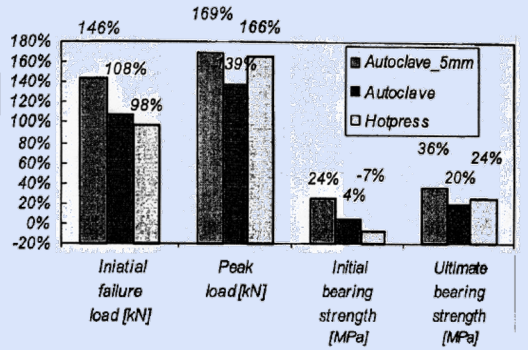


Fig. 10. Effect of fibre steering on strength of the carbon fibre bolted joints.

Bolted joints with tailored fiber orientation in literature

2006

Improving the Efficiency of Fiber Steered Composite Joints using Load Path Trajectories*

R. Li,[1] D. Kelly,[1,†] A. Crosky,[2] H. Schoen[2] and L. Smollich[2]
[1]School of Mechanical and Manufacturing Engineering
University of New South Wales, Sydney 2052, Australia
[2]School of Materials Science and Engineering
University of New South Wales, Sydney 2052, Australia

(Received February 16, 2005)
(Accepted August 23, 2005)

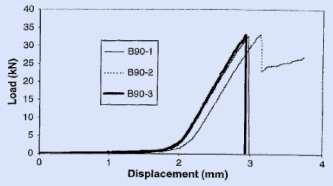


Figure 9. Test curves for 90 mm wide baseline specimens.

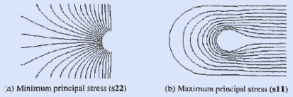


Figure 2. Principal stress trajectories for fiber placement.

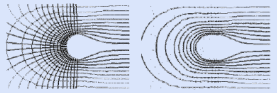


Figure 3. Reduction of fiber over stacking near the bearing surface.

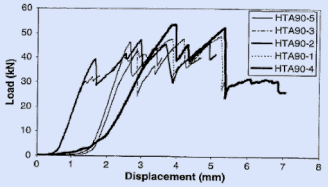


Figure 10. Test curves for 90 mm wide steered fiber specimens.

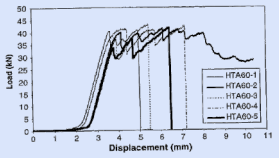


Figure 12. Test curves for 60 mm wide steered fiber specimens.

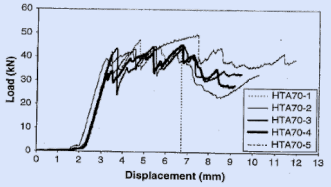


Figure 11. Test curves for 70 mm wide steered fiber specimens.

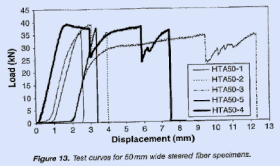


Figure 13. Test curves for 50 mm wide steered fiber specimens.

2006

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Composite Structures 76 (2006) 260–271
COMPOSITE STRUCTURES
www.elsevier.com/locate/compstruct

Improvement of bearing strength of laminated composites ☆

A. Crosky [a], D. Kelly [b,*], R. Li [b], X. Legrand [c], N. Huong [a], R. Ujjin [b]
[a] School of Materials Science and Engineering, University of New South Wales, Sydney, NSW 2052, Australia
[b] School of Mechanical and Manufacturing Engineering, University of New South Wales, Sydney, NSW 2052, Australia
[c] Ecole Nationale des Arts et Industrie Textiles, Laboratoire GEMTEX, 9 rue de l'Ermitage – BP 30329, 59100 Roubaix, France

Available online 1 August 2006

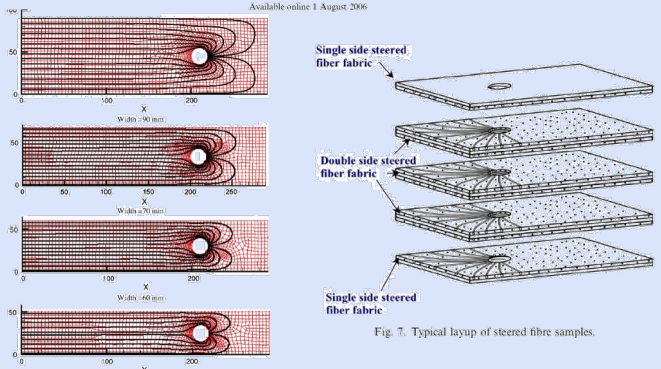


Fig. 7. Typical layup of steered fibre samples.

Fig. 15. Dominant load path trajectories (hole diameter = 20 mm).

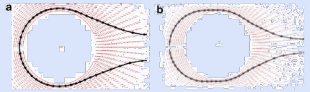


Fig. 8. Modification of fibre steering patterns: (a) FEA s11 trajectory and (b) s11 shifted 5 mm away from edge.

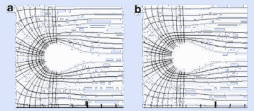


Fig. 9. Reduction of fibre over stacking: (a) FEA pattern and (b) modified pattern.

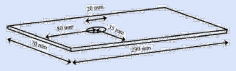


Fig. 10. Dimension of specimens.

Table 2
Bearing test results

Group	Ultimate failure mode	Peak load (kN)	Ultimate strength (MPa)	Weight (g)	Bearing area (mm²)
Baseline	Bearing [12]	9.55	367.80	42.50	26.40
Steered	Net section [14]	22.86	441.24	49.73	51.83
Modified steered	Net section [14]	25.65	500.40	56.58	51.27

2016

Zur Erlangung des akademischen Grades
Doktor der Ingenieurwissenschaften
der Fakultät für Maschinenbau
Karlsruher Institut für Technologie (KIT)

genehmigte
Dissertation
von

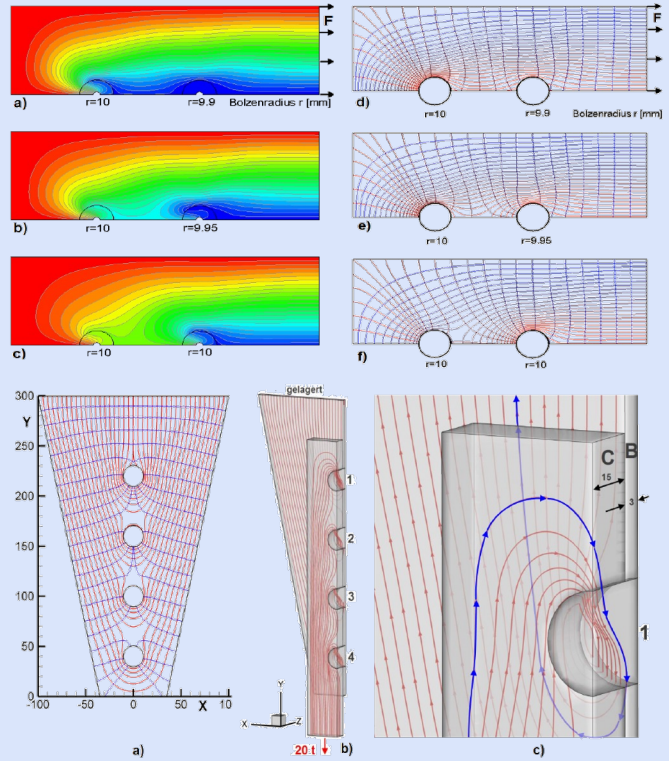
Dipl.-Ing. Herbert Moldenhauer

Die orthotrope Wärmeleitung als numerischer Integrator allgemeiner Richtungsfelder mit Anwendung zur optimalen Faserplatzierung und Kraftflussvisualisierung

Tag der Einreichung: 21. Juni 2016
Tag der mündlichen Prüfung: 12. September 2016

Hauptreferent: Prof. Dr. rer. nat. Claus Mattheck
Koreferent: Prof. Dr.-Ing. Frank Henning

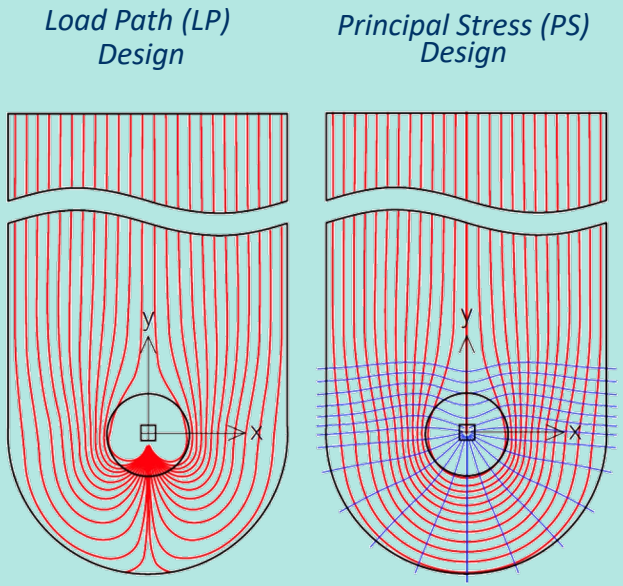
Die Visualisierung des Kraftflusses in Stahlbaukonstruktionen



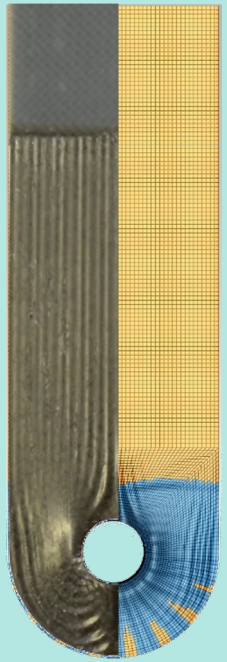
Bolted joints with tailored fiber orientation

Steps for optimizing design process

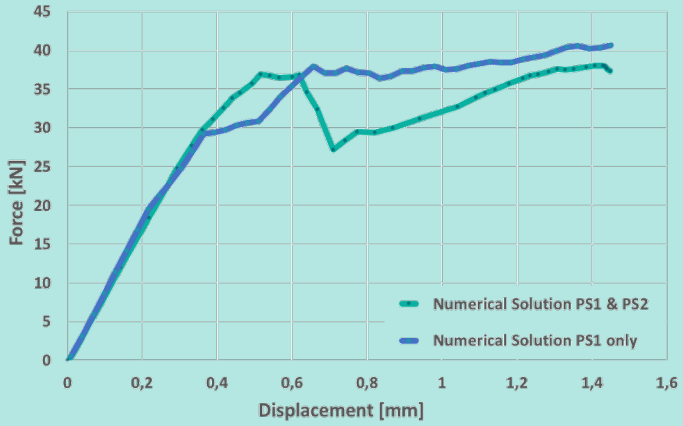
VA patter design based on isotropic calculations

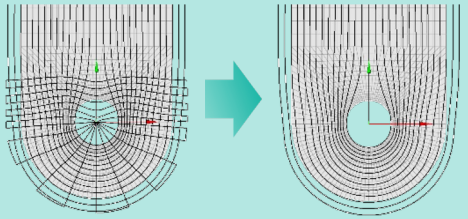


Experimental evaluation and model calibration



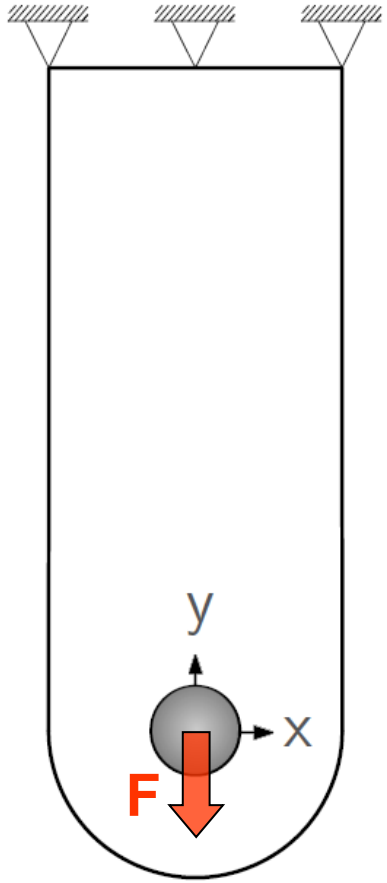
Optimization of VA pattern design

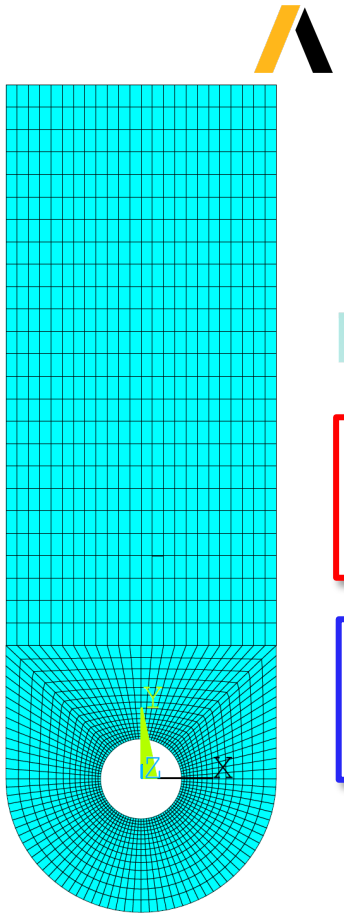




VA pattern design based on isotropic calculations

Principal Stress (PS) Design

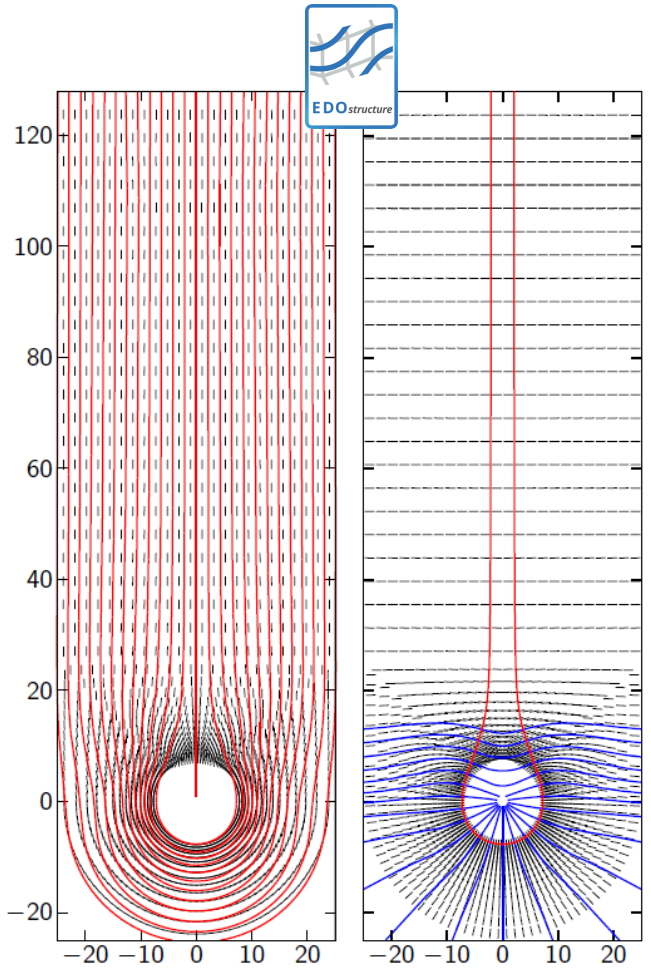




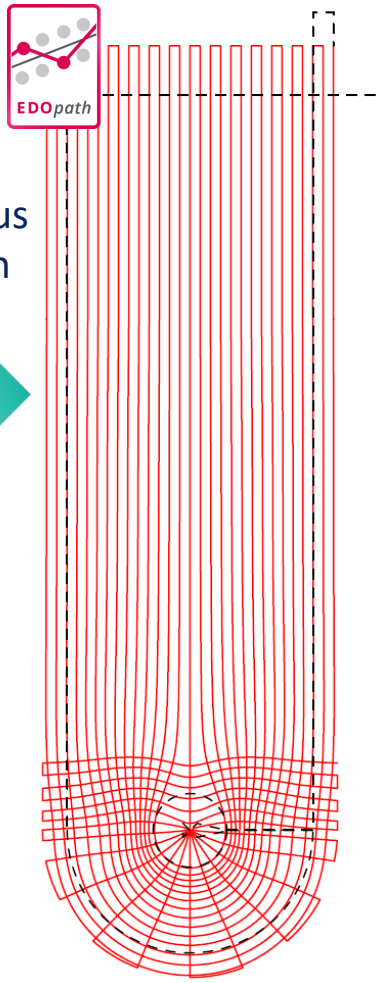
Calculation of PS directions

$$\tan 2\alpha_1 = \frac{2\sigma_{12}}{\sigma_{11} - \sigma_{22}}$$

$$\alpha_2 = \alpha_1 + \frac{\pi}{2}$$



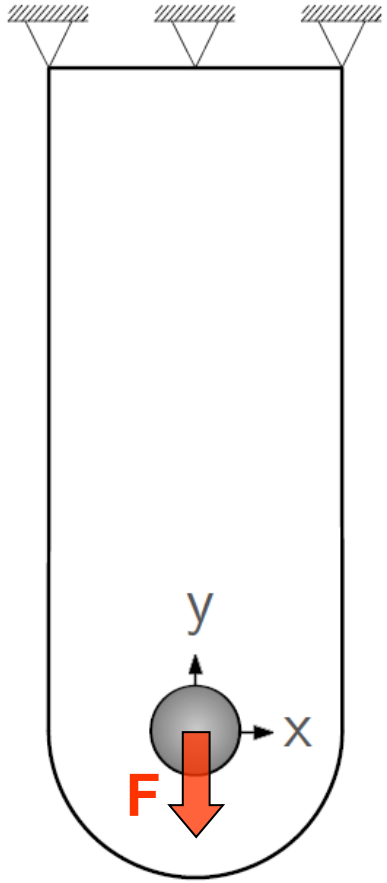
Continuous CNC path for TFP

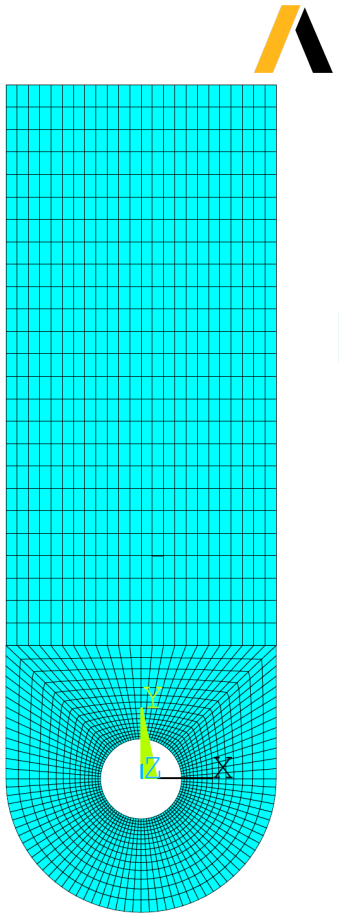


----- Contour line

VA pattern design based on isotropic calculations

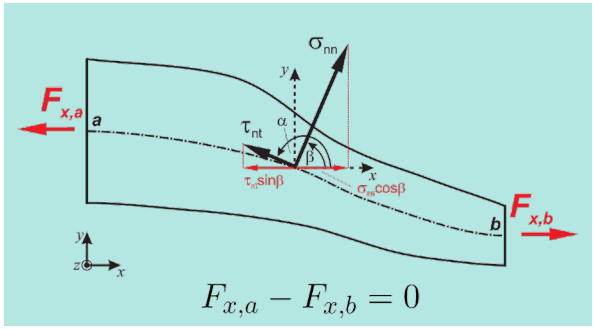
Load Path (LP) Design [1]

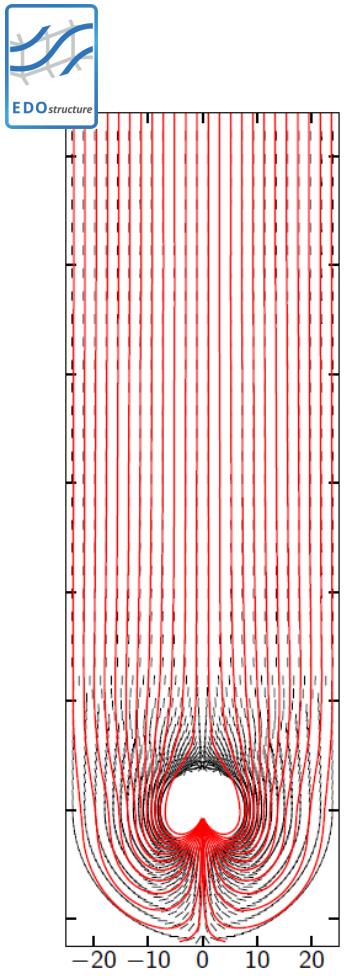




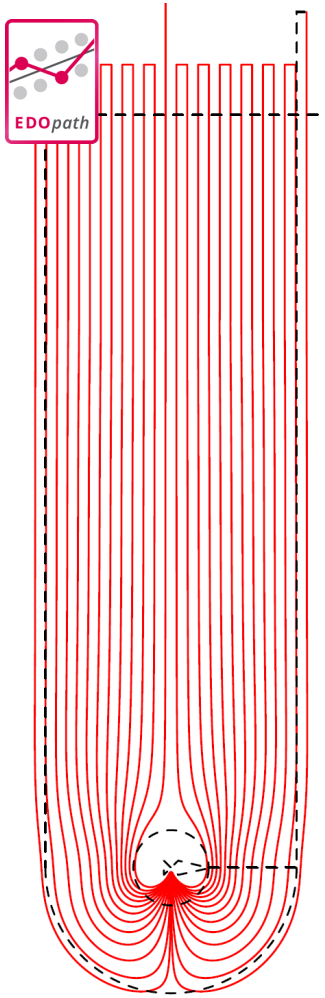
Calculation of
Load Path directions

$$\tan \alpha_y = \frac{\sigma_{12}}{\sigma_{11}}$$





Continuous
CNC path
for TFP

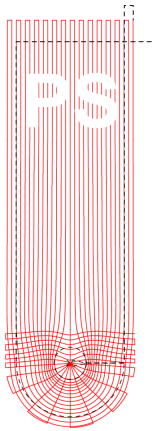


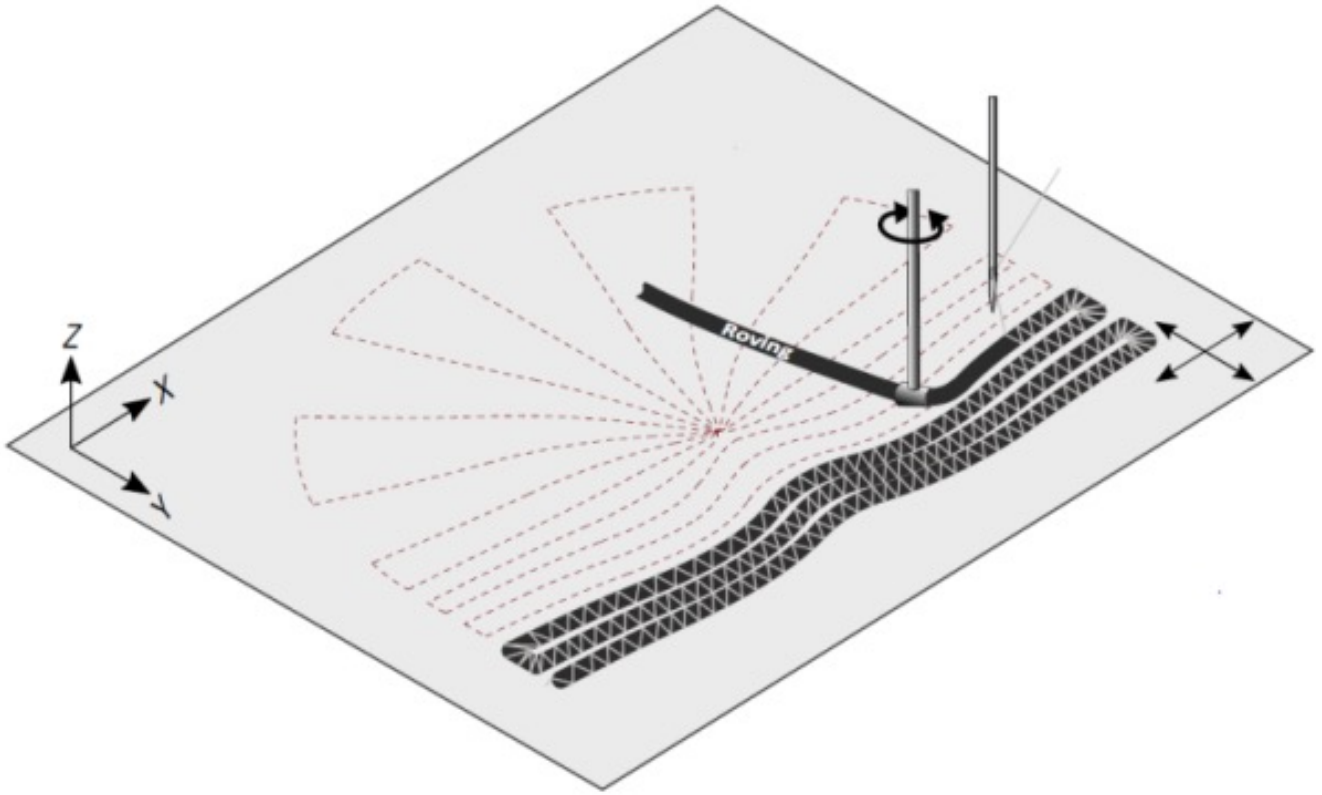
----- Contour line

[1] Kelly, D. & Elsley, M. A Procedure for Determining Load Paths in Elastic Continua Engineering Computation (**1995**), 12, 415-424

Experimental evaluation and model calibration

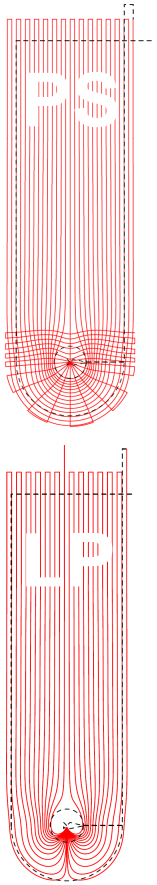
Manufacturing of specimen

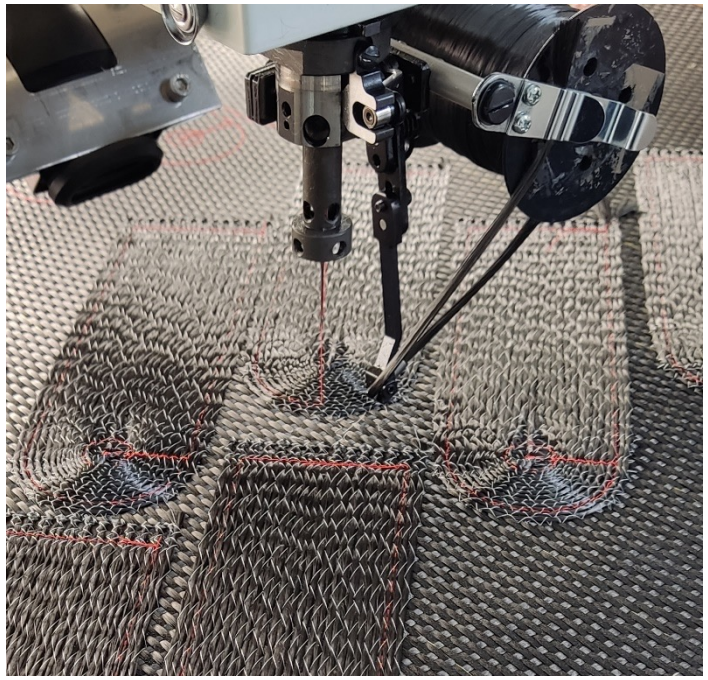




Experimental evaluation and model calibration

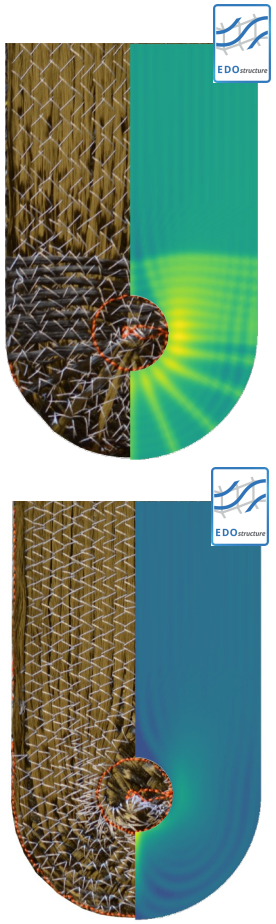
Manufacturing of specimen



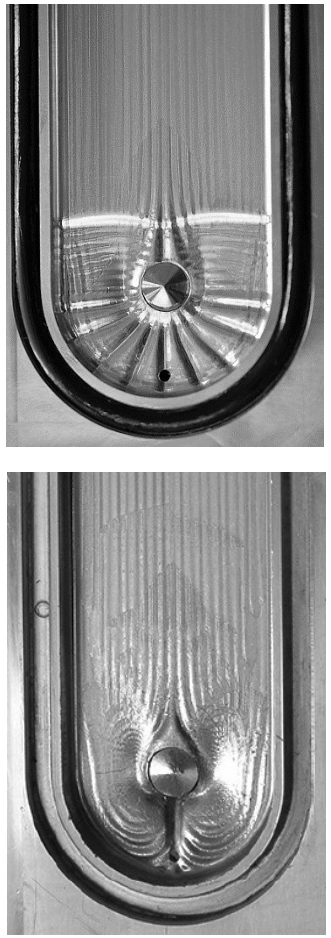


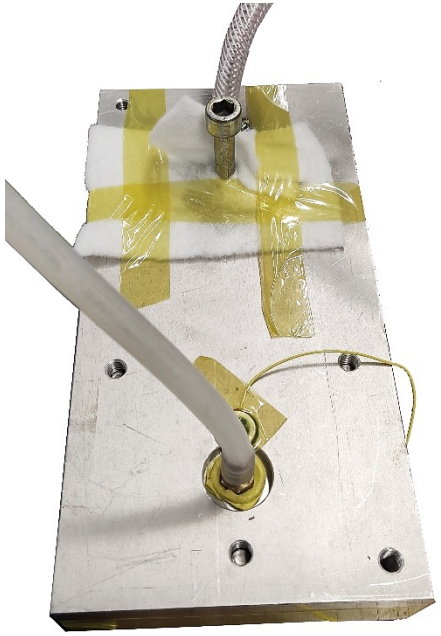
Roving material: CF-HT, 400 tex (6k)

Base material: CF-HT woven fabric, m_A = 380 g/m²



Thickness adapted RTM molds

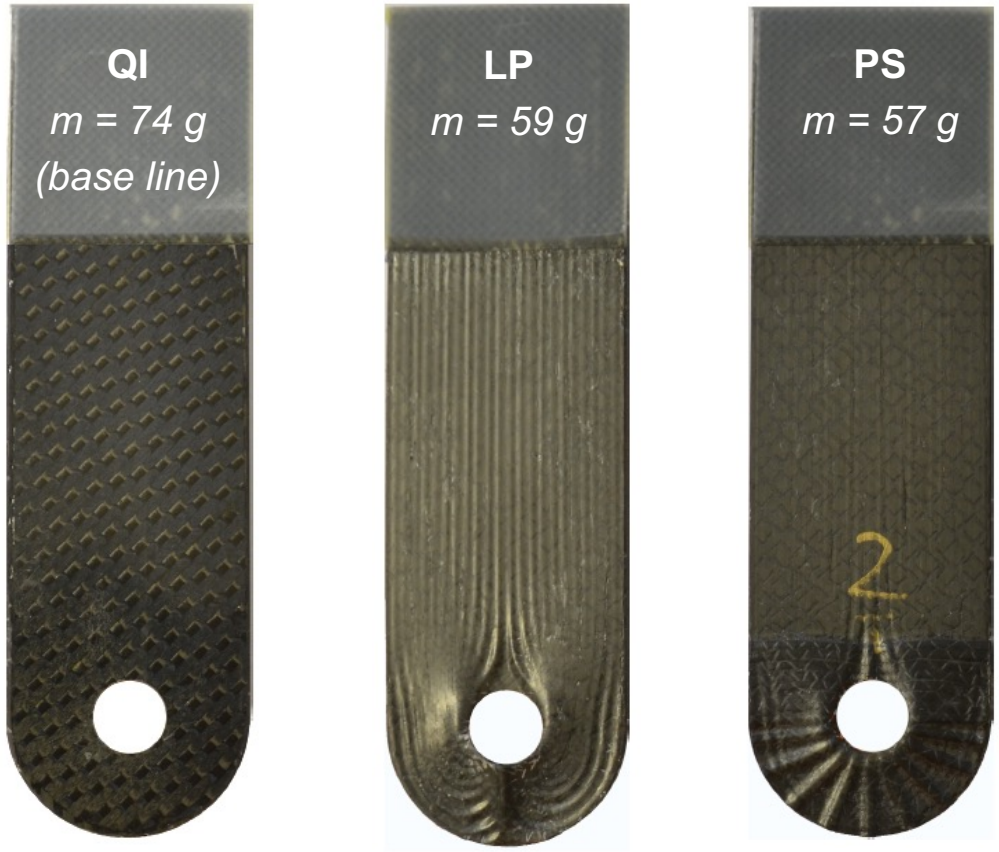




Epoxy resin: L20 + EPH 161

Experimental evaluation and model calibration

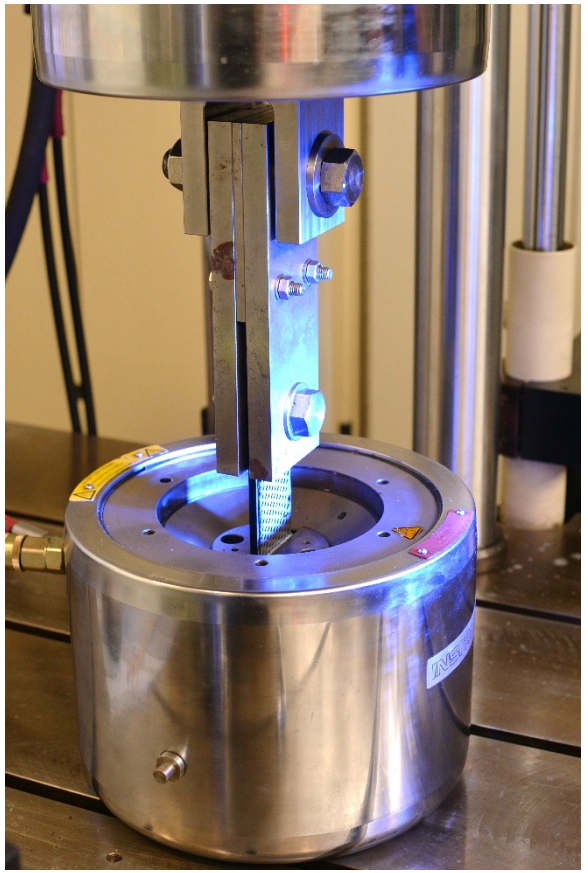
Specimen specification and experimental setup [2]



$[0/90/\pm45]_{4S}$
(base material only)

$[LP/\pm45]_{4S}$

$[PS2/PS1/\pm45]_{4S}$



Test setup

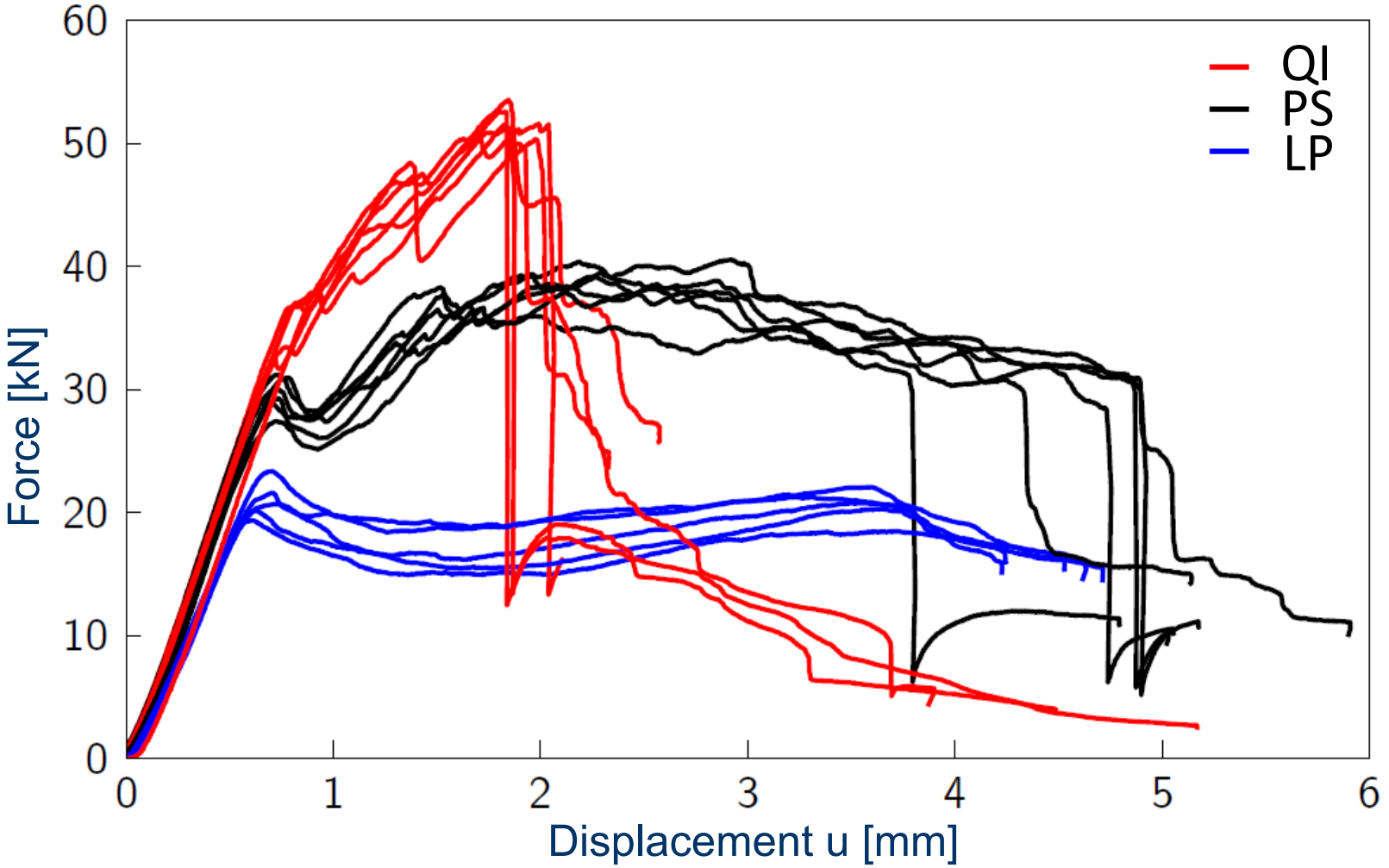
- Instron 8088 with hydraulic clamping
- 250 kN load cell
- Preload: 50 N
- Test speed 1 mm/min
- Number of specimens: 6

Variable-axial specimens are about 22 % lighter than QI type

[2] Selvaraj, K. & Spickenheuer, A. et. al. Bolted joints made of carbon fiber reinforced plastics using the tailored fiber placement technology: numerical and experimental failured analysis. In: Aachen Dresden International Textile Conference (**2012**) Dresden, ISBN 1867-6405

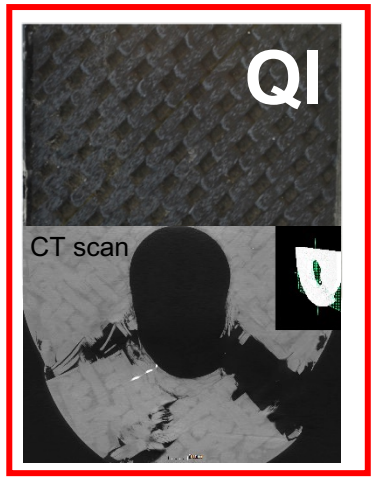
Experimental evaluation and model calibration

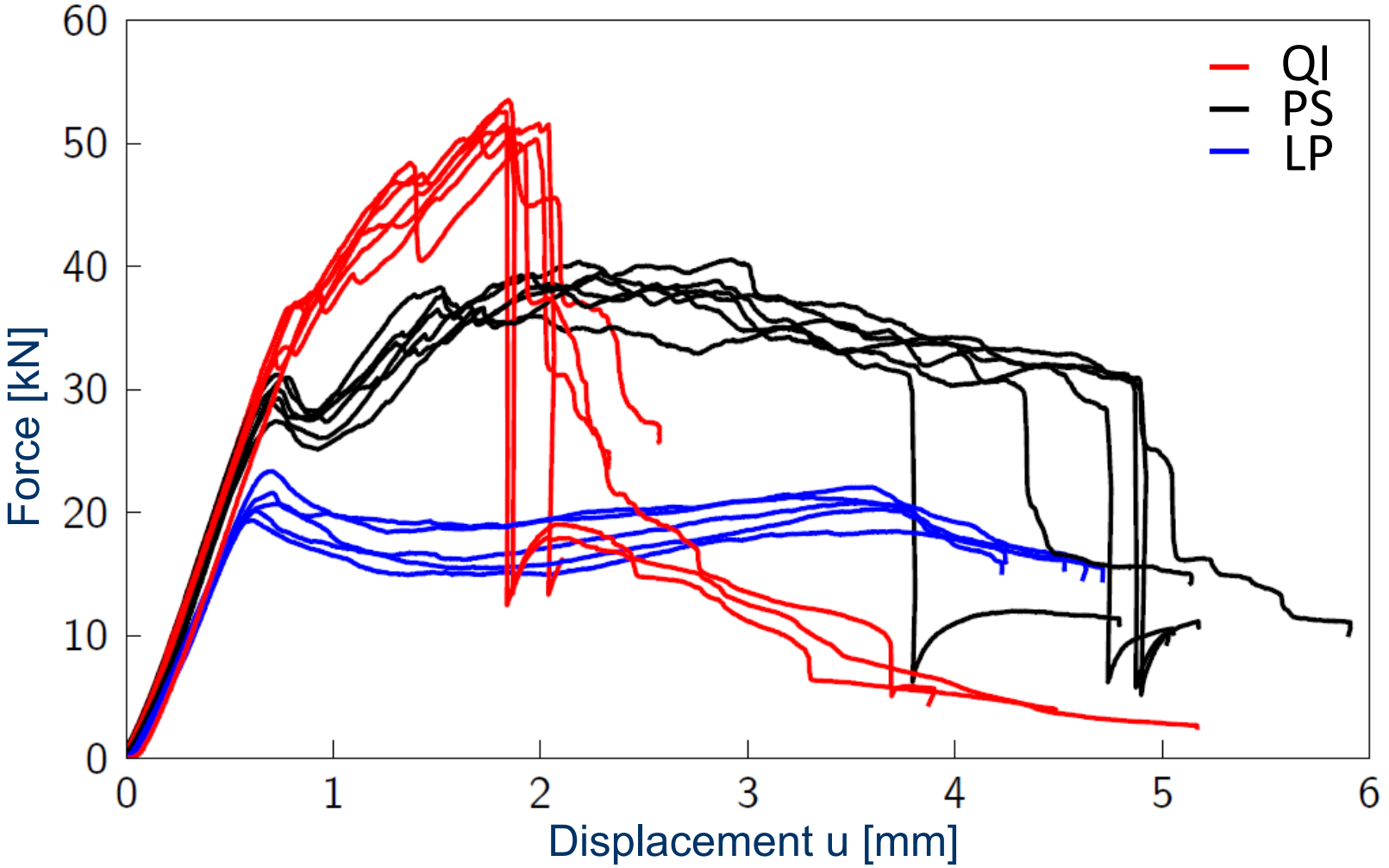
Results: Tensile test force-displacement diagram

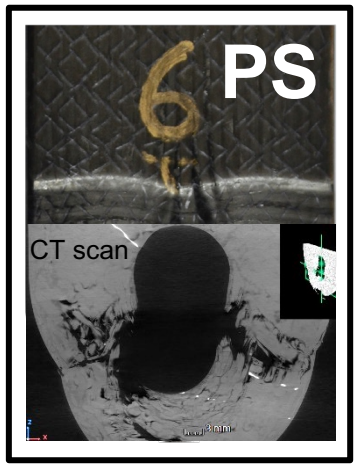


Experimental evaluation and model calibration

Results: Tensile test force-displacement diagram

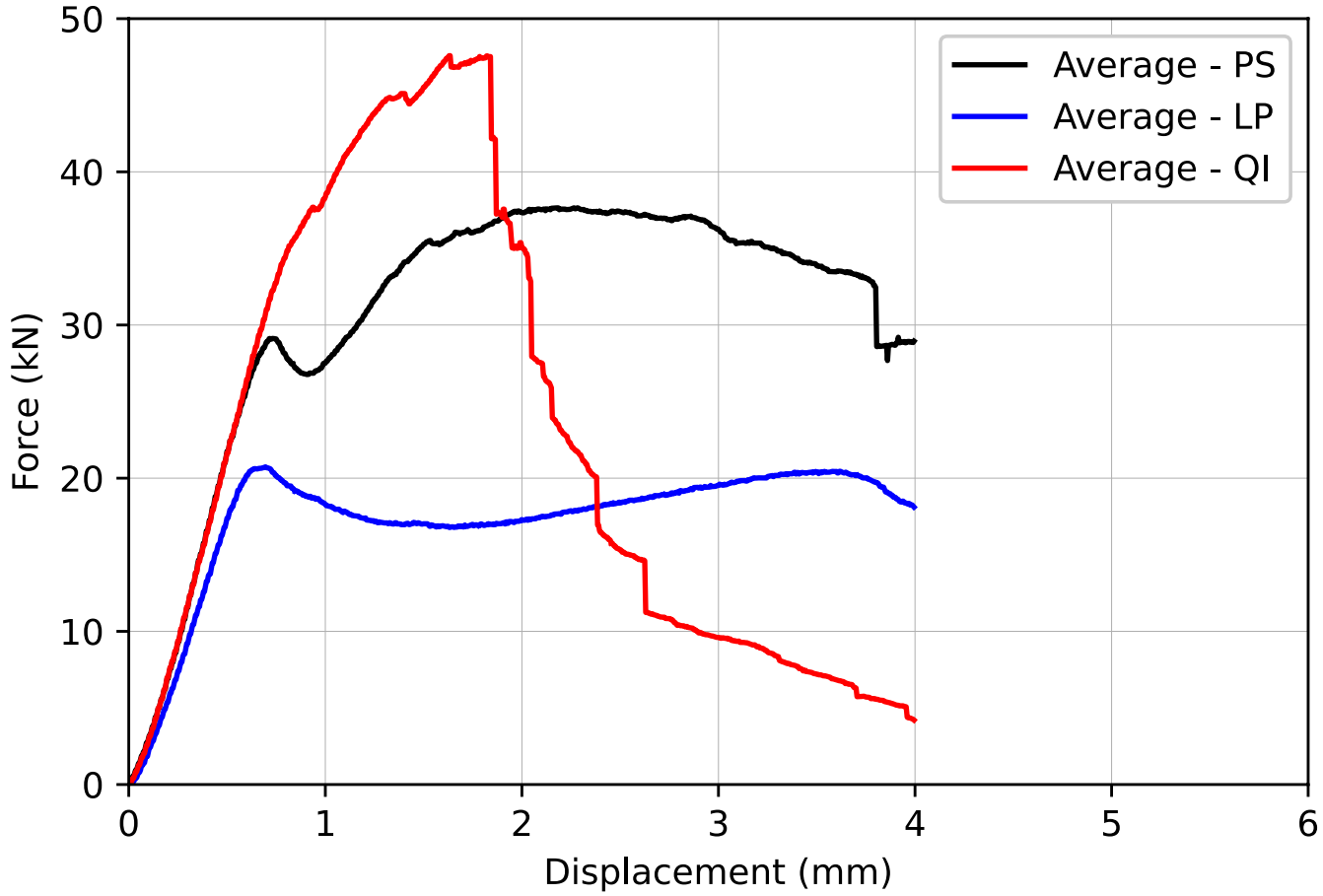


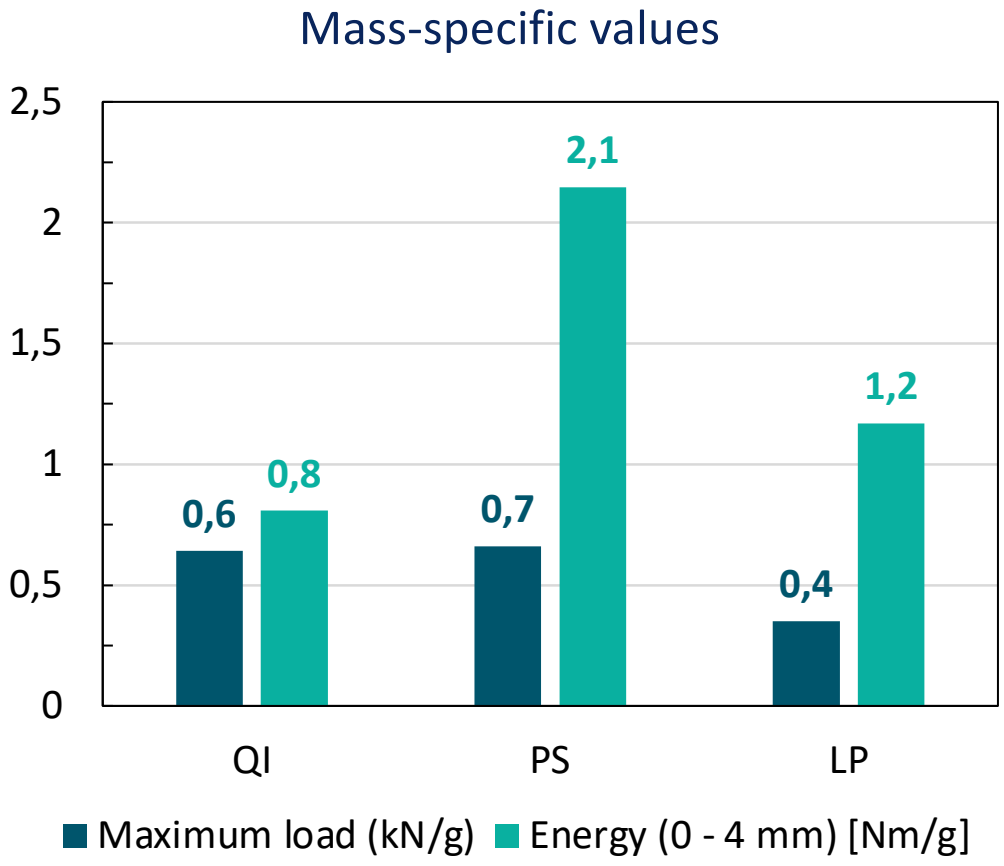




Experimental evaluation and model calibration

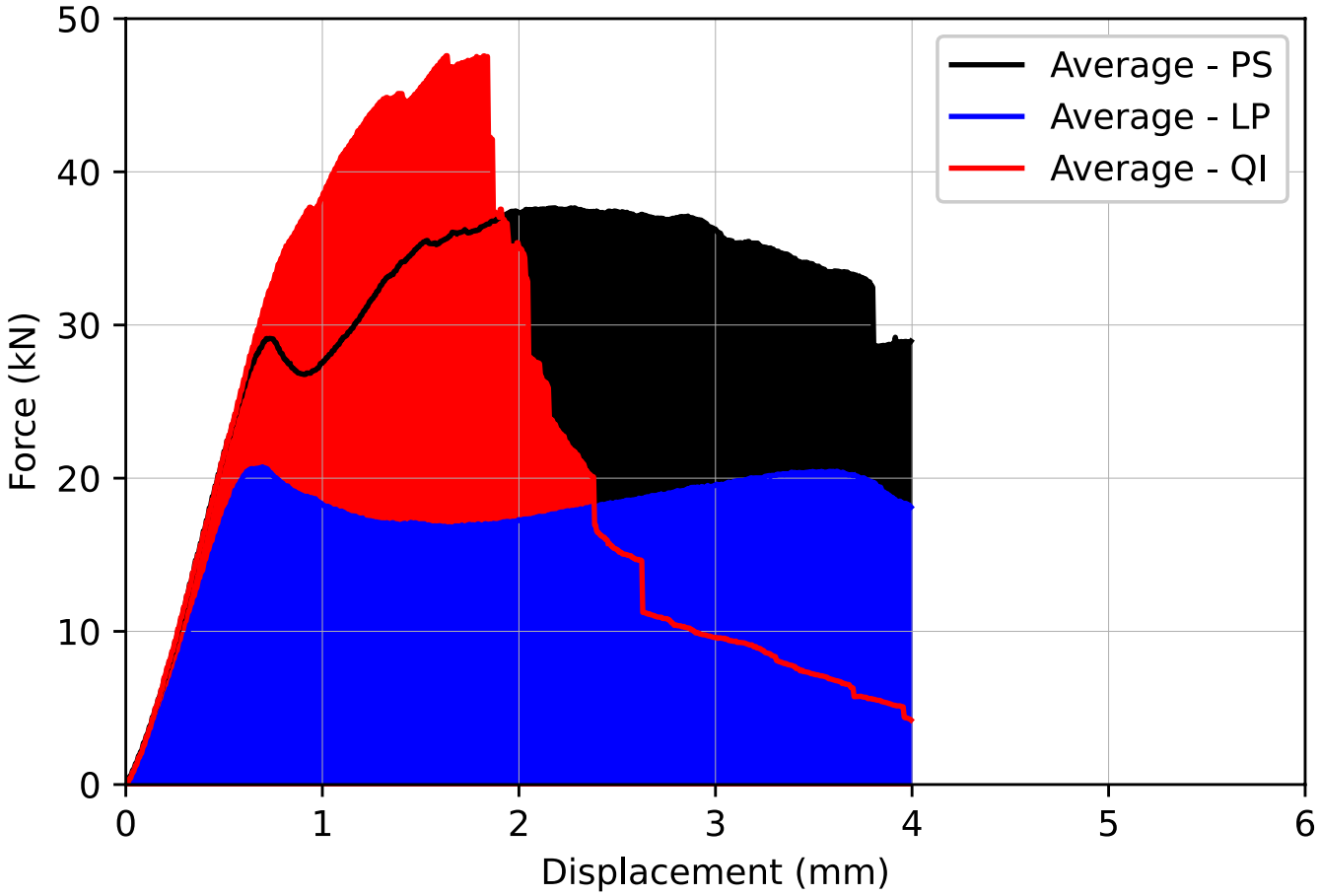
Results: Quasi-plastic deformation energy

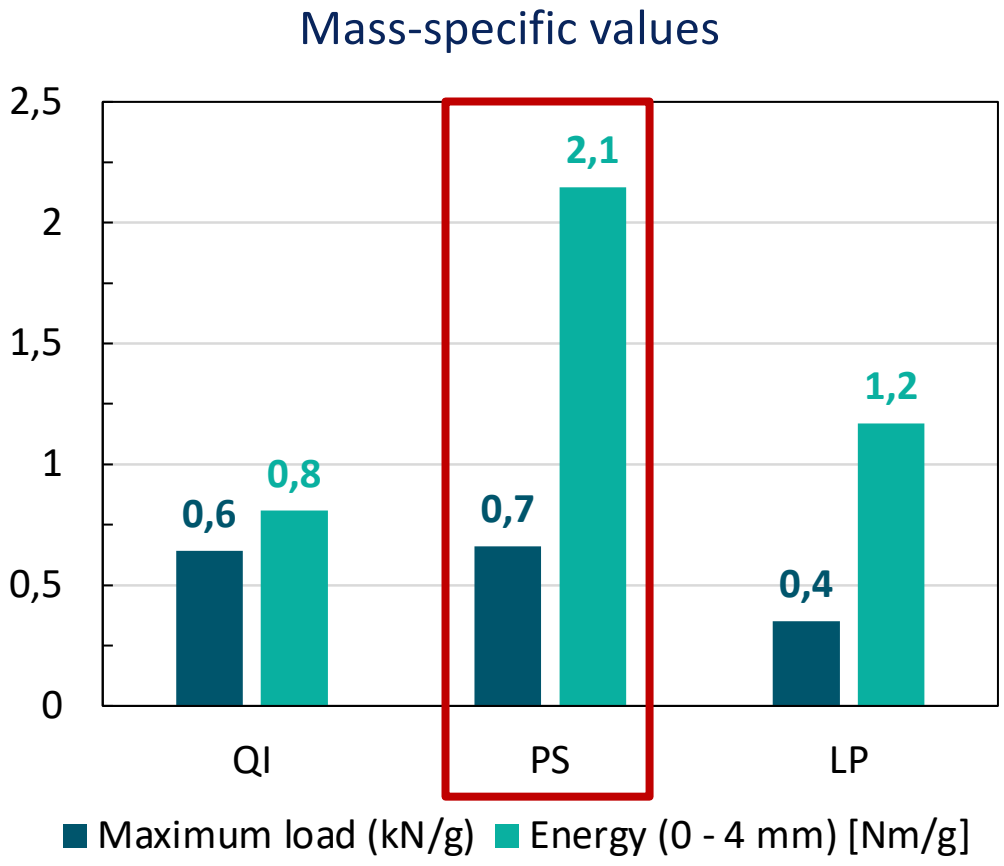




Experimental evaluation and model calibration

Results: Quasi-plastic deformation energy





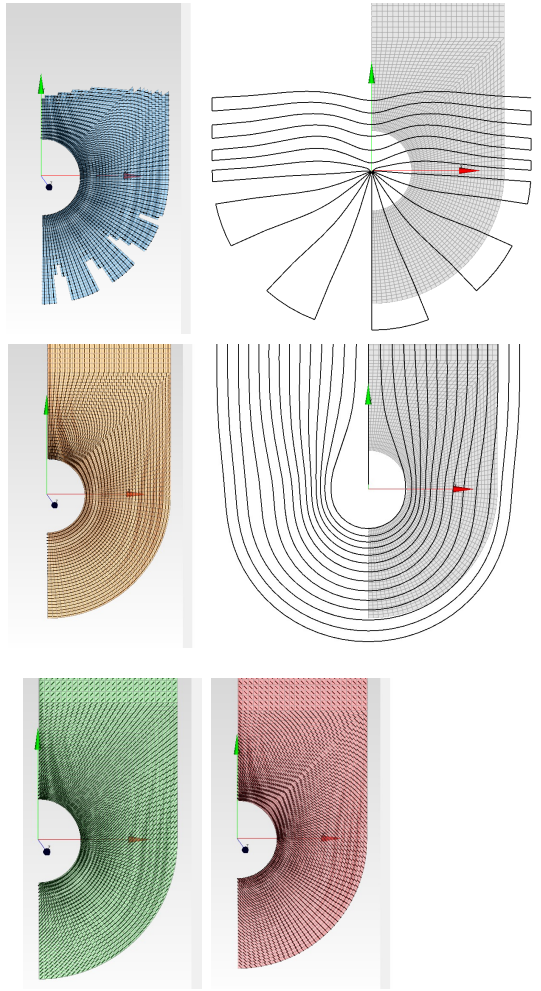
Model calibration

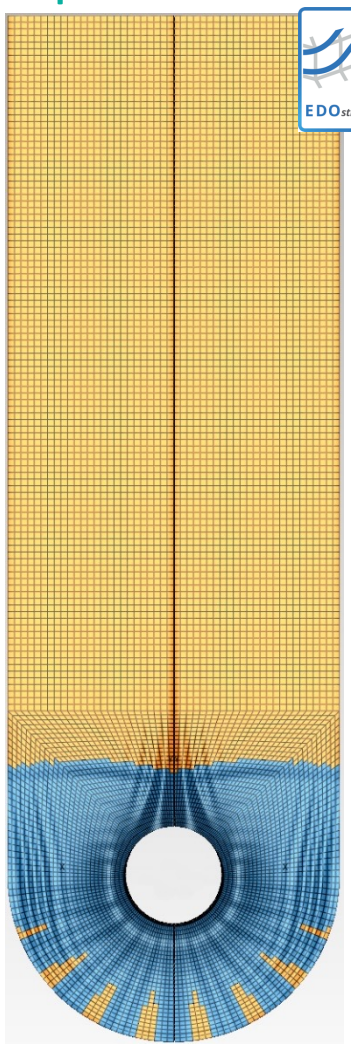
FE-modelling and material parameters

PS2 layer

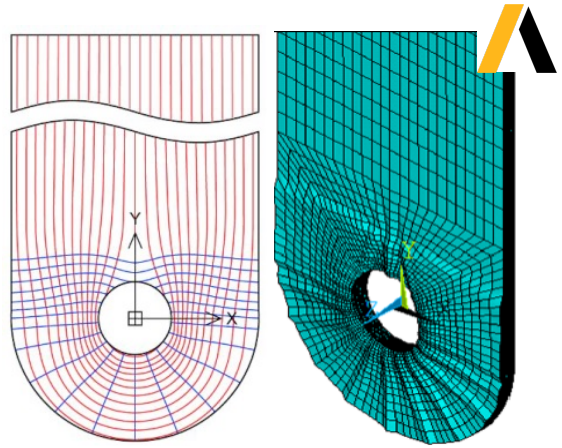
PS1 layer

Base material layer





Numerical material parameters (φ = 55 %)	
Fiber, Matrix	**Composite**
$E_{\parallel,f}$ = 238,000 Mpa	$\sigma_{\parallel,t}$ = 1,409 Mpa
$E_{\perp,f}$ = 16,000 MPa	$\sigma_{\parallel,c}$ = -7,40 MPa
$G_{\perp,f}$ = 50,000 MPa	$\sigma_{\perp,t}$ = 80 MPa
$\nu_{\perp\parallel,f}$ = 0.27	$\sigma_{\perp,c}$ = -140 MPa
E_M = 3,150 MPa	$\tau_{\perp\parallel} = \tau_{\perp\perp}$ = 69 MPa
G_M = 1,150 MPa	
ν_M = 0.37	



Model calibration

Progressive damage simulation with parameter identification by FEMU

HASHIN Failure Criterion [3]

$$\text{Fiber} \begin{cases} X_{FT} = \left(\frac{\sigma_{11}}{F_{1T}}\right)^2 + \left(\frac{\sigma_{12}^2 + \sigma_{13}^2}{F_6}\right) & \sigma_{11} \geq 0 \\ X_{FC} = \left(\frac{\sigma_{11}}{F_{1C}}\right)^2 & \sigma_{11} < 0 \end{cases}$$

$$\text{Matrix} \begin{cases} X_{MT} = \left(\frac{\sigma_{22}}{F_{2T}}\right)^2 + \left(\frac{\sigma_{23}}{F_4}\right)^2 + \frac{\sigma_{12}^2 + \sigma_{13}^2}{F_6^2} & \sigma_{22} \geq 0 \\ X_{MC} = \frac{\sigma_{22}}{F_{2C}}\left[\left(\frac{F_{2C}}{2F_4}\right)^2 - 1\right] + \left(\frac{\sigma_{22}}{2F_4}\right)^2 + \left(\frac{\sigma_{23}}{F_4}\right)^2 + \frac{\sigma_{12}^2}{F_6^2} & \sigma_{22} < 0 \end{cases}$$

Progressive damage modelling [3]

$$\mathbf{D} = \begin{bmatrix} \frac{C_{11}}{(1-d_f)} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{21} & \frac{C_{22}}{(1-d_m)} & C_{23} & 0 & 0 & 0 \\ C_{31} & C_{32} & \frac{C_{33}}{(1-d_m)} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{C_{44}}{(1-d_s)} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{C_{55}}{(1-d_s)} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{C_{66}}{(1-d_s)} \end{bmatrix}^{-1}$$

$$d_f = \begin{cases} d_{ft} & \sigma_{11} \geq 0 \\ d_{fc} & \sigma_{11} < 0 \end{cases} \qquad d_m = \begin{cases} d_{mt} & \sigma_{22} \geq 0 \\ d_{mc} & \sigma_{22} < 0 \end{cases}$$

$$d_s = 1 - (1-d_{ft})(1-d_{fc})(1-d_{mt})(1-d_{mc})$$

[3] Ansys 2022 R1 Documentation

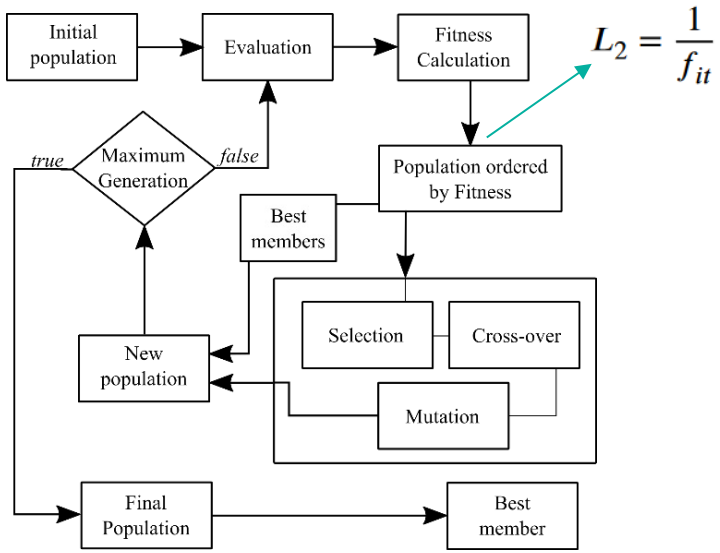
Model calibration

Progressive damage simulation with parameter identification by FEMU

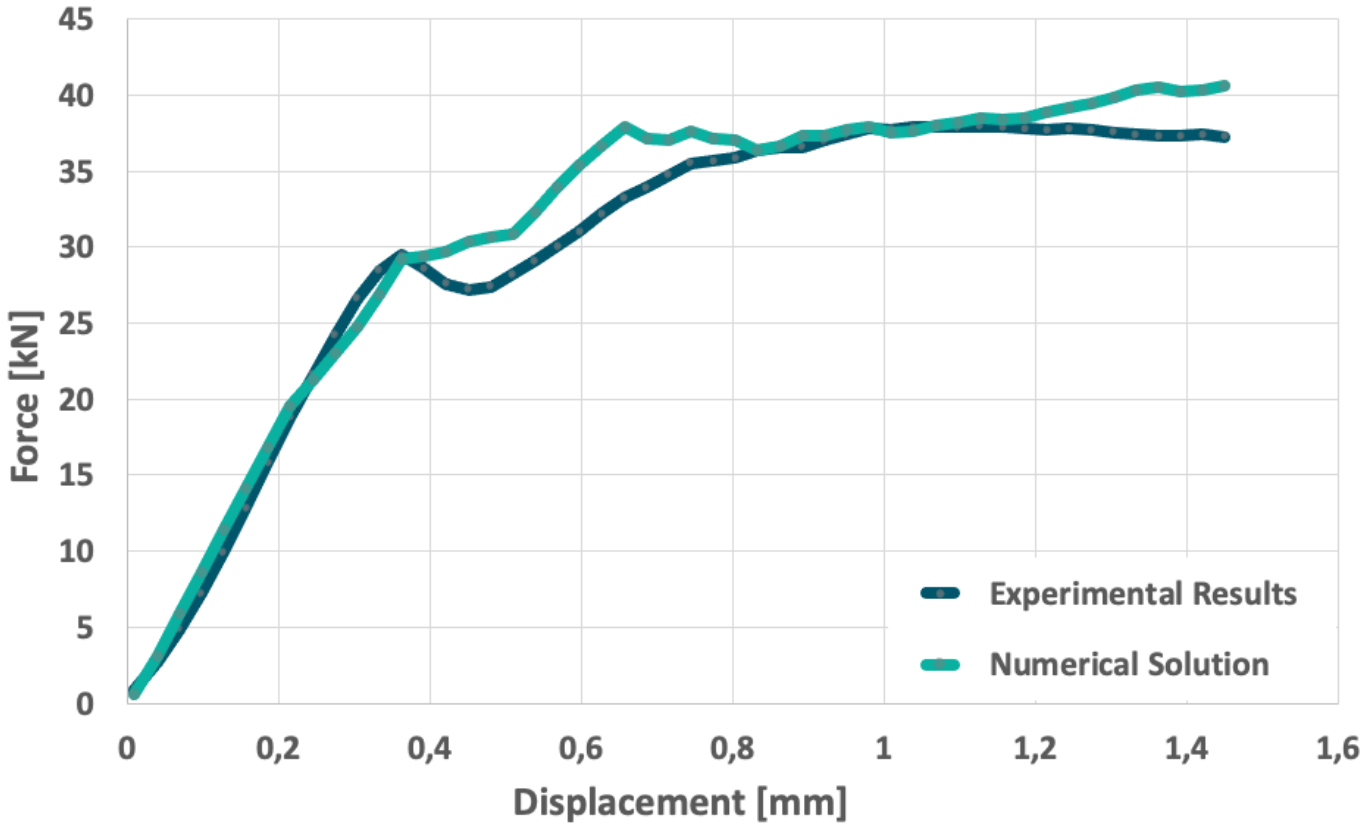
Stiffness degradation parameters [4] $\boldsymbol{\rho} = \{ d_{ft} \quad d_{fc} \quad d_{mt} \quad d_{mc} \}$

$$\min_{\rho \in [0,1]} L_2(\rho) = \min_{\rho \in [0,1]} \frac{1}{n_{ptos}} \sqrt{\sum_{i=1}^{n_{ptos}} \left(\frac{y_i^E - y_i^N(\rho)}{y_i^E} \right)^2}$$

Genetic Algorithm-based [4]

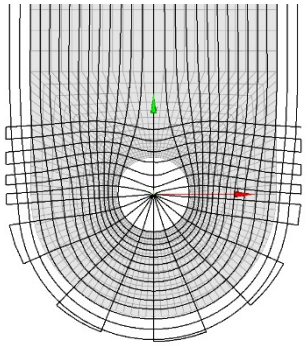


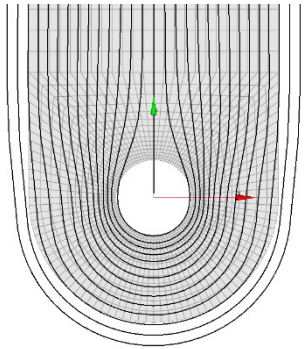
PS Design – Comparison exp. vs. num. results



[4] Almeida Jr. et al. Computers & Structures 276 (**2023**). doi: 10.1016/j.compstruc.2022.106939

Conclusion and Outlook





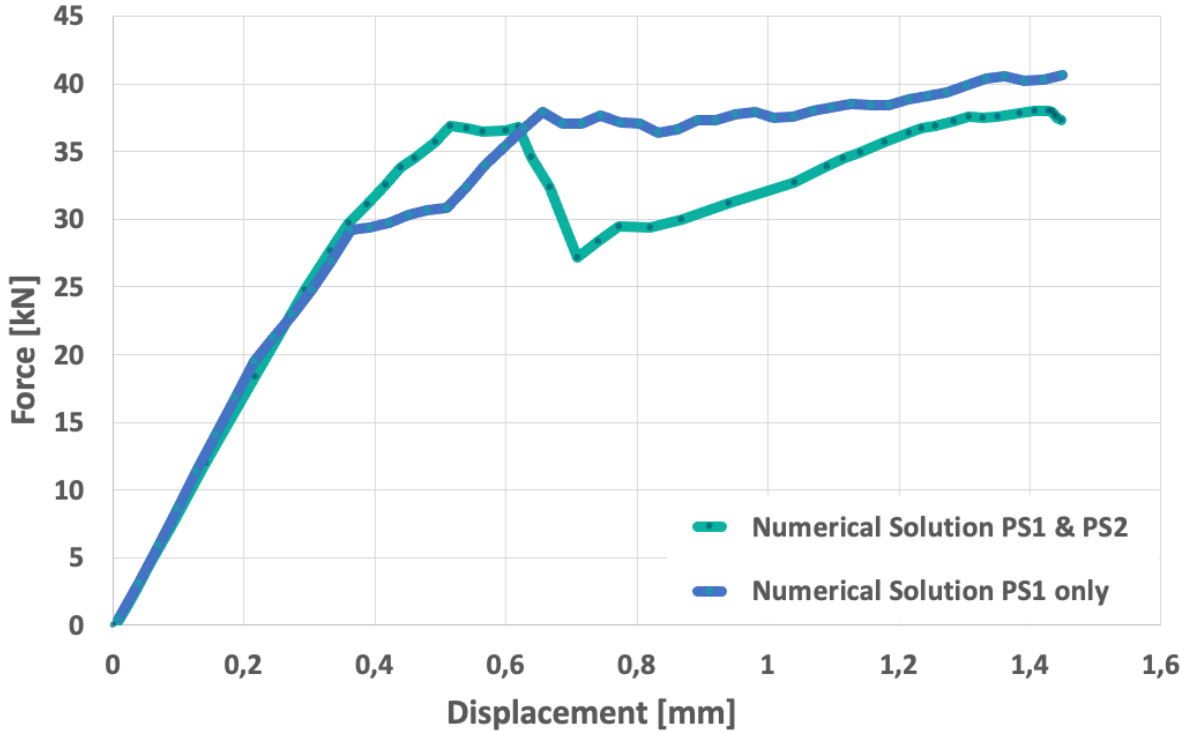
Bolt joint loaded composites with a variable-axial fiber design shows improved quasi-plastic behavior compared to QI multi-axial laminate.

- Optimality based PS design shows higher mass energy absorption than LP design
- By help of experimental tests a progressive damage modelling setup was identified

Optimization of variable-axial fiber patterns by using, e.g., DFPO [5]

- Optimizing for maximal mass-specific loads
- Optimizing for even higher energy absorption

Comparison PS1+PS2 vs. PS1 only pattern specimen



[5] Bittrich, L. & Spickenheuer, A. et. al. Optimizing variable-axial fiber-reinforced composite laminates: The direct fiber path optimization concept, Mathematical Problems in Engineering (**2019**). ID 8260563

Contact

Prof. Dr.-Ing. Axel Spickenheuer
Leibniz-Institut für Polymerforschung Dresden e. V.
Phone: +49 351 4658 374
E-Mail: spickenheuer@ipfdd.de
Web: www.ipfdd.de/tfp-technology

Research group *Complex Structural Components*

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