Fracture toughness and crack resistance curves for fiber tension and compression failure modes in polymer composites under high rate loading

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4a Technologietag

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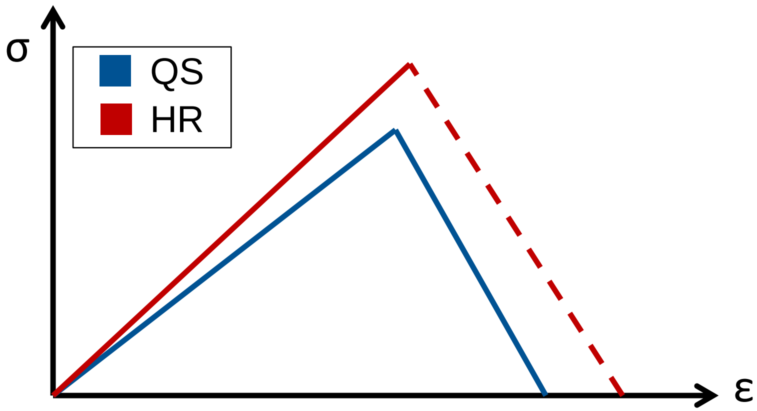
Agenda

- Motivation
- Fracture Toughness Characterization Strategy
- Experimental Setup and Results
- Static and Dynamic R-curves for CFRP and GFRP
- Conclusion and Outlook

Motivation

Dynamic material characterization

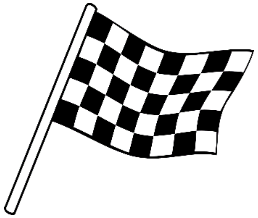


Property	Quasi-static (QS)	Dynamic (HR)
Stiffness	✓	✓
Strength	✓	✓
Damage evolution	✓	✗

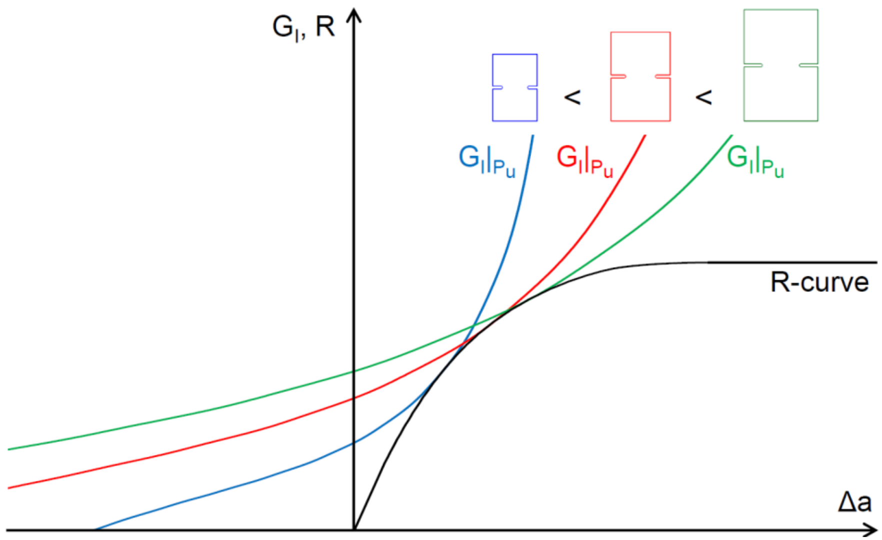
Research gap and goal of the presented work

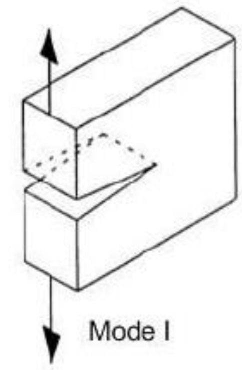
- Energy-based damage models (e.g. MAT 262 in LS-DYNA) require specification of fracture toughness parameters

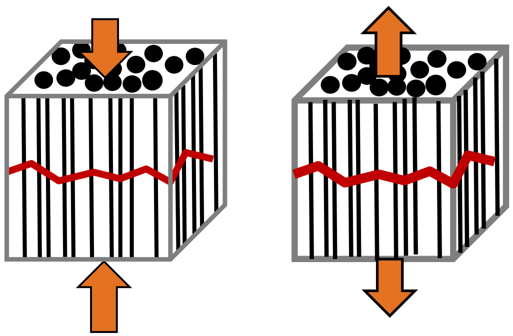
→ **Experimental characterization of Fracture Toughness parameter for energy intensive intralaminar fiber failure modes under high rate loading**



Characterization Strategy







- Based on the relations between the energy release rate (G_I), the size effect law and the R-curve References: [Bažant & Planas, CRC Press 1997], [Catalanotti et al., Compos Part A 2014:56]

- Only ultimate force (P_u) needs to be recorded
- Crack tip must not be determined
- Specimen geometry is very suitable for dynamic loading (here split-Hopkinson bars are used)

Characterization Strategy

$$G_I|_{P_u}(a + \Delta a) = \frac{1}{4wE_x}\sqrt{\frac{1 + \rho\left(E_x, E_y, G_{xy}, \mu_{xy}\right)}{2}}\left(\frac{P_u(w)}{t}\right)^2 \phi\left(\alpha_0 + \frac{\Delta a}{w}, \rho\right)$$

Geometry and material

- E_x supposed to be most significant

→ Magnitude of $E_x(\dot{\varepsilon})$ from QS and HR tests (UNC-/UNT-specimens)

→ $G_{xy}(\dot{\varepsilon})$ from QS and HR tests (UNT-specimen) and from literature

Size effect

- $P_u(w)$ determined from tests

→ Magnitude of $P_u(w,\dot{\varepsilon})$ from QS and HR tests (DENC-/DENT-specimens)

Dimensionless function

- Determined by using Virtual Crack Closure Technique (VCCT) in a Finite Element (FE) model

→ Determination of Φ for QS and HR material data sets

Energy Release Rate

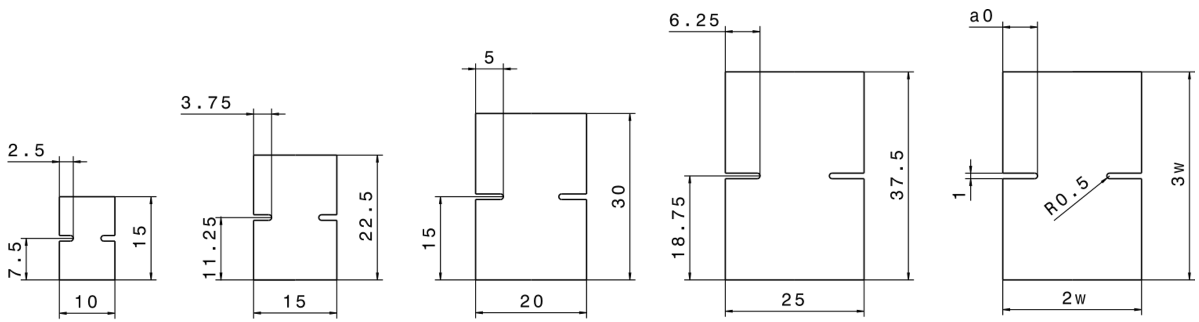
- Calculation of G_I based on QS fracture theory → Check if QS fracture theory is applicable for HR results from SHB tests

Experimental work

Specimen geometries for the determination of the size effect

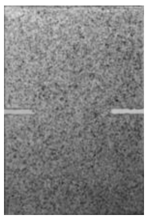
layup: $[90/0]_{ns}$

DENC



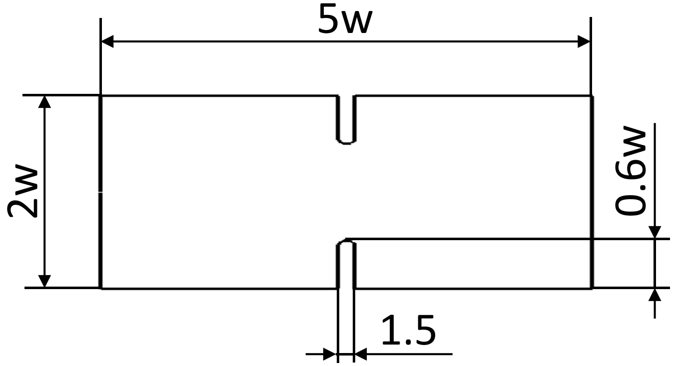
A B C D length ratios

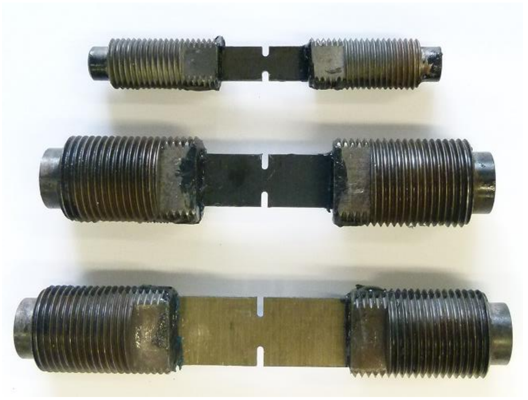
machined



prepared

DENT





w = 4

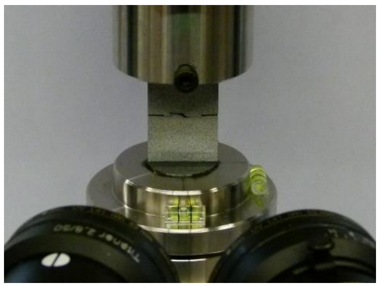
w = 6

w = 8

Experimental work

Test setup of compression test

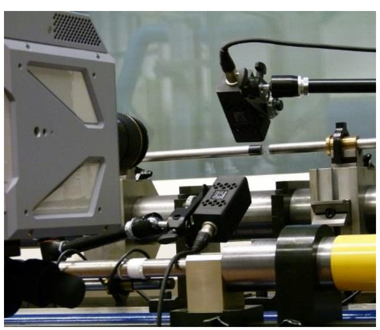
QS



- Standard Electromechanical testing machine
- Self alignment device
- Optical Measurement and Digital Image Correlation (DIC)

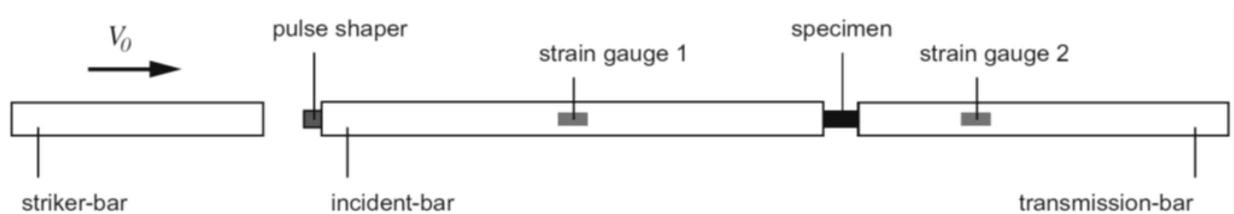
$$\sigma_u = \frac{P_u}{A_s}$$

HR



- Split-Hopkinson Pressure Bar (SHPB)
- Optical Measurement with High Speed Camera and DIC
- FE-Simulation for optimized SHPB setup (Striker velocity, Pulse Shaper,…)

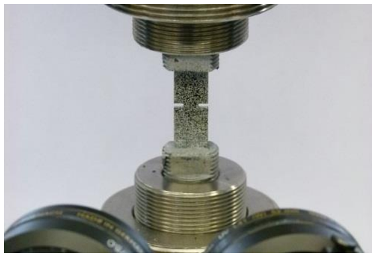
$$\sigma_{s1} = \frac{A_b}{A_s} E_b \epsilon_T \quad (1 - \text{wave}) \qquad \sigma_{s2} = \frac{A_b}{A_s} E_b (\epsilon_I + \epsilon_R) \quad (2 - \text{wave})$$



Experimental work

Test setup of tension test

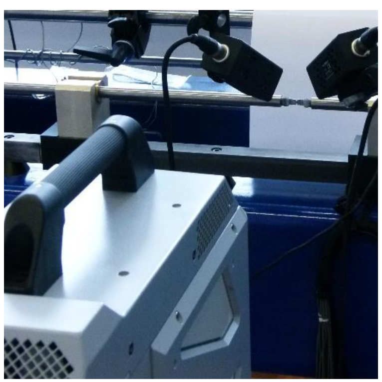
QS



- Standard Electromechanical testing machine
- Optical Measurement and Digital Image Correlation (DIC)

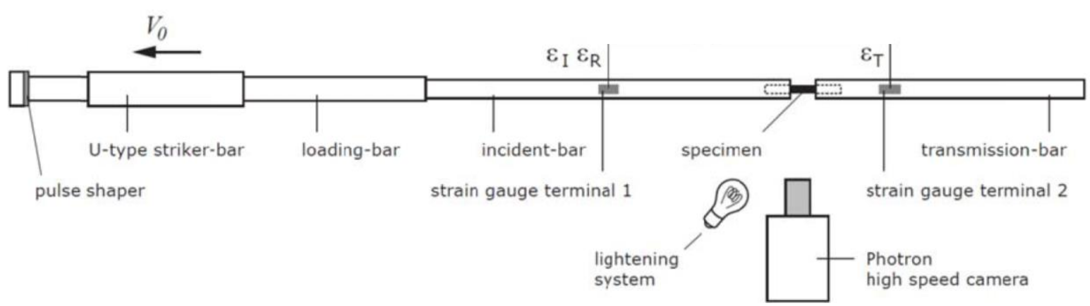
$$\sigma_u = \frac{P_u}{A_s}$$

HR



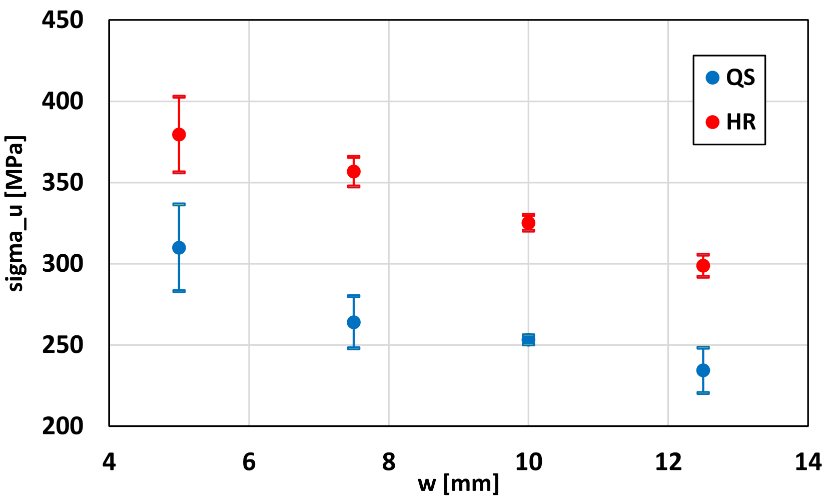
- Split-Hopkinson Tension Bar (SHTB)
- Optical Measurement with High Speed Camera and DIC
- FE-Simulation for optimized SHTB setup (Striker velocity, Pulse Shaper,…)

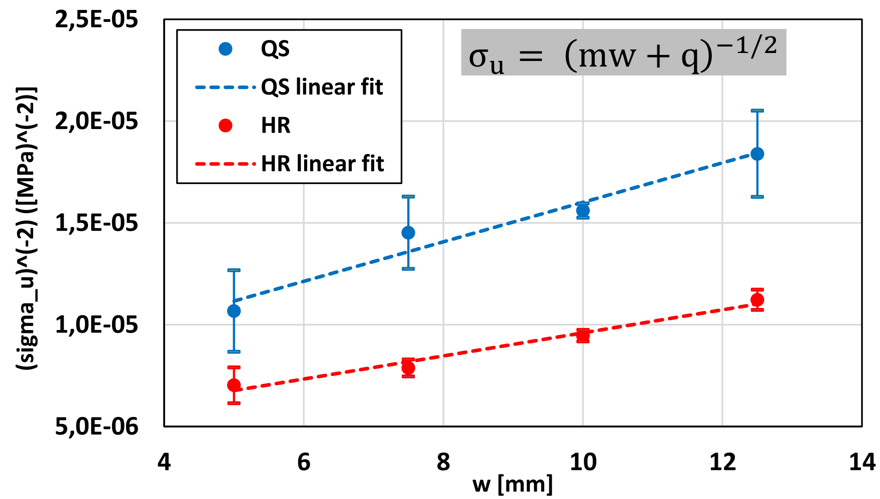
$$\sigma_{s1} = \frac{A_b}{A_s} E_b \epsilon_T \quad (1 - \text{wave}) \qquad \sigma_{s2} = \frac{A_b}{A_s} E_b (\epsilon_I + \epsilon_R) \quad (2 - \text{wave})$$

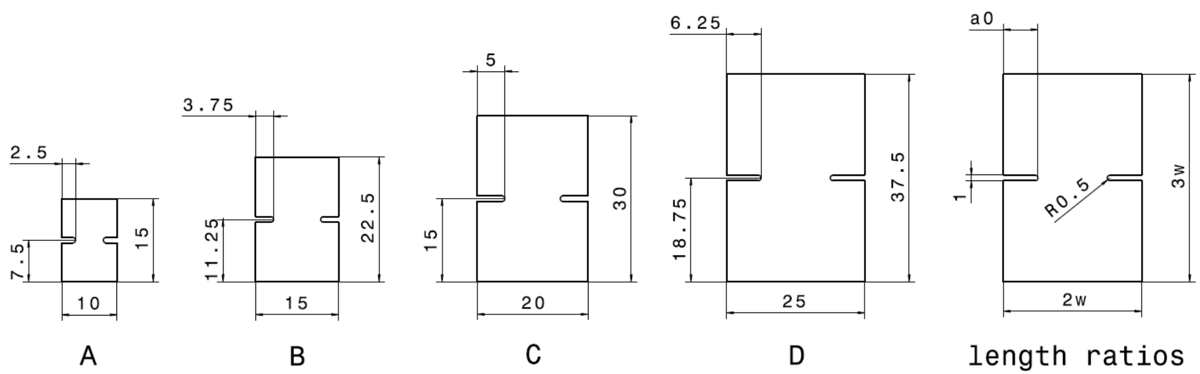


Experimental work

Results: Compression tests of CFRP (UD IM7-8552)

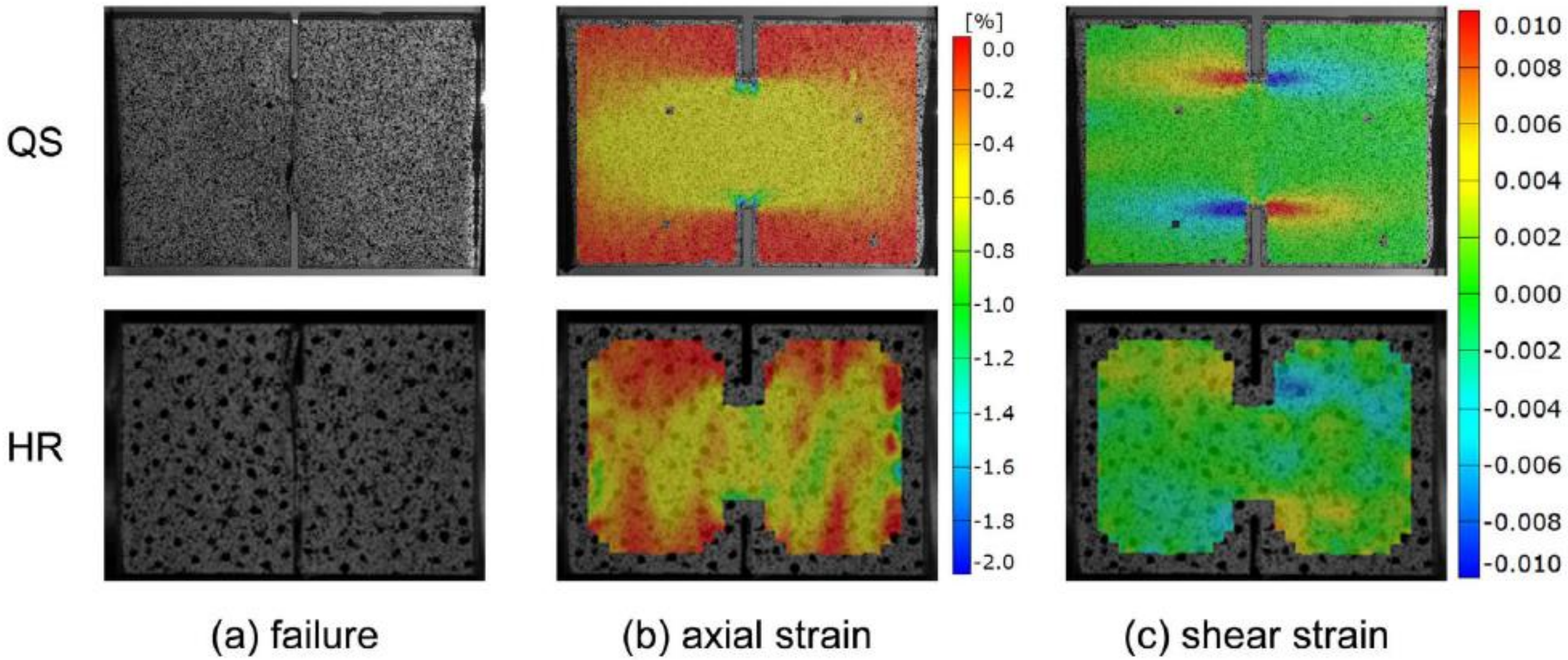






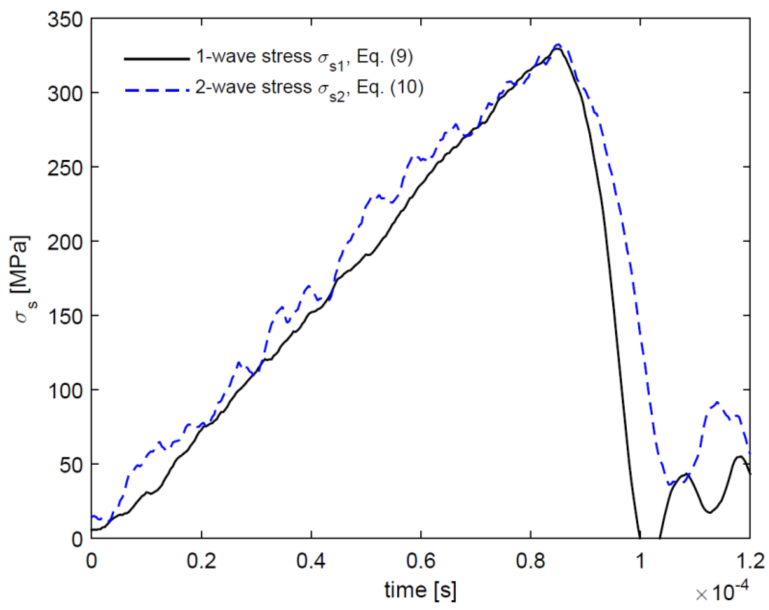
Experimental work

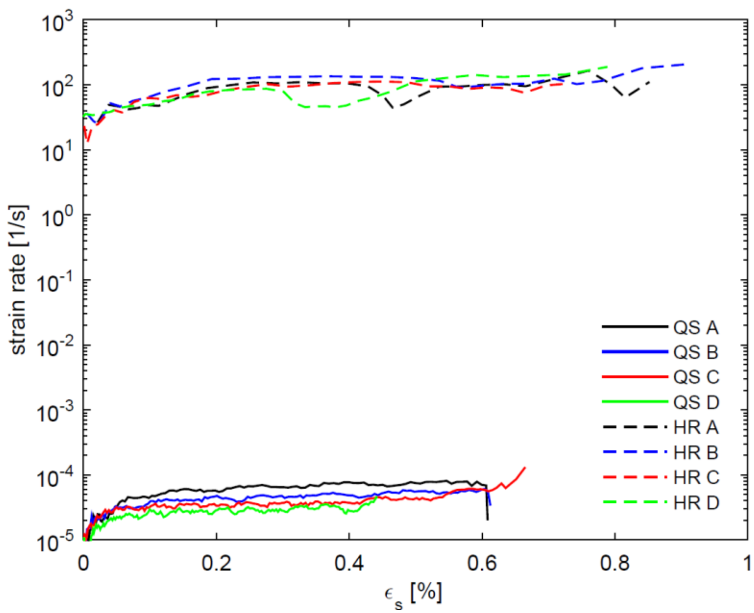
Results: Compression tests of CFRP



Experimental work

Results: Compression tests of CFRP





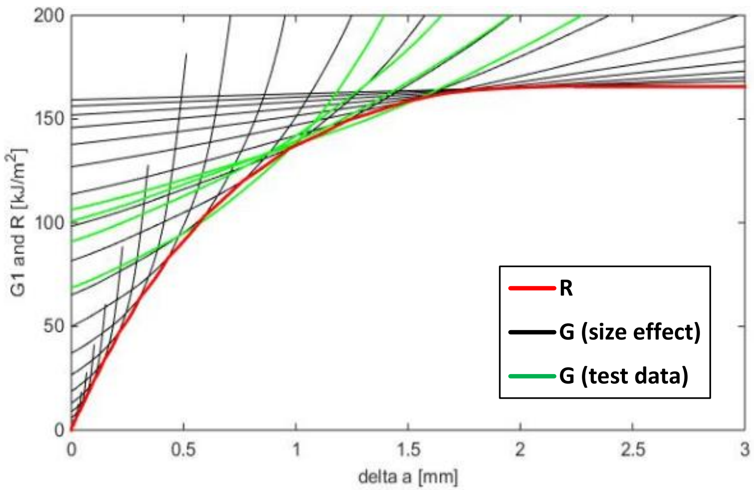
- DENC-specimens are in stress-equilibrium before damage initiation
- Approximately the same strain rate before failure is achieved for all specimen types

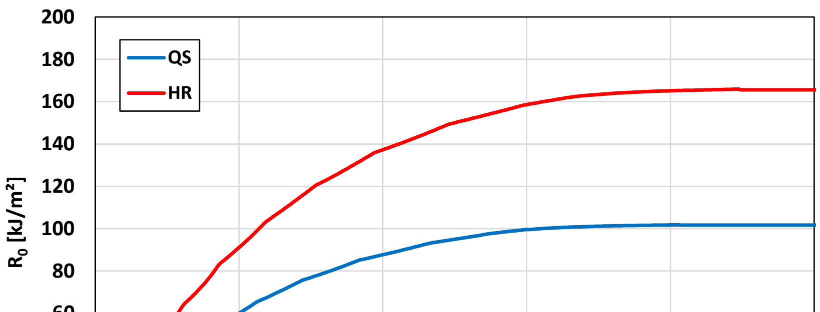
Calculation of the R-curve

CFRP Compression

$$G_I|_{P_u}(a+\Delta a) = \frac{1}{4wE_x}\sqrt{\frac{1+\rho\left(E_x, E_y, G_{xy}, \mu_{xy}\right)}{2}} \left(\frac{P_u(w)}{t}\right)^2 \phi\left(\alpha_0 + \frac{\Delta a}{w}, \rho\right)$$

Geometry and material	Size effect	Dimensionless fct.





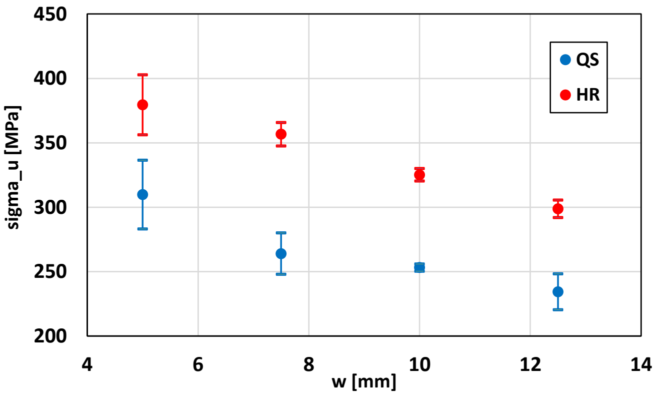
$$R_{ss} = \lim_{n\to\infty} R_0 = \frac{\sqrt{2(1+\rho)}}{E}\frac{\phi_0}{m}$$

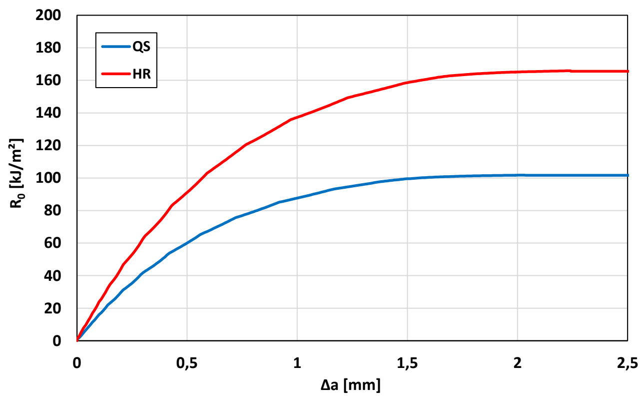
	QS	HR	HR/QS
R_{ss} [kJ/m²]	101,6	165,6	1,63
l_{fpz} [mm]	2,04	2,24	1,10

Calculation of the R-curve

CFRP (UD IM7-8552)

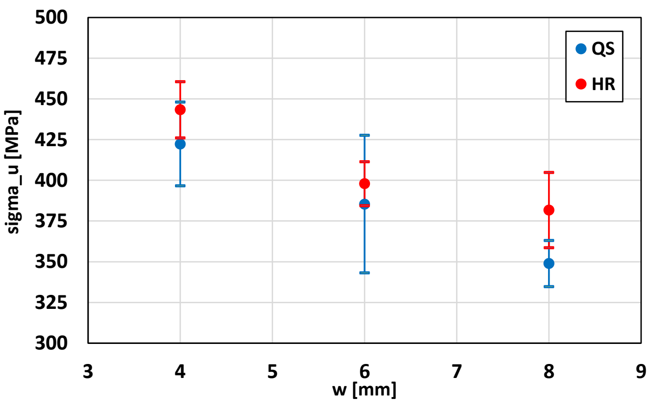
Compression

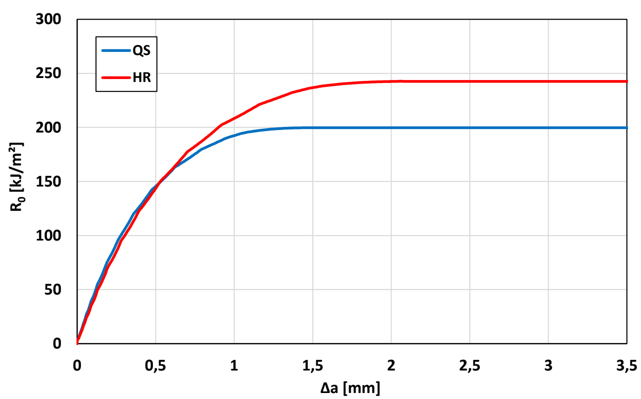




	R_{ss} [kJ/m²]
QS	101,6
HR	156,6
HR/QS	1,63

Tension



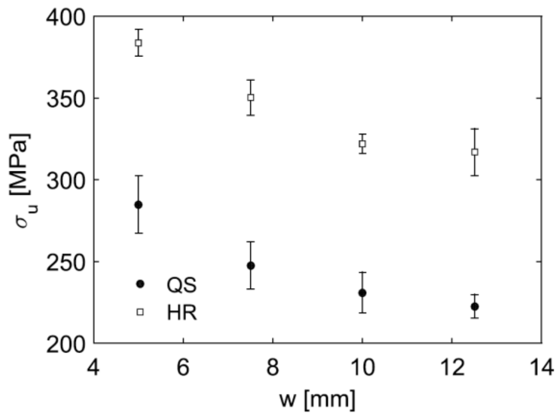


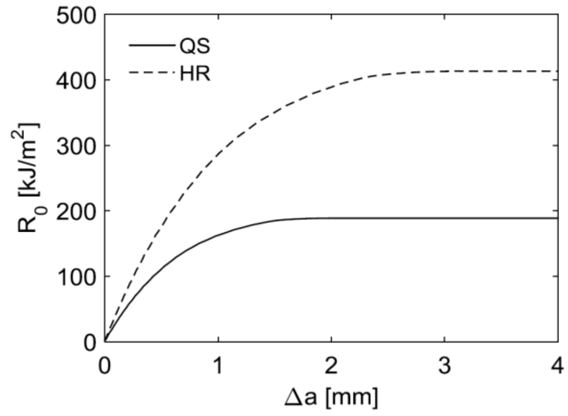
	R_{ss} [kJ/m²]
QS	199,7
HR	242,5
HR/QS	1,22

Calculation of the R-curve

GFRP (Saertex NCF E-Glass / Silka Biresin Epoxy CR80-CH80-2)

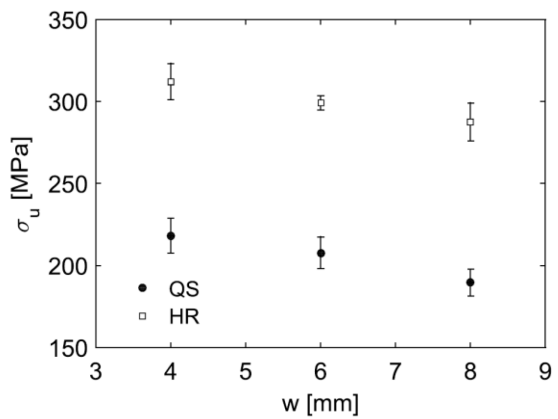
Compression

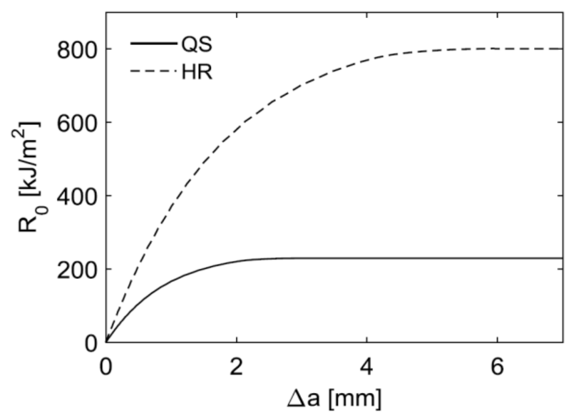




	R_{ss} [kJ/m²]
QS	188,7
HR	413,2
HR/QS	2,19

Tension





	R_{ss} [kJ/m²]
QS	229,6
HR	800.7
HR/QS	3,49

Conclusion

- The developed method enables a reliable determination of the R-curve and fracture toughness associated with the fiber failure modes for UD composites under high rate loading.
- Significant strain rate effects on the fracture toughness for fiber failure were observed for the investigated UD CFRP and UD GFRP composites.
- The strain rate effect on the fracture toughness is more pronounced for the GFRP composite, particularly for tensile loading.

Outlook

- Validation of the determined fracture toughness values (OHT/OHC tests)
- Extension of the method to other material systems, e.g. fabric composites (ongoing work)

Thank you for your attention!