Simulation von Delamination in Mehrschichtverbunden

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4a Technologietag 2015 – Leichtbau und Composites

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Einleitung und Motivation

Delamination ist in faserverstärkten Verbunden wegen des schwachen Interfaces zwischen den Schichten ein sehr häufiger Fehler

Auftreten in allen Phasen (Herstellung, Transport, Montage, Einsatz) der Strukturlebensdauer möglich

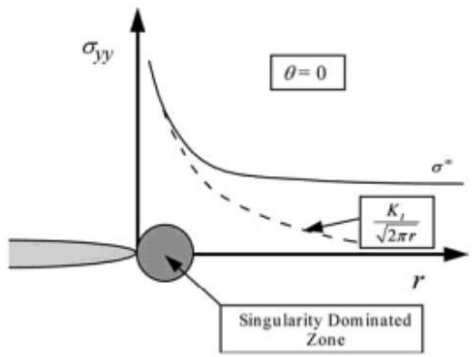
Mögliche Auslöser

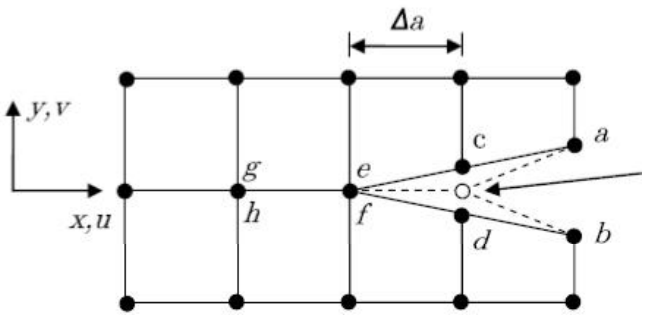
- Spannungen durch Härtungsschrumpf
- Temperatur und Feuchte
- Stoßbelastungen
- Gebogene Strukturen
- Sprunghafte Strukturveränderungen (z.B.: Verbindungselemente)

Methodik
Simulation von Delamination

Bruchmechanik

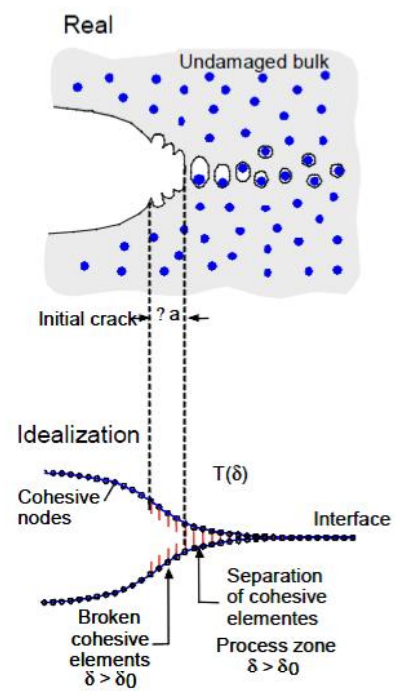
$$G = \frac{\sigma_\infty^{\,2}\pi a}{E} = \frac{K^2}{E}$$

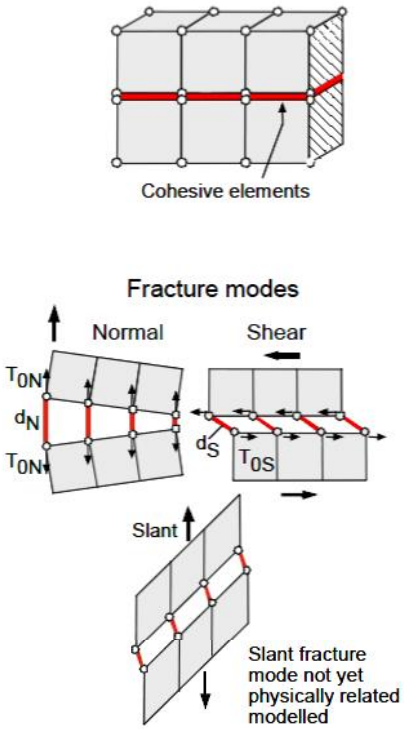




‘Virtual Crack Closure Technique’ (VCCT)

Schädigungsmechanik





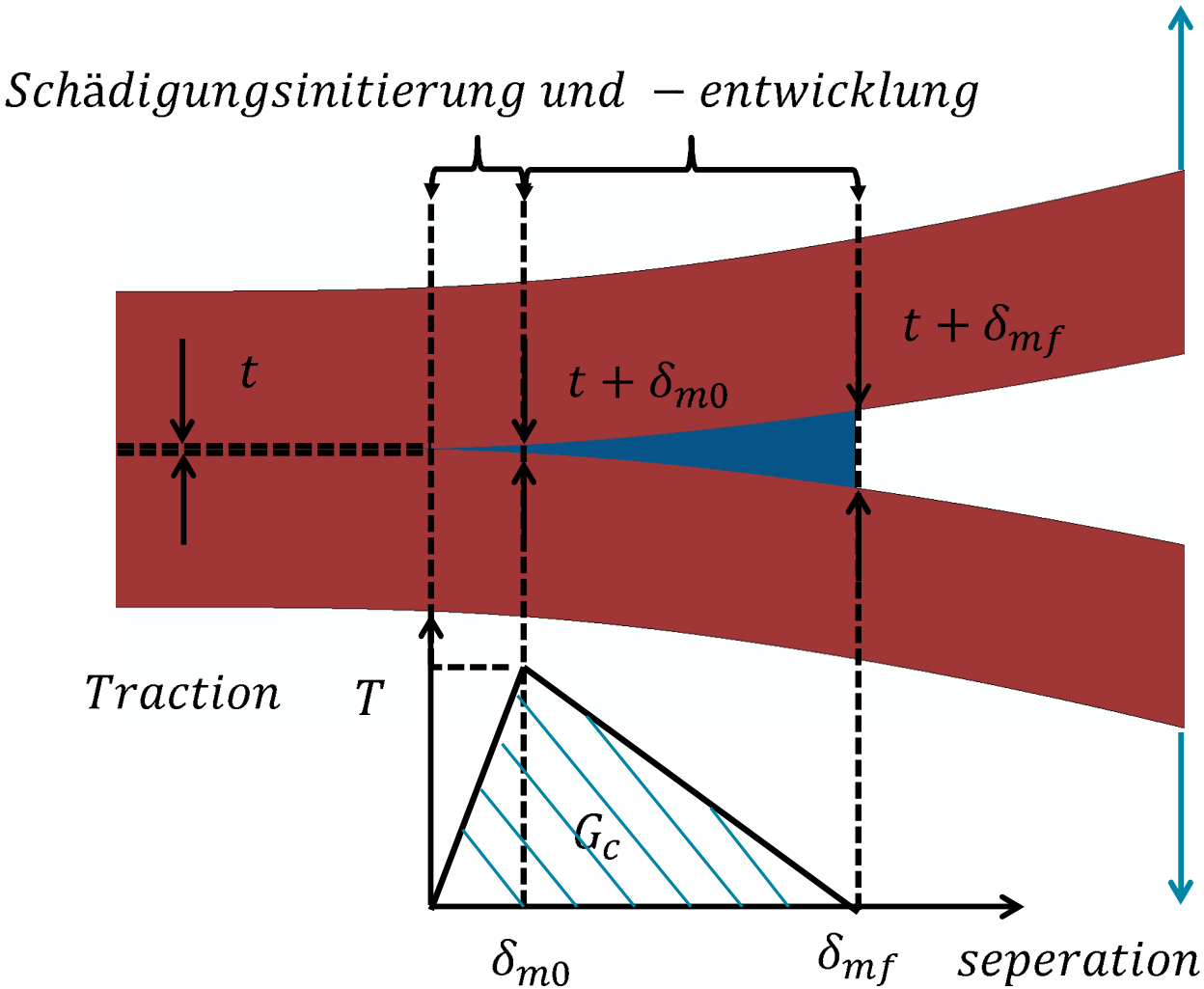
Kohäsivzonenmodell

Albert Turon Travesa, “Simulation of delamination in composites under quasi-static and fatigue loading using cohesive zone models”.

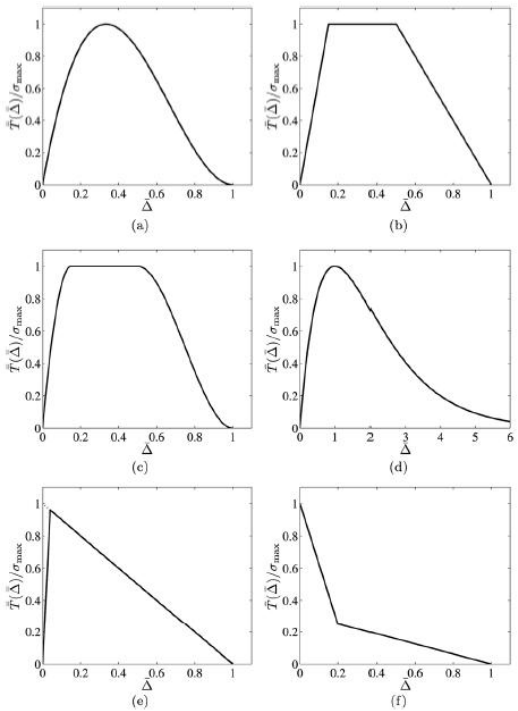
Anderson, T.L. (2005), Fracture mechanics: Fundamentals and applications, 3rd ed., Taylor & Francis, Boca Raton, FL.

Qelle : Schwalbe K H, Scheider I, Cornec A; SIAM CM 09 – The SIAM method for applying cohesvie models to damgae behaviour of engineering materials and structures, GKSS

Simulation Schädigung

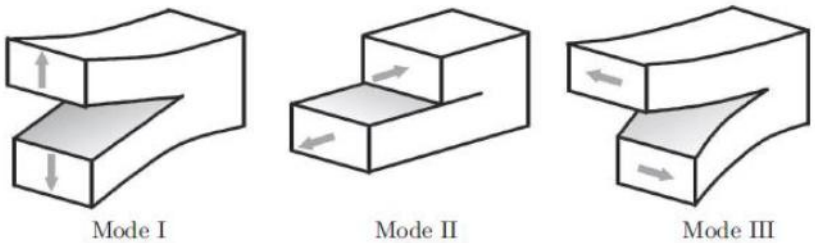


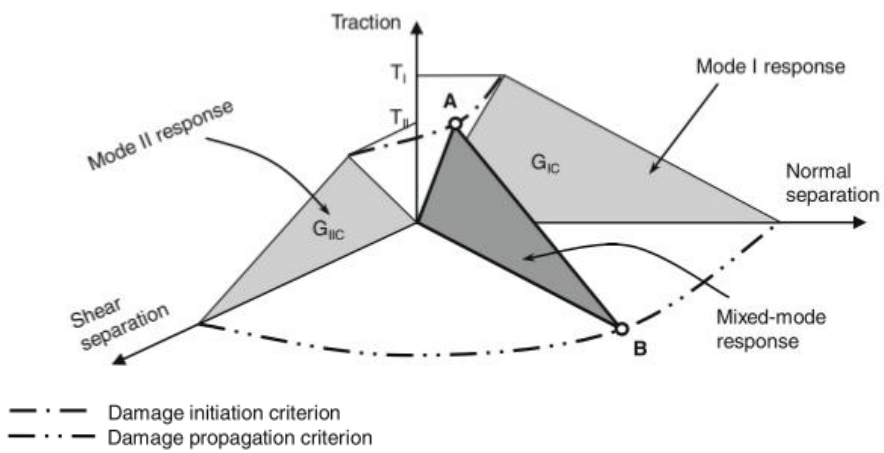
Unterschiedliche Modellierungsmöglichkeiten



Methodik
‚Mixed Mode‘

Modellierung kombinierter Bruchmoden

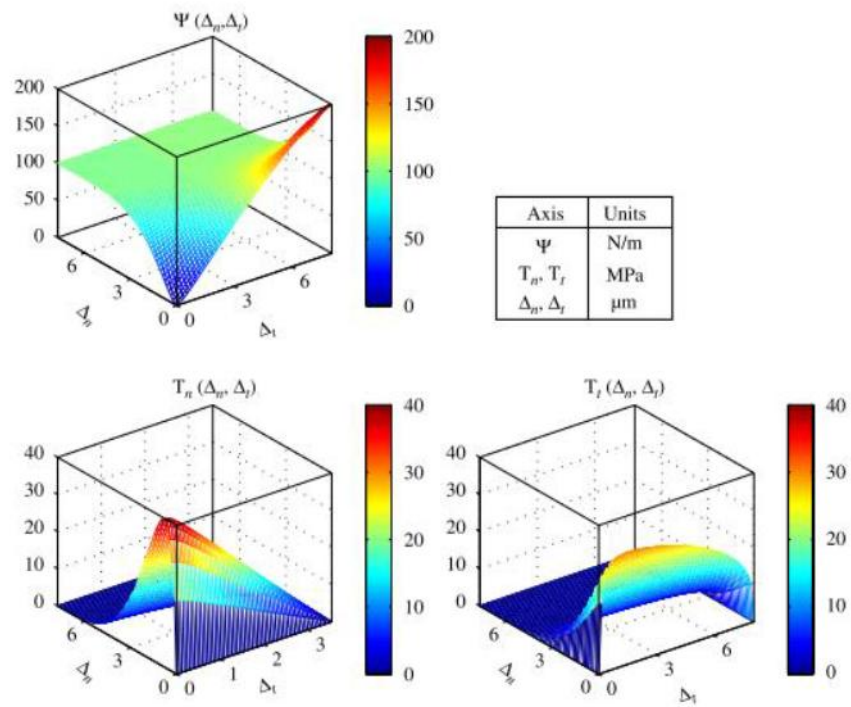




$$\delta_m = \sqrt{\langle \delta_n^2 \rangle + \delta_s^2 + \delta_t^2}$$

Benzeggagh–Kenane (BK)

$$G_{IC} + (G_{IIC} - G_{IC})\left(\frac{G_{II}}{G_I + G_{II}}\right)^{\eta} = G_I + G_{II}$$



Axis	Units
Ψ	N/m
T_n, T_t	MPa
Δ_n, Δ_t	µm

Effektive Verschiebung

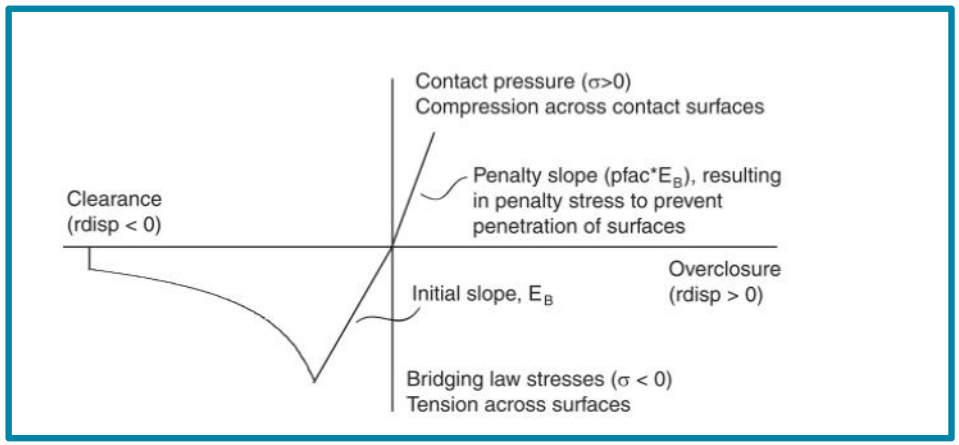
Vereinheitlichtes Potential

Khoramishad, H., Crocombe, A.D., Katnam, K.B. and Ashcroft, I.A. (2010), “Predicting fatigue damage in adhesively bonded joints using a cohesive zone model”, *International Journal of Fatigue*, Vol. 32 No. 7, pp. 1146–1158.

Park, K., Paulino, G.H. and Roesler, J.R. (2009), “A unified potential-based cohesive model of mixed-mode fracture”, *Journal of the Mechanics and Physics of Solids*, Vol. 57 No. 6, pp. 891–908.

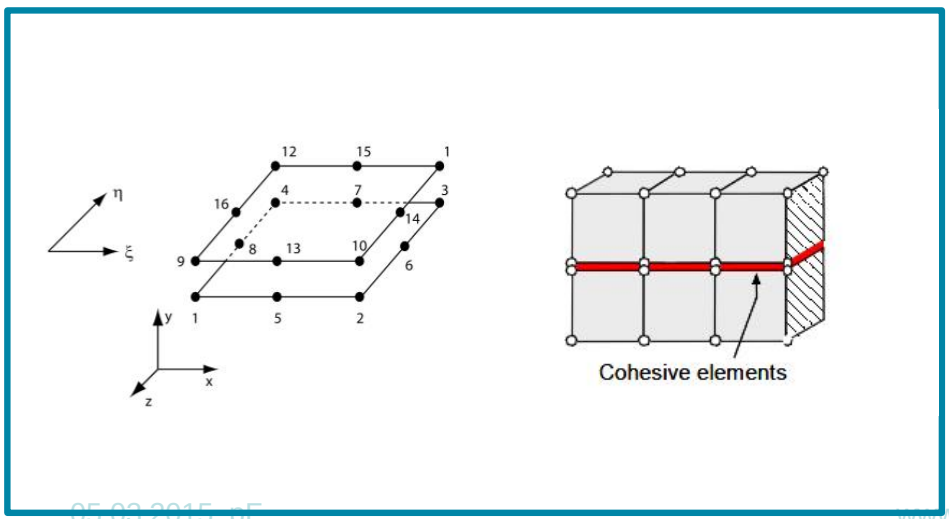
Methodik
Umsetzung in FEM

Kontakteigenschaft

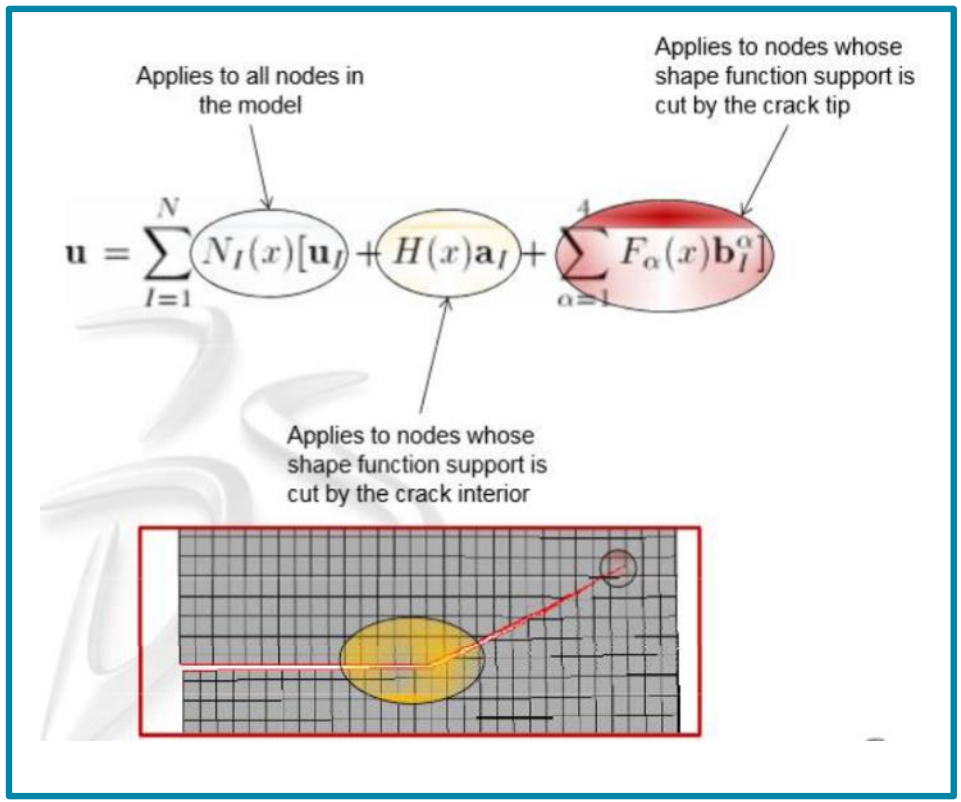


Feih, S., "Modelling cohesive laws in finite element simulations via an adapted contact procedure".

Kohäsive Elemente



X-FEM
‚eXtendend Finite Elemente Methode'



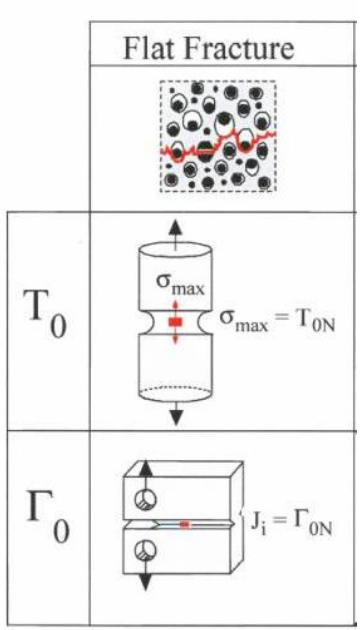
Quelle: Zhen-zhong Du, Dassault Systèmes Simulia Corp.

Qelle : Schwalbe K H, Scheider I, Cornec A; SIAM CM 09 – The SIAM method for applying cohesvie models to damgae behaviour of engineering materials and structures, GKSS

Ermittlung Modellparameter
Stand der Technik

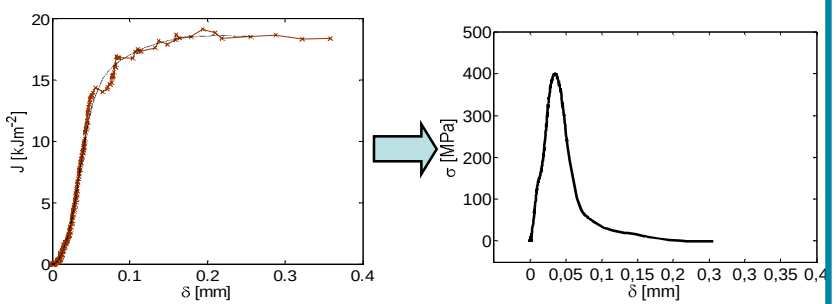
Mögliche Ansätze zur Parameteridentifikation

Direkte Bestimmung



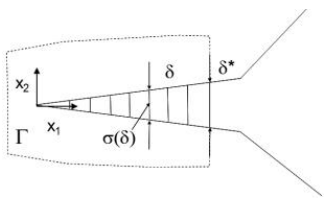
Schwalbe K H, Scheider I, Cornec A; SIAM CM 09 – The SIAM method for applying cohesvie models to damgae behaviour of engineering materials and structures, GKSS

J-Integral Methode



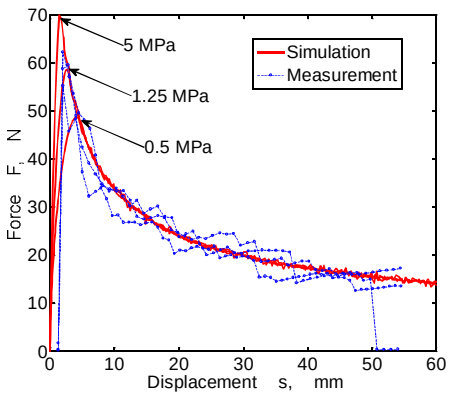
$$\sigma(\delta^*) = \frac{\partial J(\delta^*)}{\partial \delta^*}$$

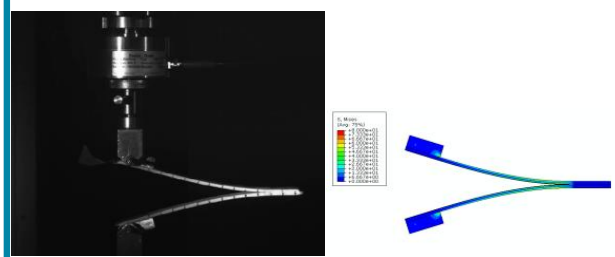
$$J = \int_\Gamma W dx_2 - \sigma_{ij} n_j \frac{\partial u_i}{\partial x_1} dS$$



Fuchs, P.F., Major, Z. and Lang, R.W. (2009), "Characterization of the failure behavior of printed circuit boards under dynamic loading conditions", *12th International Conference on Fracture 2009, ICF-12*, No. 7, pp. 5441–5449.

Nummerische Optimierung

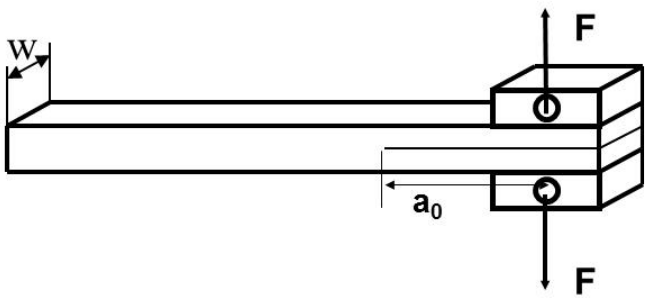


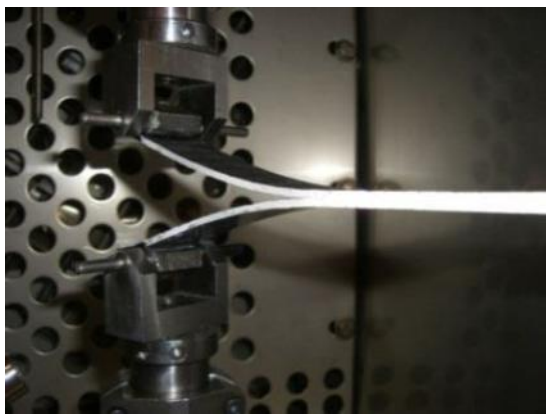


Fuchs, P.F., Pinter, G. and Fellner, K. (2013), "Local damage simulations of printed circuit boards based on in-plane cohesive zone parameters", Circuit World, Vol. 39 No. 2, pp. 60–66.

Versuche für die nummerischen Optimierung

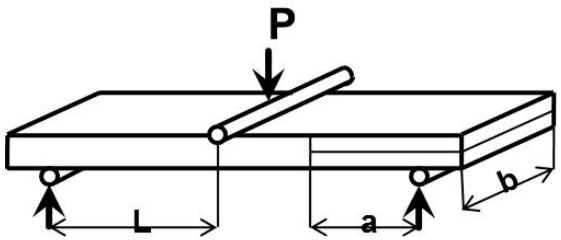
DCB





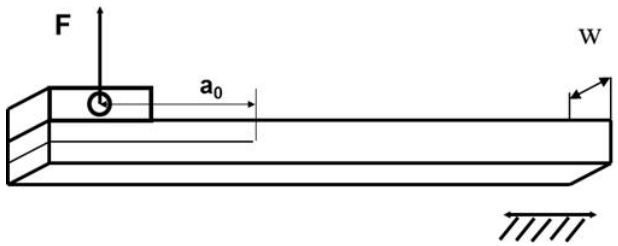
Double Canitlever Beam
(Mode I Versuch)

ENF



End Notched Flexure
(Mode II Versuch)

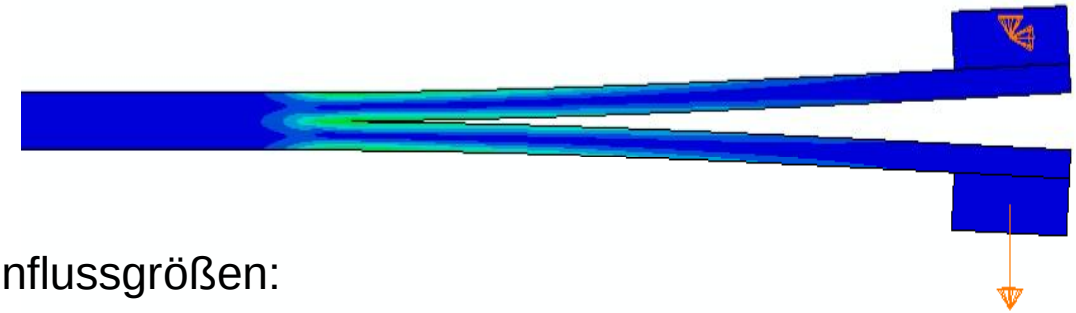
FRMM

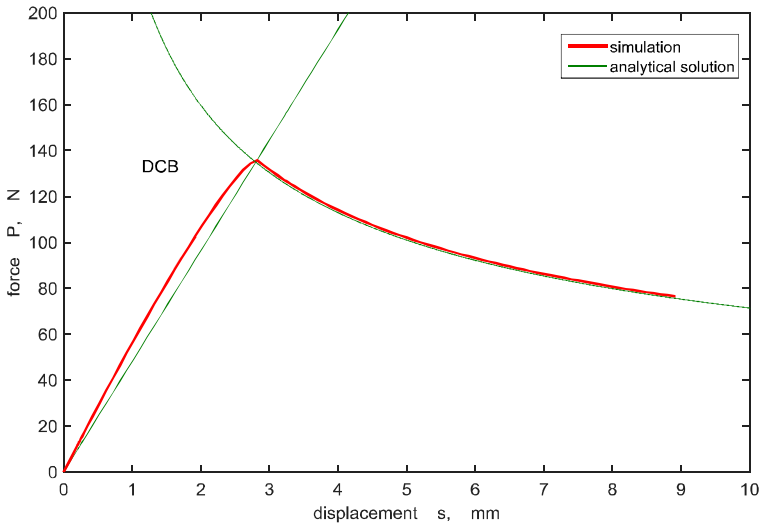


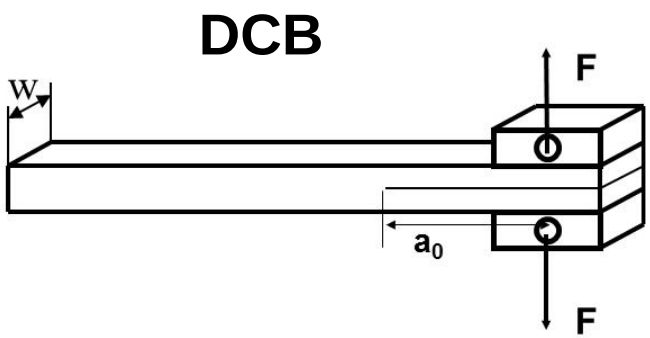
Fixed Ratio Mixed Mode
(Mixed Mode Versuch)

Ermittlung Modellparameter
Nummerische Optimierung

‚Double Cantilever Beam'
Mode I Versuch



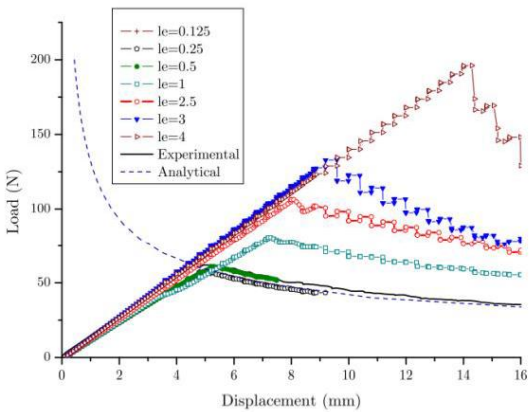




Einflussgrößen:

- Steifigkeit
- Kritische Energiefreisetzungsrate,
- Festlegung Schädigungsinitierung (z.B. Spannung oder Rissöffnung)
- Schädigungsentwicklung (z.B.: linear, bilinear oder exponentiell)
- Elementgröße

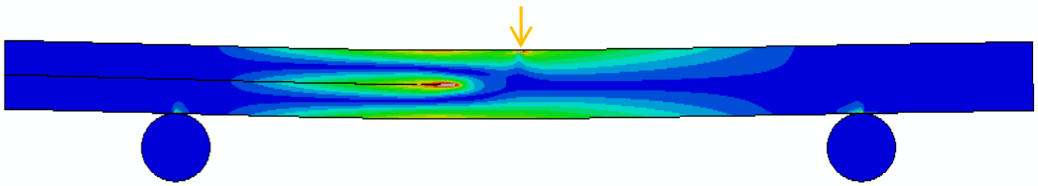
$$l_{cz} = ME\frac{G_c}{(\tau^o)^2}$$

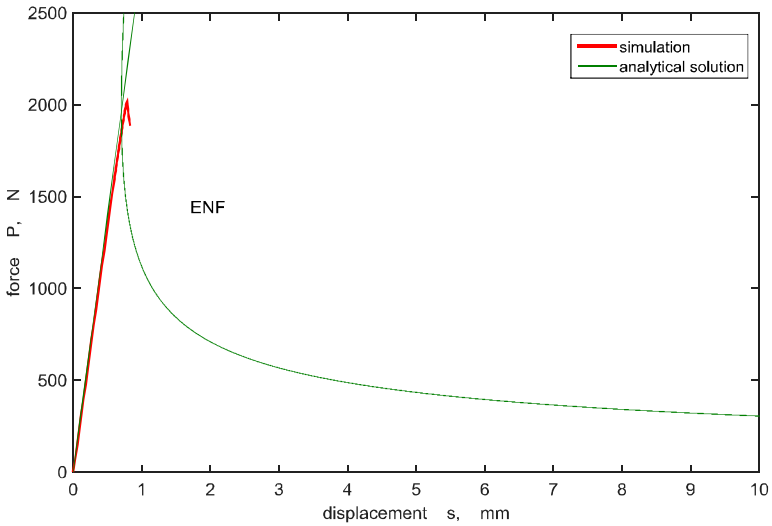


Albert Turon Travesa, "Simulation of delamination in composites under quasi-static and fatigue loading using cohesive zone models".

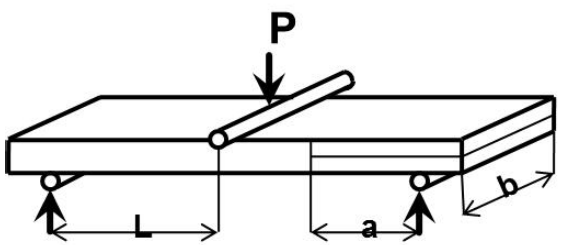
Ermittlung Modellparameter
Nummerische Optimierung

‚End Notched Flexure‘
Mode II Test





ENF

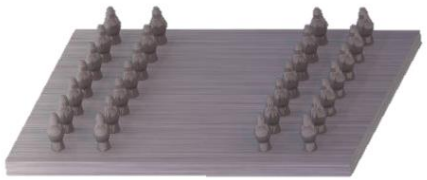


Einflussgrößen:

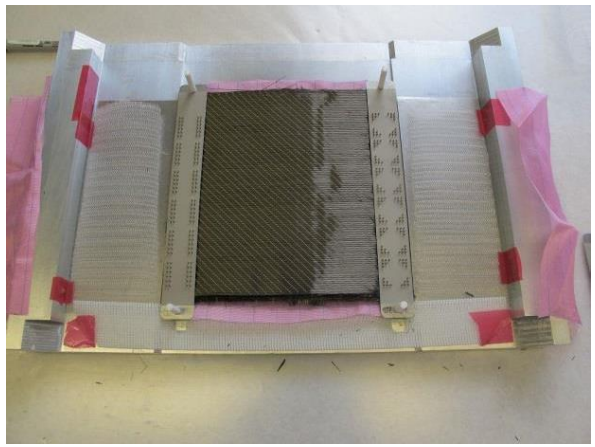
- Steifigkeit
- Kritische Energiefreisetzungsrate,
- Festlegung Schädigungsinitierung (z.B. Spannung oder Rissöffnung)
- Schädigungsentwicklung (z.B.: linear, bilinear oder exponentiell)
- Elementgröße
- Zeitschritt
- Reibung im Interface
- Reibung Auflager

Anwendungsbeispiele
Verbindungstechnik

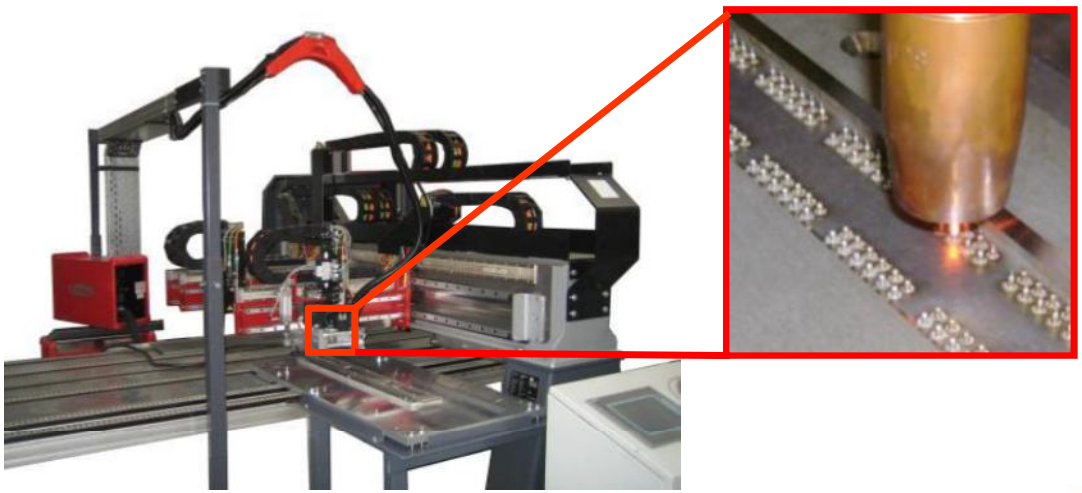
Motivation



Im ‚Kalten' Schweißprozess (CMT -Cold Metal Transfer) aufgebrachte Pins für die Verstärkung von CFK zu CFK Verbindungen (rostfreier Stahl oder Titan)



Form mit eingebrachten Metalleinsätzen

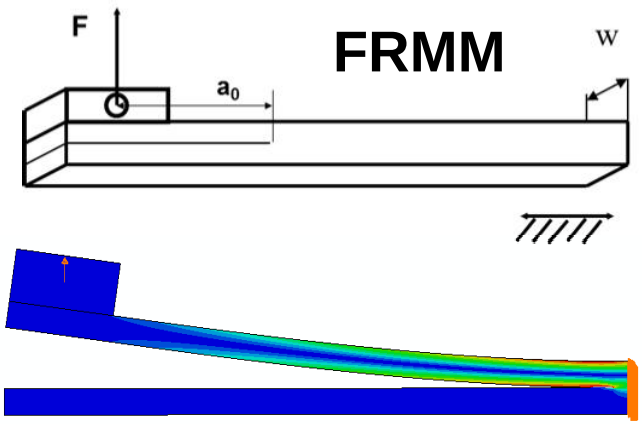


Schweißkopf dreiachsig steuerbar

Probenvorbereitung

‚Single Lap Shear Test'

Parameterermittlung Kohäsivzonenmodell

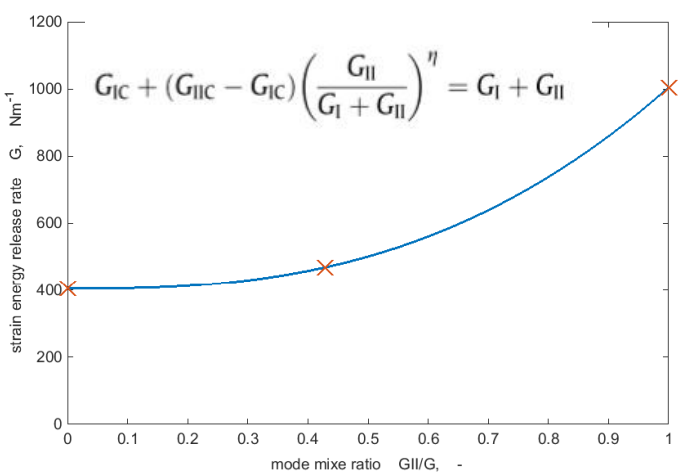


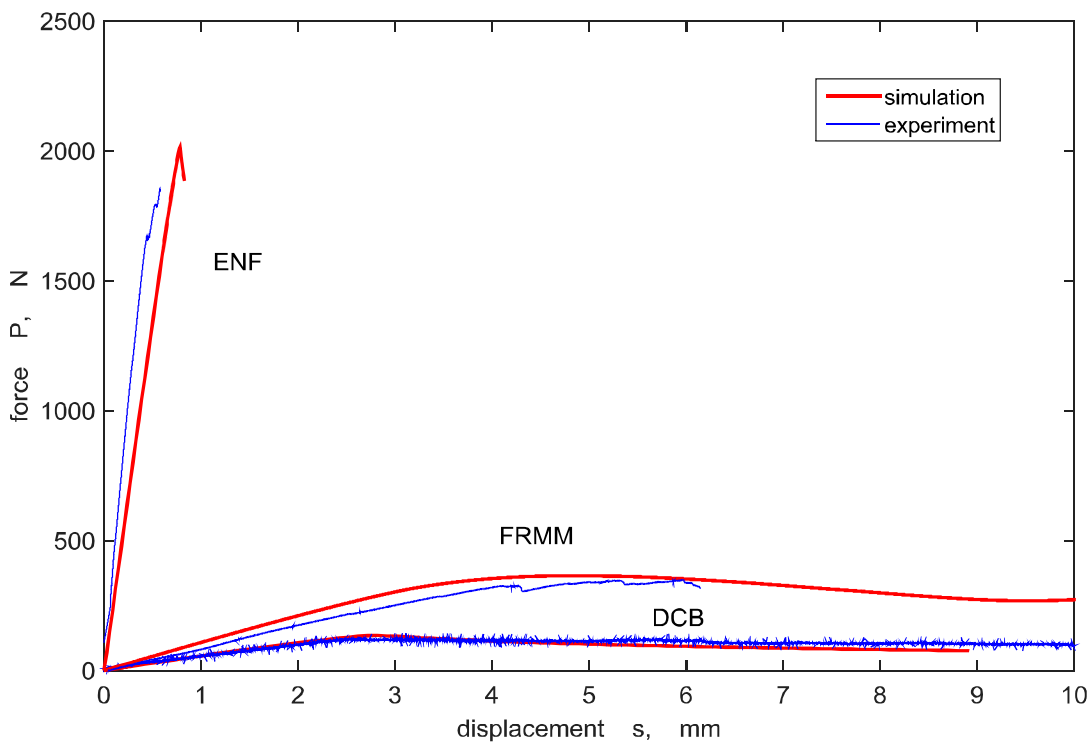
Schädigungsentwicklung: linear

Schädigungsinitiierung : Maximale Spannung

Mixed Mode: BK

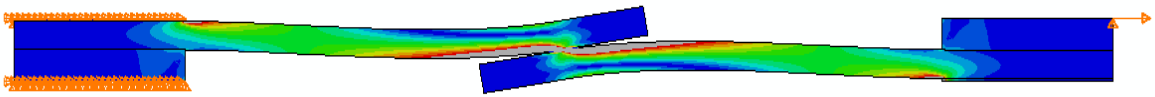
σ_0	10	MPa
τ_0	70	MPa
GI	0.405	N/m
GII	1.005	N/m
η	2.64	

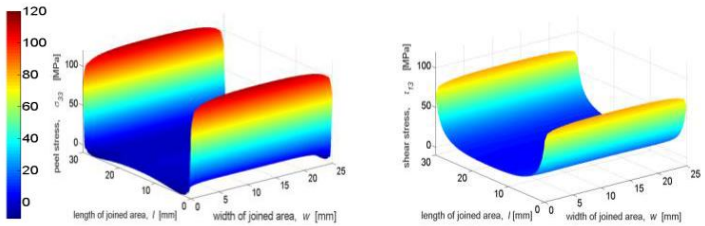




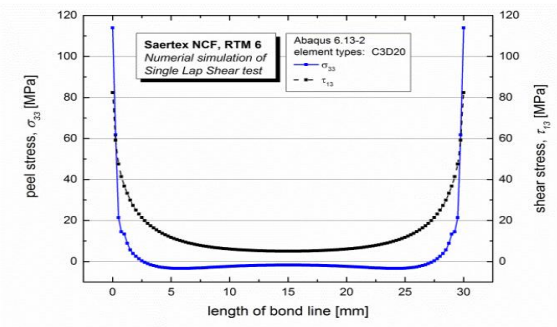
Anwendungsbeispiele
Verbindungstechnik

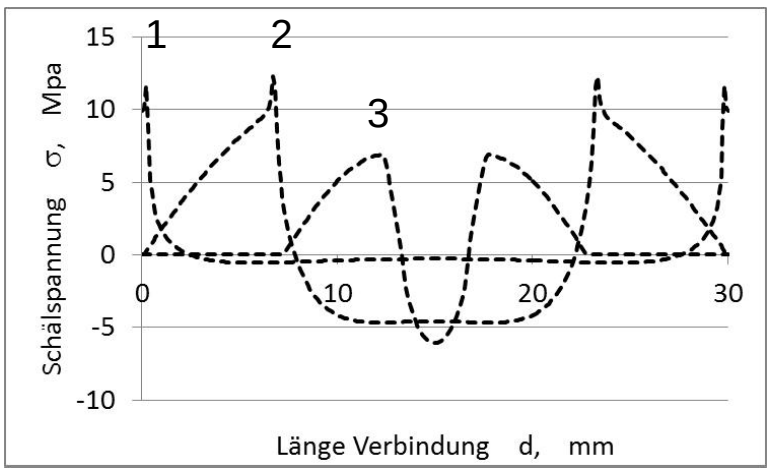
Single Lap Shear Simulation

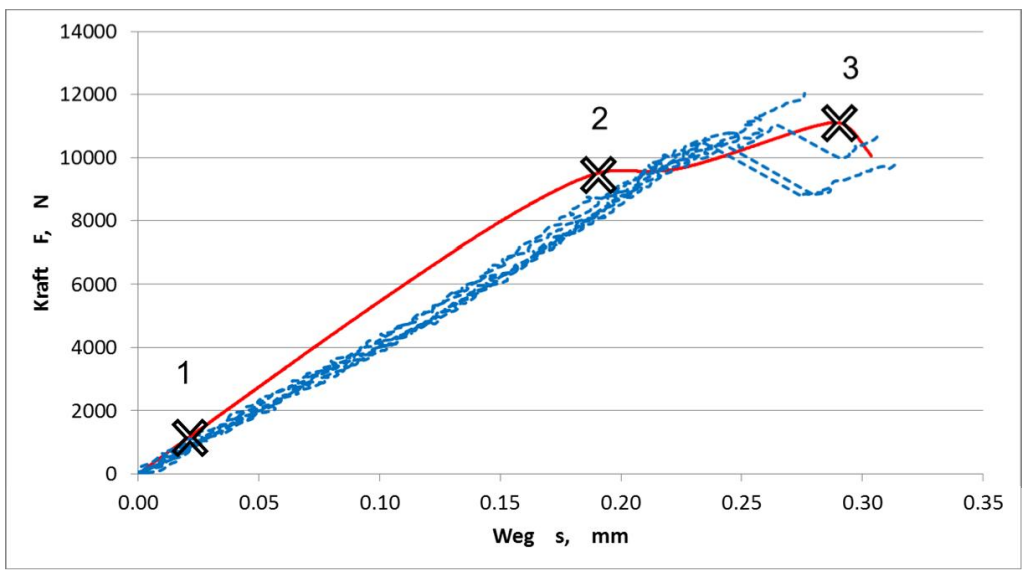


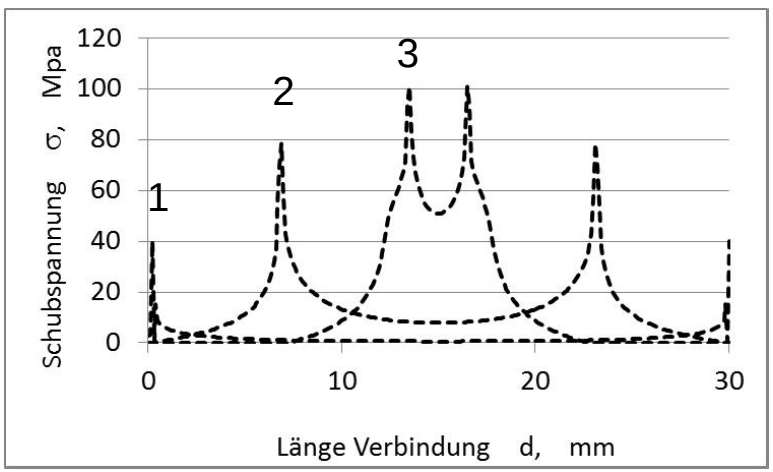


- Schädigungsverlauf
- Beurteilung Einfluss Bruchmoden

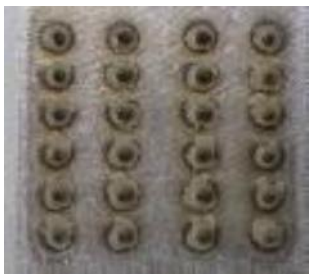




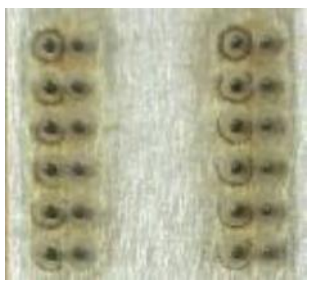




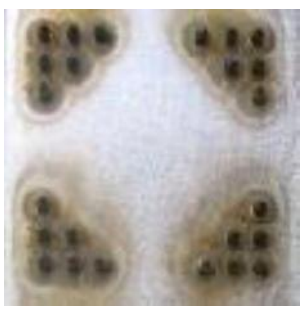
Ergebnisse



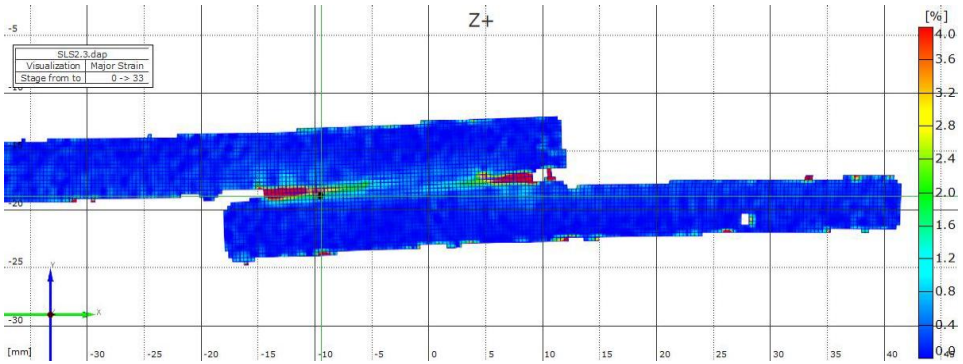
pin array 1

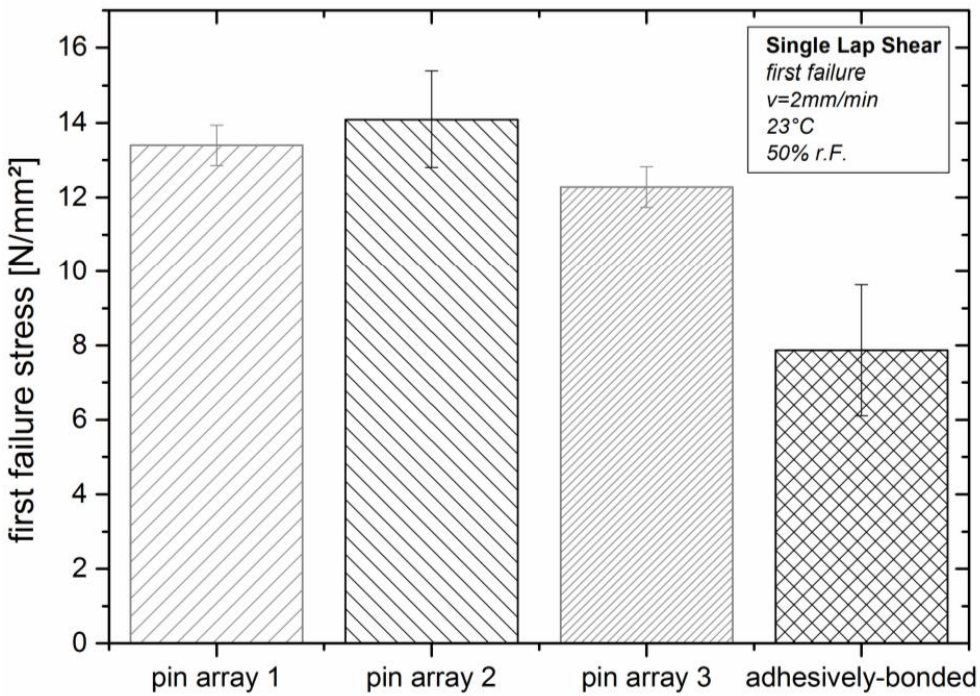


pin array 2



pin array 3

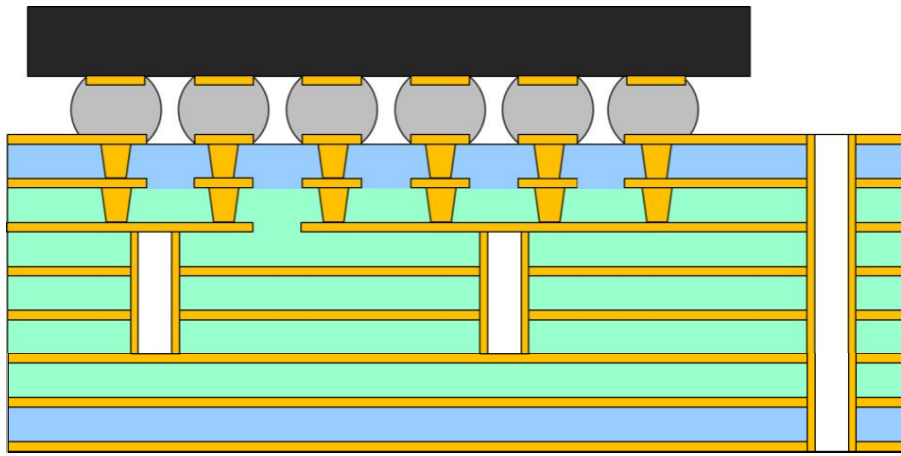


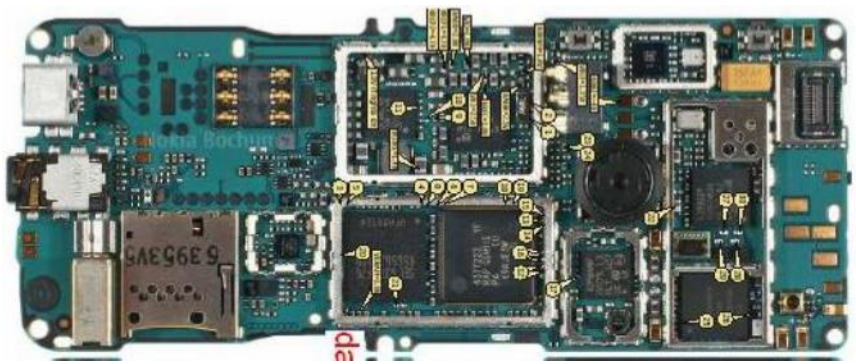


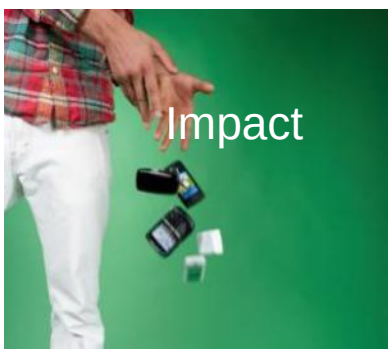
Anwendungsbeispiele
Leiterplatten

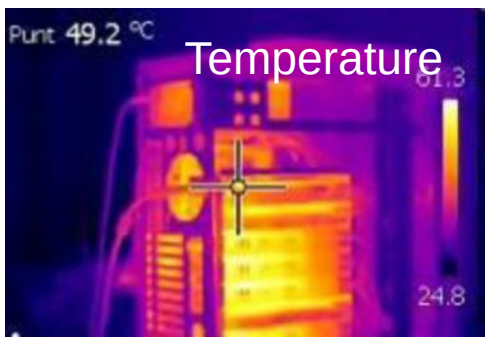
Motivation

- Multilayer Aufbauten
- Interaktion verschiedener Materialien mit signifikant unterschiedlichen thermomechanischen Eigenschaften
- Breiter Anwendungsbereich – viele verschiedene Belastungen

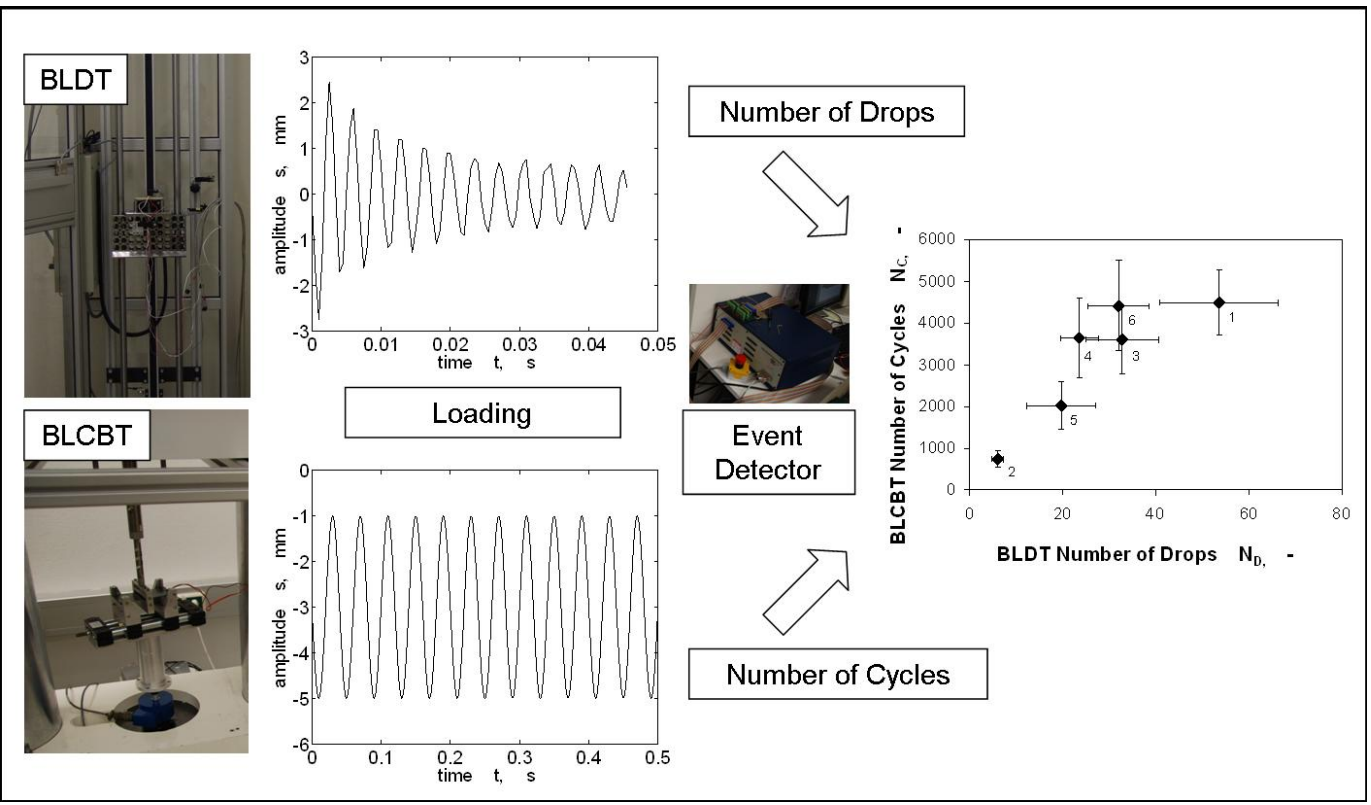


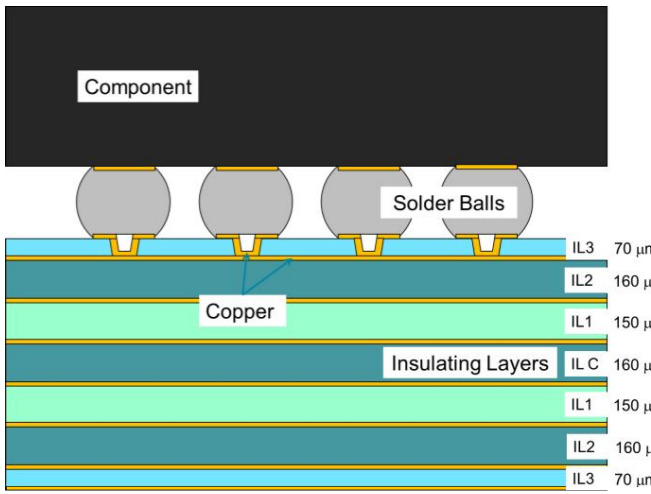


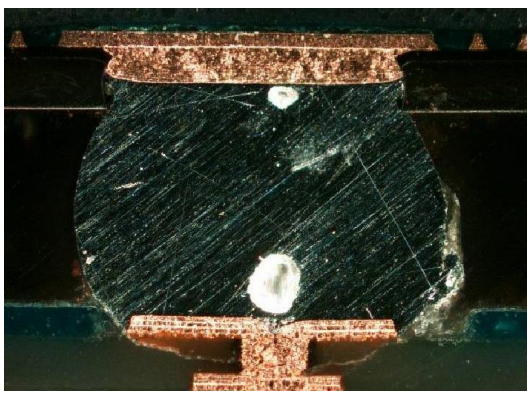




Belastungen und Fehlerbild



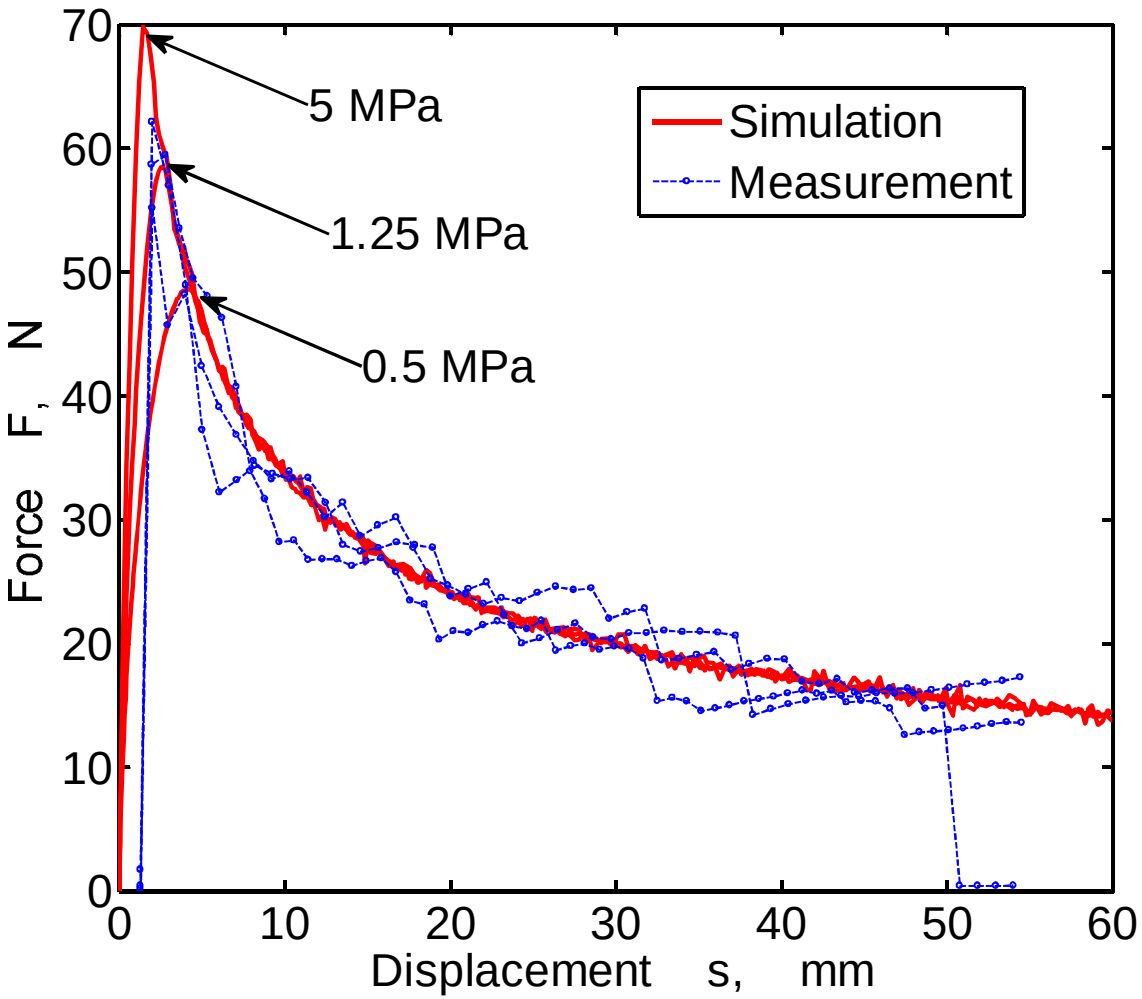


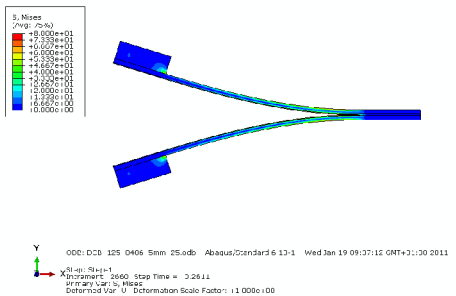


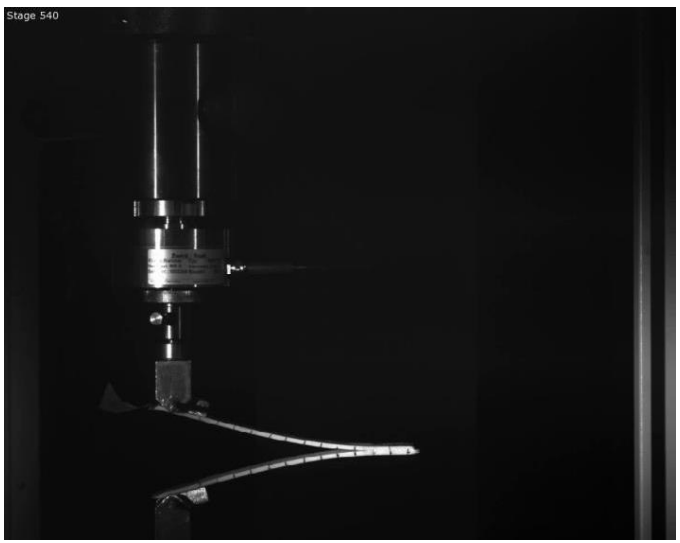
Fuchs, P. and Major, Z. (2011), "Cyclic bend tests for the reliability evaluation of printed circuit boards under dynamic loads", *Frattura ed Integrità Strutturale No.* 15, pp. 64–73.

Fuchs, P.F., Pinter, G. and Krivec, T., "Design independent lifetime assessment method for PCBs under low cycle fatigue loading conditions", *EuroSimE*, Vol. 2014.

Bestimmung der Schädigungsinitierung



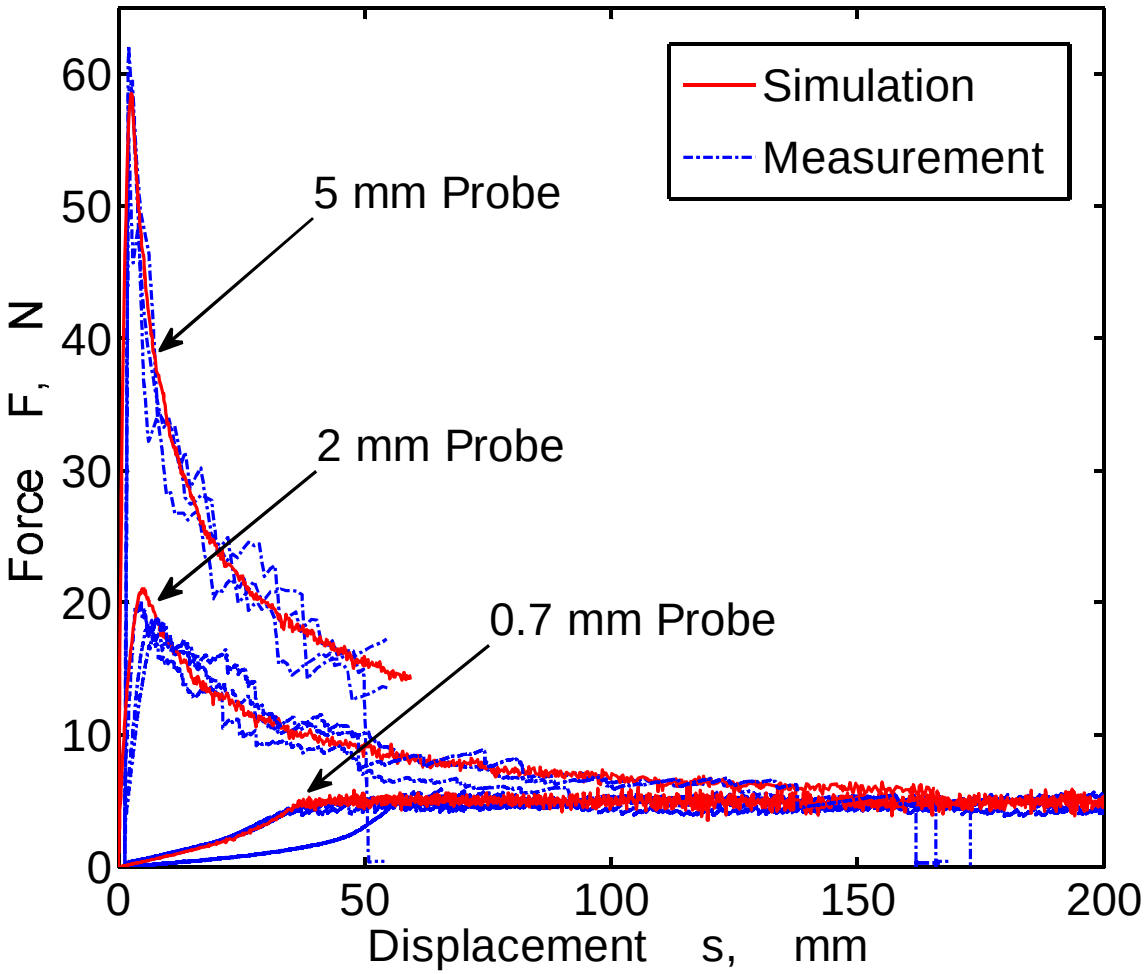


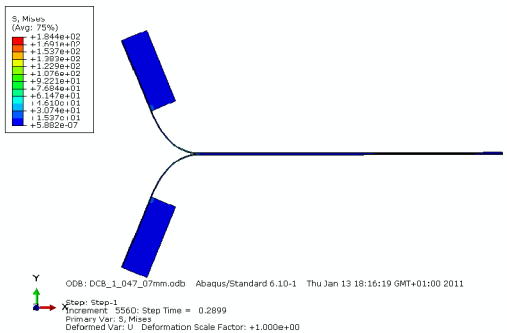


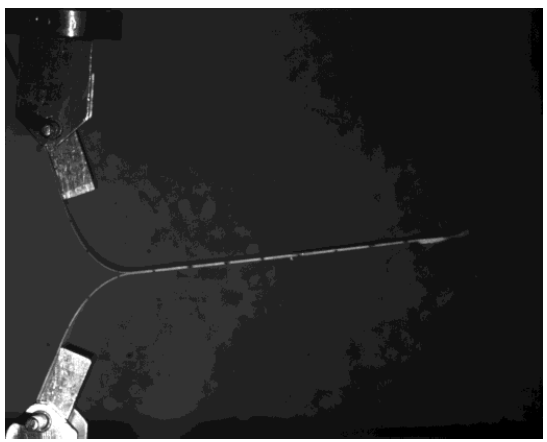
Anpassung der kohäsiven Spannung

Fuchs, P. and Major, Z. (2011), "Cyclic bend tests for the reliability evaluation of printed circuit boards under dynamic loads", *Frattura ed Integrità Strutturale No.* 15, pp. 64–73.

Bestimmung der Schädigungsinitierung

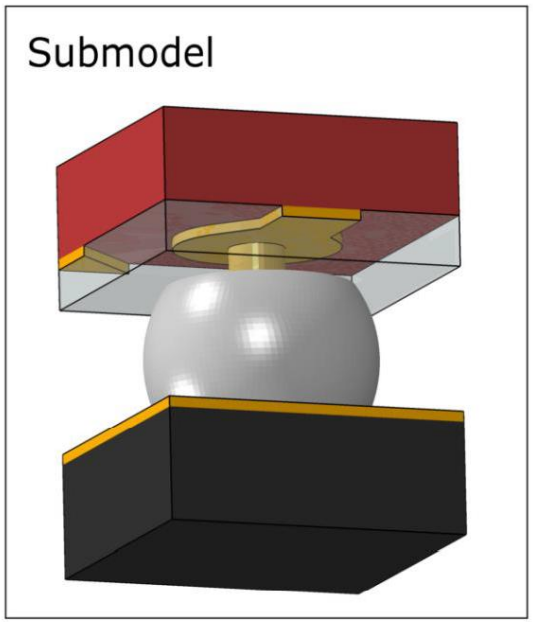


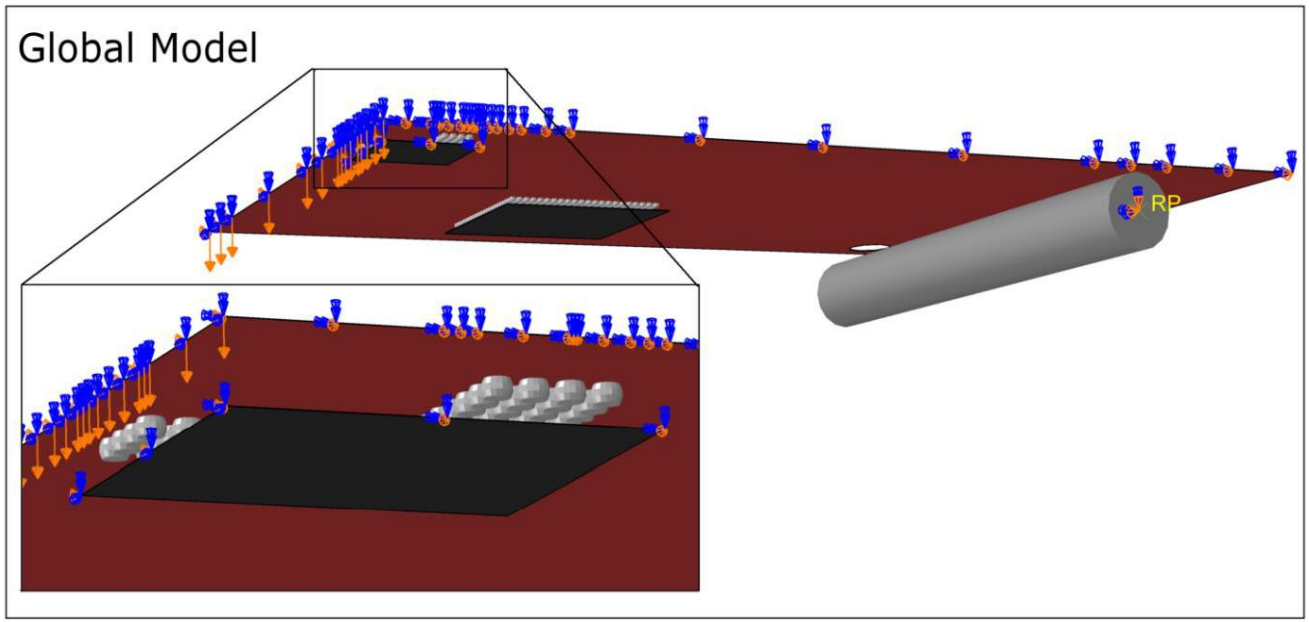




Evaluierung des Kohäsivzonenmodells anhand von Versuchen an dünnen Laminaten

Simulationsmodell

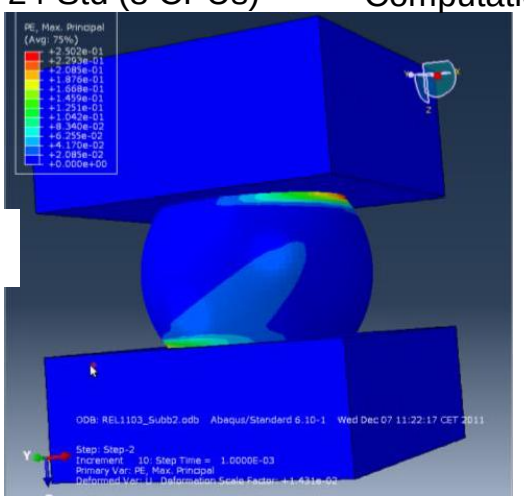




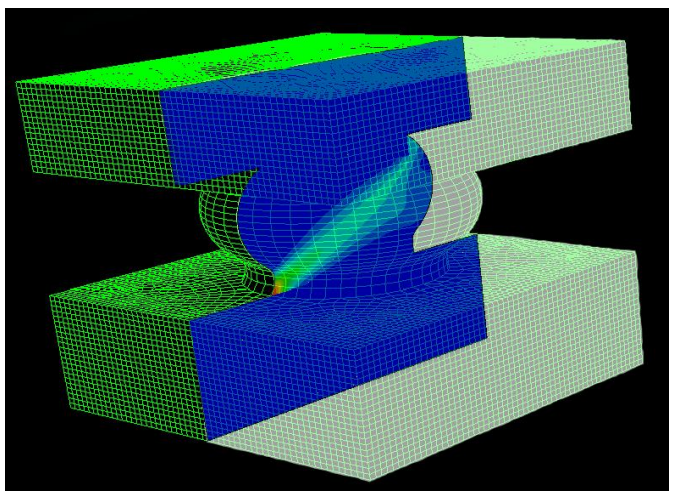
Elements: ~ 200 000
Computation time: ~ 24 Std (8 CPUs)

Elements: ~ 120 000
Computation time: ~ 1Std (8 CPUs)

3D Model

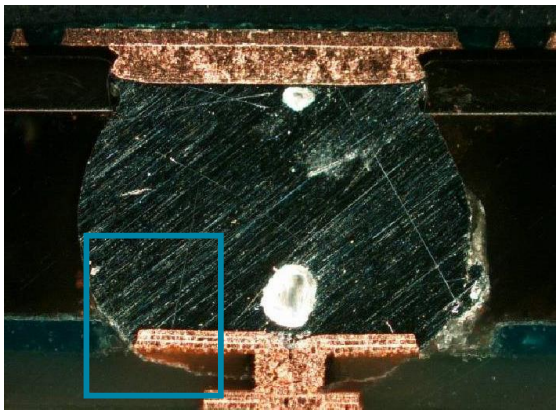


Querschnitt

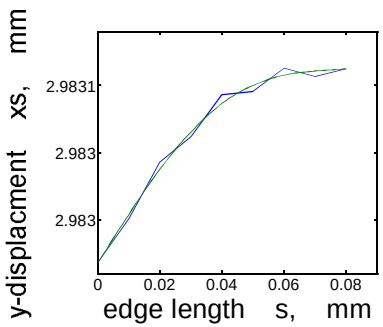


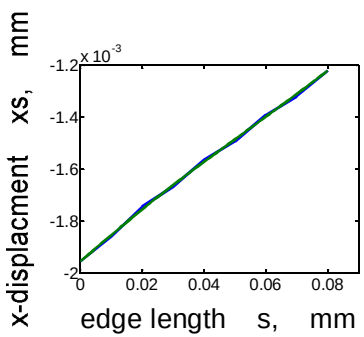
Bruchsimulation

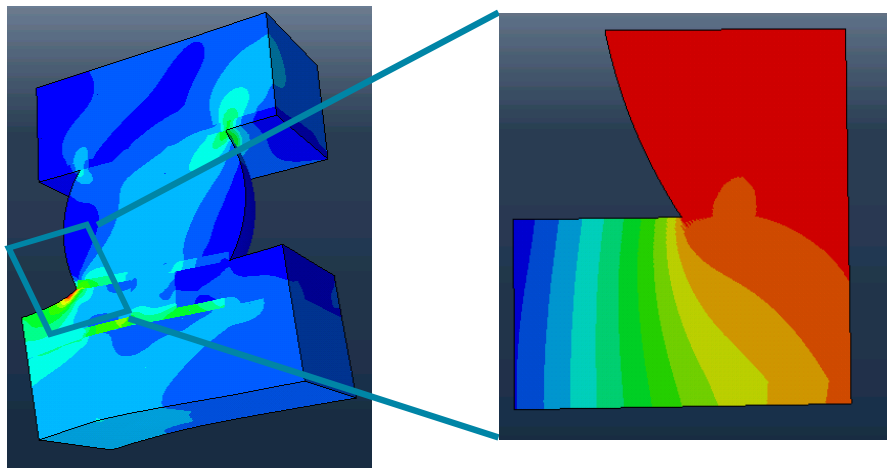
- Um das lokale Schädigungsverhalten abzubilden wurde ein 2-Stufiges Untermodell verwendet
- Der Modellierungsraum wurde auf 2D reduziert um die Rechenzeit zu reduzieren



Regarded Local Area





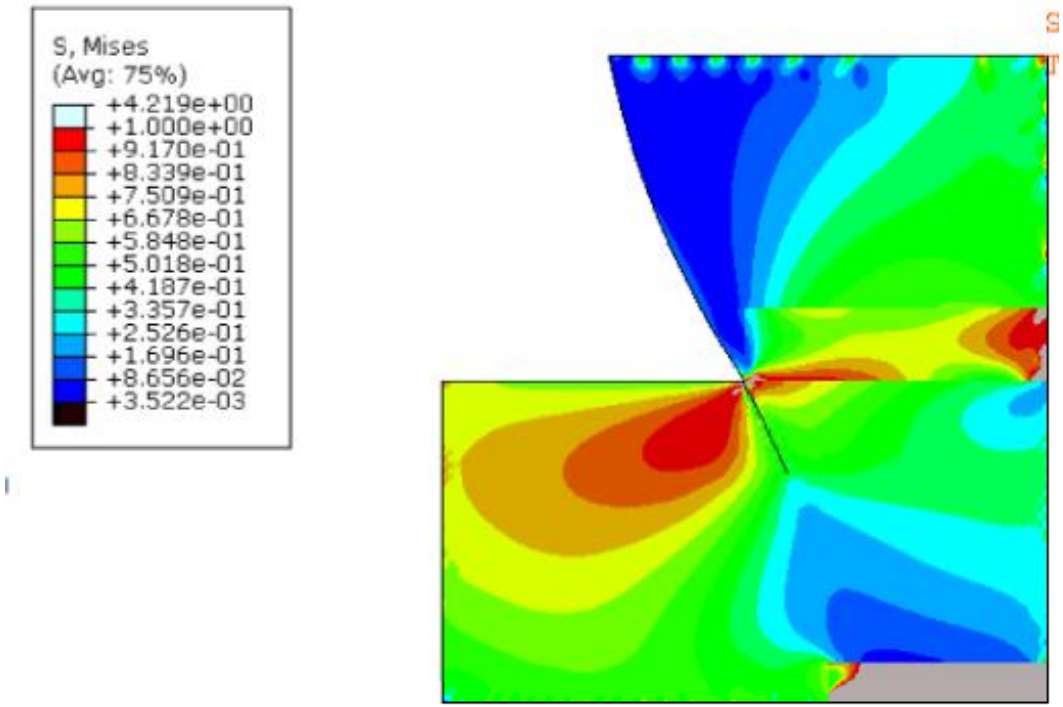


Mises Stress Sub Model

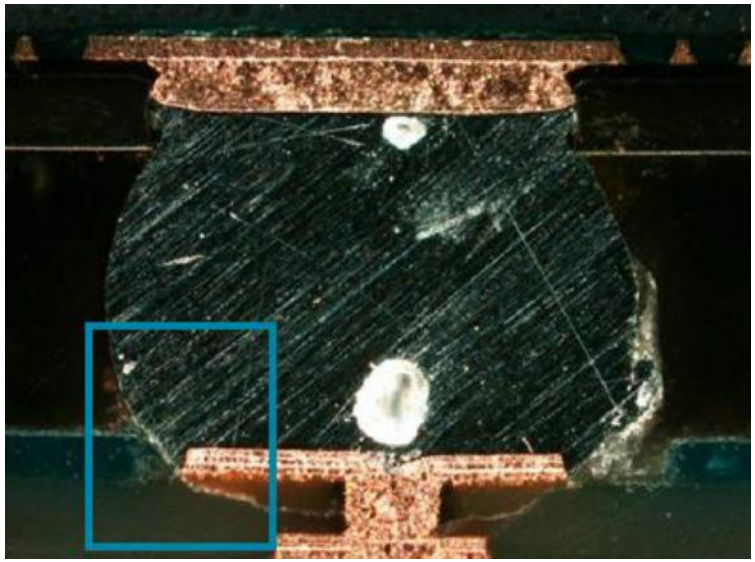
Displacement SubSub Model

Sub Model → SubSub Model

Bruchsimulation

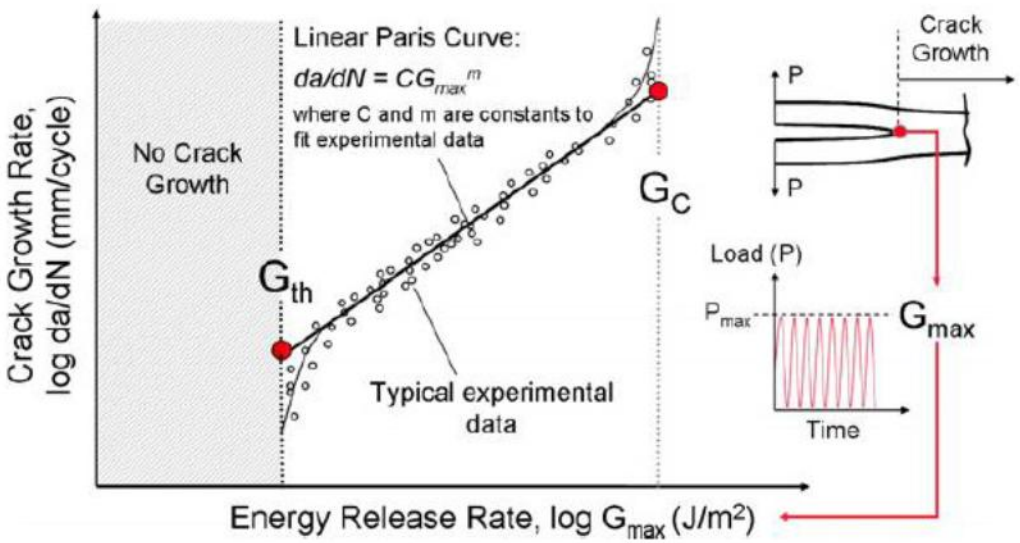


X-FEM Simulation

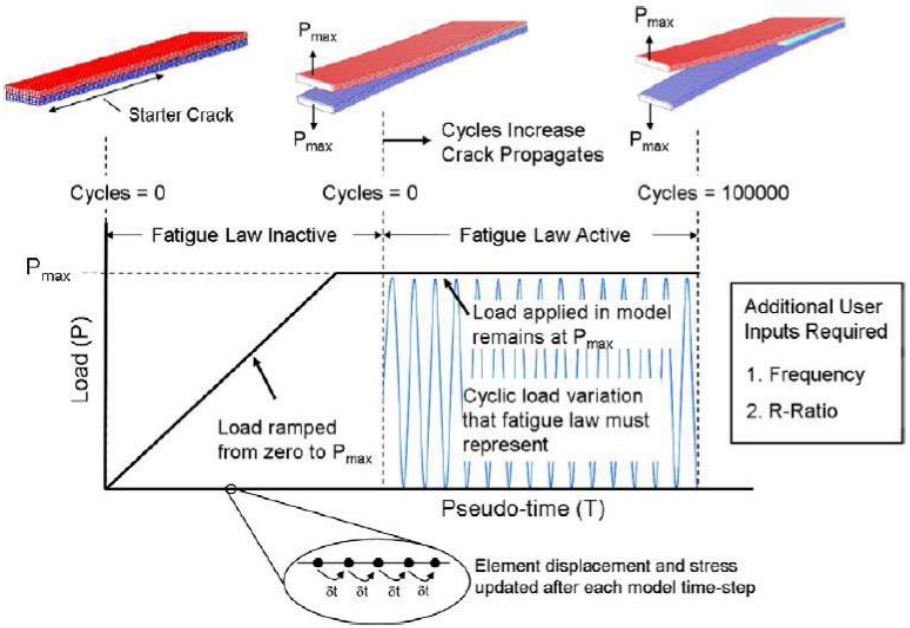


Fehlerbild Experiment

Modellierung zyklisches Kohäsivzonenmodell

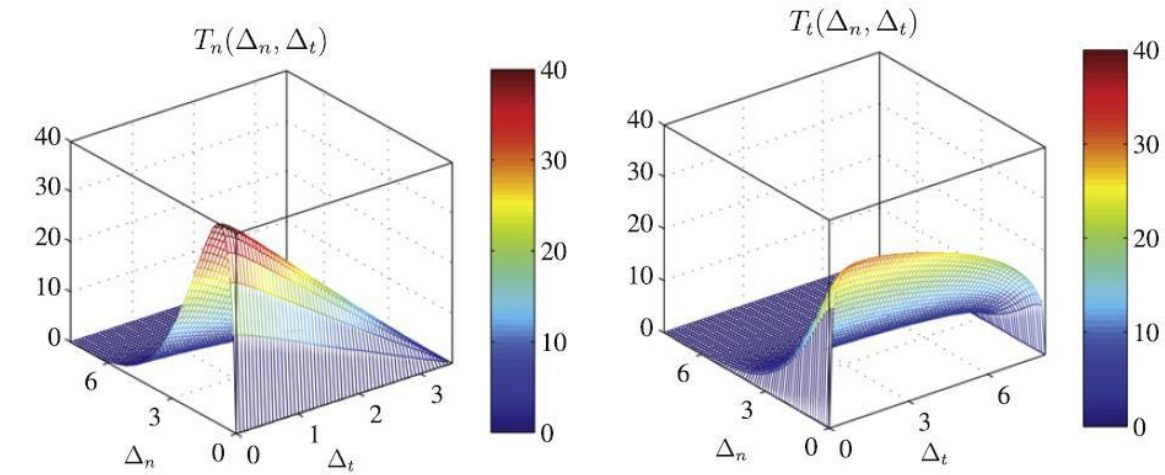


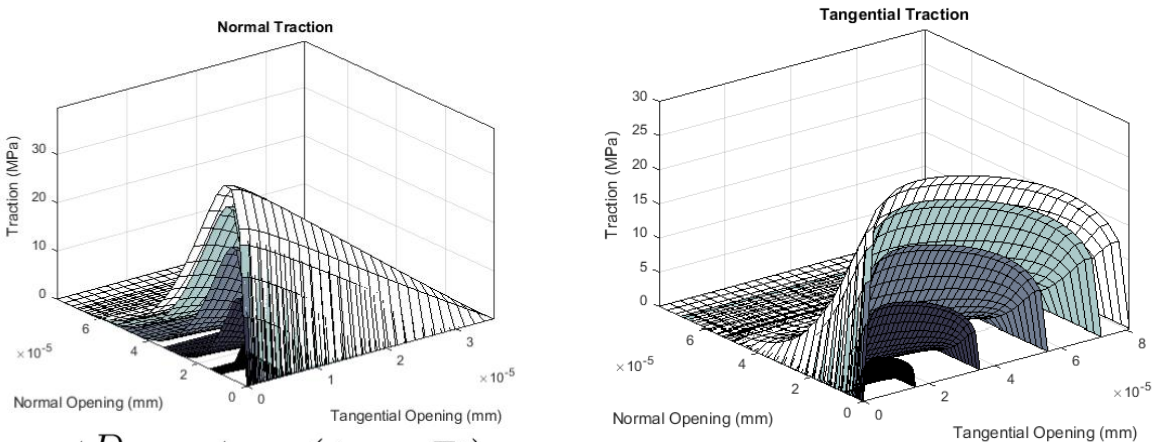
$$\frac{\partial a}{\partial t} = \frac{\partial a}{\partial N}\frac{\partial N}{\partial t}$$

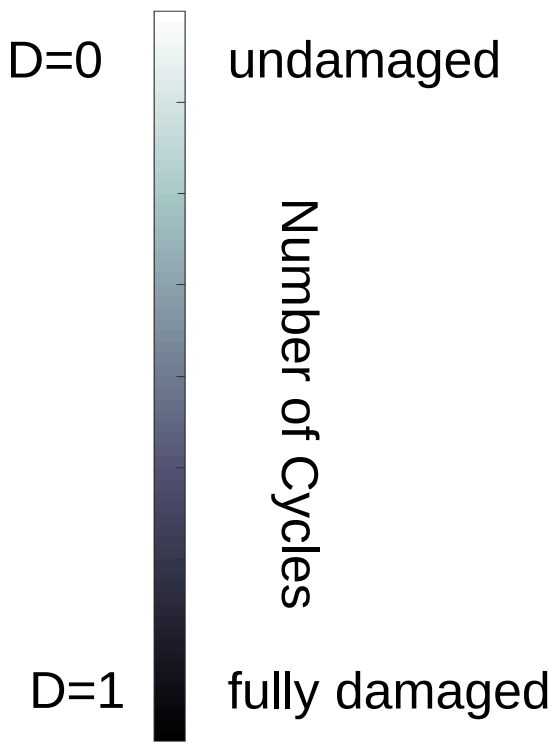


Harper, P.W. and Hallett, S.R. (2010), "A fatigue degradation law for cohesive interface elements – Development and application to composite materials", International Journal of Fatigue, Vol. 32 No. 11, pp. 1774–1787.

Modellierung zyklisches Kohäsivzonenmodell







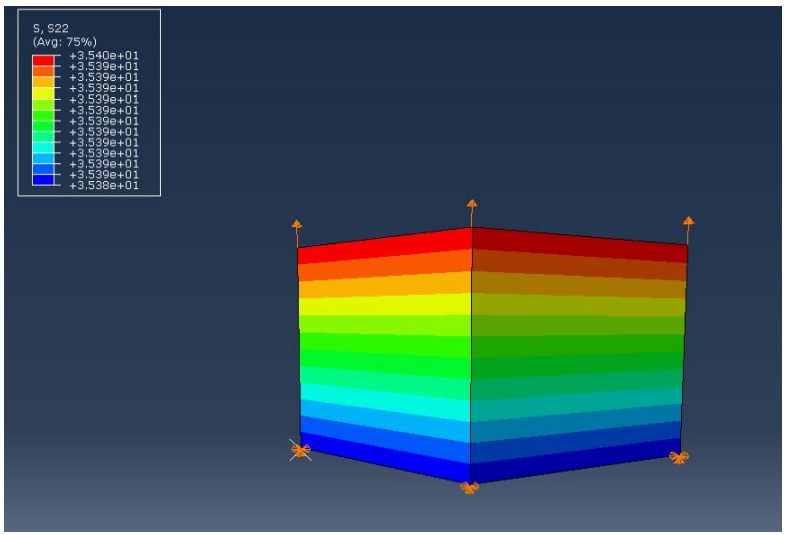
$$\phi_t^D = \phi_t * (1 - D)$$

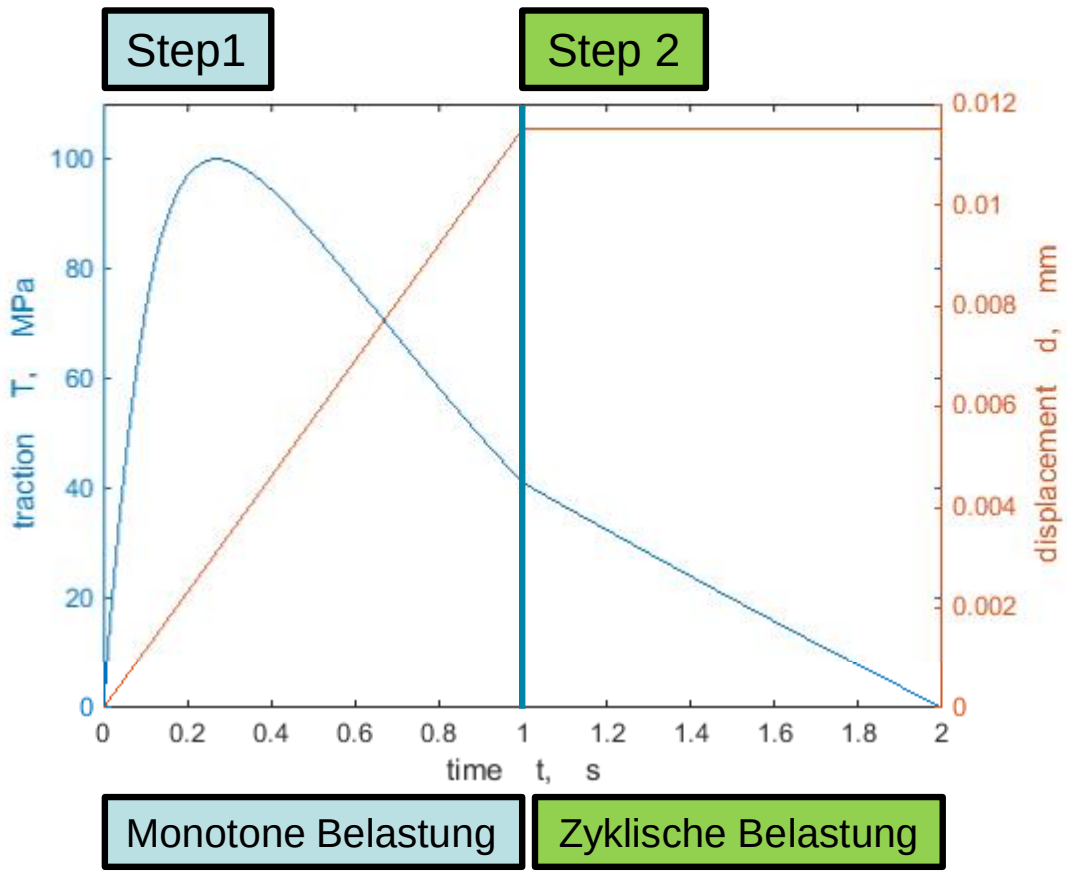
$$\phi_n^D = \phi_n * (1 - D)$$

$$\sigma_{max}^D = \sigma_{max} * \sqrt{(1 - D)}$$

$$\tau_{max}^D = \tau_{max} * \sqrt{(1 - D)}$$

‘Single Element’ Test





Zusammenfassung

- Delamination ist eine kritische Versagensart in vielen Anwendungen von Verbundwerkstoffen
- Möglichkeiten der Simulation in der Bruch- und Schädigungsmechanik
- Phänomenologisches Kohäsivzonenmodell bringt für die Anwendung in der Simulation viele Vorteile
- Herausfordernde Bestimmung der Kohäsivzonenmodellparameter
- Vielseitige Anwendbarkeit für das Verständnis und die Interpretation von Delamination als Basis für die Bauteiloptimierung

Danksagung

Die vorliegende Forschungsarbeit wurde an der Polymer Competence Center Leoben GmbH im Rahmen des Kompetenzzentren-Programms COMET des Bundesministeriums für Verkehr, Innovation und Technologie und des Bundesministeriums für Wirtschaft, Familie und Jugend unter Beteiligung der Montanuniversität Leoben, der Austria Technologie & Systemtechnik AG, AT&S und der Andritz Hydro AG durchgeführt und mit Mitteln des Bundes und der Länder Steiermark, Niederösterreich und Oberösterreich gefördert.

Teile der Forschungsarbeit wurden weiters durch das FFG TAKE OFF Projekt Composite+composite Joints with Enhanced damage toleranCe (CoJEC) gefördert.