

Nordic LS-DYNA Users' Conference 2022, Gothenburg



New material MAT_307:

A viscoelastic-viscoplastic constitutive formulation to model adhesives during the complete manufacturing-crashworthiness process chain

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DigiBody – Optimizing of Joining Technology

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Motivation: Adhesive Process chain

■ Manufacturing

- Adhesive is applied to body in white during assembly
- Curing is activated by elevated temperatures during the drying process after cathodic dip painting
- Joining different materials may result in $\Delta\alpha$ -problem
- Viscous fingering effect if joining partners separate

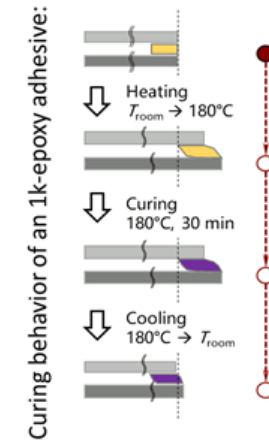
■ Crashworthiness

- Complex plasticity behavior with volume change under plastic deformation and non-associated flow rules
- Temperature and cure dependent material damage

■ Already existing or proposed material models

- *MAT_252 (TAPO), *MAT_277, UMAT for a modified TAPO model [Matzenmiller and Kühlmeier, 2018]

Schematic sketch of $\Delta\alpha$ -problem



[DuPont]

Viscous fingering



[LWF KS2-Specimens]

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Motivation

2

*New material *MAT_307 / *MAT_GENERALIZED_ADHESIVE_CURING*

- *Input and General Set-up*
- *Curing Kinetics and Viscoelasticity*
- *Plasticity and Damage*

3

Material Calibration

4

Summary and Outlook

*MAT_GENERALIZED_ADHESIVE_CURING / *MAT_307



		1	2	3	4	5	6	7	8
General parameters	MID	RO	GASC	IDOC	INCR	QCURE			
Curing kinetics	CKOPT	CK1	CK2	CK3	CK4	CK5	CK6	CK7	
Chemical expansion	CEOPT	CE1	CE2	CE3	CE4				
Thermal expansion	TEOPT	TE1	TE2						
Horizontal temp. shift	THOPT	TH1	TH2	TH3	TH4				
Vertical temp. shift	TVOPT	TV1	TV2						
Horizontal doc shift	PHOPT	PH1	PH2	PH3	PH4	PH5	PH6		
Vertical doc shift	PVOPT	PV1	PV2	PV3	PV4				
Plasticity	PL1OPT	PL11	PL12	PL13	PL14	PL15			
	PL2OPT	PL21	PL22	PL23	PL24	PL25	PL26		
Damage and failure	DAOPT	DAEVOFLG	DATRIAX	DA1	DA2	DA3	DA4	DA5	
	DA6	DA7	DA8	DA9	DA10	DA11	DA12	DA13	
Prony series expansion	G1	BETAG1	K1	BETAK1					
	Gi	BETAGi	Ki	BETAKi					
	G18	BETAG18	K18	BETAK18					



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*MAT_307: Curing Kinetics and Viscoelasticity

*MAT_307: Curing Kinetics and Consequences



	1	2	3	4	5	6	7	8
Card 1	MID	RO	GASC	IDOC	INCR	QCURE		
Card 2	CKOPT	CK1	CK2	CK3	CK4	CK5	CK6	CK7
Card 3	CEOPT	CE1	CE2	CE3	CE4			
...	...	...	...	...	...	...	...	...

■ Evolution of degree of cure p

- Follows an ODE with general form

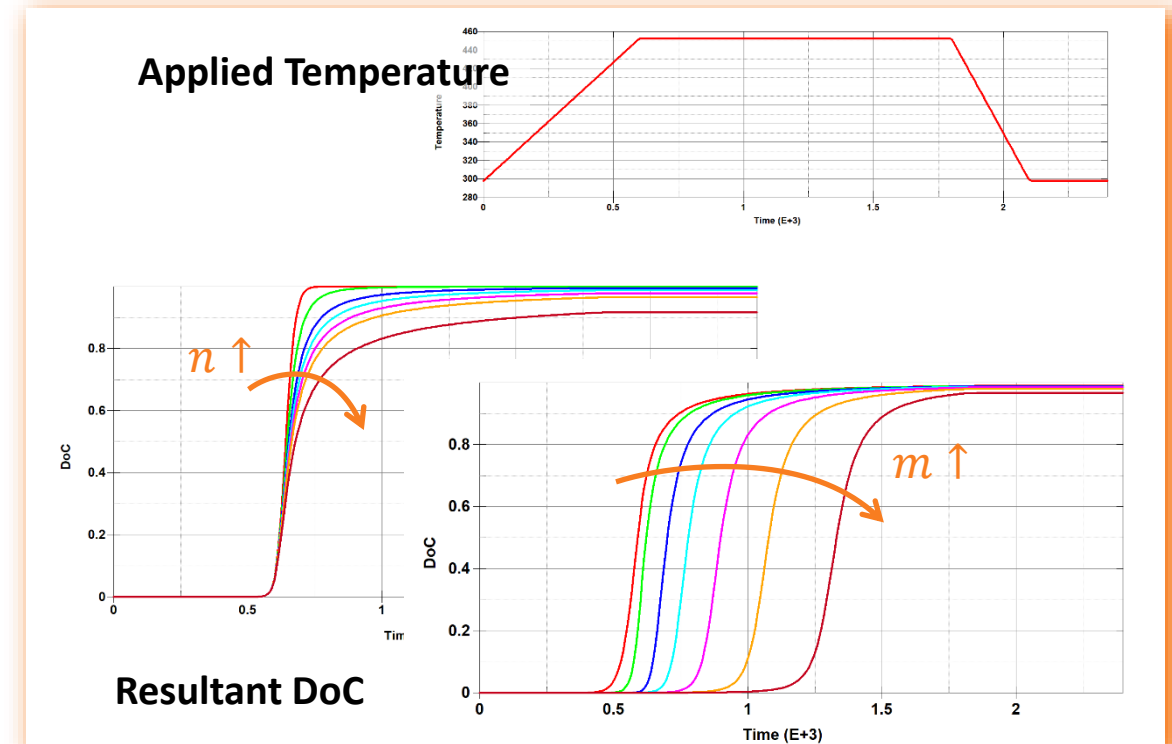
$$\frac{dp}{dt} = K_1(T) \cdot (1 - p)^{n_1} + K_2(T) \cdot p^m \cdot (1 - p)^{n_2}$$

- Direct input for $K_i(T)$ or Arrhenius approach

■ Heat generated by chemical reaction

■ Chemical expansion

- as secant or differential form



*MAT_307: Viscoelasticity – Shifting Operations



- Prony series expansion for shear modulus $G(t)$ and bulk modulus $K(t)$

$$G(t) = G_{\infty} + \sum_i G_i \cdot e^{-\beta_i^G t} = G_0 - \sum_i G_i + \sum_i G_i \cdot e^{-\beta_i^G t}$$

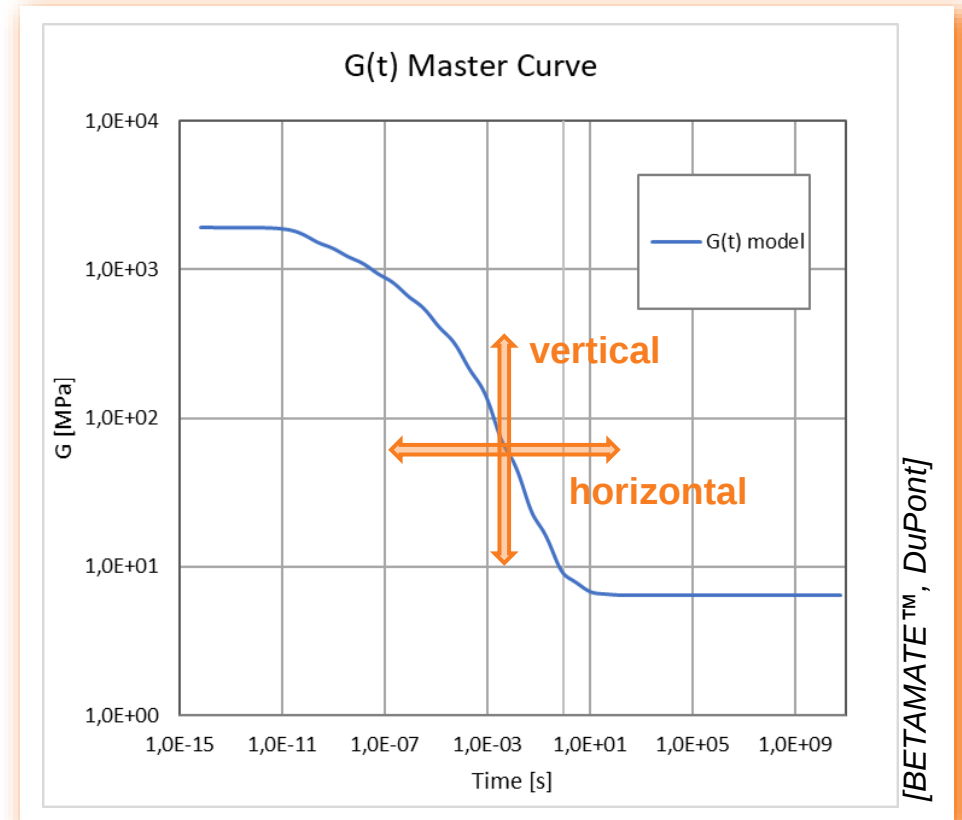
- Horizontal shift operations of a master curve

- Scaling of the decay parameters β_i^G and β_i^K
- Scaling factors are a_T^G, a_p^G for shear and a_T^K, a_p^K for bulk

- Vertical shift operations of a master curve

- Scaling of G_i and K_i or of $G(t)$ and $K(t)$
- Scaling factors are b_T^G, b_p^G for shear and b_T^K, b_p^K for bulk

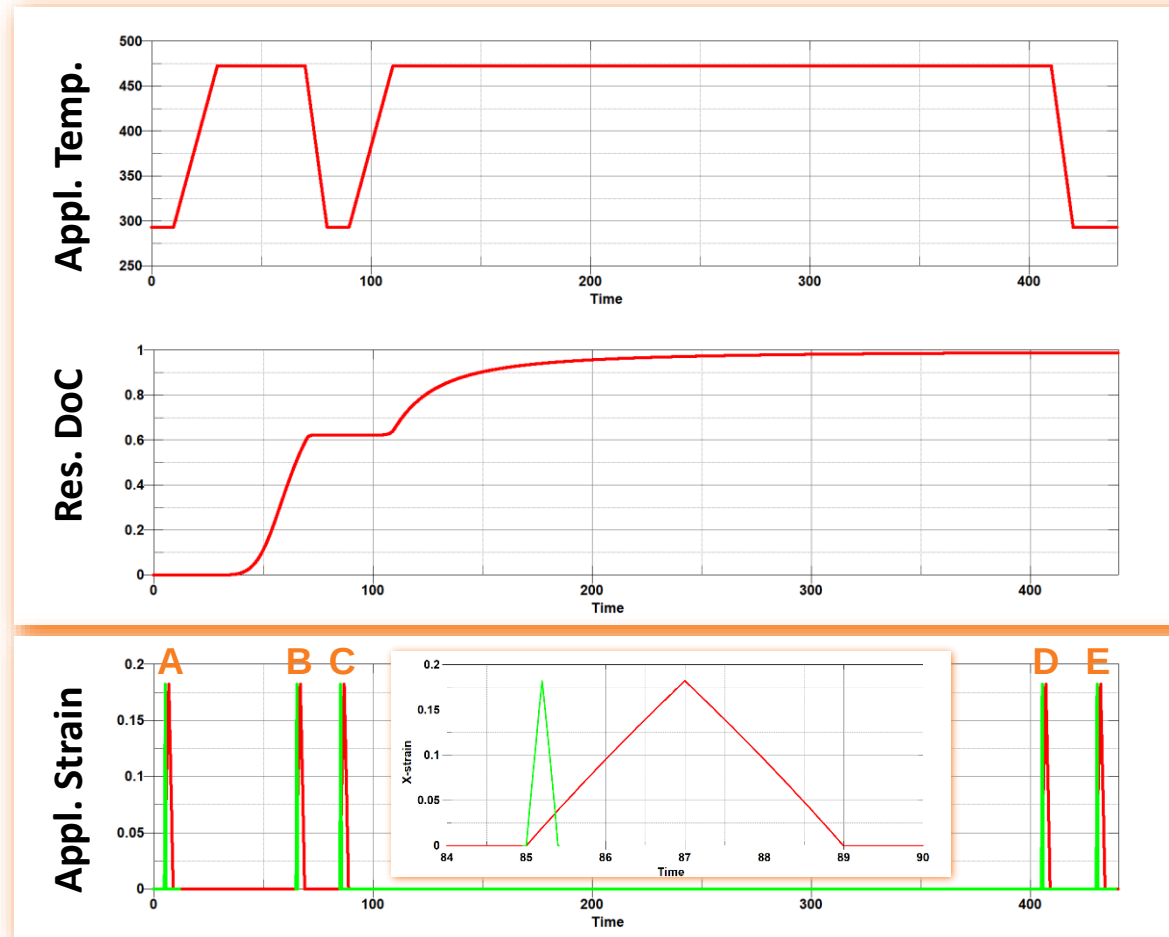
	1	2	3	4	5	6	7	8
...	...	...	...	...	...	...	...	...
Card 5	THOPT	TH1	TH2	TH3	TH4			
Card 6	TVOPT	TV1	TV2					
Card 7	PHOPT	PH1	PH2	PH3	PH4	PH5	PH6	
Card 8	PVOPT	PV1	PV2	PV3	PV4			
...	...	...	...	...	...	...	...	...



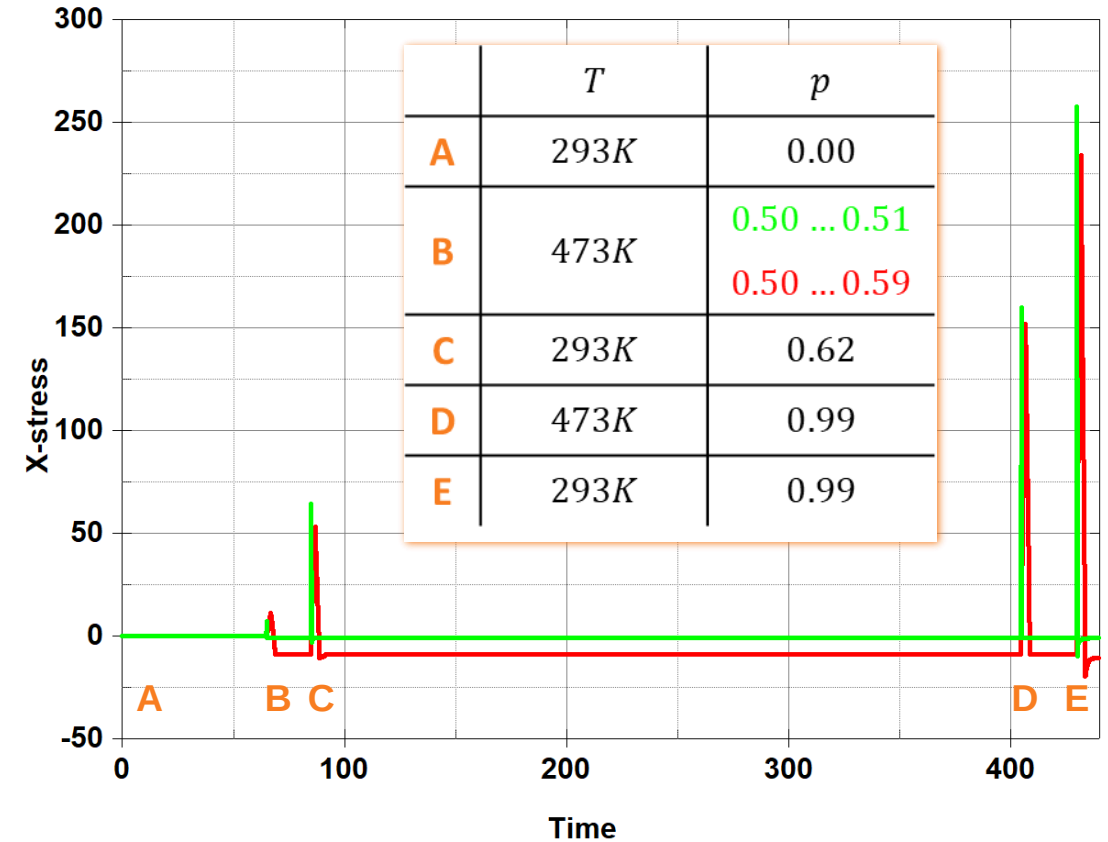
*MAT_307: Viscoelasticity – Proof of Concept



■ Single element relaxation and hysteresis test



Stress response



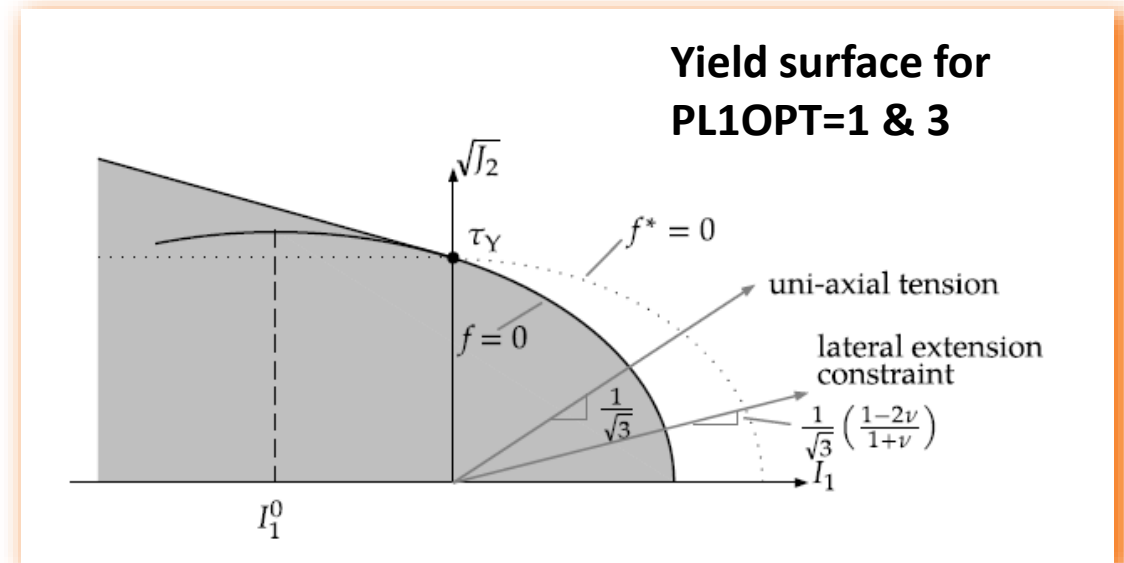
*MAT_307: Plasticity and damage

*MAT_307: Plasticity



	1	2	3	4	5	6	7	8
...	...	...	...	...	...	...	...	...
Card 9	PL1OPT	PL11	PL12	PL13	PL14	PL15		
Card10	PL2OPT	PL21	PL22	PL23	PL24	PL25	PL26	
...	...	...	...	...	...	...	...	...

- Plasticity formulation based on (extended) TAPO
 - Non-associated I_1 - J_2 - plasticity
 - Cap in tension and Drucker & Prager in compression
 - Distortional hardening with respect to temperature
- Card 9 defines flow function f and potential f^*
- Card 10 defines the yield strength τ_Y as function of temperature T and degree of cure p



*MAT_307: Material Damage D_1

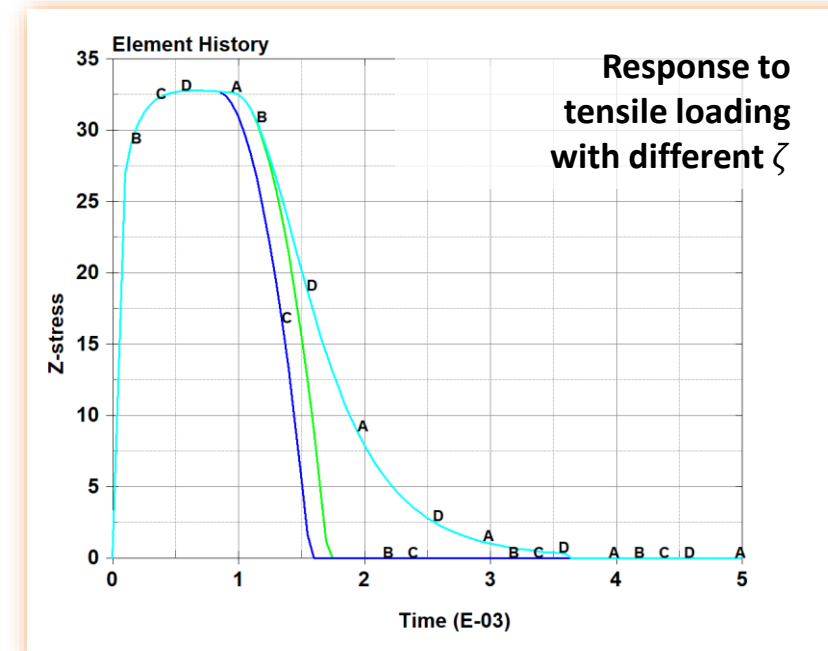


	1	2	3	4	5	6	7	8
...	...	...	...	...	...	...	...	...
Card11	DAOPT	DAEVOFLG	DATRIAX	DA1	DA2	DA3	DA4	DA5
Card12	DA6	DA7	DA8	DA9	DA10	DA11	DA12	DA13
...	...	...	...	...	...	...	...	...

- Empirical isotropic damage model based on Lemaitre [1985]

$$\dot{D}_1 = \dot{D}_1(\zeta, \dot{\zeta}) = n \left\langle \frac{\zeta - \gamma^c}{\gamma^f - \gamma^c} \right\rangle^{n-1} \frac{\dot{\zeta}}{\gamma^f - \gamma^c}, \quad \dot{\zeta} \in \{\dot{\epsilon}, \dot{\epsilon}_v, \dot{\epsilon}\}$$

- Parameter DAOPT defines the strain thresholds γ^f and γ^c
- Parameter DAEVOFLG defines effective strain measure ζ
 - arc length of damage plastic strain rate,
 - arc length of plastic strain rate,
 - arc length of viscoelastic strain rate



*MAT_307: (Pre-)Damage D_2



	1	2	3	4	5	6	7	8
...	...	...	...	...	...	...	...	...
Card11	DAOPT	DAEVOFLG	DATRIAX	DA1	DA2	DA3	DA4	DA5
Card12	DA6	DA7	DA8	DA9	DA10	DA11	DA12	DA13
...	...	...	...	...	...	...	...	...

■ Damage description

- Damage equivalent to reduction of the effective adhesive area

$$\tilde{A} = (1 - D_2)A_0$$

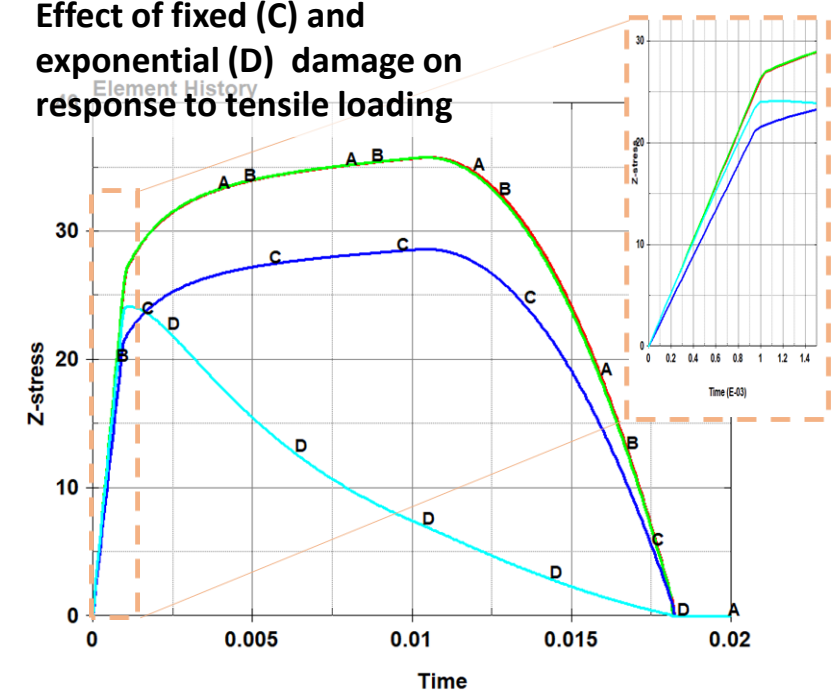
- Area reduction can be defined as function of thickness strain

$$(1 - D_2) = \delta_A(\varepsilon_{33})$$

- Exponential approach or direct input of $\delta_A(\varepsilon_{33})$ available

- Active and reversible in liquid phase, but remains fixed in solid phase

Effect of fixed (C) and exponential (D) damage on response to tensile loading



Agenda



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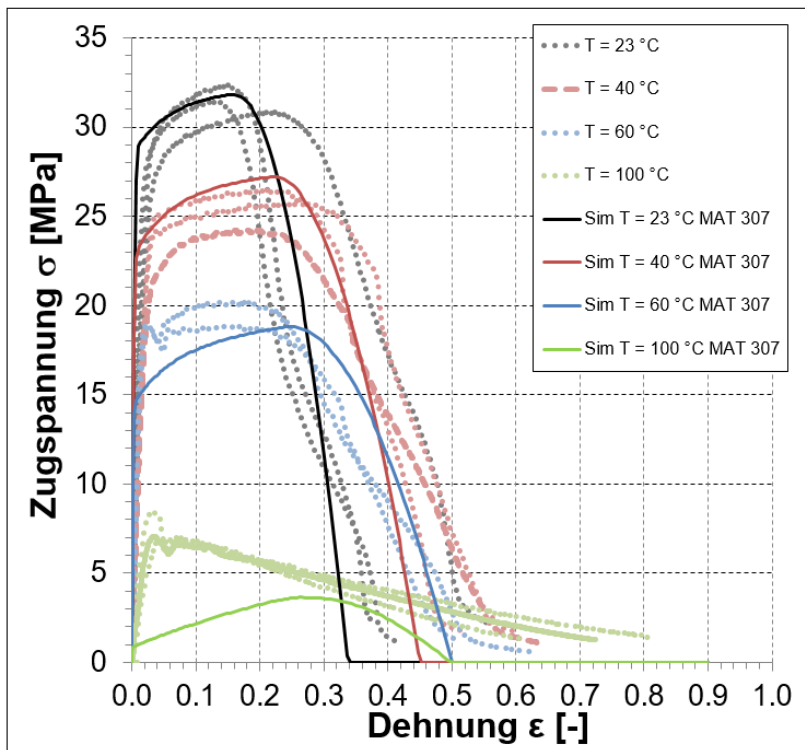
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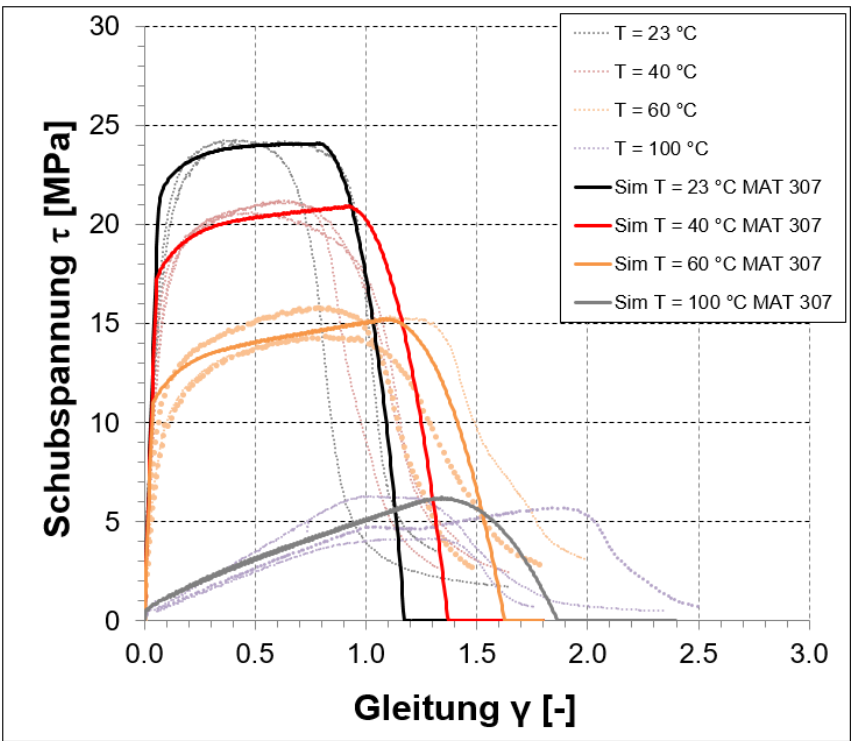
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Calibration – Temperature dependence



Werkstoff	S235JRG2C
Probenform	Kopfzugprobe
Oberfläche	Korund gestrahlt
Klebstoff	Betamate
Klebfläche	176,71 mm ²
Klebschichtdicke	0,3 mm
Aushärtegradbestimmung	Restreaktionsenthalpie D
Aushärtegrad	99.99%
Prüfbedingungen:	Prüfgeschw.: = 0,018 mm/min



Werkstoff	S235JRG2C
Probenform	Dicke Scherzugprobe
Oberfläche	Korund gestrahlt
Klebstoff	Betamate
Klebfläche	100 mm ²
Klebschichtdicke	0,3 mm
Aushärtegradbestimmung	Restreaktionsenthalpie DSC
Aushärtegrad	99.99%
Prüfbedingungen:	Prüfgeschw.: = 0,036 mm/min

[BETAMATE™, DuPont]



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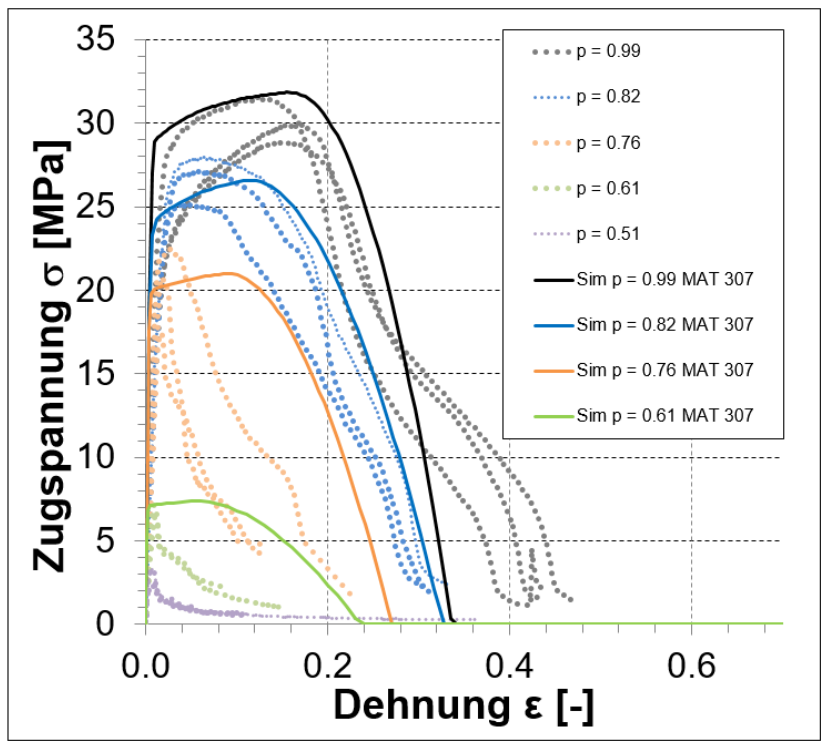


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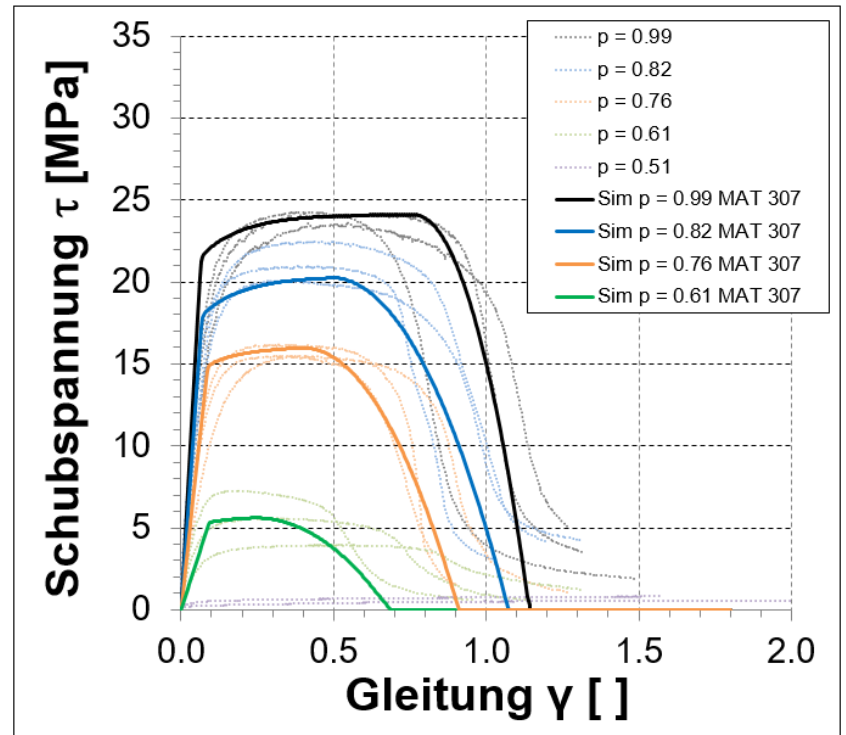


Genau. Richtig.

Calibration – Dependence on degree of cure



Werkstoff	S235JRG2C
Probenform	Kopfzugprobe
Oberfläche	Korund gestrahlt
Fügeverfahren	Kleben
Klebstoff	Betamate
Kleblfläche	176.7145868
Klebschichtdicke	0,3 mm
Prüfbedingungen:	
Prüfgeschw.: = 0,018 mm/min	
Prüftemperatur: 23 °C	



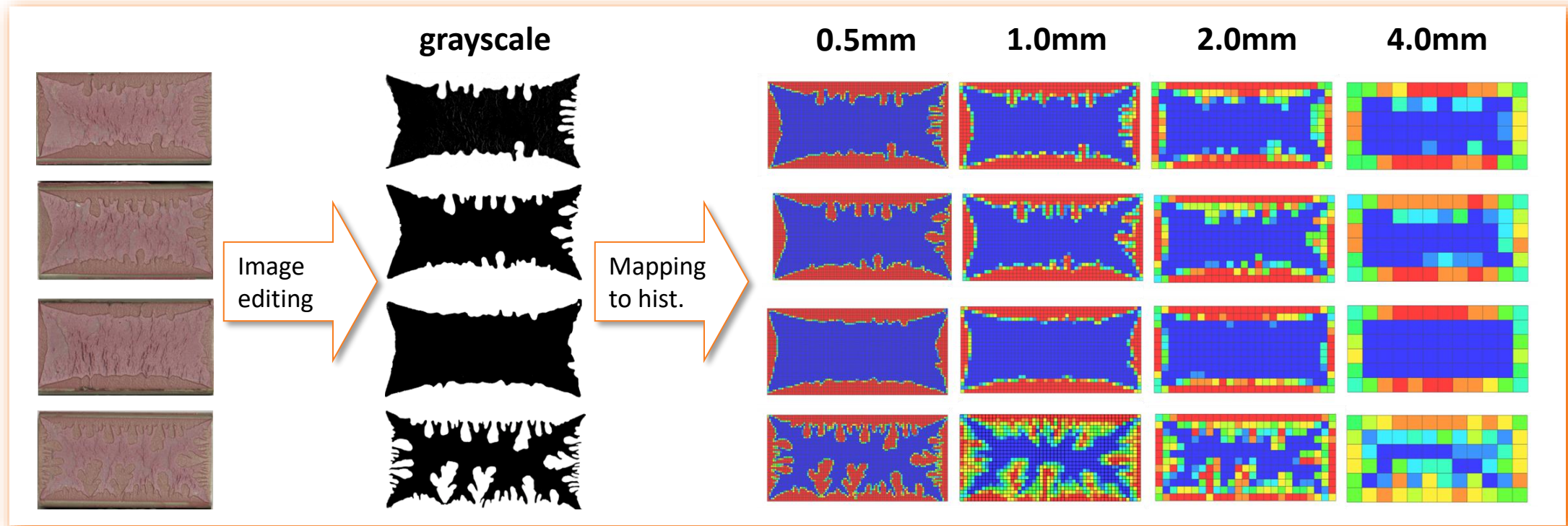
Werkstoff	S235JRG2C
Probenform	Dicke Scherzugprobe
Oberfläche	Korund gestrahlt
Fügeverfahren	Kleben
Klebstoff	Betamate
Überlappungslänge	5 mm
Klebschichtdicke	0,3 mm
Prüfbedingungen:	
Prüfgeschw.: = 0,036 mm/min	
Prüftemperatur: 23 °C	

[BETAMATE™, DuPont]

*MAT_307: (Pre-)Damage – First Validation

■ Preparation of validation examples

- Experimental data provided by LWF (KS2-specimen, separated in liquid state)
- Mapping to numerical model by DYNAmore's mapping tool envyo®

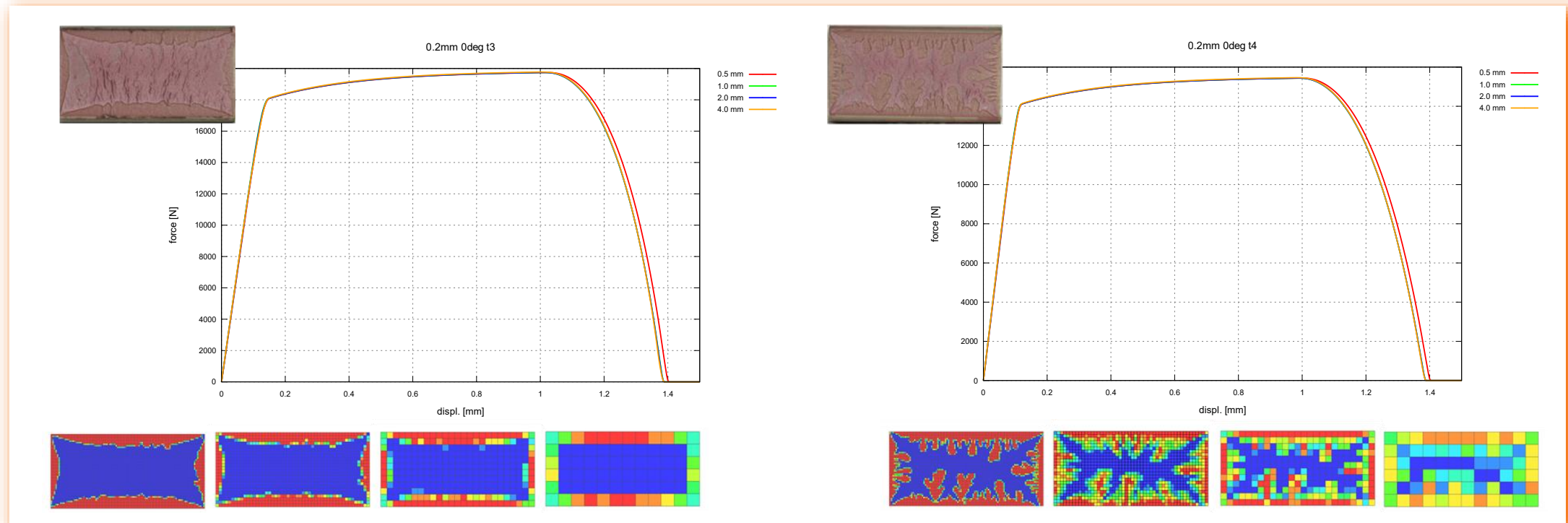


*MAT_307: (Pre-)Damage – First Validation



■ Effect on mesh size on shear behavior

- Almost perfect match independent of the mesh size of the target mesh
- Similar results for other specimens and (pre-)loading scenarios



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Summary and Outlook



Introduced new LS-DYNA material *MAT_GENERALIZED_ADHESIVE_CURING / *MAT_307:

- Combines and extends the properties of existing material models in LS-DYNA (*MAT_277, *MAT_252) and of a modified TAPO model (UMAT, Kühlmeyer and Matzenmiller)
 - Curing kinetics with induced chemical shrinkage and heating
 - Visco-elastic behavior with temperature and degree of cure depending, horizontal and vertical shifts
 - Non-associated $I_1 - J_2$ plasticity with distortional hardening
 - Empirical isotropic damage model for material damage
 - (Pre-) damage formulation for the effect of viscous fingering
- Successful material calibration
- Future work will concentrate on possibly necessary extensions with respect to curing kinetics and viscous fingering



Thank you for your attention!

DigiBody wird durch das Bundesministerium für Wirtschaft und Klimaschutz aufgrund eines Beschlusses des Deutschen Bundestages gefördert



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