16th LS-DYNA Forum 2022 , Bamberg

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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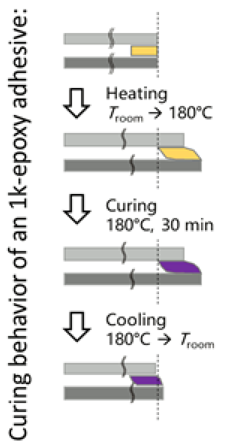
Motivation: Adhesive Process chain

- 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

Schematic sketch of Δα– problem



[DuPont]

Viscous fingering

[LWF KS2-Specimens]

- Already existing or proposed material models
  - *MAT_252 (TAPO), *MAT_277, UMAT for a modified TAPO model [Matzenmiller and Kühlmeyer, 2018]

Agenda

1 *Motivation*

2 *New material *MAT_307 / *MAT_GENERALZED_ADHESIVE_CURING*
- *Input and general set-up*
- *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				

Option

*MAT_307: Visco-elasticity

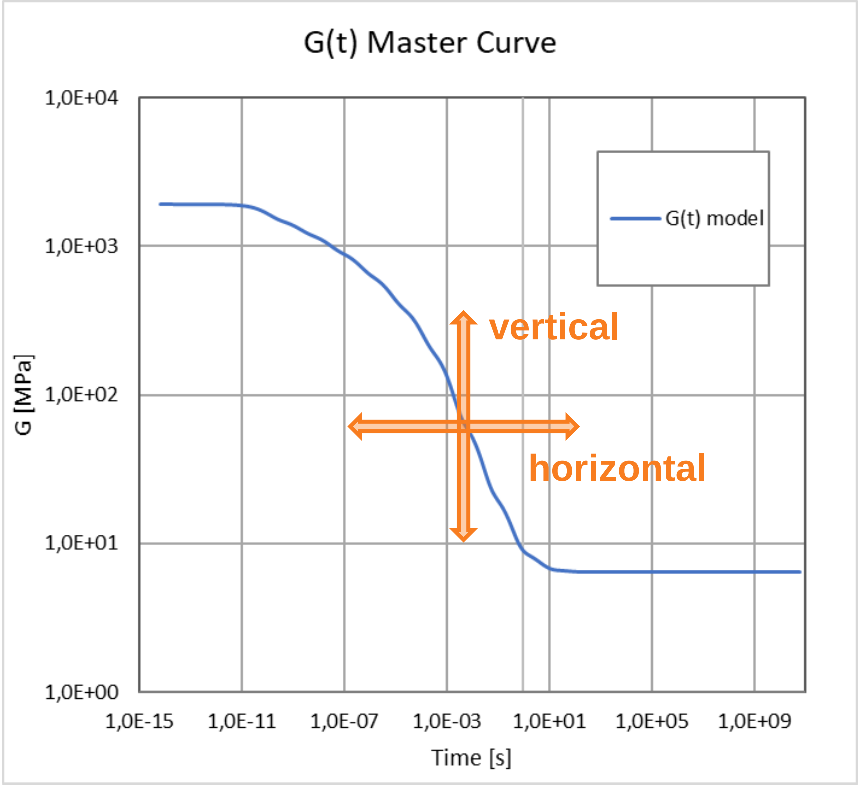
*MAT_307: Viscoelasticity – Shifting Operations

- 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

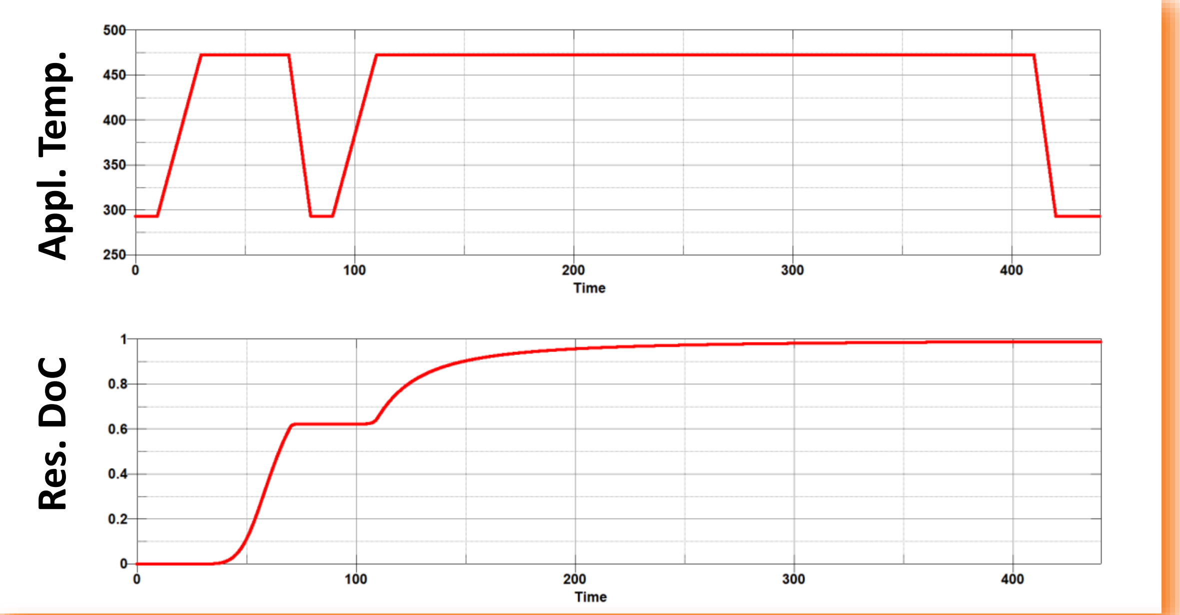
	1	2	3	4	5	6	7	8
...	...	...	...	...	...	...	...	...
Card 5	THOPT	TH1	TH2	TH3	TH4			
Card 6	TVOPT	TV1	TV2					
Card 7	PHOPT	PH1	PH2	PH3	PH4	PH5	PH6	
Card 8	PVOPT	PV1	PV2	PV3	PV4			
...	...	...	...	...	...	...	...	...

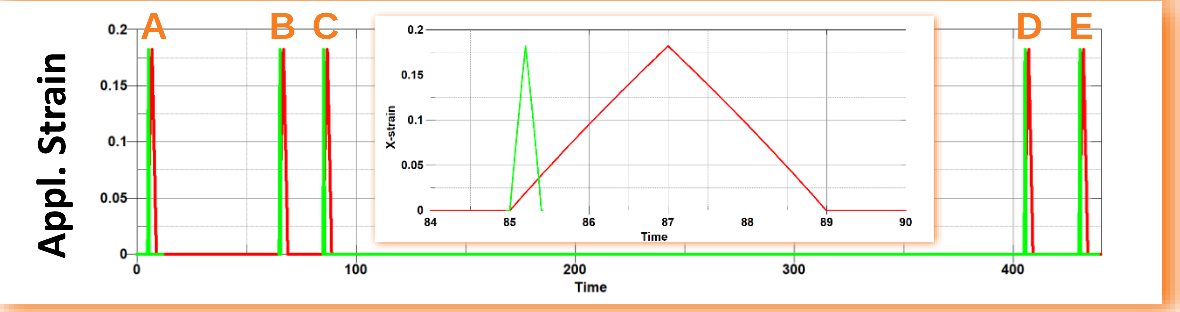


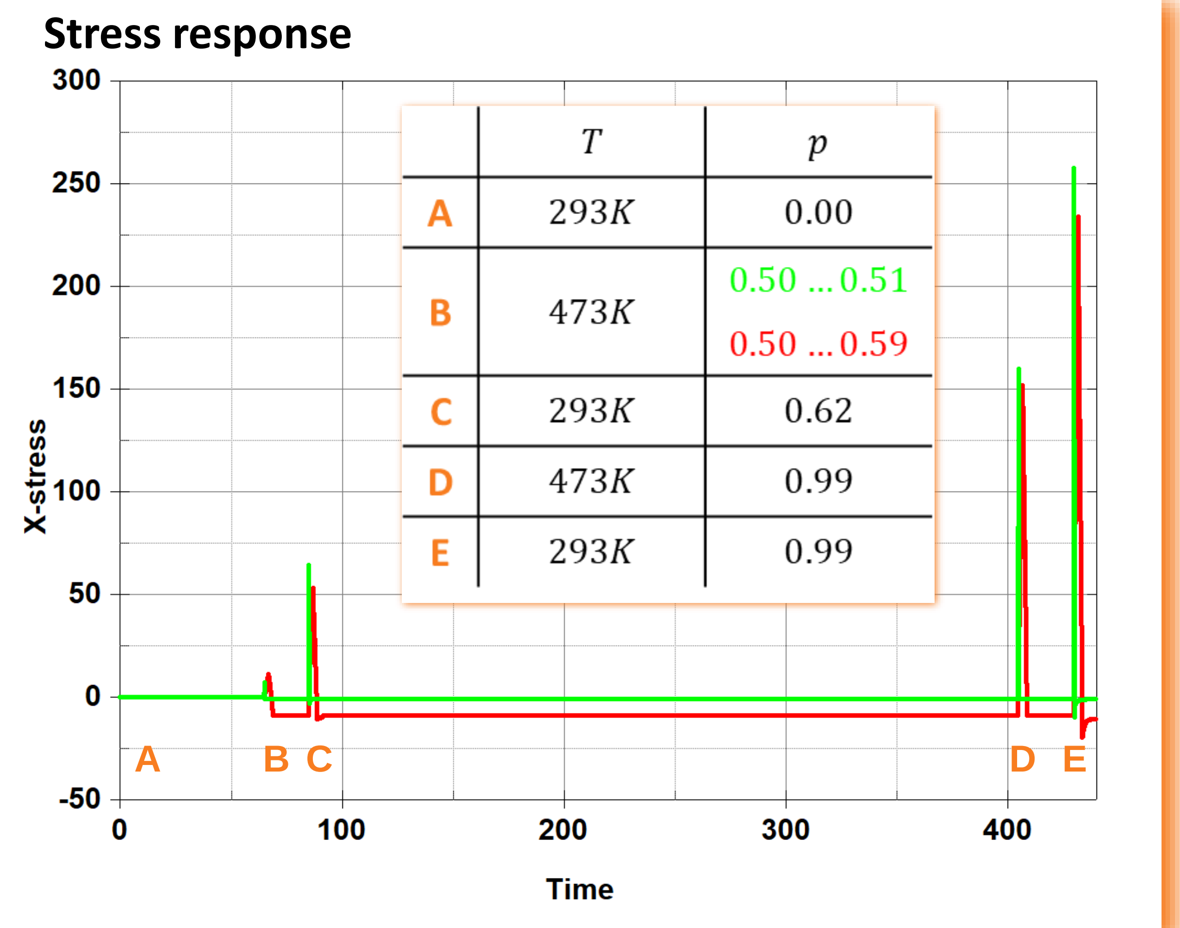
[BETAMATE™, DuPont]

*MAT_307: Viscoelasticity – Proof of Concept

- Single element relaxation and hystersis test







	T	p
A	$293K$	0.00
B	$473K$	0.50 ... 0.51 0.50 ... 0.59
C	$293K$	0.62
D	$473K$	0.99
E	$293K$	0.99

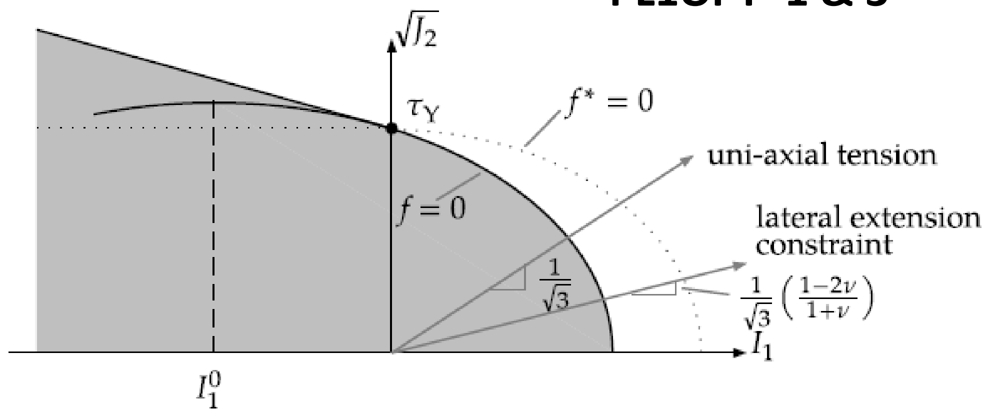
*MAT_307: Plasticity and damage

*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

Yield surface for PL1OPT=1 & 3



*MAT_307: Damage and Failure

	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**
…	…	…	…	…	…	…	…	…

- Two damage mechanisms are considered
  - Material damage based on *MAT_252 (TAPO, Matzenmiller and Burbulla 2013) denoted by D_1
  - (Pre-) damage formulation for the effect of viscous fingering with damage parameter D_2

- Effective stress tensor $\tilde{\boldsymbol{\sigma}}$ is given as

$$\tilde{\boldsymbol{\sigma}} = \frac{\sigma}{(1 - D_1)(1 - D_2)}$$

- Integration point failure is initiated as soon as one of the damage parameters is 1.0

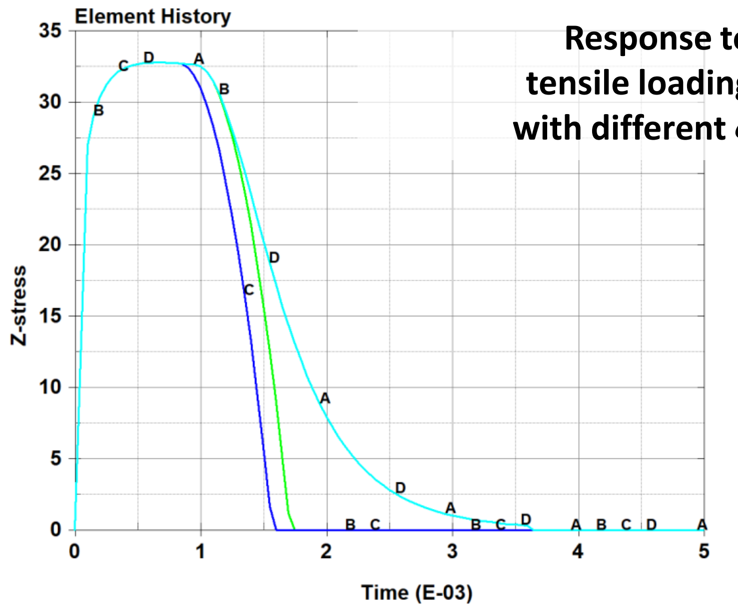
*MAT_307: Material Damage D_1

	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]

$$\dot{D}_1 = \dot{D}_1(\zeta, \dot{\zeta}) = n \left\langle \frac{\zeta - \gamma^{\mathrm{c}}}{\gamma^{\mathrm{f}} - \gamma^{\mathrm{c}}} \right\rangle^{n-1} \frac{\dot{\zeta}}{\gamma^{\mathrm{f}} - \gamma^{\mathrm{c}}}, \qquad \dot{\zeta} \in \{\dot{r}, \dot{\gamma}_{\mathrm{v}}, \dot{\gamma}\}$$

- 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



Response to tensile loading with different ζ

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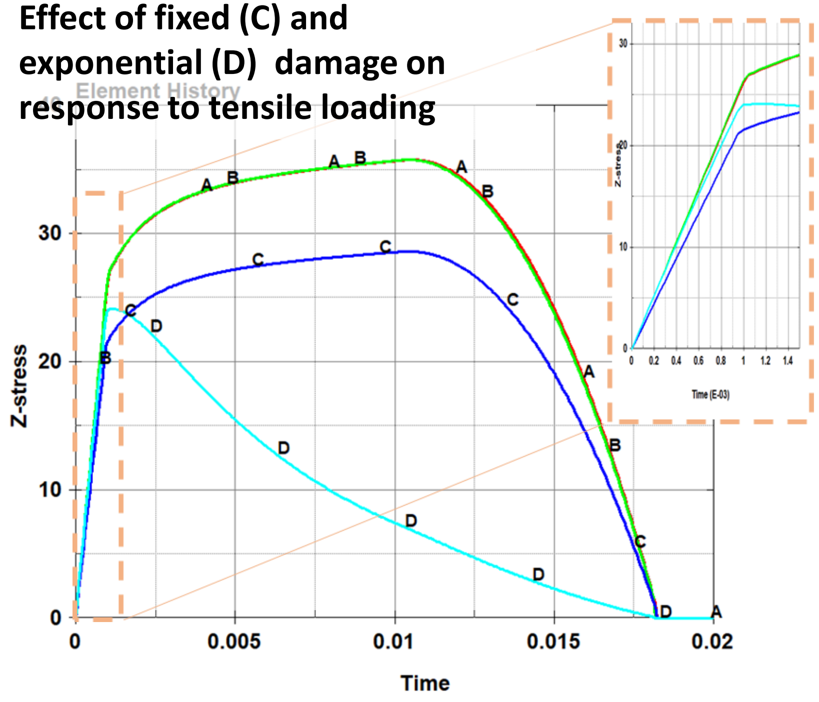
*MAT_307: (Pre-)Damage D_2

	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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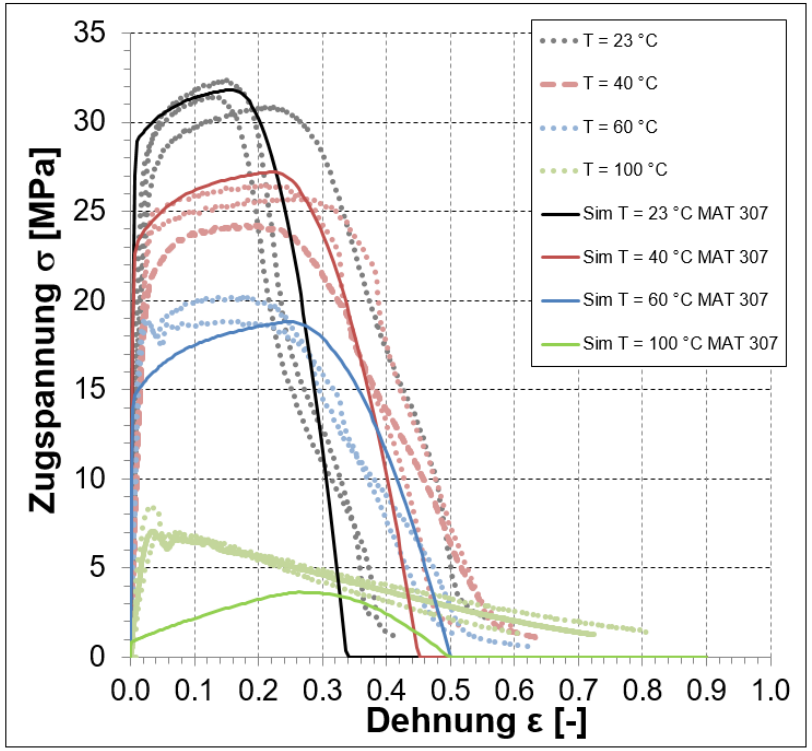
2 *New material *MAT_307 / *MAT_GENERALZED_ADHESIVE_CURING*

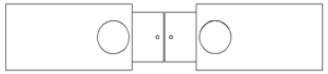
3 ***Material calibration***

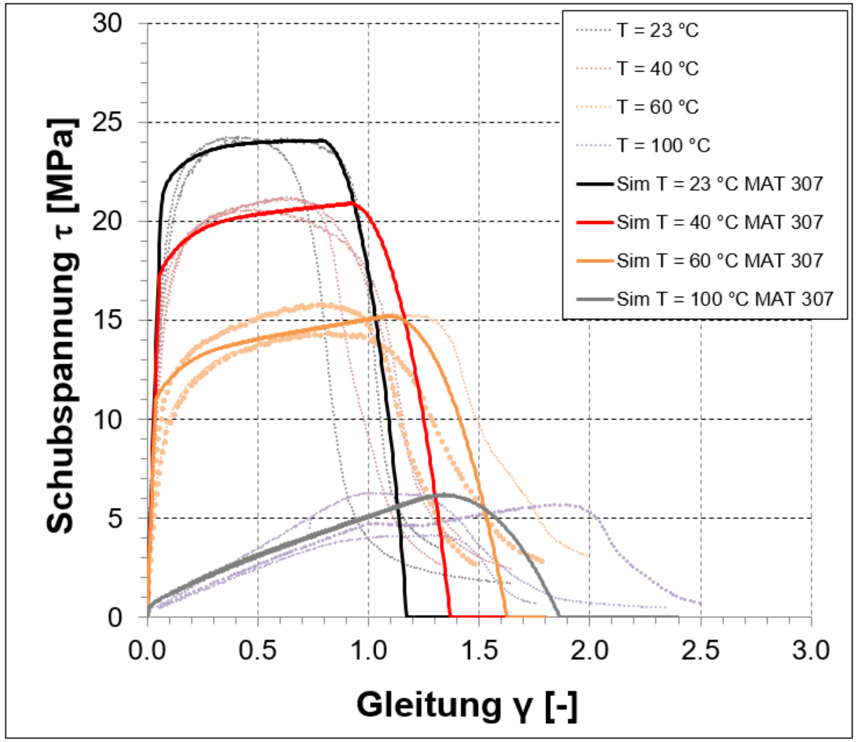
4 *Summary and Outlook*

Calibration – Temperature dependence

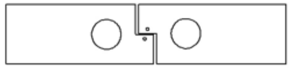


Werkstoff
S235JRG2C
Probenform
Kopfzugprobe
Oberfläche
Korund gestrahlt
Klebstoff
Betamate
Klebfläche
176,71 mm^2
Klebschichtdicke
0,3 mm
Aushärtegradbestimmu
Restreaktionsenthalpie D
Aushärtegrad
99.99%
Prüfbedingungen:
Prüfgeschw.: = 0,018 mm/min





Werkstoff
S235JRG2C
Probenform
Dicke Scherzugprobe
Oberfläche
Korund gestrahlt
Klebstoff
Betamate
Klebfläche
100 mm²
Klebschichtdicke
0,3 mm
Aushärtegradbestimmung
Restreaktionsenthalpie DSC
Aushärtegrad
99.99%
Prüfbedingungen:
Prüfgeschw.: = 0,036 mm/min



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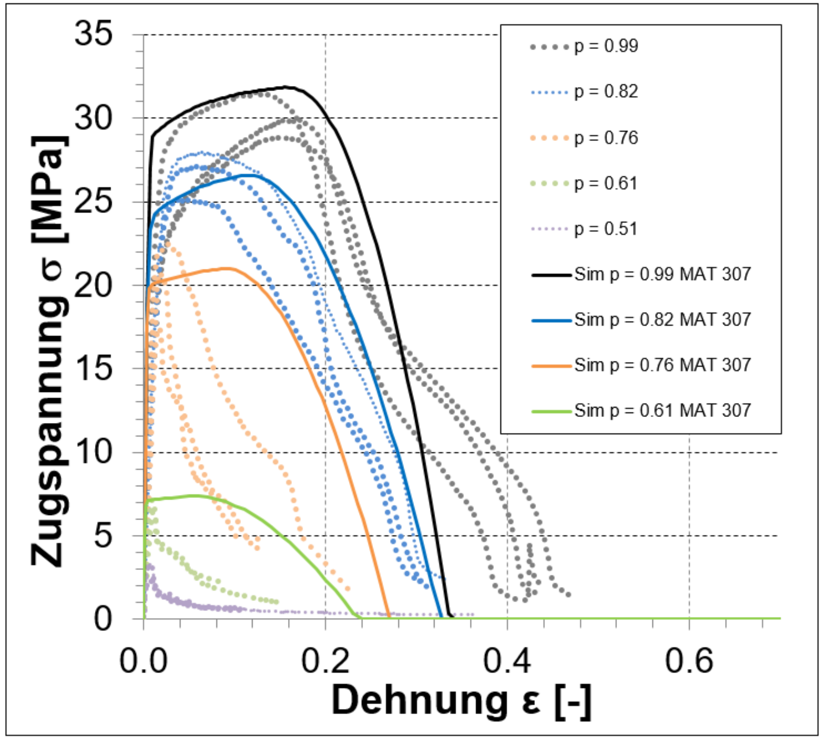
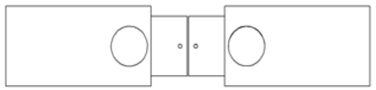
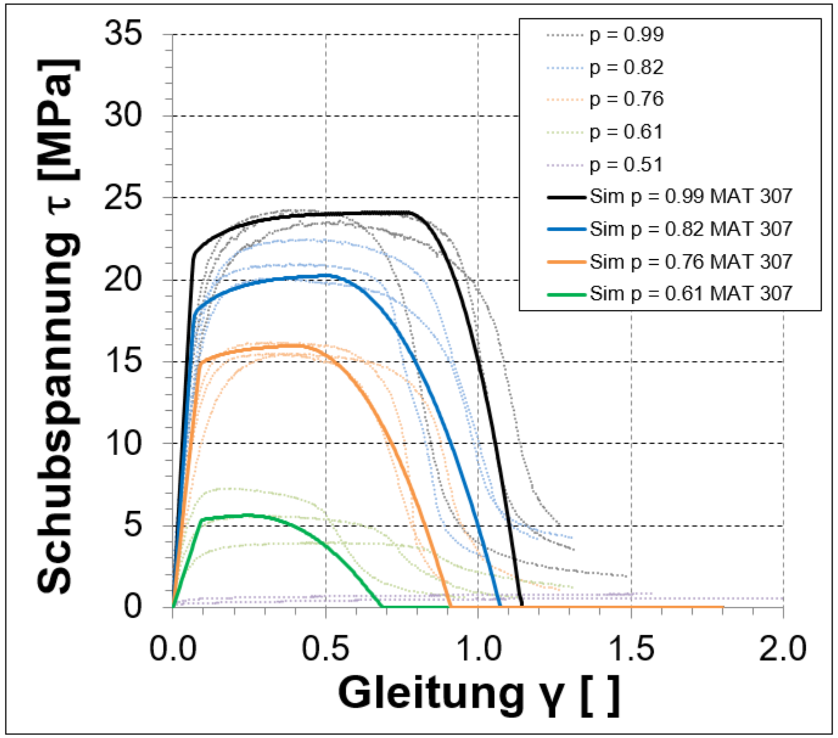
Calibration – Dependence on degree of cure

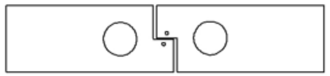


Werkstoff
S235JRG2C
Probenform
Kopfzugprobe
Oberfläche
Korund gestrahlt
Fügeverfahren
Kleben
Klebstoff
Betamate
Klebfläche
176.7145868
Klebschichtdicke
0,3 mm
Prüfbedingungen:
Prüfgeschw.: = 0,018 mm/min
Prüftemperatur: 23 °C





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]

Agenda

Summary and Outlook

Introduced new LS-DYNA material *MAT_GENERALZED_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 kintecs 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 nessecary extensions with respect to curing kintecs 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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