Recent enhancement for modelling adhesives in the closed manufacturing crashworthiness process chain

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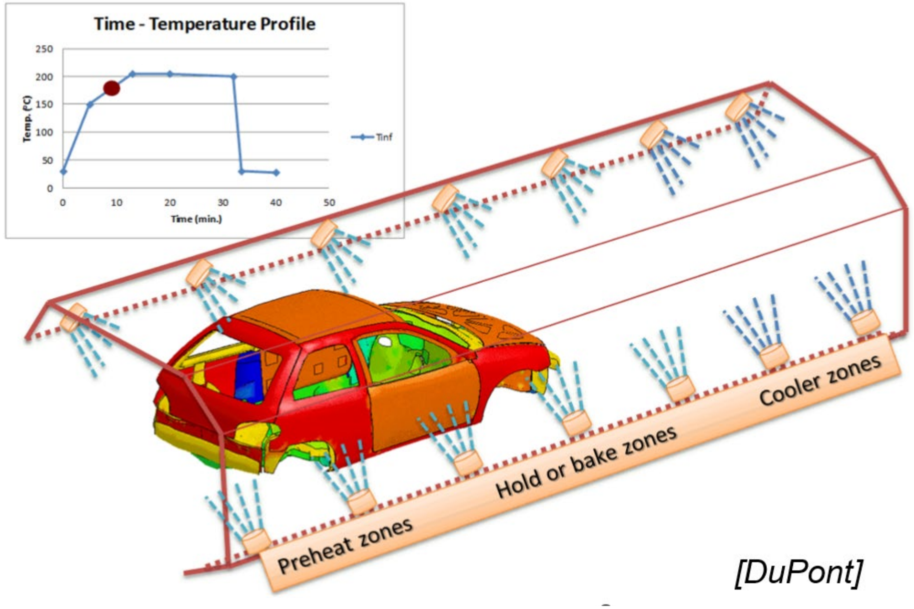

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This Presentation is a Sequel

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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Recap

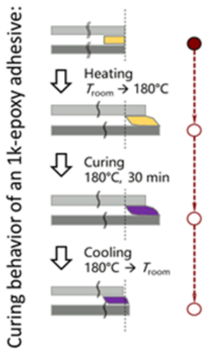
Most important points from last year’s presentation

Recap

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 $\Delta\alpha-$ problem



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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]

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Recap

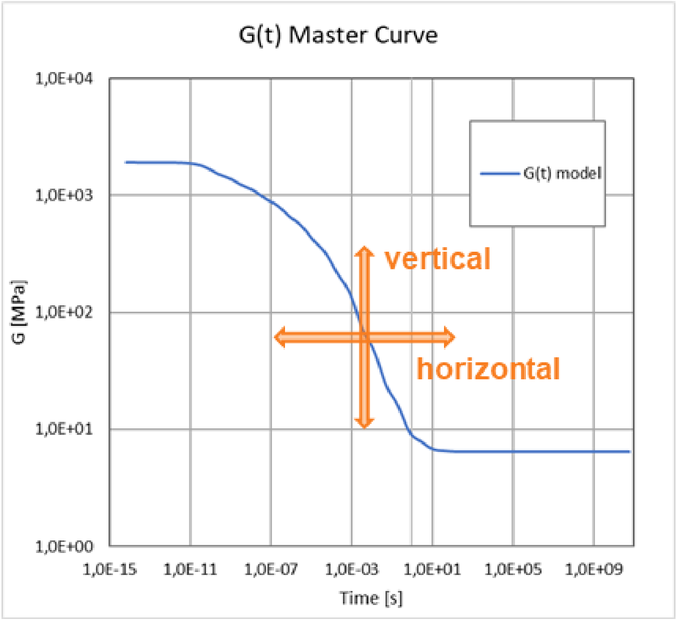
*MAT_307: Viscoelasticity – Shifting Operations

- 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]

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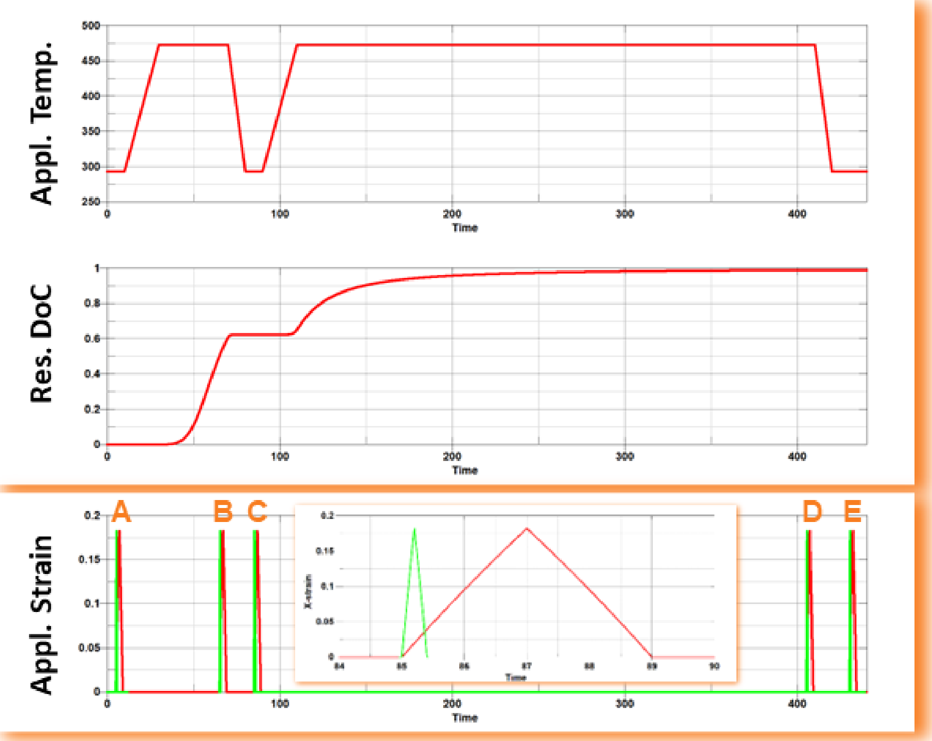
Recap

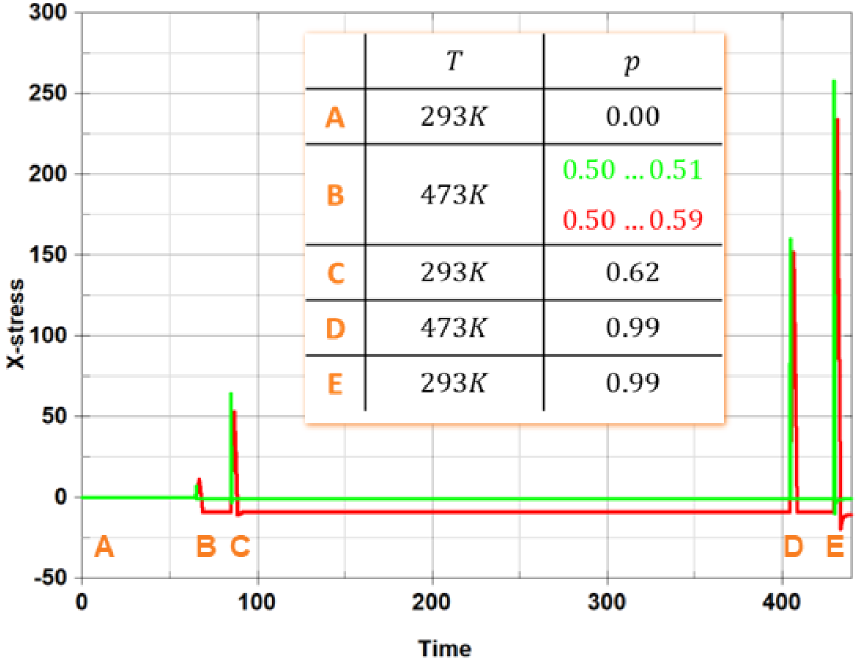
*MAT_307: Viscoelasticity – Proof of Concept

DIGIBODY

- Single element relaxation and hystersis test

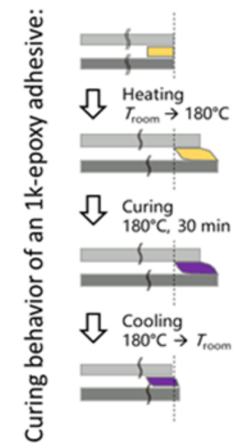


Stress response



	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

Schematic sketch of $\Delta\alpha$– problem



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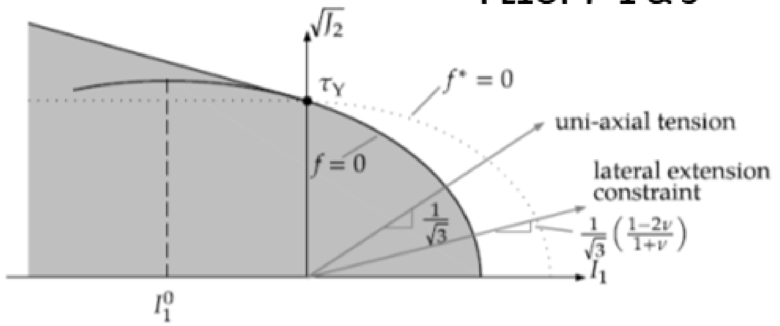
Recap

*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



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Recap

*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

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Recap

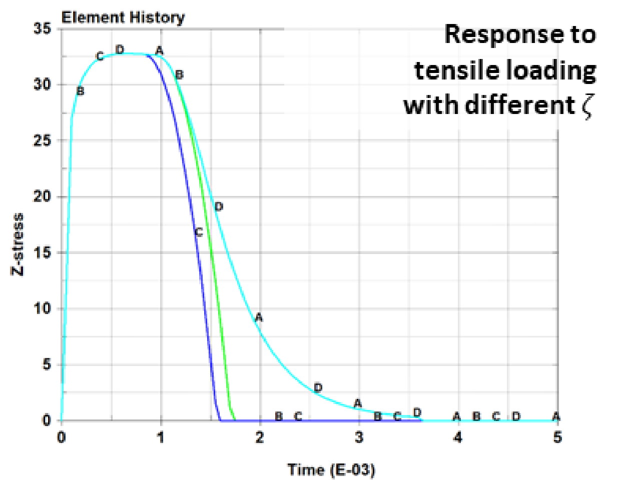
*MAT_307: Material Damage D_1

	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



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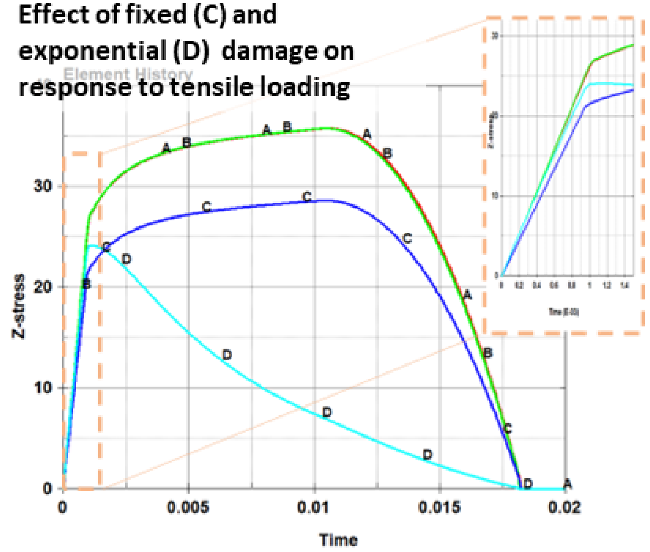
Recap

*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



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Viscous fingering

[LWF KS2-Specimens]

Recap

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 kinetics and viscous fingering

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Curing Kinetics

New parameters and new curing models

Curing Kinetics

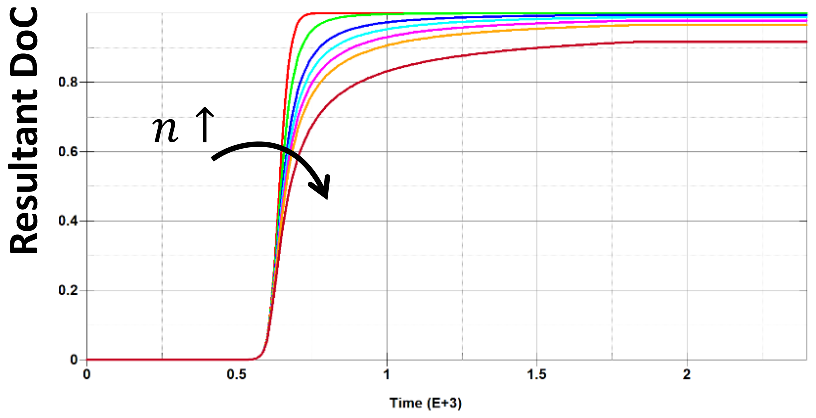
(Extended) Sourer-Kamal-Model

- Evolution equation for degree of cure p:

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

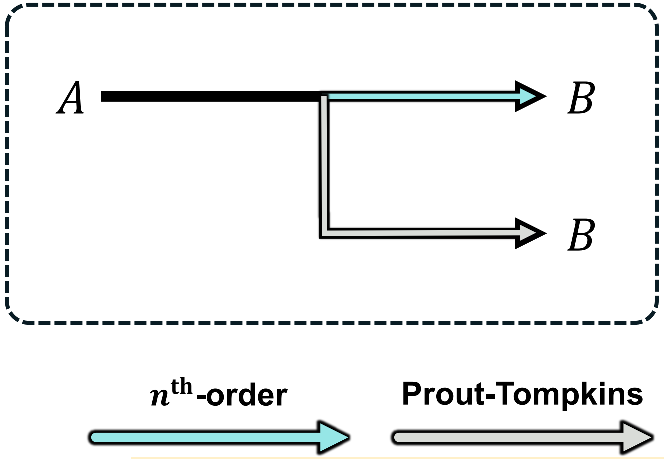
- Different options for expressions $K_i(T)$, but mostly used:

$$K_i(T) = k_i \cdot \exp\left(\frac{-Q_i}{RT}\right)$$



- Chemical interpretation:
  - System of two species A and B, with concentrations c_1 and c_2
  - Sum of concentrations is always 1.0
  - Identifying $c_2 = p$ and, thus, $c_1 = 1 - p$ gives

$$\dot{c_1} = -K_1(T) \cdot c_1^{n_1} - K_2(T) \cdot c_1^{n_2} \cdot c_2^m$$
$$\dot{c_2} = K_1(T) \cdot c_1^{n_1} + K_2(T) \cdot c_1^{n_2} \cdot c_2^m$$

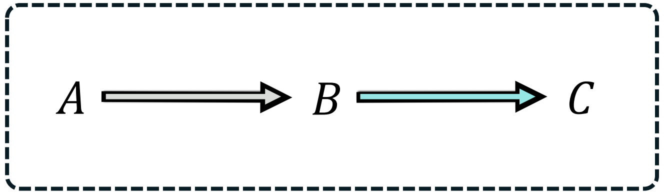


Curing Kinetics

Three Species models

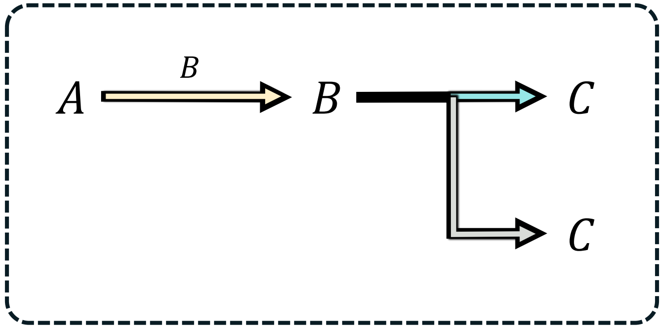
- System of three species A, B and C, with concentrations c_1, c_2 and c_3, respectively
- Three options available
  - System 1:

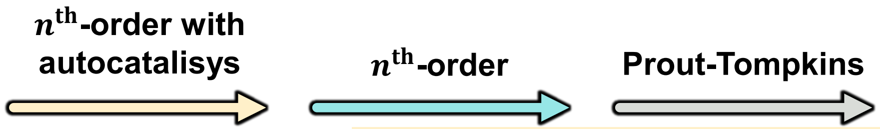
$$
\begin{aligned}
\dot{c}_1 &= -K_1(T) \cdot c_1^{n_1} \cdot c_2^{m_1} \\
\dot{c}_2 &= K_1(T) \cdot c_1^{n_1} \cdot c_2^{m_1} - K_2(T) \cdot c_2^{n_2} \\
\dot{c}_3 &= K_2(T) \cdot c_2^{n_2}
\end{aligned}
$$



  - System 2:

$$
\begin{aligned}
\dot{c}_1 &= \\
\dot{c}_2 &= -K_2(T) \cdot c_2^{n_2} \cdot c_3^{m_2} - K_3(T) \cdot c_2^{n_3} \\
\dot{c}_3 &= K_2(T) \cdot c_2^{n_2} \cdot c_3^{m_2} + K_3(T) \cdot c_2^{n_3}
\end{aligned}
$$



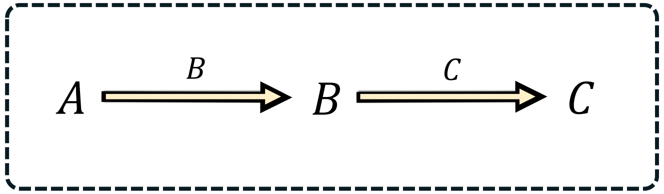


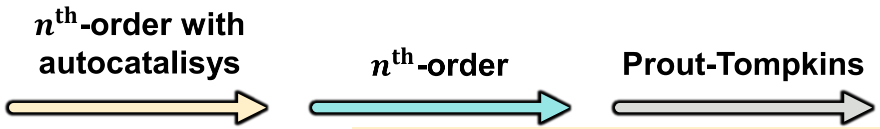
Curing Kinetics

Three Species models

- System of three species A, B and C, with concentrations c_1, c_2 and c_3, respectively
- Three options available:
  - System 3:

$$
\begin{aligned}
\dot{c}_1 &= -K_1(T)\cdot(1+k_{c1}\cdot c_2)c_1^{n_1}\\
\dot{c}_2 &= \underbrace{K_1(T)\cdot(1+k_{c1}\cdot c_2)c_1^{n_1}}_{B} - \overbrace{K_2(T)\cdot(1+k_{c2}\cdot c_3)c_2^{n_2}}^{C}\\
\dot{c}_3 &= K_2(T)\cdot(1+k_{c2}\cdot c_3)c_2^{n_2}
\end{aligned}
$$

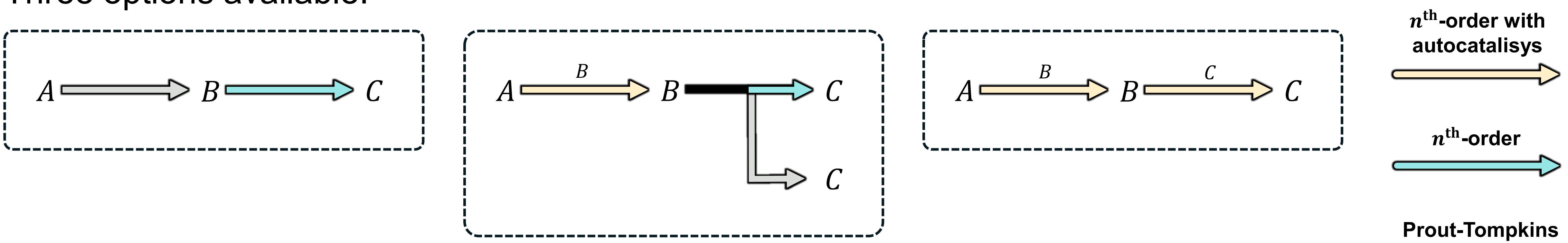




Curing Kinetics

Three Species models

- System of three species A, B and C, with concentrations c_1, c_2 and c_3, respectively
- Three options available:

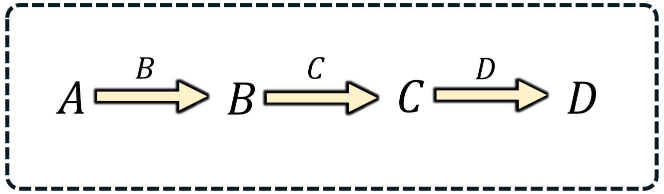


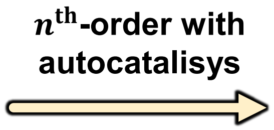
- Sum of concentrations is always 1.0
  - Product $c_3 = 1. - c_1 - c_2$ can be eliminated from the systems
  - Only system of two ordinary differential equations to be solved
- Degree of cure p is a function of the concentrations: $p = 1 - c_1 - c_2 + F_1 \cdot c_2$

Curing Kinetics

Four Species models

- System of four species A, B, C and D, with concentrations c_1, c_2, c_3 and c_4, respectively
- One option available:



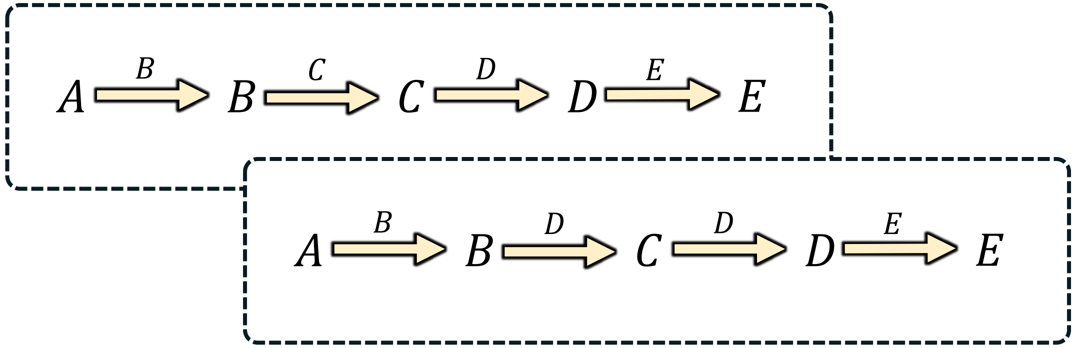


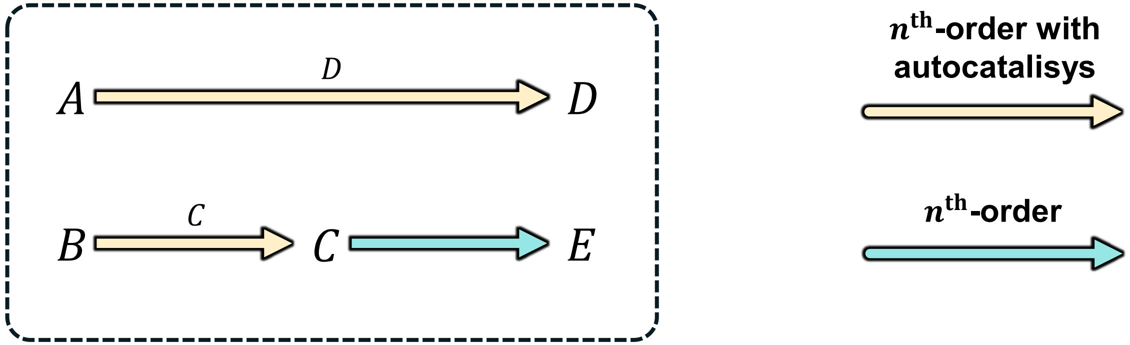
- Sum of concentrations is always 1.0
  - Product c_4 can be eliminated from the systems
  - System of three ODEs to be solved
- Degree of cure p is a function of the concentrations: $p = (1. - c_1 - c_2 - c_3) + F_1 \cdot (c_2 + c_3) + F_2 \cdot c_3$

Curing Kinetics

Five Species models

- System of five species A, B, C, D and E, with concentrations c_1, c_2, c_3, c_4 and c_5, respectively
- Three options available:





- Sum of concentrations of each system of reactions is always 1.0
  - c_5 can be eliminated from the system
  - System of four ODEs to be solved
  - c_4 and c_5 can be eliminated from the system
  - System of three ODEs to be solved
- Degree of cure p is a function of the concentrations

$$p = (1. - c_1 - c_2 - c_3 - c_4) + F_1 \cdot (c_2 + c_3 + c_4) + F_2 \cdot (c_3 + c_4) + F_3 \cdot c_4$$

$$p = F_1 \cdot (1 - c_1) + (1. - F_1)\big(F_2(1. - c_2) + (1. - F_2)(1. - c_2 - c_3)\big)$$

Curing Kinetics

Model free kinetics

- So far, scalar parameters $(k_i, Q_i, k_{ci}, n_i, m_i)$ for a pre-defined model had to be defined

- Alternative approach: Model free kinetics option
  - Evolution equation for degree of cure p

$$\dot{p} = \exp(\ln(A'(p))) \cdot \exp\left(-\frac{Q(p)}{RT}\right)$$

  - Direct, tabulated input of the logarithmic scaling function $\ln(A'(p))$ and the activation energy $Q(p)$

Visco-Elasticity

New input possibilities

Visco-Elasticity

Prony-Series input

- Behavior is governed by the Prony-series expansion for shear and bulk modulus

$$G(t) = G_\infty + \sum_{i=1}^{n_G} G_i e^{-\beta_i^G t}, \qquad K(t) = K_\infty + \sum_{i=1}^{n_K} K_i e^{-\beta_i^K t}$$

- Standard input:
  - Individual input for $G_i, K_i, \beta_i^G, \beta_i^K$
  - Maximum flexibility of visco-elastic response (frequency dependent Poisson's ratio ν)
  - Input restricted to $n_G \leq 18$ and $n_K \leq 18$

- Feedback
  - "Would be great to have more Prony-series terms"
  - "We always assume a constant ν"

Visco-Elasticity

Prony-Series input

- Behavior is governed by the Prony-series expansion for shear and bulk modulus

$$G(t) = G_\infty + \sum_{i=1}^{n_G} G_i e^{-\beta_i^G t}, \qquad K(t) = K_\infty + \sum_{i=1}^{n_K} K_i e^{-\beta_i^K t}$$

- New parameter VIOPT. If value less then zero, then...
  - ... a constant value for ν and, consequently, $K_i = \frac{2+2\nu}{3(1-2\nu)} G_i$ are assumed
  - ... the decay constants match: $\beta_i^G = \beta_i^K$
- Two options for VIOPT
  - -1: Input of E_i, that are internally translated into shear relaxation moduli $G_i = \frac{1}{2+2\nu} E_i$
  - -2: Direct input of shear relaxation moduli G_i
- Up to 25 Prony-series terms possible

Visco-Elasticity

Prony-Series input

Card 13a. The keyword reader assumes the input deck includes this version of Card 13 if, in the first instantiation of this card, the value in the first entry is ≥ 0.0. Input up to 18 instantiations of this card. The next keyword ("*") card terminates this input if using fewer than 18 cards. The number of terms for the shear behavior may differ from that for the bulk behavior: insert zero to exclude a term.

Gi	BETAGi	Ki	BETAKi				

Card 13b. The keyword reader assumes the input deck includes this version of Card 13 if the value in the first entry is < 0.0

VIOPT	NUE						

Card 14a. Include this card if VISOPT = -1 on Card 13b. Input up to 13 instantiations of this card. The next keyword ("*") card terminates this input if using fewer than 13 cards.

Ei	BETAi	Ej	BETAj				

Card 14b. Include this card if VISOPT = -2. Include up to 13 instantiations of this card. The next keyword ("*") card terminates this input if using fewer than 13 cards.

Gi	BETAi	Gj	BETAj				

Visco-Elasticity

Prony-Series input example

- Assume constant value $\nu = 0.0 \rightarrow K_i = {}^2/_3\ G_i,\ \ E_i = 2\ G_i$
- Following input is equivalent:

Standard Input

```
... (Cards 1 to 12)
$         Gi    beta Gi           Ki    beta_Ki
 3.000E-01 1.000E-01 2.000E-01 1.000E-01
 6.000E+00 1.000E+00 4.000E+00 1.000E+00
 9.000E+01 1.000E+02 6.000E+01 1.000E+02
 1.500E+03 1.000E+04 1.000E+03 1.000E+04
```

VIOPT < 0

```
... (Cards 1 to 12)
$     VIOPT          nu
         -1         0.0
$         Ei    beta Ei           Ej    beta Ej
 6.000E-01 1.000E-01 1.200E+01 1.000E+00
 1.800E+02 1.000E+02 3.000E+03 1.000E+04
```

```
... (Cards 1 to 12)
$     VIOPT          nu
         -2         0.0
$         Gi    beta Gi           Gj    beta Gj
 3.000E-01 1.000E-01 6.000E+00 1.000E+00
 9.000E+01 1.000E+02 1.500E+03 1.000E+04
```

Summary and Outlook

Summary and Outlook

- New curing kinetics options
  - Chemical systems with two, three, four, or five species
  - Model-free kinetics approach with tabulated input for activation energies and logarithmic scaling function
  - Approaches validated with experimental and simulation data
- New input for Prony-series terms
  - Assume a frequency-independent Poisson's ratio
  - Only define series expansion of Young's or shear modulus
  - Higher number of Prony-series terms
- Need to look into the plasticity algorithm when material is used in a cohesive element

Stay tuned: This could be the second part of a trilogy!

Thank You

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