Infoday Automotive and Aerospace Applications, Berlin, December 1st, 2022

A new material model for continuous fiber reinforced plastics in crashworthiness analysis

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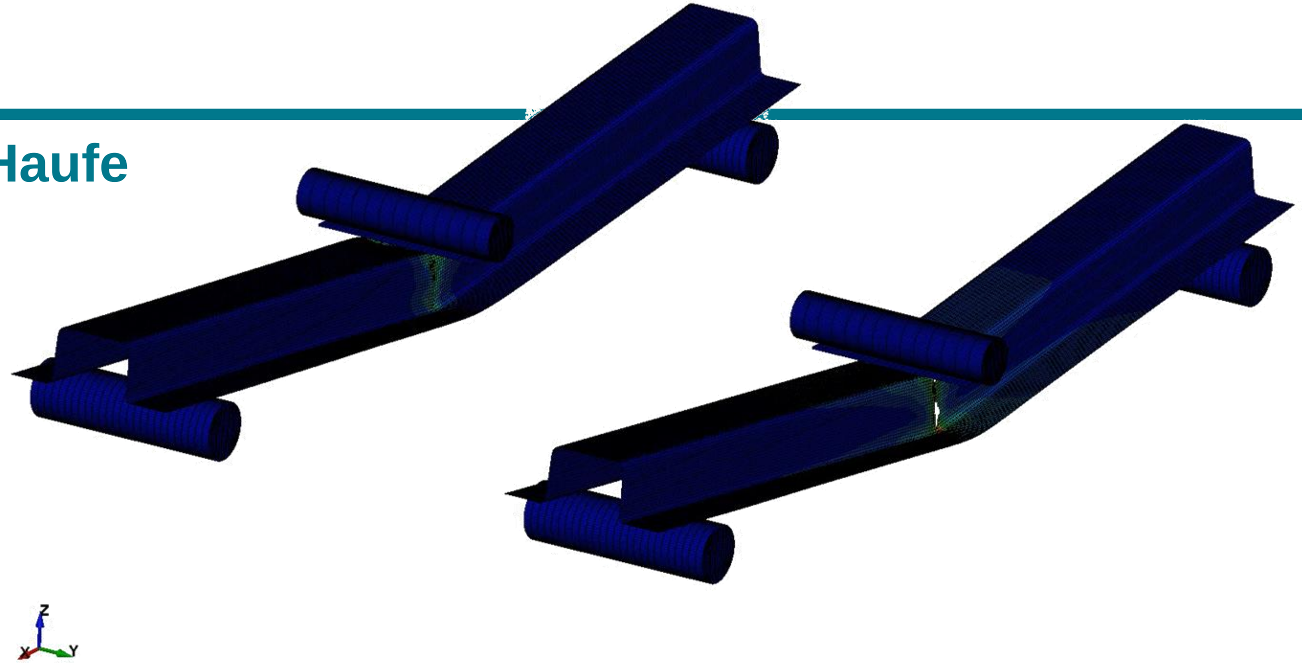
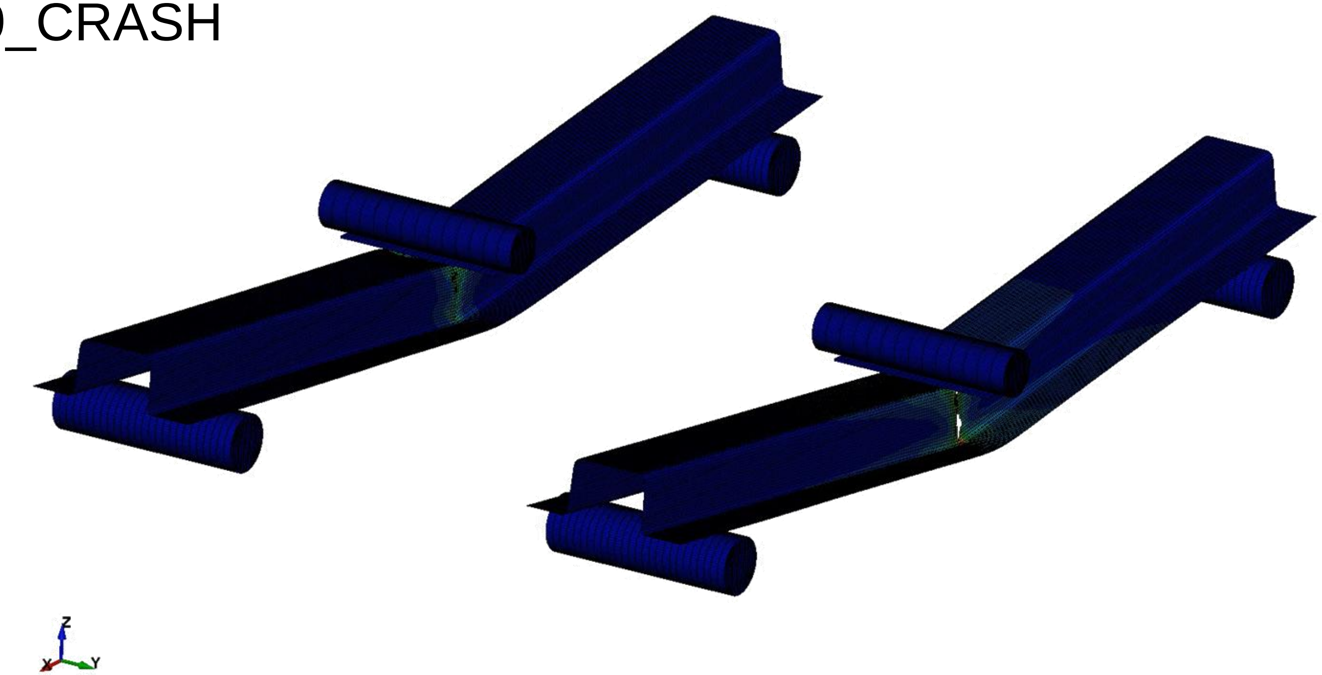


Agenda

- Motivation
- General Properties of Material *MAT_249_CRASH
- Damage and Failure Modelling in *MAT_249_CRASH
- Examples
- Summary



Motivation…

… to do something

- Project for material model development and implementation with
  - Dr. Michael Wrensch, Eric Chowson (Brose)
  - Dr. David Scheliga, Alexander Huf, Dr. Sebastian Schmeer (IVW, Uni KL)

- Goal: Material model for a composite with a woven reinforcement
  - Focus on thermoplastic matrix material
  - Pre-shearing of material during draping (thermoforming) should be considered
  - Considerable fiber shearing before material failure expected

Motivation…

… for a new material implementation

- Standard composite materials in LS-DYNA for crashworthiness are tailored for UD-reinforcements

Overview over Available Composite Models in LS-DYNA

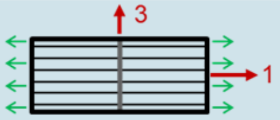
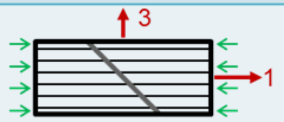
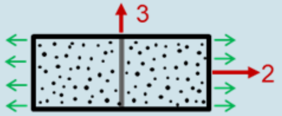
	Element	Failure criteria	Rate dependency	Remarks
***MAT_022:** COMPOSITE_DAMAGE	Shell, Tshell, Solid	Chang-Chang	-	ALPH doesn't affect stress vs. strain relationship. (same for 054/055)
***MAT_054/055:** ENHANCED_COMPOSITE_DAMAGE	Shell, Tshell, Solid	54: Chang-Chang 55: fiber: as 54 matrix: Tsai-Wu	rate dependent strength via *DEFINE_CURVE	fiber strengths can be reduced after matrix failure. Minimum stress limit factor. Crash front algorithm.
***MAT_058:** LAMINATED_COMPOSITE_FABRIC	Shell, Tshell (1,2,6), Solid	Modified Hashin	rate dependent Strengths and strains via *DEFINE_CURVE	Smooth increase of damage. Special control of shear behavior Minimum stress limit factor. Crash front algorithm.
***MAT_059:** COMPOSITE_FAILURE_MODEL	Shell, Tshell, Solid, SPH		-	Similar to 054. Crash front algorithm. Minimum stress limit factor.
***MAT_158:** RATE_SENSITIVE_COMPOSITE_FABRIC	Shell, Tshell	Modified Hashin	Viscosity based on isotropic viscoelasticity	Same as 058.
***MAT_261:** LAMINATED_FRACTURE_DAIMLER_PINHO	Shell, Tshell, Solid	Pinho	rate (and element size) dependent strengths and fracture toughness via *DEFINE_CURVE/ _TABLE	Considers the state-of-the-art Puck's criterion for inter-fiber failure
***MAT_262:** LAMINATED_FRACTURE_DAIMLER_CAMANHO	Shell, Tshell, Solid	Camanho	as *MAT_261	Considers the state-of-the-art Puck's criterion for inter-fiber failure

Motivation…

… for a new material implementation

- Standard composite materials in LS-DYNA for crashworthiness are tailored for UD-reinforcements

*MAT_LAMINATED_COMPOSITE_FABRIC (*MAT_058) – Failure

Failure mode	FS=0.0	FS=1.0	FS=-1.0
		Failure is assumed whenever e_m^2 >0	
 Tensile fiber mode	$e_m^2 = \left(\frac{\sigma_{11}}{X_T}\right)^2 - 1$	$e_m^2 = \left(\frac{\sigma_{11}}{X_T}\right)^2 + \left(\frac{\sigma_{12}}{S_C}\right)^2 - 1$	$e_m^2 = \left(\frac{\sigma_{11}}{X_T}\right)^2 - 1$
		Failure is assumed whenever e_d^2 >0	
 Compressive fiber mode	$e_d^2 = \left(\frac{\sigma_{11}}{X_C}\right)^2 - 1$	$e_d^2 = \left(\frac{\sigma_{11}}{X_C}\right)^2 + \left(\frac{\sigma_{12}}{S_C}\right)^2 - 1$	$e_d^2 = \left(\frac{\sigma_{11}}{X_C}\right)^2 - 1$
		Failure is assumed whenever ε_m^2 >0	
 Tensile matrix mode	$\varepsilon_m^2 = \left(\frac{\sigma_{22}}{Y_T}\right)^2 + \left(\frac{\sigma_{12}}{S_C}\right)^2 - 1$	$\varepsilon_m^2 = \left(\frac{\sigma_{22}}{Y_T}\right)^2 + \left(\frac{\sigma_{12}}{S_C}\right)^2 - 1$	$\varepsilon_m^2 = \left(\frac{\sigma_{22}}{Y_T}\right)^2 - 1$
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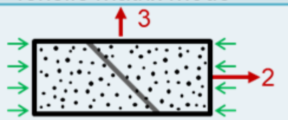
 Compressive matrix mode	$\varepsilon_d^2 = \left(\frac{\sigma_{22}}{Y_C}\right)^2 + \left(\frac{\sigma_{12}}{S_C}\right)^2 - 1$	$\varepsilon_d^2 = \left(\frac{\sigma_{22}}{Y_C}\right)^2 + \left(\frac{\sigma_{12}}{S_C}\right)^2 - 1$	$\varepsilon_d^2 = \left(\frac{\sigma_{22}}{Y_C}\right)^2 - 1$
			Failure if ε_s^2 >0 $\varepsilon_s^2 = \left(\frac{\sigma_{12}}{S_C}\right)^2 - 1$

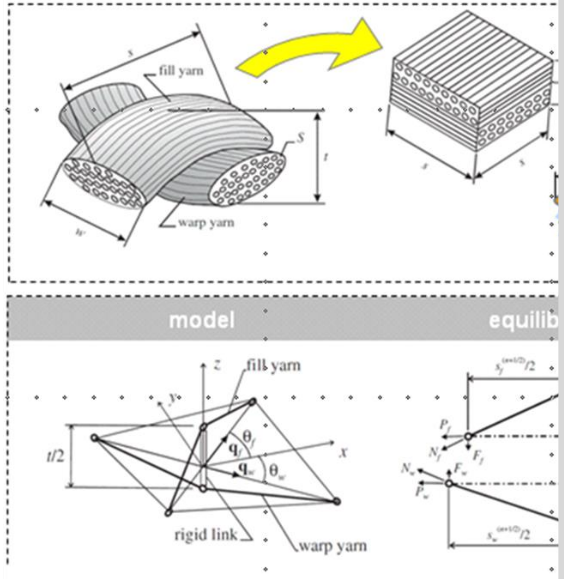
Motivation…

… for a new material implementation

- Materials for woven structures focus on dry fabrics and/or draping behavior

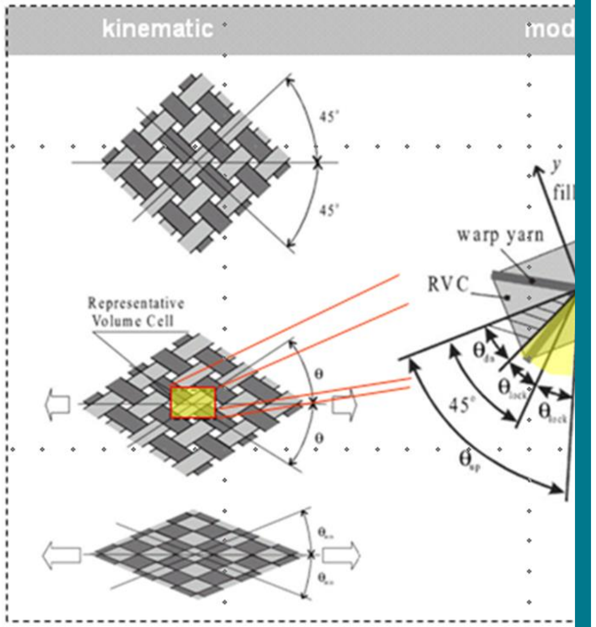
***MAT_VISCOELASTIC_LOOSE_FABRIC (*MAT_234)**

- micro-mechanical approach
- assumes symmetric woven fabric and



***MAT_MICROMECHANICS_DRY_F**

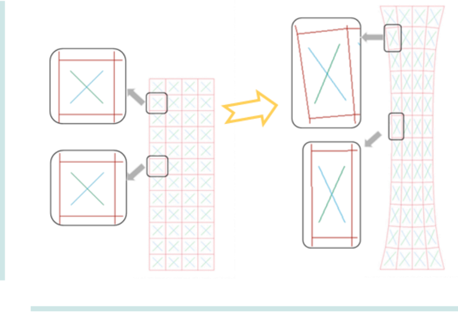
- locking angle accounted for by a redu
- assumes symmetric woven fabric



Basis for a new material model

***MAT_REINFORCED_THERMOPLASTIC (*MAT_249)**

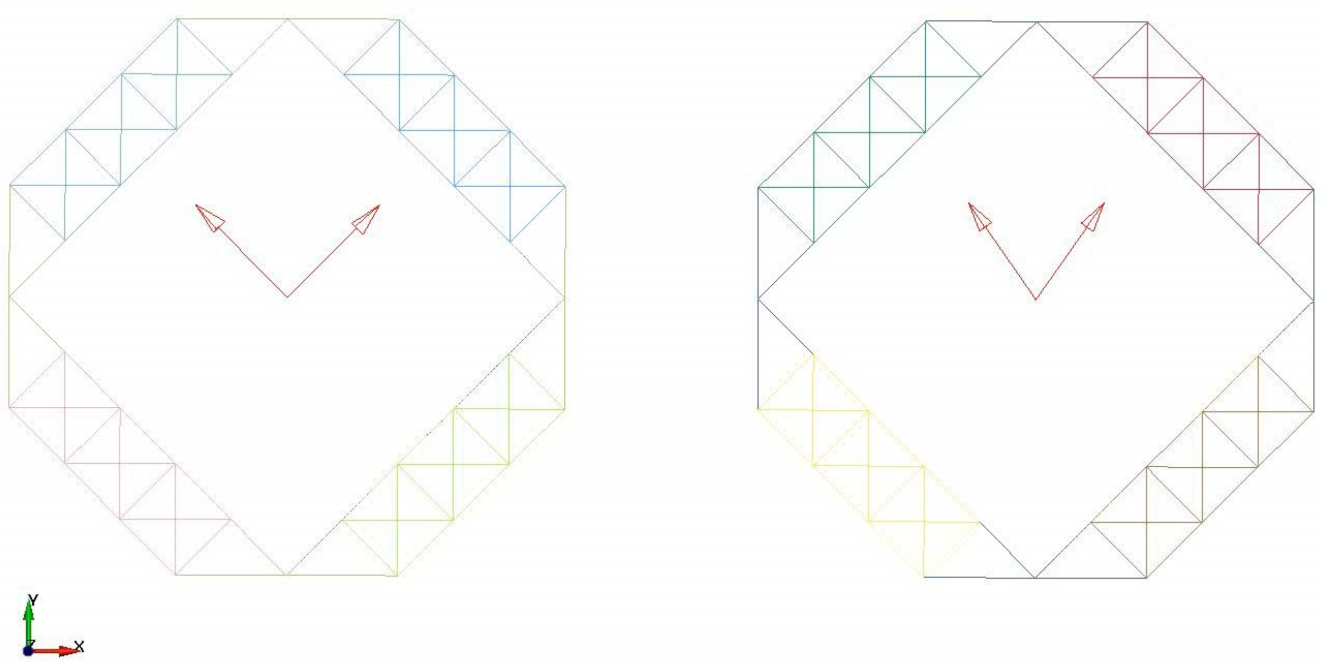
	1	2	3	4	5	6	7	8
Card 1	MID	RO	EM	LCEM	PRM	LCPRM	LCSIGY	BETA
Card 2	NFIB	AOPT	XP	YP	ZP	A1	A2	A3
Card 3	V1	V2	V3	D1	D2	D3	MANGLE	THICK
Card 4	IDF1	ALPH1	EF1	LCF1	G23_1	G31_1		
Card 5	G12	LCG12	ALOC12	GLOC12	METH12			
Card 6	IDF2	ALPH2	EF2	LCF2	G23_2	G31_2		
Card 7	G23	LCG23	ALOC23	GLOC23	METH23			
Card 8	IDF3	ALPH3	EF3	LCF3	G23_3	G31_3		
Opt C	POSTV							



- up to three fiber families can be accounted for
- non-linear hyper-elastic material formulation for each family
  - internally, a fiber is represented by a vector
  - deformation gradient provides necessary information to compute current orientation and strain of the fiber
- anisotropic transverse shear properties can be defined

*MAT_249_CRASH: General properties

Input, coupling approaches, elastic-plastic behavior, …



*MAT_249_CRASH: General properties

Input

- Full name: *MAT_REINFORCED_THERMOPLASTIC_CRASH

- Keyword input:
  - Matrix input
  - Material coordinate system
  - Fiber contributions
  - Damage and failure

	1	2	3	4	5	6	7	8
Card 1	MID	RO	EM	PRM	LCSIGY	BETA	PFL	VISC
Card 2	NFIB	AOPT	XP	YP	ZP	A1	A2	A3
Card 3	V1	V2	V3	D1	D2	D3	MANGLE	THICK
ViscCard	VG1	VB1	VG2	VB2	VG3	VB3	VG4	VB4
Card 5	IDF1	ALPH1	EF1	LCF1	G23_1	G31_1	DAMF1	DAMM1
Card 6	G12	LCG12	ALOC12	GLOC12	METH12	DAMM12		
Card 7	IDF2	ALPH2	EF2	LCF2	G23_2	G31_2	DAMF2	DAMM2
Card 8	G23	LCG23	ALOC23	GLOC23	METH23	DAMM23		
Card 9	IDF3	ALPH3	EF3	LCF3	G23_3	G31_3	DAMF3	DAMM3
Opt C	POSTV	VISCS	IHIS					

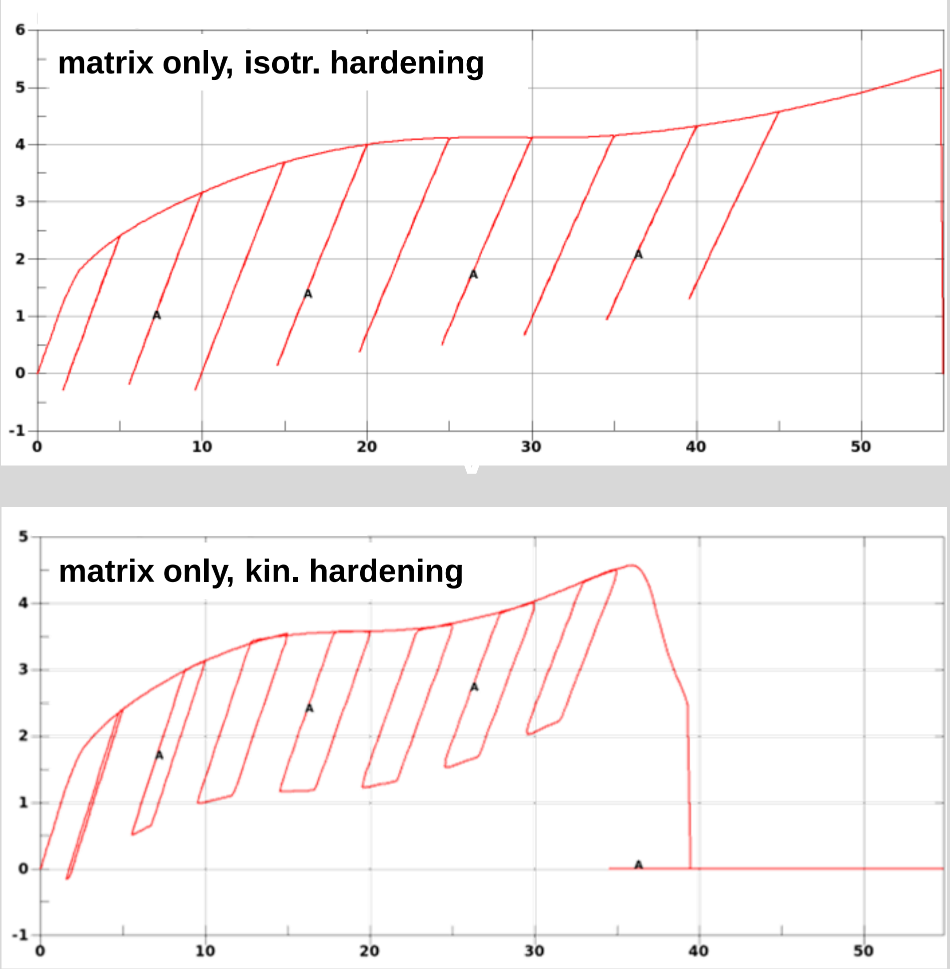
- Additive split between
  - Isotropic, elastic-plastic matrix
  - Anisotropic, hyper-elastic fibers

*MAT_249_CRASH: General properties

Elastic-plastic properties of matrix

- Isotropic and hypo-elastic formulation
- Von Mises plasticity
  - Tabular data for yield stress
    - Flow curves
    - Strain rate dependency
  - Strain hardening algorithm
    - Kinematic
    - Isotropic
    - Mixed strain hardening

Response to cyclic loading



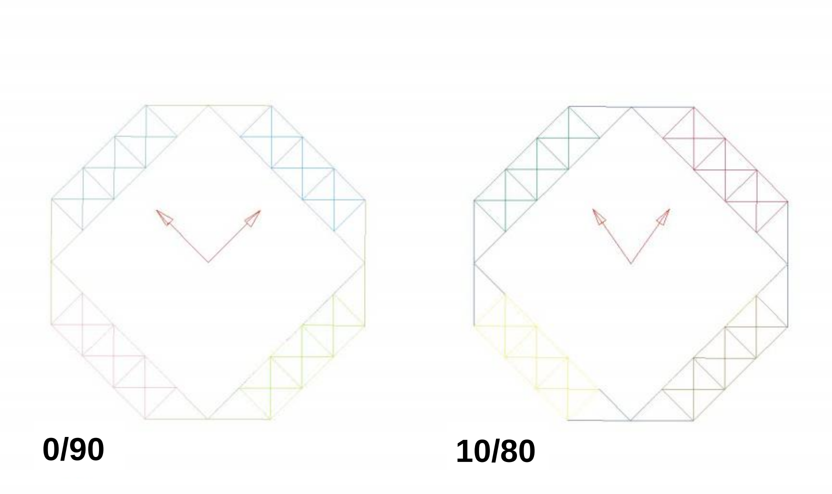
*MAT_249_CRASH: General properties

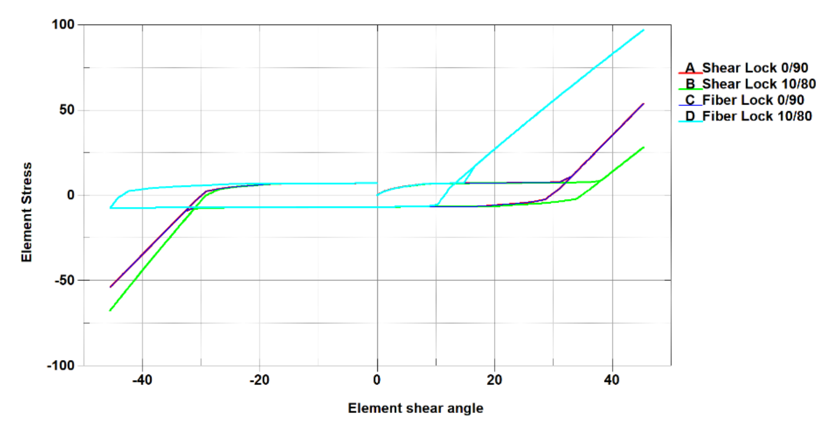
Hyper-elastic fiber formulation

- Up to three fiber families can be accounted for
  - Internally represented by vectors
  - Based on deformation gradient, current orientation and strain of each family is computed
- Fiber stretch and compression
  - Tabular input for non-linear strain-stress response
  - Transverse shear stiffness in fiber direction can be defined
- Shear stress response
  - Based on reorientation of neighboring fiber families
  - Locking (shear or fiber) angle can be defined
  - Tabular input for non-linear elastic or elastic-plastic response

Vector representation

Response to shear loading





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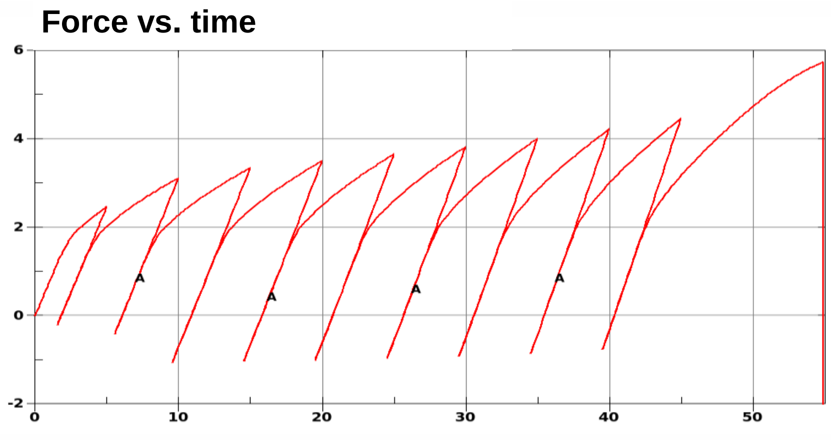
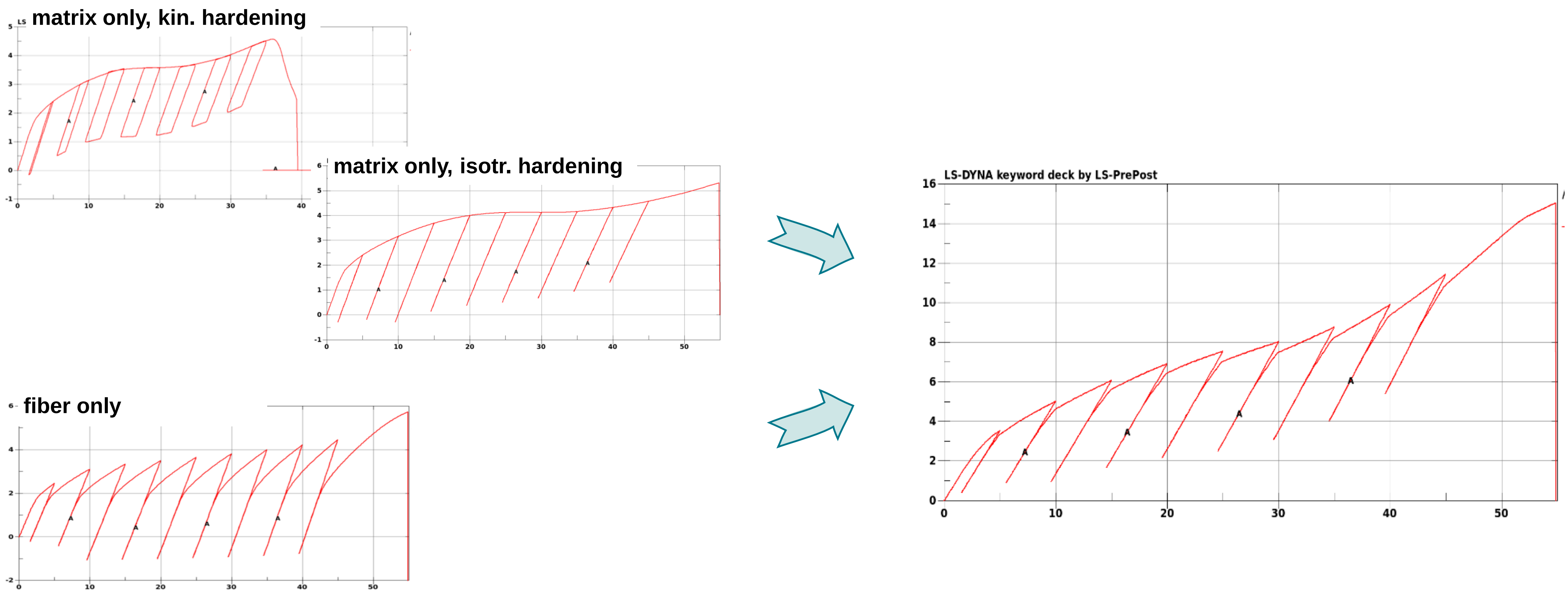
Response to cyclic shear loading



*MAT_249_CRASH: General properties

Material characterization: In-plane shear behavior

- Cyclic loading to separate the effects

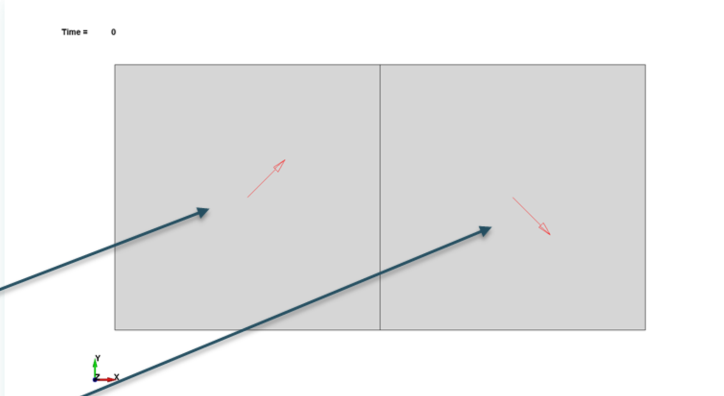


*MAT_249_CRASH: General properties

Advanced data output and fiber definition

- Output control
  - Parameter POSTV defines additional history variables for post-processing
  - Additional data are written to the list prior to the algorithmic history variables
- Element-wise fiber orientation definition
  - Parameter IHIS defines how history data in *INITIAL_HISTORY_SHELL are interpreted
  - Fiber orientations with respect to global or material coordinate system possible

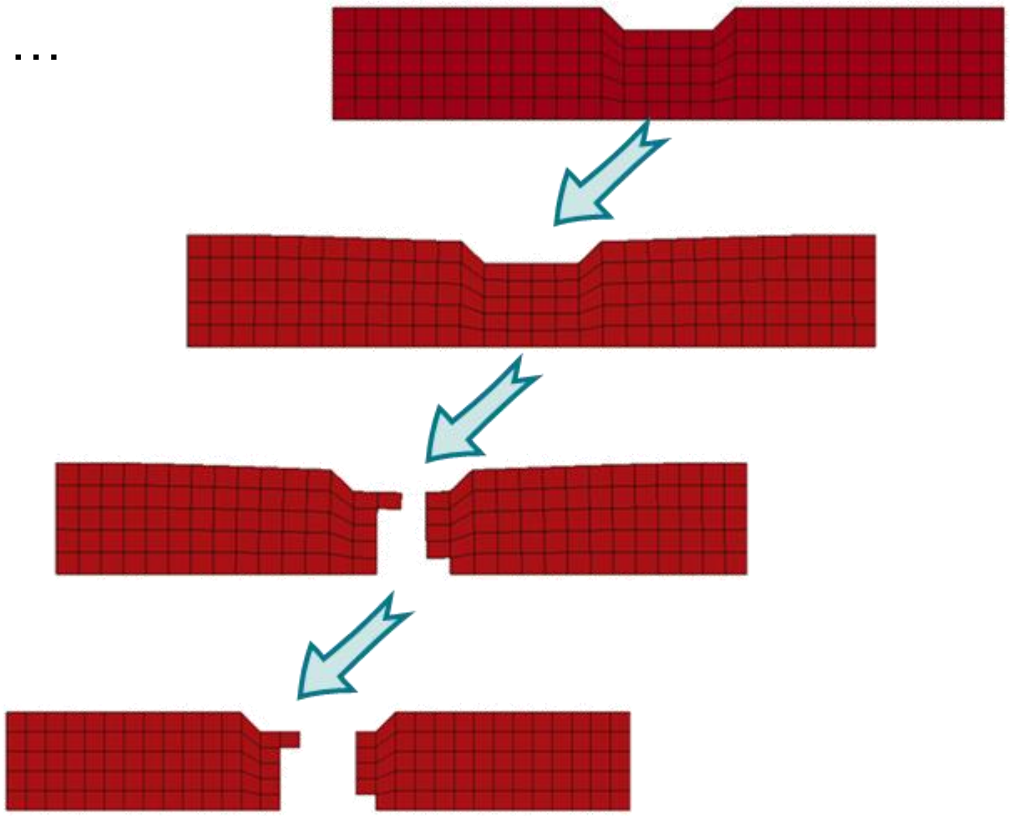
```
*MAT_REINFORCED_THERMOPLASTIC
Mat_1
$#     mid        ro        em      lcem       prm     lcprm    lcsigy      beta
         1  1.130E-6      20.0         0       0.3         0         0       0.0
$#    nfib      aopt        xp        yp        zp        a1        a2        a3
         1       2.0       0.0       0.0       0.0       1.0       0.0       0.0
…
$#   postv      ihis
         8         1
*INITIAL_STRESS_SHELL
$      eid    nplane    nthick     nhisv    ntensr     large    nthint   nthhisv
         1         1         1         7         0         0
$        t     sigxx     sigyy     sigzz     sigxy     sigyz     sigzx       eps
 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00
$#------1|--------2|--------3|--------4|--------5|--------6|--------7|
0.000e+00 0.000e+00 0.000e+00 0.000e+00 1.000e+00 1.000e+00 0.000e+00
$      eid    nplane    nthick     nhisv    ntensr     large    nthint   nthhisv
         2         1         1         7         0         0
$        t     sigxx     sigyy     sigzz     sigxy     sigyz     sigzx       eps
 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00 0.000e+00
$#------1|--------2|--------3|--------4|--------5|--------6|--------7|
 0.000e+00 0.000e+00 0.000e+00 0.000e+00 1.000e+00-1.000e+00 0.000e+00
```



Vector plot of initial fiber orientation

*MAT_249_CRASH: Damage and Failure

Basic concept, fiber and matrix softening algorithms, …



*MAT_249_CRASH: Damage and Failure

A phenomenological approach

- Tabular input data relating fiber state to several softening mechanisms
  - Fiber length change damage fiber and matrix
  - Individual softening parameters for fiber stretch and compression
  - Reorientation of fibers induces softening in the matrix
- Matrix deformation cannot trigger damage or failure
- Artificial fiber viscosity can be defined to avoid snapback of elements in the vicinity of a crack

Damage and failure

	1	2	3	4	5	6	7	8
Card 1	MID	RO	EM	PRM	LCSIGY	BETA	PFL	VISC
Card 2	NFIB	AOPT	XP	YP	ZP	A1	A2	A3
Card 3	V1	V2	V3	D1	D2	D3	MANGLE	THICK
ViscCard	VG1	VB1	VG2	VB2	VG3	VB3	VG4	VB4
Card 5	IDF1	ALPH1	EF1	LCF1	G23_1	G31_1	DAMF1	DAMM1
Card 6	G12	LCG12	ALOC12	GLOC12	METH12	DAMM12		
Card 7	IDF2	ALPH2	EF2	LCF2	G23_2	G31_2	DAMF2	DAMM2
Card 8	G23	LCG23	ALOC23	GLOC23	METH23	DAMM23		
Card 9	IDF3	ALPH3	EF3	LCF3	G23_3	G31_3	DAMF3	DAMM3
Opt C	POSTV	VISCS	IHIS					

*MAT_249_CRASH: Damage and Failure

Fiber softening algorithms

- Tabular data input
  - Define softening parameter d_i^f vs. fiber strain λ_i

$$\hat{\boldsymbol{\sigma}}_T^f = \sum_i \left(1 - d_i^f(\lambda_i)\right) \boldsymbol{\sigma}_{T_i}^f$$

  - Softening of tensile and compressive stresses can be considered individually

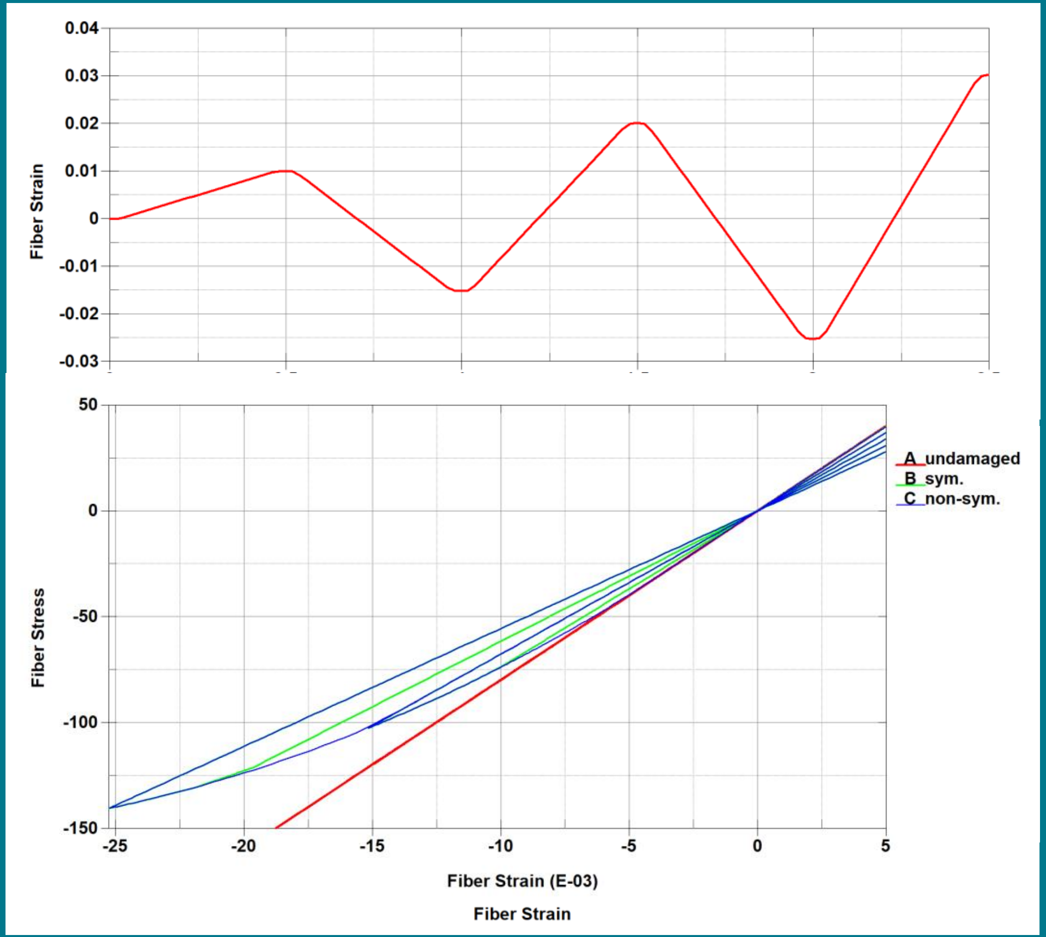
$$d_i^{f,c}(t^n, \lambda_i) = \max(d_i^{f,c}(t^{n-1}, \lambda_i), \mathrm{DAMC}i(\lambda_i))$$
$$d_i^{f,t}(t^n, \lambda_i) = \max(d_i^{f,t}(t^{n-1}, \lambda_i), \mathrm{DAMT}i(\lambda_i))$$

  - Fiber damage of fiber i is defined as

$$d_i^f(\lambda_i) = \begin{cases} d_i^{f,c}, & \lambda_i < 0 \\ d_i^{f,t}, & \lambda_i \geq 0 \end{cases}$$

- Integration point fails if all fibers are completely damaged, i.e. $\min_i d_i^f = 1$.

One element, uniaxial test



*MAT_249_CRASH: Damage and Failure

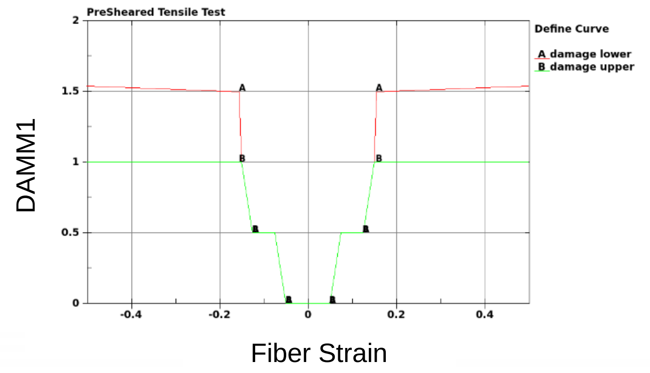
Matrix softening mechanisms

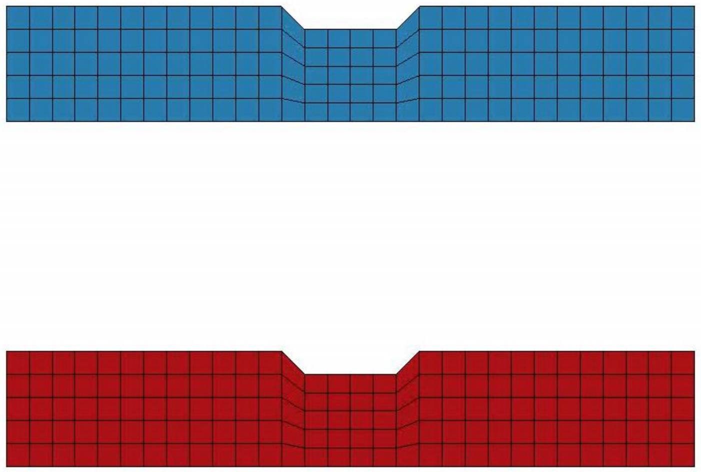
- Matrix is damaged if fibers are shortened or elongated
  - Tabular input data (softening vs. fiber strain)
  - Strain rate effects can be accounted for

- Matrix is damaged if fibers reorient
  - Tabular input data (softening vs. shear angle of neighboring fibers)

- A fully damaged matrix not necessarily triggers failure of an integration point
  - Failure is initiated if softening parameter exceeds 1.5
  - Naturally, stress softening is limited to 1.0

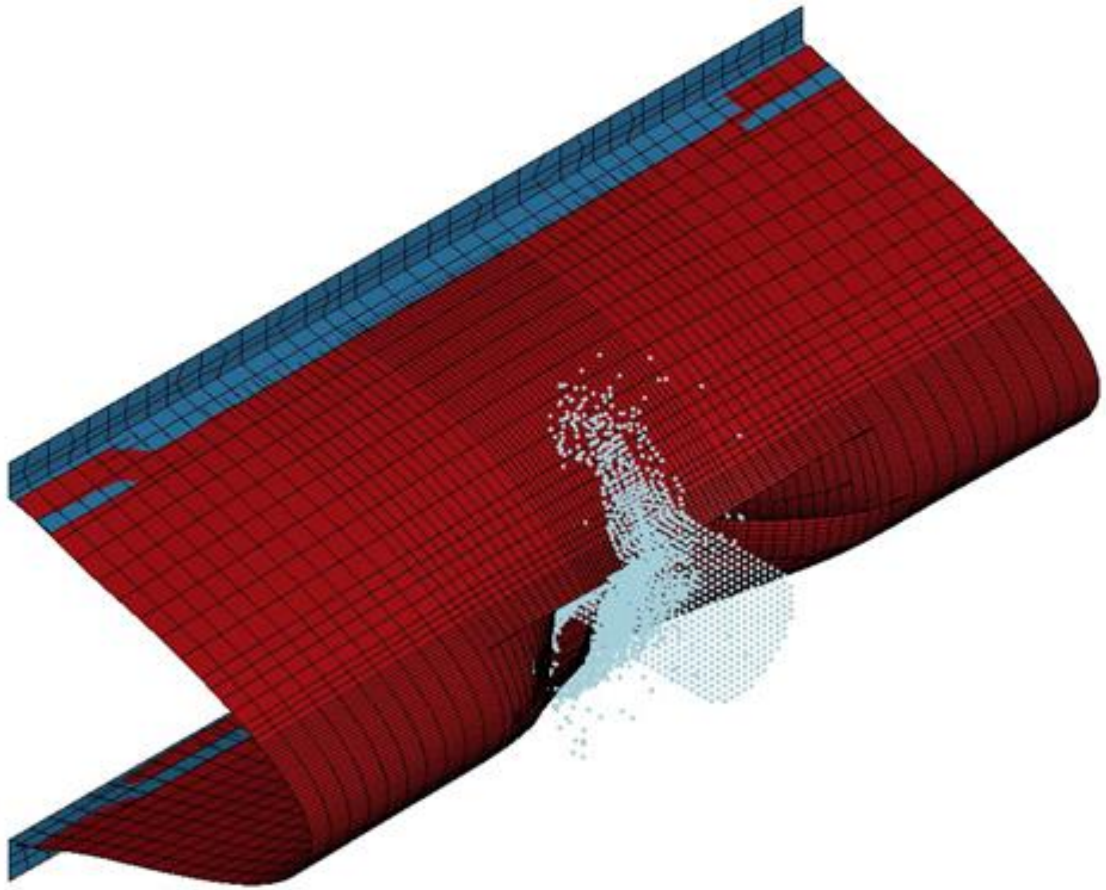
Uniaxial tensile test in fiber direction





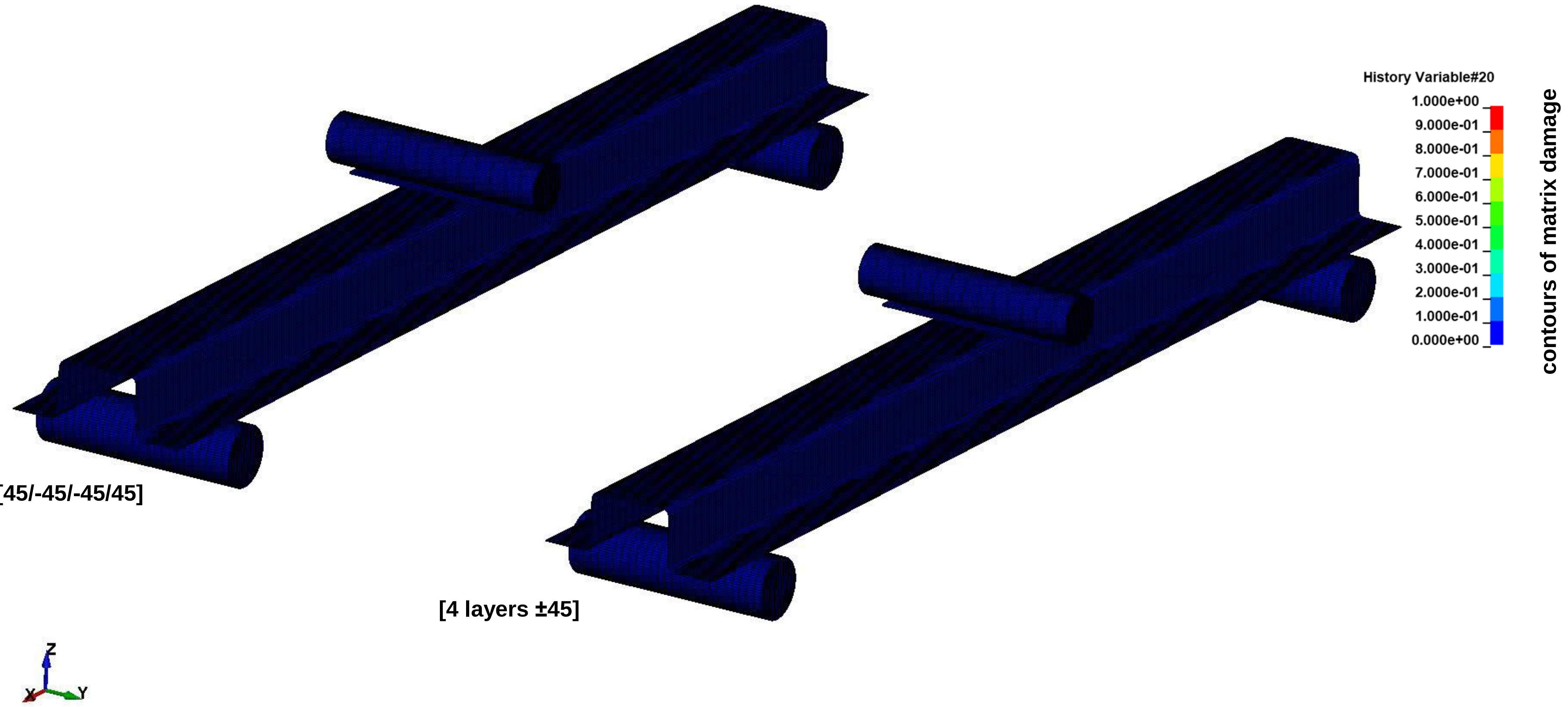
Examples

Proof of concept



Ex 1: Three-point bending of a hat-profile

Comparison of an NCF and a woven reinforcement



Ex 1: Three-point bending of a hat-profile

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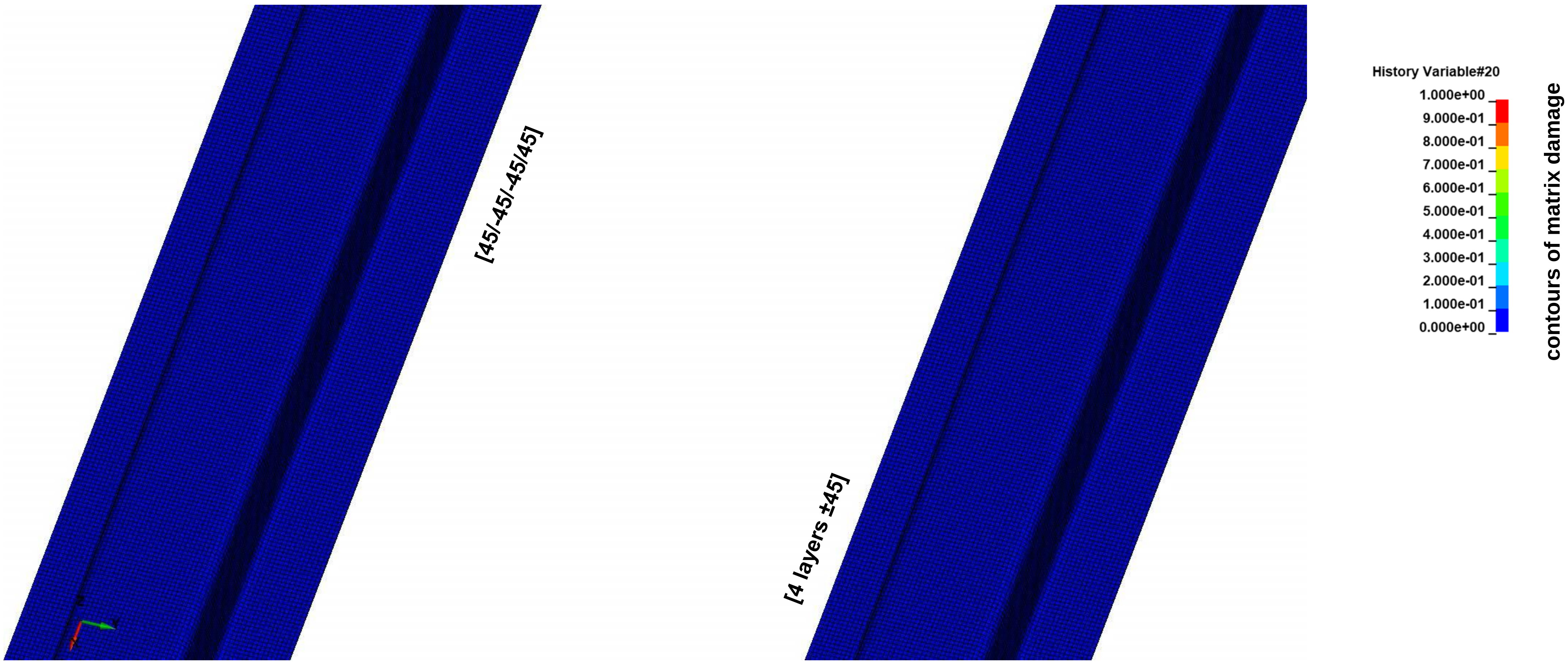
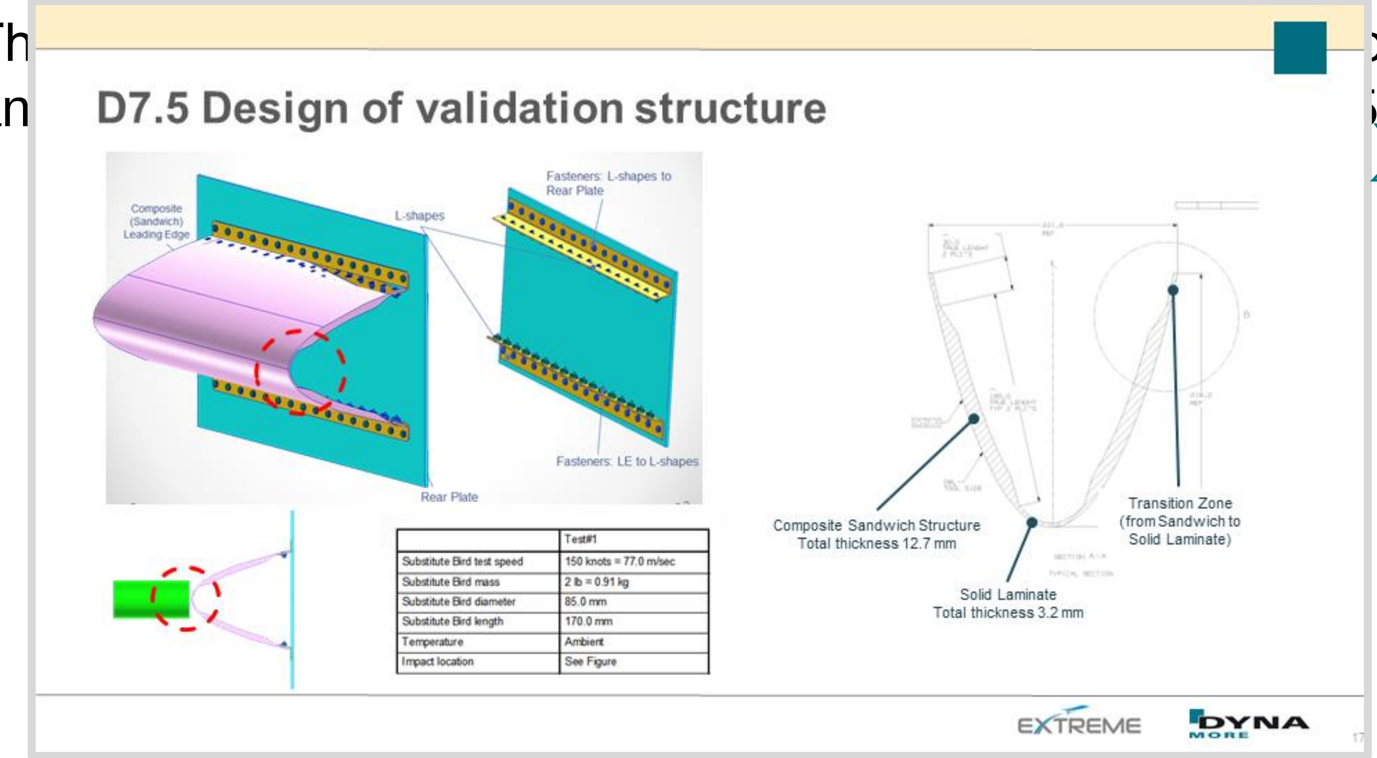


Ex 2: Impact example

Set-up

- Based on validation example from the EXTREME project
  - The aim of the EXTREME project is to develop novel material characterization methods and in-situ measurement techniques, material models and simulation methods for the design and manufacture of aerospace composite structures under EXTREME dynamic loadings.
  - Th … pean Uni … an … 549.

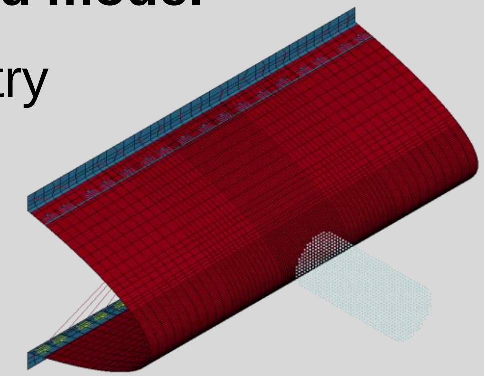

D7.5 Design of validation structure

	Test#1
Substitute Bird test speed	150 knots = 77.0 m/sec
Substitute Bird mass	2 lb = 0.91 kg
Substitute Bird diameter	85.0 mm
Substitute Bird length	170.0 mm
Temperature	Ambient
Impact location	See Figure

EXTREME DYNA MORE 17

Simplified model

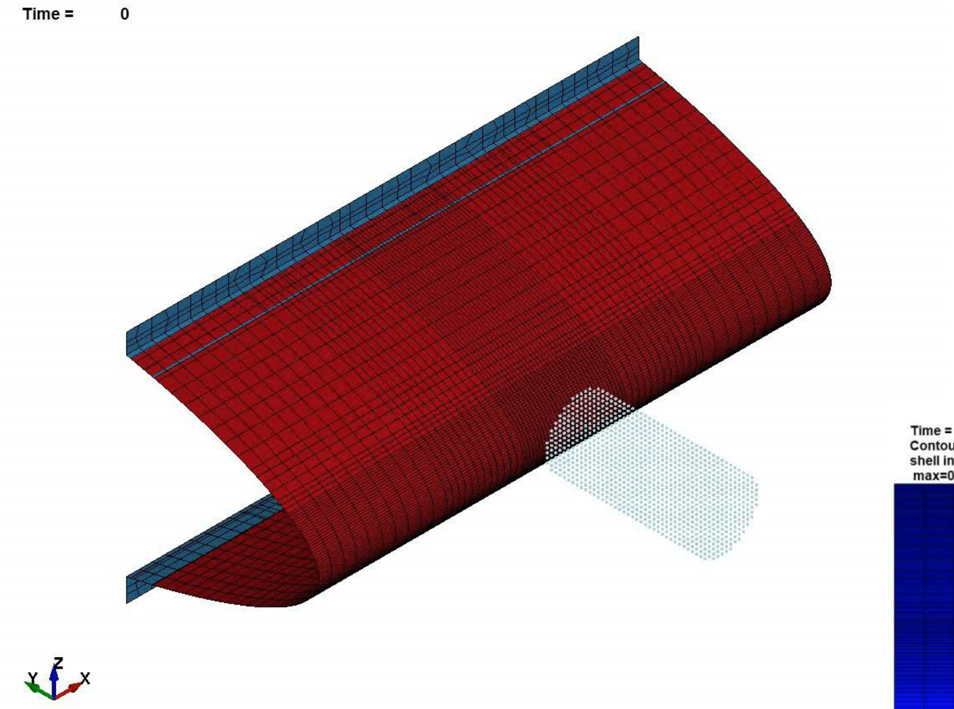
- Geometry

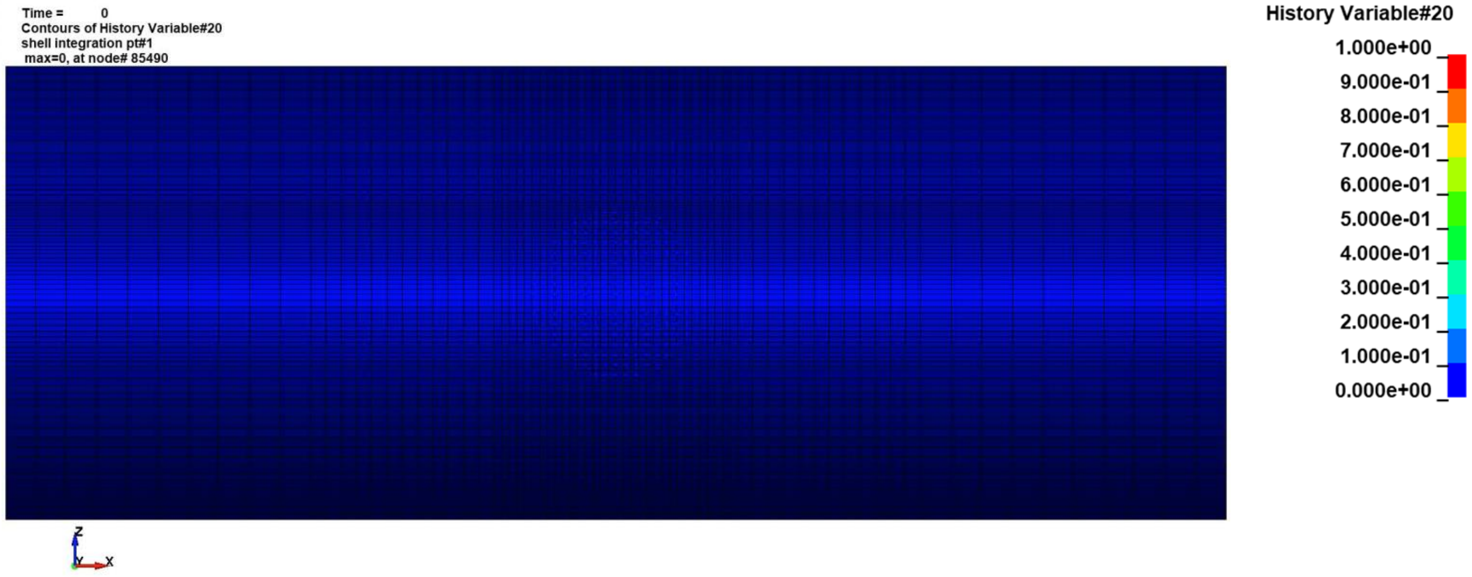


- Shell model
- Constant thickness (3.2mm)
- Same lay-up everywhere

Ex 2: Impact example

Results for quasi-isotropic composite

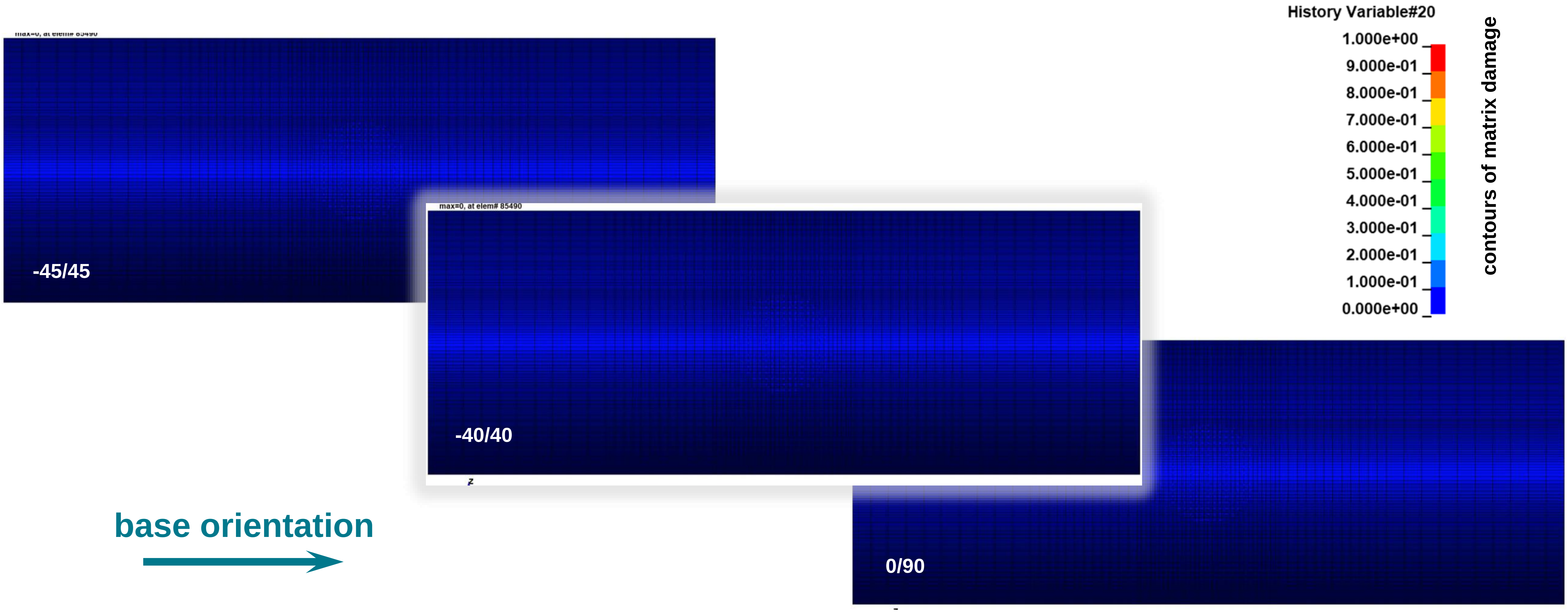




contours of matrix damage

Ex 2: Impact example

Results for different simple composites with woven reinforcements



Summary

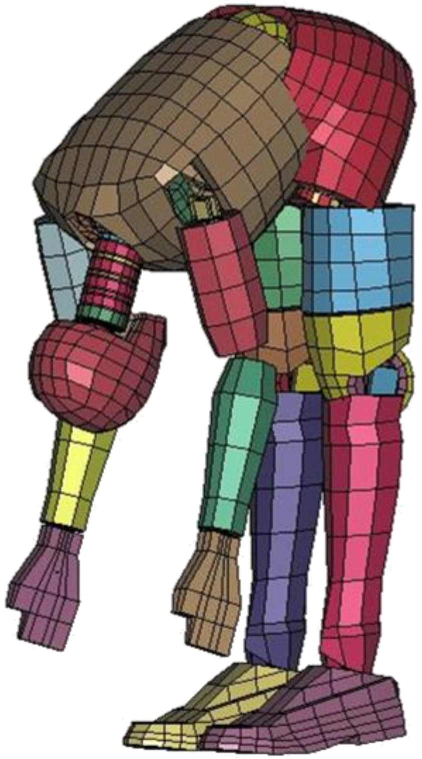
Summary

- Discussed new material model *MAT_249_CRASH
  - Additive split between an isotropic, elastic-plastic matrix and anisotropic, hyper-elastic fibers
  - Phenomenological description of damage and failure
  - Damage due to fiber elongation and compression considered individually

- Showed some applications
  - Pre-shearing of material from draping (thermoforming) can be considered
  - Fiber shearing before material failure can occur
  - Applicable to woven textiles, UD layers and NCFs

- Calibration of the model successfully completed in the project with Brose and the IVW

Thank You



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