



eGISSMO: Ein Werkzeug zur Schädigungsmodellierung auch für Kunststoffe

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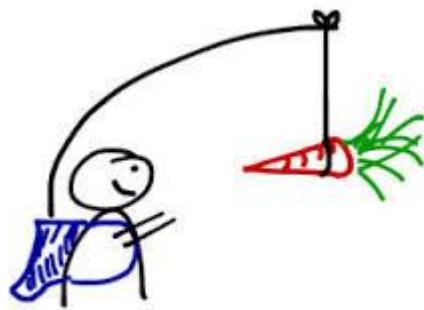
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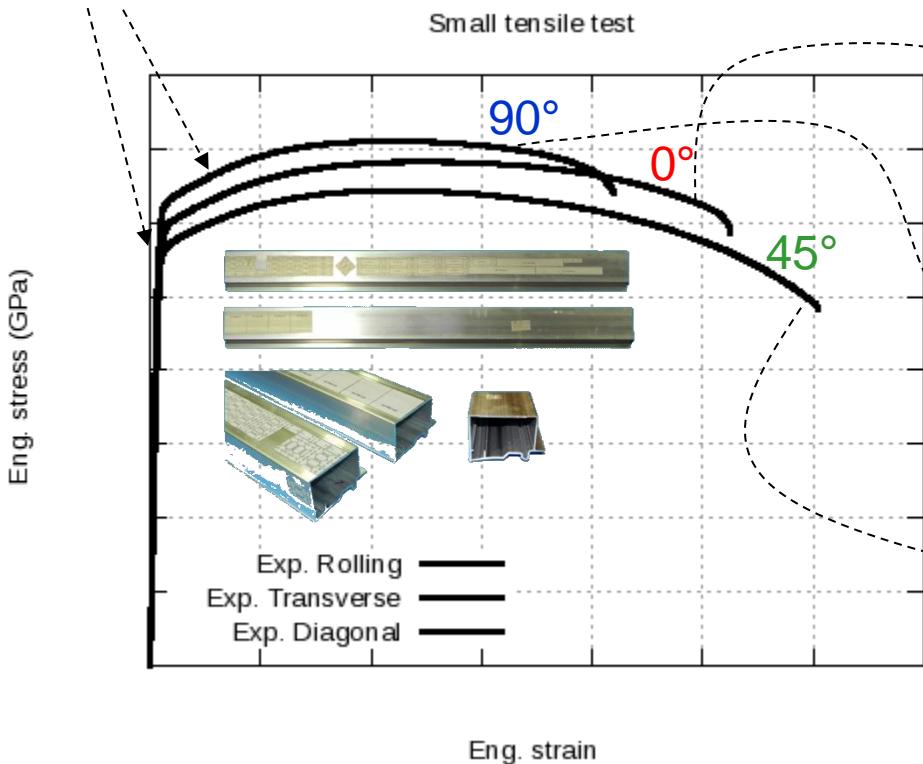
Motivation



Motivation: orthopropy

Typical aluminum extrusion – mechanical behavior

Yield stress can be direction-dependent



0° – R=0.4



90° – R=0.8



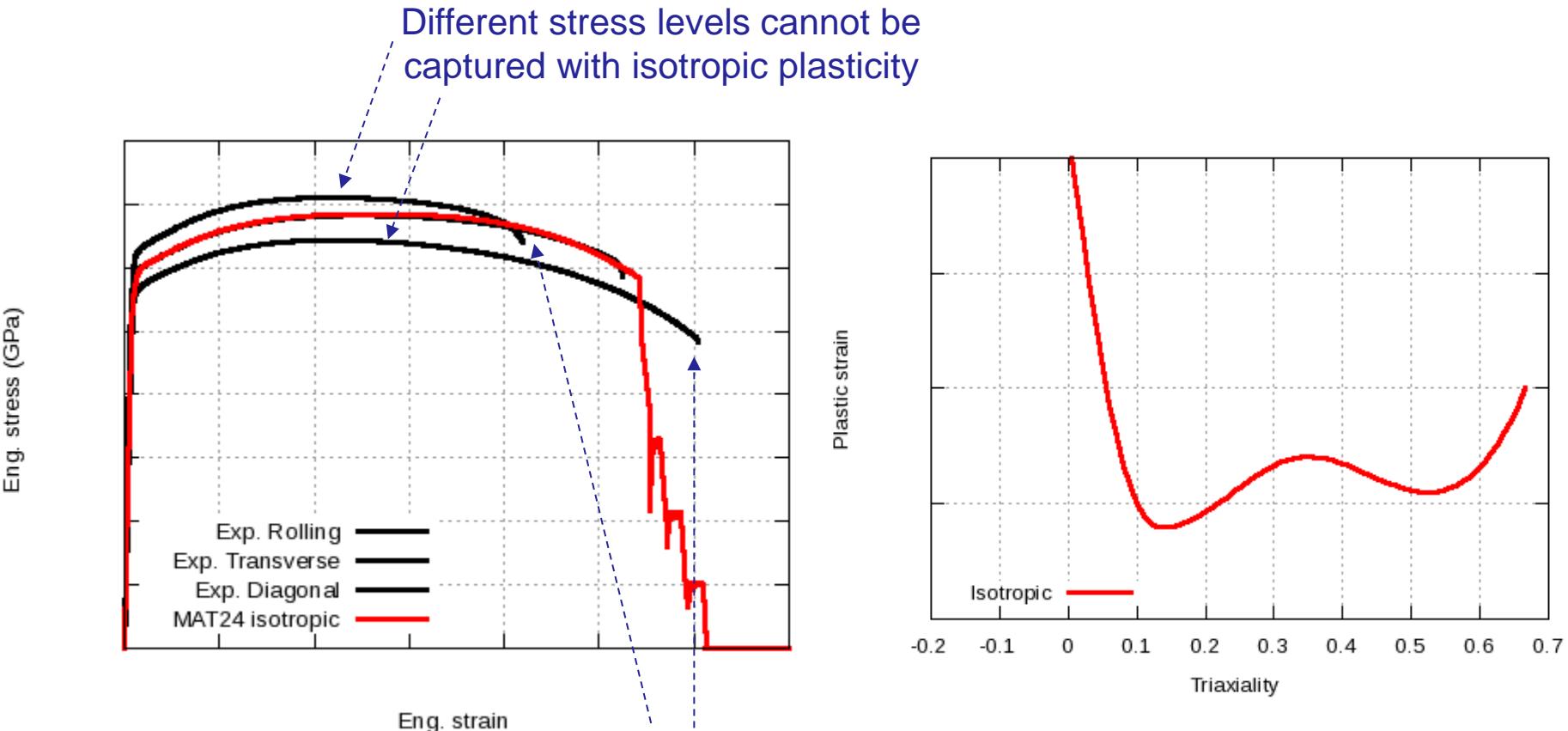
45° – R=2.0



Plastic straining and fracture can be strongly orientation dependent

Motivation: orthopropy

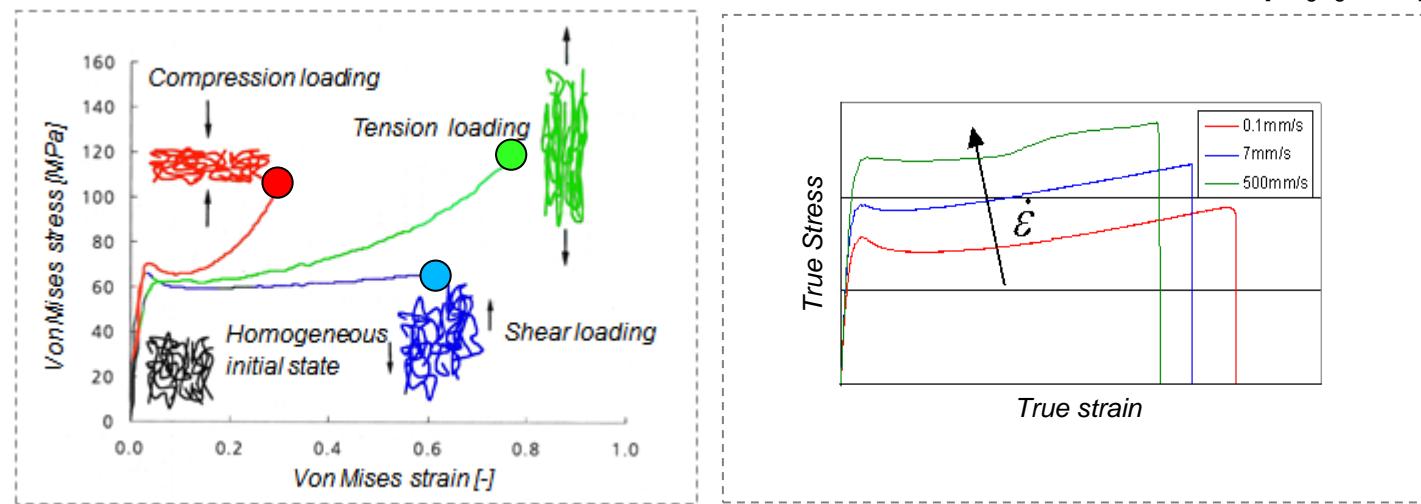
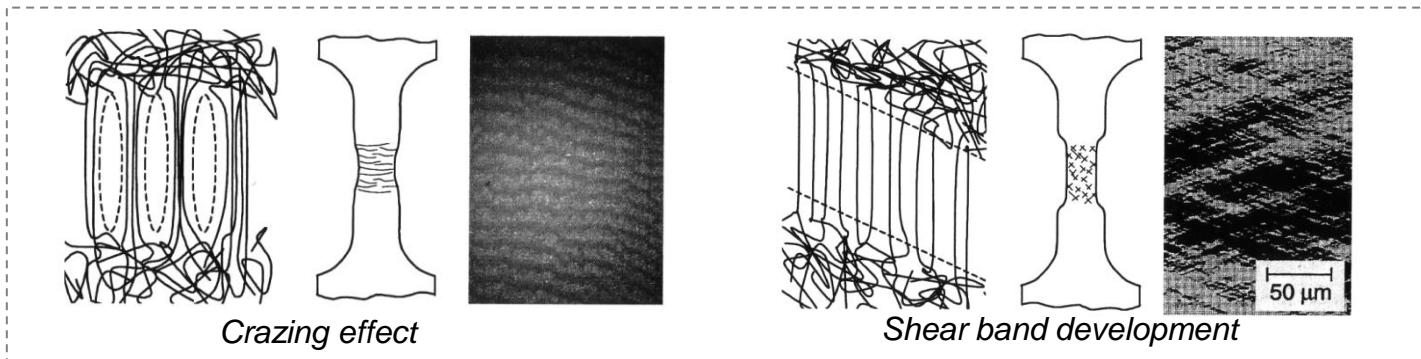
Limitations of isotropic material and failure models
(e.g., *MAT_024 + eGISSMO)



Motivation: crazing

Polymers

- Visco-elasticity, plasticity, crazing and the development of shear bands may be dominating the loading behaviour:





PLASTICITY

Metals vs. (unreinforced) polymers

Anisotropy of metallic sheet-like materials

The Lankford parameter (R-value)

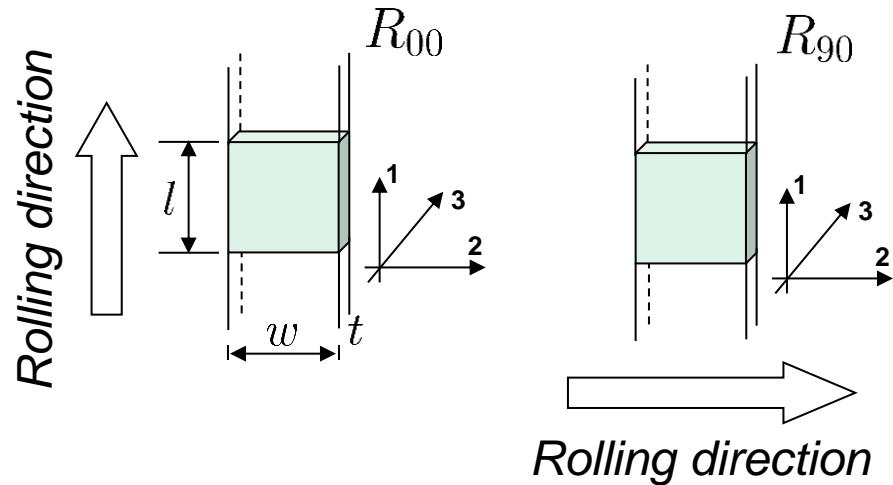
- Definition:

$$R = \frac{d\varepsilon_{22}^p}{d\varepsilon_{33}^p}$$

- In case of isochoric flow:

$$d\varepsilon_{11}^p + d\varepsilon_{22}^p + d\varepsilon_{33}^p = 0$$

$$R = -\frac{d\varepsilon_{22}^p}{d\varepsilon_{11}^p + d\varepsilon_{22}^p}$$



$R > 1.0 \rightarrow$ less thinning

$R < 1.0 \rightarrow$ more thinning

Experimental data of extruded Aluminium

Fictitious experimental data (similar to typically observed in aluminum extrusions)

Direction	Yield Stress	Lankford Parameter	Eng. Fracture Strain	*normalized values
Extrusion direction (0°)	1.00*	0.50	1.00*	
Transverse direction (90°)	1.02	0.80	0.90	
Diagonal direction (45°)	0.99	1.80	1.10	

Barlat & Lian's formulation is extended in such manner that the yield stress depends on the material direction and loading state.

Available in LS-DYNA as MAT_036 and HR=7:

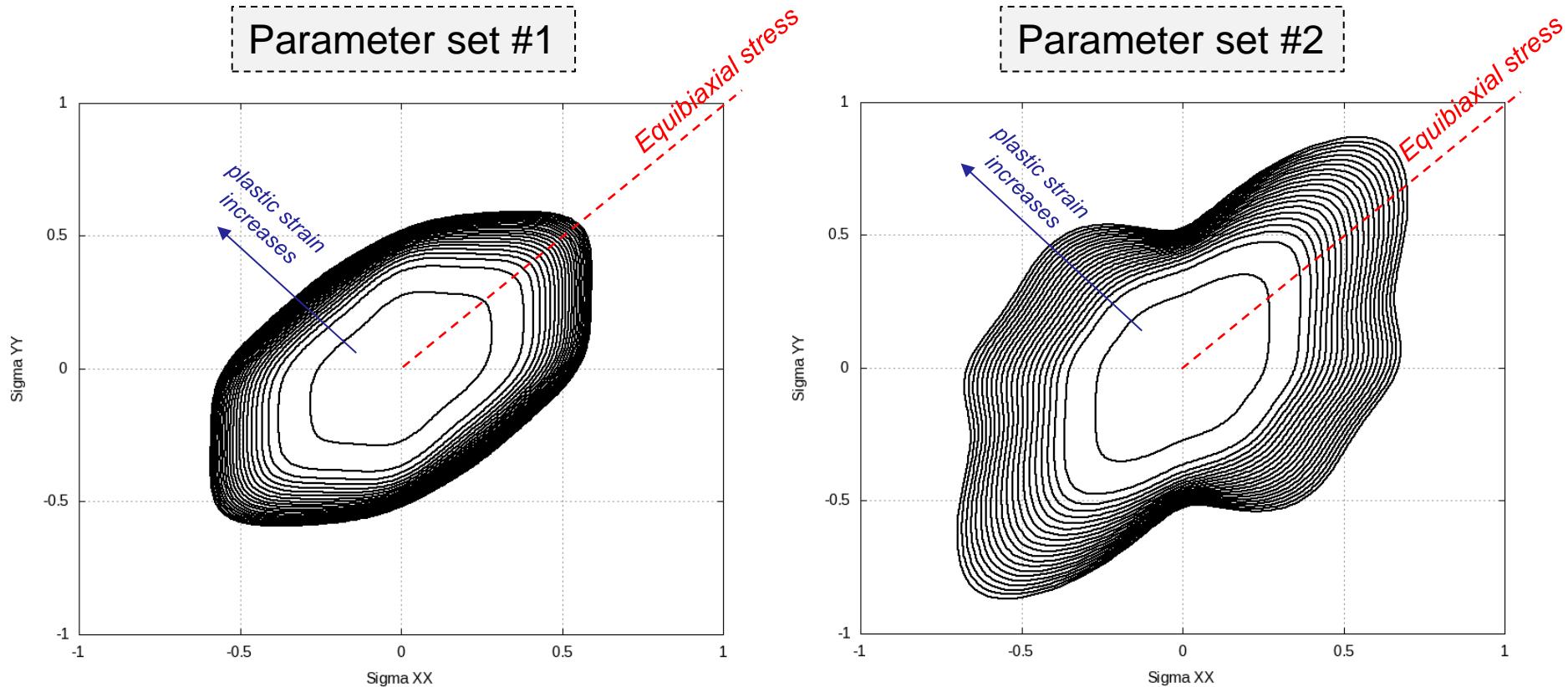
$$\Phi(\boldsymbol{\sigma}) = a |K_1 + K_2|^m + a |K_1 - K_2|^m + c |2K_2|^m - 2\sigma_y^m = 0$$

$$\sigma_Y(\boldsymbol{\sigma}, \varepsilon^p) = \alpha_{00}\sigma_Y^{00}(\varepsilon^p) + \alpha_{45}\sigma_Y^{45}(\varepsilon^p) + \alpha_{90}\sigma_Y^{90}(\varepsilon^p) + \alpha_B\sigma_Y^B(\varepsilon^p) + \alpha_{shear}\sigma_Y^{shear}(\varepsilon^p)$$

Fitting yield surfaces for such materials

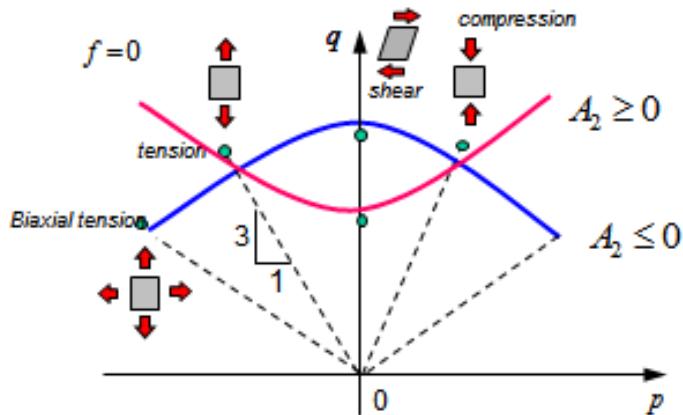
Yield surface with *MAT_036 (HR=7)

The extended formulation of *MAT_036 is very flexible and extremely useful in order to match experimental data. Nevertheless, different sets of parameters may lead to non-convex and non-monotonic yield surfaces.



Material modeling of polymers in LS-DYNA

Isotropic plasticity with SAMP-1 (*MAT_187)

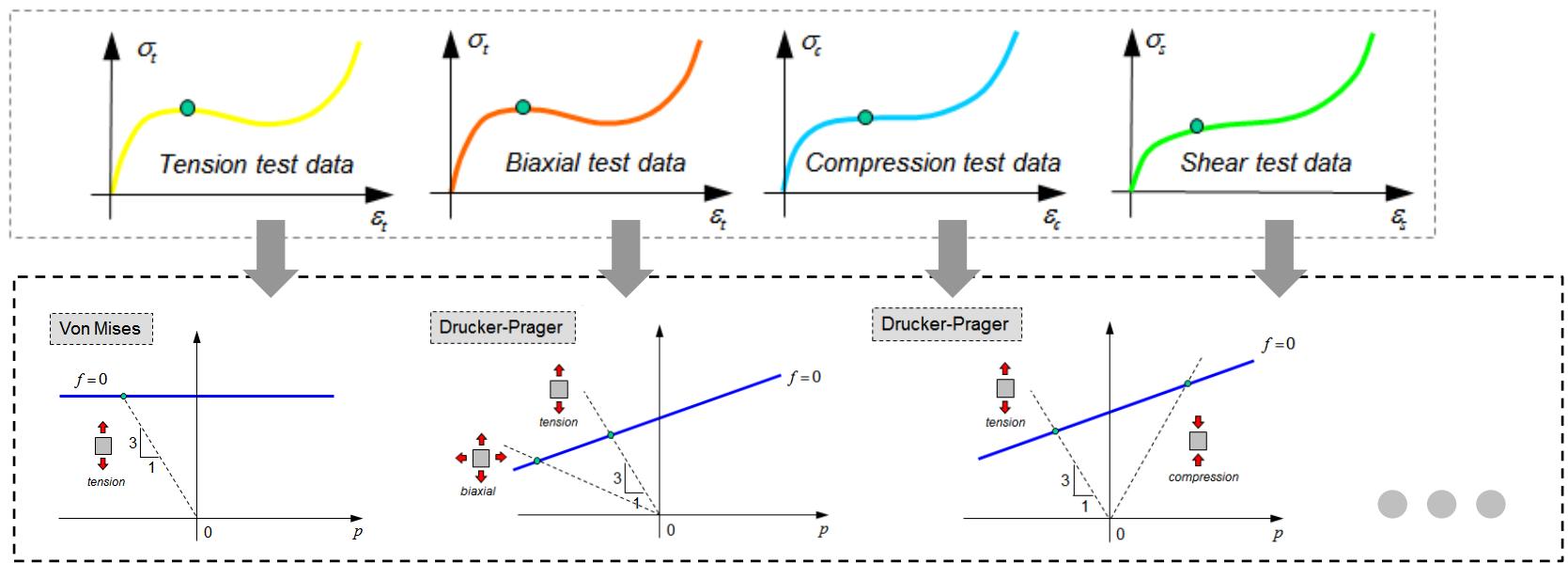


Yield surface:

$$f(p, \sigma_{vm}, \bar{\varepsilon}^{pl}) = \sigma_{vm}^2 - A_0 - A_1 p - A_2 p^2 \leq 0$$

Condition for convexity :

$$A_2 \leq 0 \Leftrightarrow \sigma_s \geq \frac{\sqrt{\sigma_t \sigma_c}}{\sqrt{3}}$$





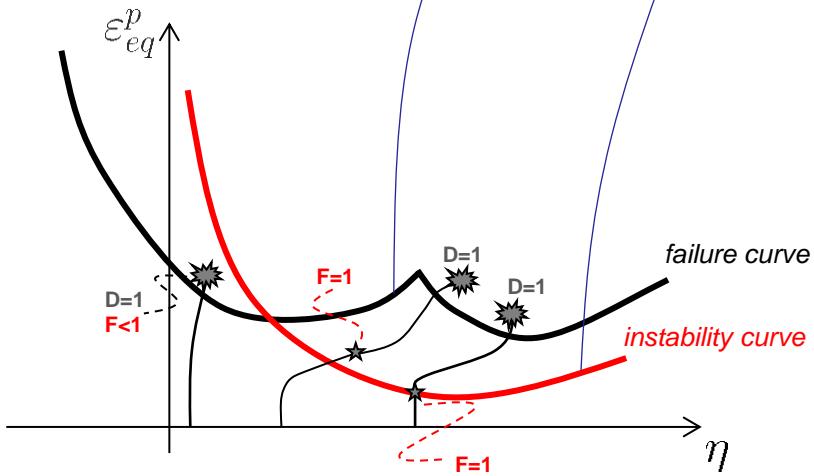
DAMAGE / FAILURE with isotropic GISSMO



Material modeling in LS-DYNA

GISSMO – Isotropic damage/failure model through *MAT_ADD_EROSION

*MAT_ADD_EROSION								
\$	MID	EXCL	MXPRES	MNEPS	EFFEPS	VOLEPS	NUMFIP	NCS
\$	10							
\$	MNPRES	SIGP1	SIGVM	MXEPS	EPSSH	SIGTH	IMPULSE	FAILTM
\$	IDAM	DMGTYp	LCSDG 100	ECRIT -200	DMGEXP 2.0	DCRIT	FADEXP 2.0	LCREGD 400
\$	1	1	NAHSV 14	LCSRS	REGSHR 1.0	REGBIAX 0.0		
\$	SIZFLG	REFSZ						



At every step, an instability measure and the damage are accumulated through:

$$\Delta F = \frac{n}{\varepsilon_{crit}(\eta)} F^{(1-\frac{1}{n})} \Delta \varepsilon_{eq}^p$$

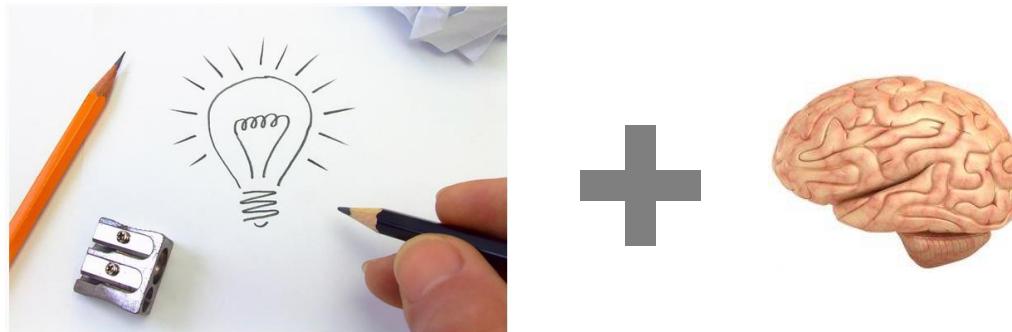
$$\Delta D = \frac{n}{\varepsilon_f(\eta)} D^{(1-\frac{1}{n})} \Delta \varepsilon_{eq}^p$$

If $F=1.0$, damage and stress are coupled:

$$\sigma^* = \sigma \left(1 - \left(\frac{D - D_{crit}}{1 - D_{crit}} \right)^m \right)$$



DAMAGE / FAILURE with the extended GISSMO Damage Model



Modulares Konzept: Plastizitätsmodell und isotropes Schädigungsmodell: GISSMO

Plastizität

$$\dot{\sigma}_{eff} = C(\dot{\varepsilon} - \dot{\varepsilon}_p)$$

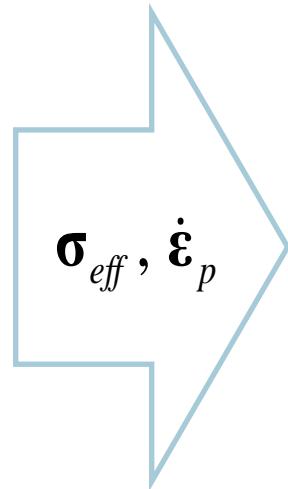
$$\dot{\varepsilon}_p = \lambda \frac{\partial g(\sigma_{eff})}{\partial \sigma_{eff}}$$

$$\dot{q} = \lambda \frac{\partial q}{\partial \lambda}$$

$$f(\sigma_{eff}, q) \leq 0, \quad \lambda \geq 0$$

$$f(\sigma_{eff}) = \text{Mises / Hill...}$$

$$g(\sigma_{eff}) = f(\sigma_{eff})$$



Damage

$$\sigma = (1-d)\sigma_{eff}$$

$$\dot{d} = nd^{(1-\frac{1}{n})} \frac{\dot{\varepsilon}_p}{\varepsilon_{fail}(\eta, \theta)}$$

$$d = \int \Delta d \leq 1$$

Modulares Konzept: Plastizitätsmodell und isotropes Schädigungsmodell: GISSMO

Plastizität

$$\dot{\sigma}_{eff} = C(\dot{\varepsilon} - \dot{\varepsilon}_p)$$

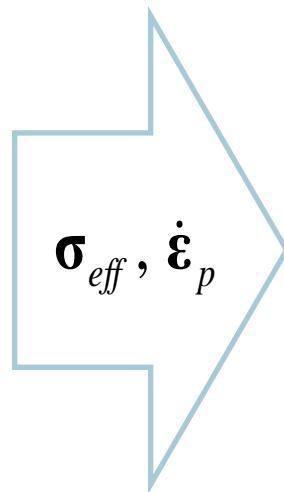
$$\dot{\varepsilon}_p = \lambda \frac{\partial g(\sigma_{eff})}{\partial \sigma_{eff}}$$

$$\dot{q} = \lambda \frac{\partial q}{\partial \lambda}$$

$$f(\sigma_{eff}, q) \leq 0, \quad \lambda \geq 0$$

$$f(\sigma_{eff}) = \text{Mises / Hill...}$$

$$g(\sigma_{eff}) = f(\sigma_{eff})$$



Damage

$$\sigma = \left(1 - \left(\frac{d - d_{crit}}{1 - d_{crit}} \right)^{FADEXP} \right) \sigma_{eff}$$

$$\dot{d} = nd^{\left(1-\frac{1}{n}\right)} \frac{\dot{\varepsilon}_p}{\varepsilon_{fail}(\eta, \theta, l_c, \dot{\varepsilon}_p)}$$

$$\dot{f} = nf^{\left(1-\frac{1}{n}\right)} \frac{\dot{\varepsilon}_p}{\varepsilon_{crit}(\eta, \dot{\varepsilon}_p)}$$

$$d = \int \Delta d \leq 1$$

$$f = \int \Delta f \leq 1 \Rightarrow d_{crit} = d$$

Modulares Konzept: Plastizitätsmodell und anisotropes Schädigungsmodell: MAT_ADD_GENERALIZED_DAMAGE

Plastizität

$$\dot{\sigma}_{eff} = C(\dot{\epsilon} - \dot{\epsilon}_p)$$

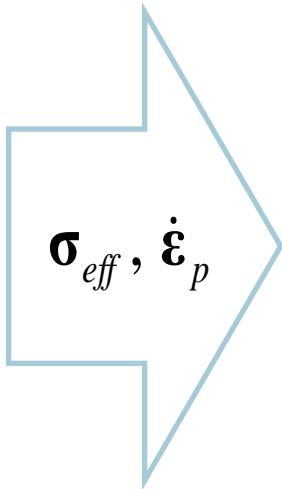
$$\dot{\epsilon}_p = \dot{\lambda} \frac{\partial g(\sigma_{eff})}{\partial \sigma_{eff}}$$

$$\dot{q} = \dot{\lambda} \frac{\partial q}{\partial \lambda}$$

$$f(\sigma_{eff}, q) \leq 0, \quad \dot{\lambda} \geq 0$$

$$f(\sigma_{eff}) = \text{Mises / Hill...}$$

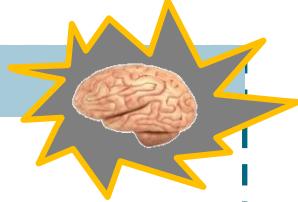
$$g(\sigma_{eff}) = f(\sigma_{eff})$$



Damage

$$\sigma = M \sigma_{eff} \quad M = \begin{pmatrix} d_{11} & d_{12} & d_{13} & 0 & 0 & 0 \\ d_{21} & d_{22} & d_{23} & 0 & 0 & 0 \\ d_{31} & d_{32} & d_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & d_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & d_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & d_{66} \end{pmatrix}$$

wobei $d_{ij} = f_{ij}(d_1, d_2, d_3)$



$$\dot{d}_1 = n_1 d_1^{1-\frac{1}{n_1}} \frac{\dot{\epsilon}_1^{eq}}{\epsilon_1^f(\eta, \theta)} \quad \dot{\epsilon}_1^{eq} = f_1(\dot{\epsilon}_{xx}^p, \dot{\epsilon}_{yy}^p, \dot{\epsilon}_{zz}^p, \dot{\epsilon}_{xy}^p, \dot{\epsilon}_{yz}^p, \dot{\epsilon}_{zx}^p) \text{ or } HIS_1$$

$$\dot{d}_2 = n_2 d_2^{1-\frac{1}{n_2}} \frac{\dot{\epsilon}_2^{eq}}{\epsilon_2^f(\eta, \theta)} \quad \dot{\epsilon}_2^{eq} = f_2(\dot{\epsilon}_{xx}^p, \dot{\epsilon}_{yy}^p, \dot{\epsilon}_{zz}^p, \dot{\epsilon}_{xy}^p, \dot{\epsilon}_{yz}^p, \dot{\epsilon}_{zx}^p) \text{ or } HIS_2$$

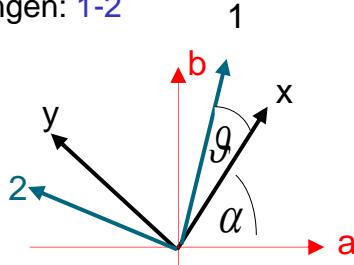
$$\dot{d}_3 = n_3 d_3^{1-\frac{1}{n_3}} \frac{\dot{\epsilon}_3^{eq}}{\epsilon_3^f(\eta, \theta)} \quad \dot{\epsilon}_3^{eq} = f_3(\dot{\epsilon}_{xx}^p, \dot{\epsilon}_{yy}^p, \dot{\epsilon}_{zz}^p, \dot{\epsilon}_{xy}^p, \dot{\epsilon}_{yz}^p, \dot{\epsilon}_{zx}^p) \text{ or } HIS_3$$

$$\text{entweder: } d_i = \int \dot{d}_i dt \quad \max(d_1, d_2, d_3) \leq 1$$

$$\text{oder: } \dot{d} = \sqrt{\left(\dot{d}_1^{ep}\right)^2 + \left(\dot{d}_2^{ep}\right)^2 + \left(\dot{d}_3^{ep}\right)^2} \dot{\epsilon}_p^2 \quad d = \int \dot{d} dt \leq 1$$

Koordinatensysteme (im ESZ)

- Elementkoordinatensystem: a-b
- Materialrichtung=Walzrichtung= x-y
- Hauptdehnungen: 1-2



$$\begin{pmatrix} \dot{\varepsilon}_{xx}^p & \dot{\varepsilon}_{xy}^p & \dot{\varepsilon}_{yy}^p \end{pmatrix} \Rightarrow \begin{pmatrix} \dot{\varepsilon}_1^p & b = \frac{\dot{\varepsilon}_2^p}{\dot{\varepsilon}_1^p} & g \end{pmatrix}$$

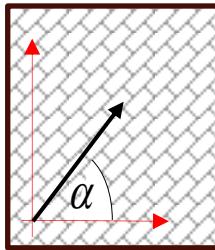
$$\begin{pmatrix} \dot{\varepsilon}_{xx}^p & \dot{\varepsilon}_{xy}^p \\ \dot{\varepsilon}_{xy}^p & \dot{\varepsilon}_{yy}^p \end{pmatrix} = \dot{\varepsilon}_1^p \begin{pmatrix} \cos^2 g + b \sin^2 g & (1-b)\sin g \cos g \\ (1-b)\sin g \cos g & \sin^2 g + b \cos^2 g \end{pmatrix}$$

$$\begin{pmatrix} \dot{\varepsilon}_{xx}^p & \dot{\varepsilon}_{xy}^p \\ \dot{\varepsilon}_{xy}^p & \dot{\varepsilon}_{yy}^p \end{pmatrix} = \dot{\varepsilon}_{00}^p \begin{pmatrix} 1 & 0 \\ 0 & b \end{pmatrix} + \dot{\varepsilon}_{90}^p \begin{pmatrix} b & 0 \\ 0 & 1 \end{pmatrix} + \frac{\dot{\varepsilon}_{45}^p}{2} \begin{pmatrix} 1+b & 1-b \\ 1-b & 1+b \\ 1+b & b-1 \\ b-1 & 1+b \end{pmatrix}$$

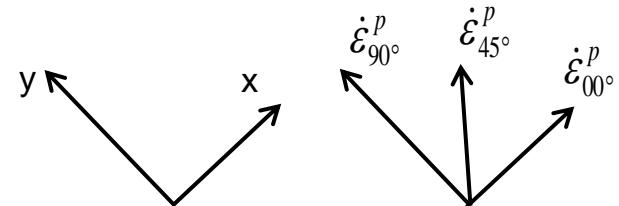
$$\dot{\varepsilon}_{45}^{ep} = 2 \left| \dot{\varepsilon}_{45}^p \right| \sqrt{\frac{1}{3} (1+b^2+b)} = 2 \left| \dot{\varepsilon}_1^p \right| 2 |\cos g \sin g| \sqrt{\frac{1}{3} (1+b^2+b)}$$

$$\dot{\varepsilon}_{90}^{ep} = 2 \left| \dot{\varepsilon}_{90}^p \right| \sqrt{\frac{1}{3} (1+b^2+b)} = 2 \left| \dot{\varepsilon}_1^p \right| (\sin^2 g - |\cos g \sin g|) \sqrt{\frac{1}{3} (1+b^2+b)}$$

$$\dot{\varepsilon}_{00}^{ep} = 2 \left| \dot{\varepsilon}_{00}^p \right| \sqrt{\frac{1}{3} (1+b^2+b)} = 2 \left| \dot{\varepsilon}_1^p \right| (\cos^2 g - |\cos g \sin g|) \sqrt{\frac{1}{3} (1+b^2+b)}$$



Schädigungsakkumulation im materiellen KOS:



$$\dot{d}_{00} = n d_{00}^{1-\frac{1}{n}} \frac{\dot{\varepsilon}_{00}^{ep}}{\varepsilon_{00}^f} \quad d_{00} = \int \dot{d}_{00} dt$$

$$\dot{d}_{90} = n d_{90}^{1-\frac{1}{n}} \frac{\dot{\varepsilon}_{90}^{ep}}{\varepsilon_{90}^f} \quad d_{90} = \int \dot{d}_{90} dt$$

$$\dot{d}_{45} = n d_{45}^{1-\frac{1}{n}} \frac{\dot{\varepsilon}_{45}^{ep}}{\varepsilon_{45}^f} \quad d_{45} = \int \dot{d}_{45} dt$$

$$\Delta d = \sqrt{\frac{\Delta d_{45}^2 + \Delta d_{00}^2 + \Delta d_{90}^2}{(\dot{\varepsilon}_{45}^{ep})^2 + (\dot{\varepsilon}_{00}^{ep})^2 + (\dot{\varepsilon}_{90}^{ep})^2}} \dot{\varepsilon}_p^2 \quad d = \int \Delta d \leq 1$$

Orthotropic/Isotropic Plasticity with orthotropic damage

Special case! [DuBois, Erhart, Haufe, Feucht]

Plastizität

$$\dot{\sigma}_{eff} = C(\dot{\epsilon} - \dot{\epsilon}_p)$$

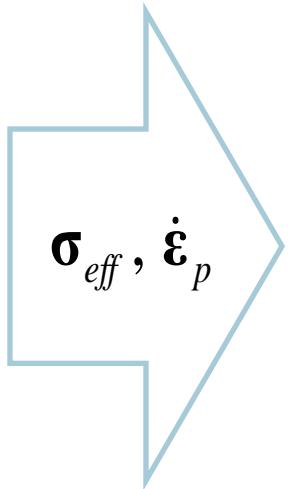
$$\dot{\epsilon}_p = \lambda \frac{\partial g(\sigma_{eff})}{\partial \sigma_{eff}}$$

$$\dot{q} = \lambda \frac{\partial q}{\partial \lambda}$$

$$f(\sigma_{eff}, q) \leq 0, \quad \lambda \geq 0$$

$$f(\sigma_{eff}) = Mises / Barlat...$$

$$g(\sigma_{eff}) = f(\sigma_{eff})$$



Damage

$$\sigma = M\sigma_{eff} \Rightarrow \begin{pmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz}=0 \\ \sigma_{xy} \\ \sigma_{yz} \\ \sigma_{zx} \end{pmatrix} = \begin{pmatrix} 1-d_{00} & 0 & 0 & 0 & 0 & 0 \\ 0 & 1-d_{90} & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1-d_{45} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \sigma_{xx}^{eff} \\ \sigma_{yy}^{eff} \\ \sigma_{zz}^{eff}=0 \\ \sigma_{xy}^{eff} \\ \sigma_{yz}^{eff} \\ \sigma_{zx}^{eff} \end{pmatrix}$$

$$\dot{d} = F(\dot{\epsilon}^p, \theta) \dot{\epsilon}^p :$$

$$\dot{d}_{00} = n d_{00}^{1-\frac{1}{n}} \frac{\dot{\epsilon}_{00}^{ep}}{\dot{\epsilon}_1^f(\eta, \theta)} \quad \dot{\epsilon}_{00}^{ep} = \sqrt{\frac{2}{3} \dot{\epsilon}_{00}^{ep} \cdot \dot{\epsilon}_{00}^{ep}} = 2 |\dot{\epsilon}_1^p \langle \cos^2 \theta - |\cos \theta \sin \theta| \rangle| \sqrt{\frac{1}{3} (1+b^2+b)}$$

$$\dot{d}_{90} = n d_{90}^{1-\frac{1}{n}} \frac{\dot{\epsilon}_{90}^{ep}}{\dot{\epsilon}_2^f(\eta, \theta)} \quad \dot{\epsilon}_{90}^{ep} = \sqrt{\frac{2}{3} \dot{\epsilon}_{90}^{ep} \cdot \dot{\epsilon}_{90}^{ep}} = 2 |\dot{\epsilon}_1^p \langle \sin^2 \theta - |\cos \theta \sin \theta| \rangle| \sqrt{\frac{1}{3} (1+b^2+b)}$$

$$\dot{d}_{45} = n d_{45}^{1-\frac{1}{n}} \frac{\dot{\epsilon}_{45}^{ep}}{\dot{\epsilon}_3^f(\eta, \theta)} \quad \dot{\epsilon}_{45}^{ep} = \sqrt{\frac{2}{3} \dot{\epsilon}_{45}^{ep} \cdot \dot{\epsilon}_{45}^{ep}} = 2 |\dot{\epsilon}_1^p \langle 2 \cos \theta \sin \theta \rangle| \sqrt{\frac{1}{3} (1+b^2+b)}$$

$$d_i = \int \dot{d}_i dt \quad \max(d_1, d_2, d_3) \leq 1$$

Orthotropic plasticity with isotropic damage

Another special case! [Mohr model (Dunand et al. 2012: Part I+II)]

Plastizität (Barlat 2003: Yld2000-2d)

$$\dot{\sigma}_{eff} = C(\dot{\varepsilon} - \dot{\varepsilon}_p)$$

$$f(\sigma_{eff}) \leq 0, \lambda \geq 0$$

$$\dot{\varepsilon}_p = \lambda \frac{\partial g(\sigma_{eff})}{\partial \sigma_{eff}}$$

$$f(\sigma_{eff}) = \sigma_{Barlat}^{eq} - \sigma_Y$$

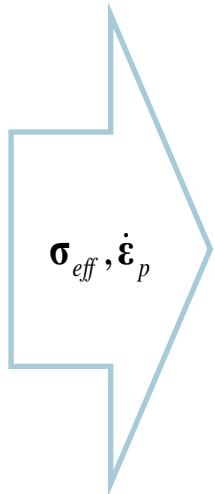
$$\sigma_{Barlat}^{eq} = \frac{1}{2a} \left(|S'_I - S''_I|^a + |2S''_H - S''_I|^a + |2S''_I - S''_H|^a + \right)^{1/a}$$

$$\sigma_Y = A(\varepsilon_0 + \varepsilon_p)^n$$

$$g(\sigma_{eff}) = f(\sigma_{eff})$$

Parameter: $A, \varepsilon_0, n, M, a_1, a_2, a_3, a_5, a_6, a_7, a_8$

„non associated fracture“



Damage (MMC + Dunand & Mohr)

$$\sigma = (1-d)\sigma_{eff}$$

$$\dot{d} = \frac{\dot{\varepsilon}_p^{orthotropic}}{\varepsilon_{fail}(\eta, \vartheta_L)} \quad d = \int \dot{d} dt \leq 1$$

$$\dot{\varepsilon}_p^{orthotropic} = \sqrt{\frac{2}{3}(\varepsilon_{11}^2 + \beta_{22}\varepsilon_{22}^2 + \beta_{33}\varepsilon_{33}^2 + 2\beta_{12}\varepsilon_{12}^2)}$$

$$\varepsilon_{fail}(\eta, \vartheta_L) = \left\{ \frac{A}{c_2} \left[\frac{\sqrt{1+c_1^2}}{3} \cos\left(\frac{\vartheta_L \pi}{6}\right) + c_1 \left[\eta + \frac{1}{3} \sin\left(\frac{\vartheta_L \pi}{6}\right) \right] \right] \right\}^{-\frac{1}{n}}$$

Parameter: $c_1, c_2, c_3 = 0, \beta_{22}, \beta_{33}, \beta_{12}$

Orthotrope Schädigung im ESZ nach DuBois et al.

=> IFLG3=0

Gissmo 00°

$$\dot{\varepsilon}_{00}^{ep} = \sqrt{\frac{2}{3} \dot{\varepsilon}_{00}^{ep} : \dot{\varepsilon}_{00}^{ep}} = 2 |\dot{\varepsilon}_1^p \langle \cos^2 \vartheta - |\cos \vartheta \sin \vartheta| \rangle| \sqrt{\frac{1}{3} (1+b^2 + b)}$$

$$\dot{f}_{00} = n f_{00}^{1-n} \frac{\dot{\varepsilon}_{00}^{ep}}{\varepsilon_{00}^{crit}(\eta, \theta)} \quad f_{00} = \int \Delta f_{00} \leq 1 \Rightarrow d_{00}^{crit} = d_{00}$$

$$\dot{d}_{00} = n d_{00}^{1-n} \frac{\dot{\varepsilon}_{00}^{ep}}{\varepsilon_{00}^f(\eta, \theta, l_c, \dot{\varepsilon}_{00}^{ep})} \quad d_{00} = \int \Delta d_{00} \leq 1 \quad d_{00}^{eff} = \left(\frac{d_{00} - d_{00}^{crit}}{1 - d_{00}^{crit}} \right)^{FADEXP_{00}}$$

Gissmo 90°

$$\dot{\varepsilon}_{90}^{ep} = \sqrt{\frac{2}{3} \dot{\varepsilon}_{90}^{ep} : \dot{\varepsilon}_{90}^{ep}} = 2 |\dot{\varepsilon}_1^p \langle \sin^2 \vartheta - |\cos \vartheta \sin \vartheta| \rangle| \sqrt{\frac{1}{3} (1+b^2 + b)}$$

$$\dot{f}_{90} = n f_{90}^{1-n} \frac{\dot{\varepsilon}_{90}^{ep}}{\varepsilon_{90}^{crit}(\eta, \theta)} \quad f_{90} = \int \Delta f_{90} \leq 1 \Rightarrow d_{90}^{crit} = d_{90}$$

$$\dot{d}_{90} = n d_{90}^{1-n} \frac{\dot{\varepsilon}_{90}^{ep}}{\varepsilon_{90}^f(\eta, \theta, l_c, \dot{\varepsilon}_{90}^{ep})} \quad d_{90} = \int \Delta d_{90} \leq 1 \quad d_{90}^{eff} = \left(\frac{d_{90} - d_{90}^{crit}}{1 - d_{90}^{crit}} \right)^{FADEXP_{90}}$$

Gissmo 45°

$$\dot{\varepsilon}_{45}^{ep} = \sqrt{\frac{2}{3} \dot{\varepsilon}_{45}^{ep} : \dot{\varepsilon}_{45}^{ep}} = 2 |\dot{\varepsilon}_1^p \langle \cos \vartheta \sin \vartheta \rangle| \sqrt{\frac{1}{3} (1+b^2 + b)}$$

$$\dot{f}_{45} = n f_{45}^{1-n} \frac{\dot{\varepsilon}_{45}^{ep}}{\varepsilon_{45}^{crit}(\eta, \theta)} \quad f_{45} = \int \Delta f_{45} \leq 1 \Rightarrow d_{45}^{crit} = d_{45}$$

$$\dot{d}_{45} = n d_{45}^{1-n} \frac{\dot{\varepsilon}_{45}^{ep}}{\varepsilon_{45}^f(\eta, \theta, l_c, \dot{\varepsilon}_{45}^{ep})} \quad d_{45} = \int \Delta d_{45} \leq 1 \quad d_{45}^{eff} = \left(\frac{d_{45} - d_{45}^{crit}}{1 - d_{45}^{crit}} \right)^{FADEXP_{45}}$$

MAGD INPUT:

IFLG1 = 2: Damage driving quantities are plastic strain rates

IFLG2 = 1: Damage strain coordinate system is material system

IFLG3 = 0: Erosion occurs when one of the damage parameters reaches unity, the damage tensor components are based on the individual parameters d00,d90,d45

*DEFINE_FUNCTION: dam11 = 1 - d00

*DEFINE_FUNCTION: dam22 = 1 - d90

*DEFINE_FUNCTION: dam44 = 1 - d45

*DEFINE_FUNCTION: dam33 = dam55 = dam66 = 1

max(d₀₀^{eff}, d₉₀^{eff}, d₄₅^{eff}) ≤ 1

$$\sigma = M \sigma_{eff} \Rightarrow \begin{pmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} = 0 \\ \sigma_{xy} \\ \sigma_{yz} \\ \sigma_{zx} \end{pmatrix} = \begin{pmatrix} 1 - d_{00}^{eff} & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 - d_{90}^{eff} & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 - d_{45}^{eff} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \sigma_{xx}^{eff} \\ \sigma_{yy}^{eff} \\ \sigma_{zz}^{eff} = 0 \\ \sigma_{xy}^{eff} \\ \sigma_{yz}^{eff} \\ \sigma_{zx}^{eff} \end{pmatrix}$$

Orthotrope Schädigung im ESZ nach DuBois et al.

=> IFLG3=1

Gissmo 00°

$$\dot{\varepsilon}_{00}^{ep} = \sqrt{\frac{2}{3} \dot{\varepsilon}_{00}^{ep} : \dot{\varepsilon}_{00}^{ep}} = 2 |\dot{\varepsilon}_1^p \langle \cos^2 \vartheta - |\cos \vartheta \sin \vartheta| \rangle| \sqrt{\frac{1}{3} (1+b^2 + b)}$$

$$\dot{f}_{00} = n f_{00}^{1-\frac{1}{n}} \frac{\dot{\varepsilon}_{00}^{ep}}{\varepsilon_{00}^{crit}(\eta, \theta)}$$

$$\dot{d}_{00} = n d_{00}^{1-\frac{1}{n}} \frac{\dot{\varepsilon}_{00}^{ep}}{\varepsilon_0^f(\eta, \theta, l_c, \dot{\varepsilon}_{00}^{ep})} \quad d_{00} = \int \Delta d_{00} \quad d_{00}^{eff} = \left(\frac{d - d_{crit}}{1 - d_{crit}} \right)^{FADEXP_{00}}$$

Gissmo 90°

$$\dot{\varepsilon}_{90}^{ep} = \sqrt{\frac{2}{3} \dot{\varepsilon}_{90}^{ep} : \dot{\varepsilon}_{90}^{ep}} = 2 |\dot{\varepsilon}_1^p \langle \sin^2 \vartheta - |\cos \vartheta \sin \vartheta| \rangle| \sqrt{\frac{1}{3} (1+b^2 + b)}$$

$$\dot{f}_{90} = n f_{90}^{1-\frac{1}{n}} \frac{\dot{\varepsilon}_{90}^{ep}}{\varepsilon_{90}^{crit}(\eta, \theta)}$$

$$\dot{d}_{90} = n d_{90}^{1-\frac{1}{n}} \frac{\dot{\varepsilon}_{90}^{ep}}{\varepsilon_0^f(\eta, \theta, l_c, \dot{\varepsilon}_{90}^{ep})} \quad d_{90} = \int \Delta d_{90} \quad d_{90}^{eff} = \left(\frac{d - d_{crit}}{1 - d_{crit}} \right)^{FADEXP_{90}}$$

Gissmo 45°

$$\dot{\varepsilon}_{45}^{ep} = \sqrt{\frac{2}{3} \dot{\varepsilon}_{45}^{ep} : \dot{\varepsilon}_{45}^{ep}} = 2 |\dot{\varepsilon}_1^p \langle \cos \vartheta \sin \vartheta \rangle| \sqrt{\frac{1}{3} (1+b^2 + b)}$$

$$\dot{f}_{45} = n f_{45}^{1-\frac{1}{n}} \frac{\dot{\varepsilon}_{45}^{ep}}{\varepsilon_{45}^{crit}(\eta, \theta)}$$

$$\dot{d}_{45} = n d_{45}^{1-\frac{1}{n}} \frac{\dot{\varepsilon}_{45}^{ep}}{\varepsilon_0^f(\eta, \theta, l_c, \dot{\varepsilon}_{45}^{ep})} \quad d_{45} = \int \Delta d_{45} \quad d_{45}^{eff} = \left(\frac{d - d_{crit}}{1 - d_{crit}} \right)^{FADEXP_{45}}$$

MAGD INPUT:

IFLG1 = 2: Damage driving quantities are plastic strain rates

IFLG2 = 1: Damage strain coordinate system is material system

IFLG3 = 1: Erosion occurs when a single damage parameter reaches unity, the damage components are based on this single damage parameter.

*DEFINE_FUNCTION: dam11 = 1-d00

*DEFINE_FUNCTION: dam22 = 1-d90

*DEFINE_FUNCTION: dam44 = 1-d45

*DEFINE_FUNCTION: dam33 = dam55 = dam66 = 1

$$\Rightarrow \dot{f} = \sqrt{\frac{\dot{f}_{00}^2 + \dot{f}_{90}^2 + \dot{f}_{45}^2}{(\dot{\varepsilon}_{00}^{ep})^2 + (\dot{\varepsilon}_{90}^{ep})^2 + (\dot{\varepsilon}_{45}^{ep})^2}} \dot{\varepsilon}_p^2 \quad f = \int \dot{f} dt \leq 1 \Rightarrow d_{crit} = d$$

$$\Rightarrow \dot{d}_{eff} = \sqrt{\frac{\dot{d}_{00}^{eff,2} + \dot{d}_{90}^{eff,2} + \dot{d}_{45}^{eff,2}}{(\dot{\varepsilon}_{00}^{ep})^2 + (\dot{\varepsilon}_{90}^{ep})^2 + (\dot{\varepsilon}_{45}^{ep})^2}} \dot{\varepsilon}_p^2 \quad d_{eff} = \int \dot{d}_{eff} dt \leq 1$$

$$\sigma = \mathbf{M} \sigma_{eff} \Rightarrow \begin{pmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} = 0 \\ \sigma_{xy} \\ \sigma_{yz} \\ \sigma_{zx} \end{pmatrix} = \begin{pmatrix} 1 - d_{00}^{eff} & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 - d_{90}^{eff} & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 - d_{45}^{eff} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \sigma_{xx}^{eff} \\ \sigma_{yy}^{eff} \\ \sigma_{zz}^{eff} = 0 \\ \sigma_{xy}^{eff} \\ \sigma_{yz}^{eff} \\ \sigma_{zx}^{eff} \end{pmatrix}$$

Isotrope Schädigung im ESZ

=> PDDT=2:

2-parameter isotropic damage tensor for volumetric/deviatoric split.

Gissmo 1:

Deviatoric strain components.
→ HISV1

Gissmo 2:

Volumetric strain components.
→ HISV2

MAGD INPUT:

IFLG1 = 0: Rates of history variables HISn.

IFLG2 = 0: Local element system (shells) or global system (solids).

IFLG3 = 1: Erosion occurs when one of the damage parameters computed reaches unity, the damage tensor components are based on the individual damage parameters d1 to d3.

$$\begin{aligned} \rightarrow \dot{d}_1 &= n_1 d_1^{1-\frac{1}{n_1}} \frac{\dot{\varepsilon}_1^{\text{eq}}}{\varepsilon_1^f(\eta, \theta)} & \dot{\varepsilon}_1^{\text{eq}} &= \dot{HIS}_1 \\ \rightarrow \dot{d}_2 &= n_2 d_2^{1-\frac{1}{n_2}} \frac{\dot{\varepsilon}_2^{\text{eq}}}{\varepsilon_2^f(\eta, \theta)} & \dot{\varepsilon}_2^{\text{eq}} &= \cdot \dot{HIS}_2 \end{aligned}$$

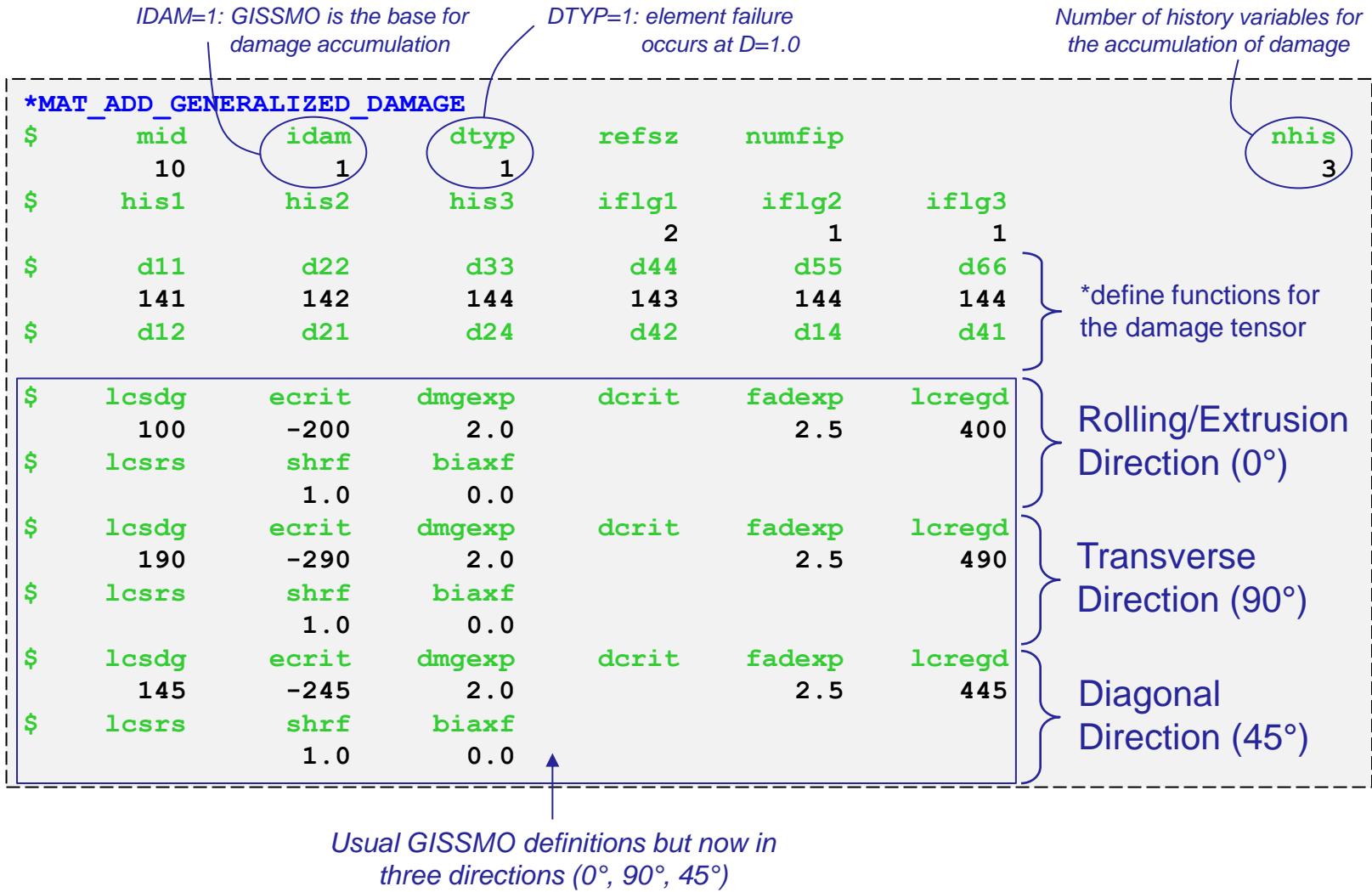
$$\sigma = \mathbf{M} \boldsymbol{\sigma}_{\text{eff}} \quad \mathbf{M} = \begin{bmatrix} 1 - \frac{2}{3}D_1 - \frac{1}{3}D_2 & \frac{1}{3}D_1 - \frac{1}{3}D_2 & \frac{1}{3}D_1 - \frac{1}{3}D_2 & 0 & 0 & 0 \\ \frac{1}{3}D_1 - \frac{1}{3}D_2 & 1 - \frac{2}{3}D_1 - \frac{1}{3}D_2 & \frac{1}{3}D_1 - \frac{1}{3}D_2 & 0 & 0 & 0 \\ \frac{1}{3}D_1 - \frac{1}{3}D_2 & \frac{1}{3}D_1 - \frac{1}{3}D_2 & 1 - \frac{2}{3}D_1 - \frac{1}{3}D_2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 - D_1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 - D_1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 - D_1 \end{bmatrix}$$

APPLICATION



Material modeling in LS-DYNA

Orthotropic damage through *MAT_ADD_GENERALIZED_DAMAGE

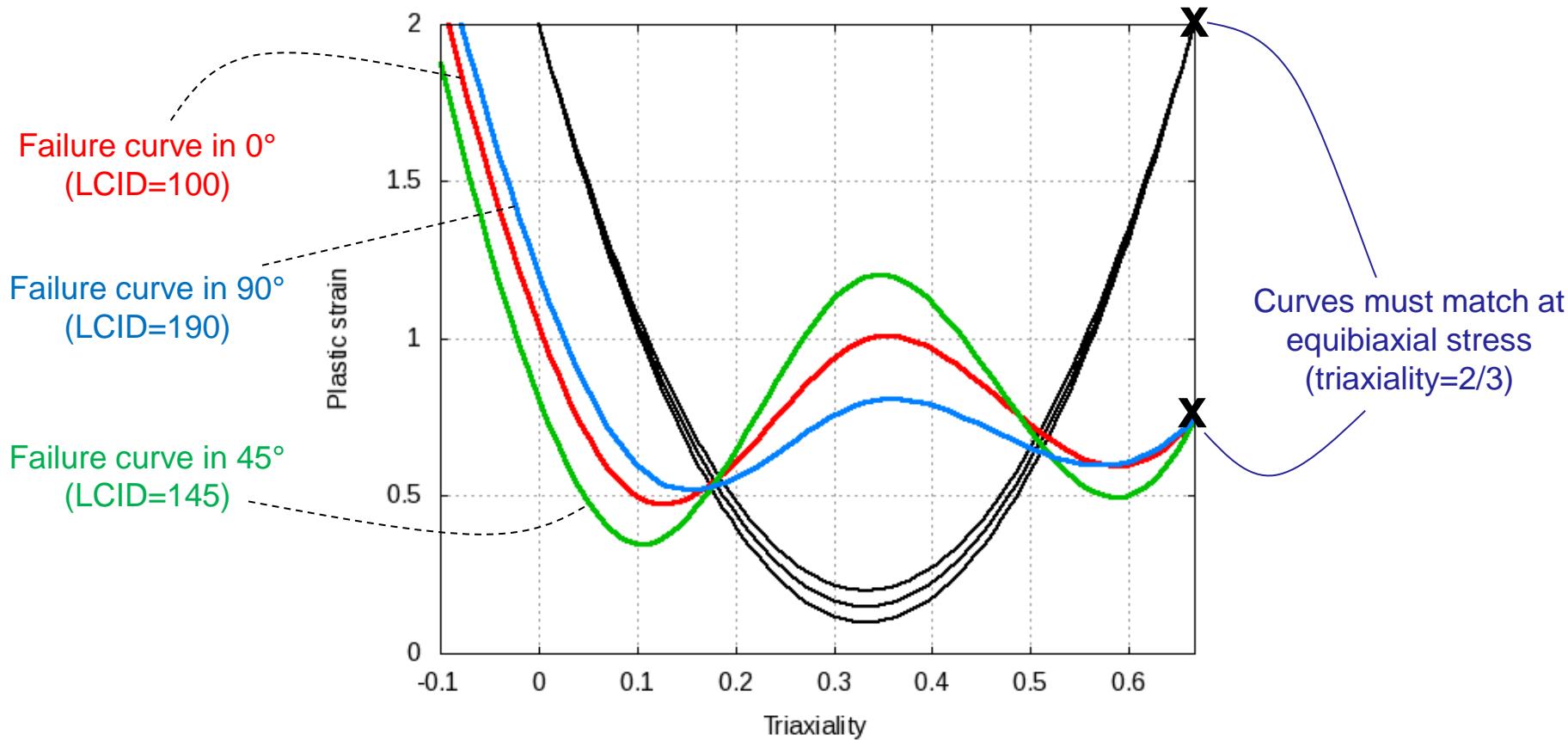




Material modeling in LS-DYNA

Orthotropic damage through *MAT_ADD_GENERALIZED_DAMAGE

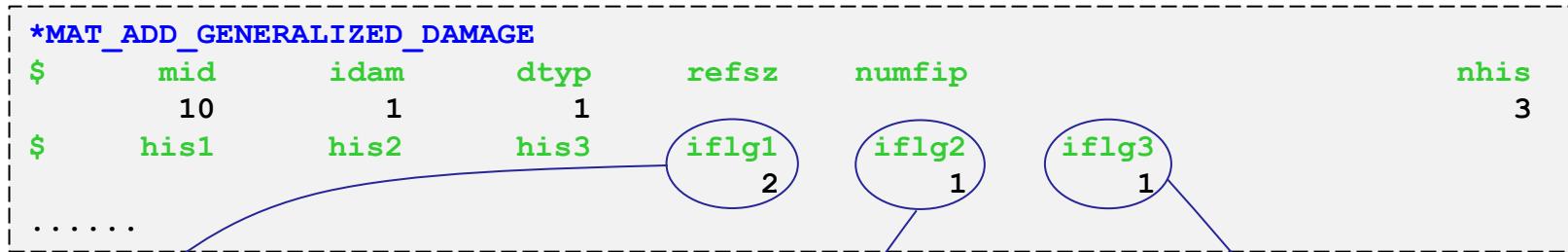
Example: The user can define three different instability (ECRIT) and failure (LCSDG) curves.
These curves can have any shape and even cross each other.



Material modeling in LS-DYNA

Orthotropic damage through *MAT_ADD_GENERALIZED_DAMAGE

*MAT_ADD_GENERALIZED_DAMAGE is very flexible and has many features embedded. For the simulation of orthotropic damage, we currently recommend the following configuration:



IFLG1=2: Predefined functions of plastic strain rate components for orthotropic damage.
IFLG2 should be set to 1.

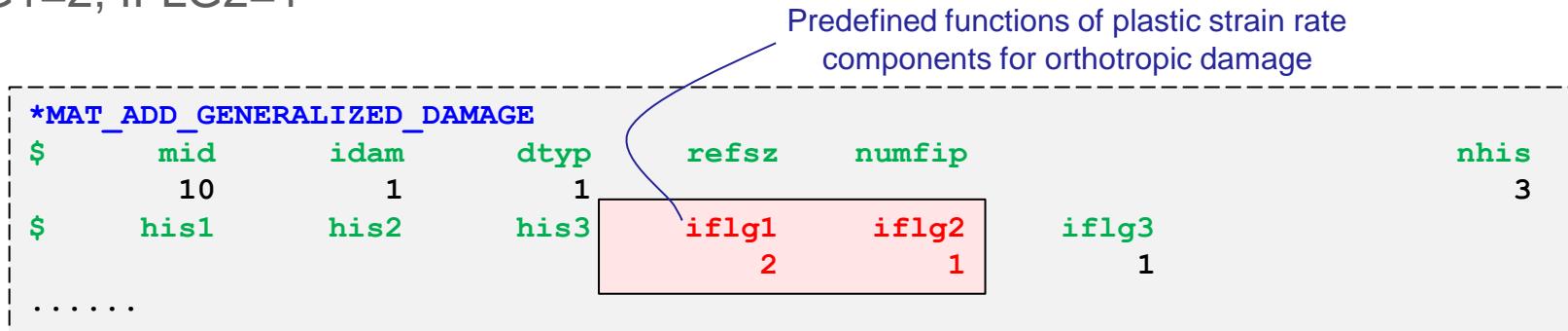
IFLG2=1: The coordinate system for the damage accumulation is the material system. It requires a non-isotropic material model with the AOPT feature

IFLG3=1: Erosion occurs when a single damage parameter D reaches unity. This single damage is also used in the damage tensor components for the coupling with the stress tensor

Material modeling in LS-DYNA

Orthotropic damage through *MAT_ADD_GENERALIZED_DAMAGE

IFLG1=2, IFLG2=1



Predefined functions

Instability

Damage

0°

$$\Delta \varepsilon_{00}^{ep} = 2 |\Delta \varepsilon_1^p| \langle \cos^2 \theta - |\cos \theta \sin \theta| \rangle \sqrt{\frac{1}{3} (1 + b + b^2)}$$

$$\Delta F_{00} = \frac{n_{00}}{\varepsilon_{00}^{crit}(\eta)} F_{00}^{\left(1 - \frac{1}{n_{00}}\right)} \Delta \varepsilon_{00}^{ep}$$

$$\Delta D_{00} = \frac{n_{00}}{\varepsilon_{00}^f(\eta)} D_{00}^{\left(1 - \frac{1}{n_{00}}\right)} \Delta \varepsilon_{00}^{ep}$$

90°

$$\Delta \varepsilon_{90}^{ep} = 2 |\Delta \varepsilon_1^p| \langle \sin^2 \theta - |\cos \theta \sin \theta| \rangle \sqrt{\frac{1}{3} (1 + b + b^2)}$$

$$\Delta F_{90} = \frac{n_{90}}{\varepsilon_{90}^{crit}(\eta)} F_{90}^{\left(1 - \frac{1}{n_{90}}\right)} \Delta \varepsilon_{90}^{ep}$$

$$\Delta D_{90} = \frac{n_{90}}{\varepsilon_{90}^f(\eta)} D_{90}^{\left(1 - \frac{1}{n_{90}}\right)} \Delta \varepsilon_{90}^{ep}$$

45°

$$\Delta \varepsilon_{45}^{ep} = 4 |\Delta \varepsilon_1^p| |\cos \theta \sin \theta| \sqrt{\frac{1}{3} (1 + b + b^2)}$$

$$\Delta F_{45} = \frac{n_{45}}{\varepsilon_{45}^{crit}(\eta)} F_{45}^{\left(1 - \frac{1}{n_{45}}\right)} \Delta \varepsilon_{45}^{ep}$$

$$\Delta D_{45} = \frac{n_{45}}{\varepsilon_{45}^f(\eta)} D_{45}^{\left(1 - \frac{1}{n_{45}}\right)} \Delta \varepsilon_{45}^{ep}$$

Material modeling in LS-DYNA

Orthotropic damage through *MAT_ADD_GENERALIZED_DAMAGE

Effect of IFLG3=1, plane stress (standard shell elements)

```
*MAT_ADD_GENERALIZED_DAMAGE
$      mid      idam      dtyp      refsz      numfip      nhis
      10          1          1
$      his1      his2      his3      iflg1      iflg2      iflg3
                  2          1          1
$      d11      d22      d33      d44      d55      d66
      141      142      144      143      144      144
$      d12      d21      d24      d42      d14      d41
.....
```

*define functions for
the damage tensor

```
*DEFINE_FUNCTION
 141
func141(d1,d2,d3)=1.0-d1
*DEFINE_FUNCTION
 142
func142(d1,d2,d3)=1.0-d2
*DEFINE_FUNCTION
 143
func143(d1,d2,d3)=1.0-d3
*DEFINE_FUNCTION
 144
func144(d1,d2,d3)=1.0
```

$$F_{n+1} = F_n + \sqrt{\frac{\Delta F_{00}^2 + \Delta F_{90}^2 + \Delta F_{45}^2}{(\Delta \varepsilon_{00}^{ep})^2 + (\Delta \varepsilon_{90}^{ep})^2 + (\Delta \varepsilon_{45}^{ep})^2}} \Delta \varepsilon_p^2$$

$$D_{n+1} = D_n + \sqrt{\frac{\Delta D_{00}^2 + \Delta D_{90}^2 + \Delta D_{45}^2}{(\Delta \varepsilon_{00}^{ep})^2 + (\Delta \varepsilon_{90}^{ep})^2 + (\Delta \varepsilon_{45}^{ep})^2}} \Delta \varepsilon_p^2$$

$$\begin{pmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \sigma_{xy} \\ \sigma_{yz} \\ \sigma_{zx} \end{pmatrix} = \begin{bmatrix} 1 - D & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 - D & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 - D & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{pmatrix} \sigma_{xx}^{eff} \\ \sigma_{yy}^{eff} \\ \sigma_{zz}^{eff} \\ \sigma_{xy}^{eff} \\ \sigma_{yz}^{eff} \\ \sigma_{zx}^{eff} \end{pmatrix}$$

*MAT_ADD_GENERALIZED_DAMAGE

Additional history variables (check in d3hsp)

e.g., *MAT_036

ND	9	Triaxiality variable, σ_m/σ_{vm}
ND+1	10	Lode parameter
ND+2	11	Single damage parameter D ($1.E-20 \leq D \leq 1$), IFLG3=1
ND+3	12	Damage parameter D1
ND+4	13	Damage parameter D2
ND+5	14	Damage parameter D3
ND+6	15	Damage threshold DCRIT1
ND+7	16	Damage threshold DCRIT2
ND+8	17	Damage threshold DCRIT3
ND+12	20	History variable HIS1
ND+13	21	History variable HIS2
ND+14	22	History variable HIS3
ND+15	23	Angle between principal and material axes (in radians)
ND+21	29	Characteristic element size (used in LCREG)



FICTITIOUS DATA

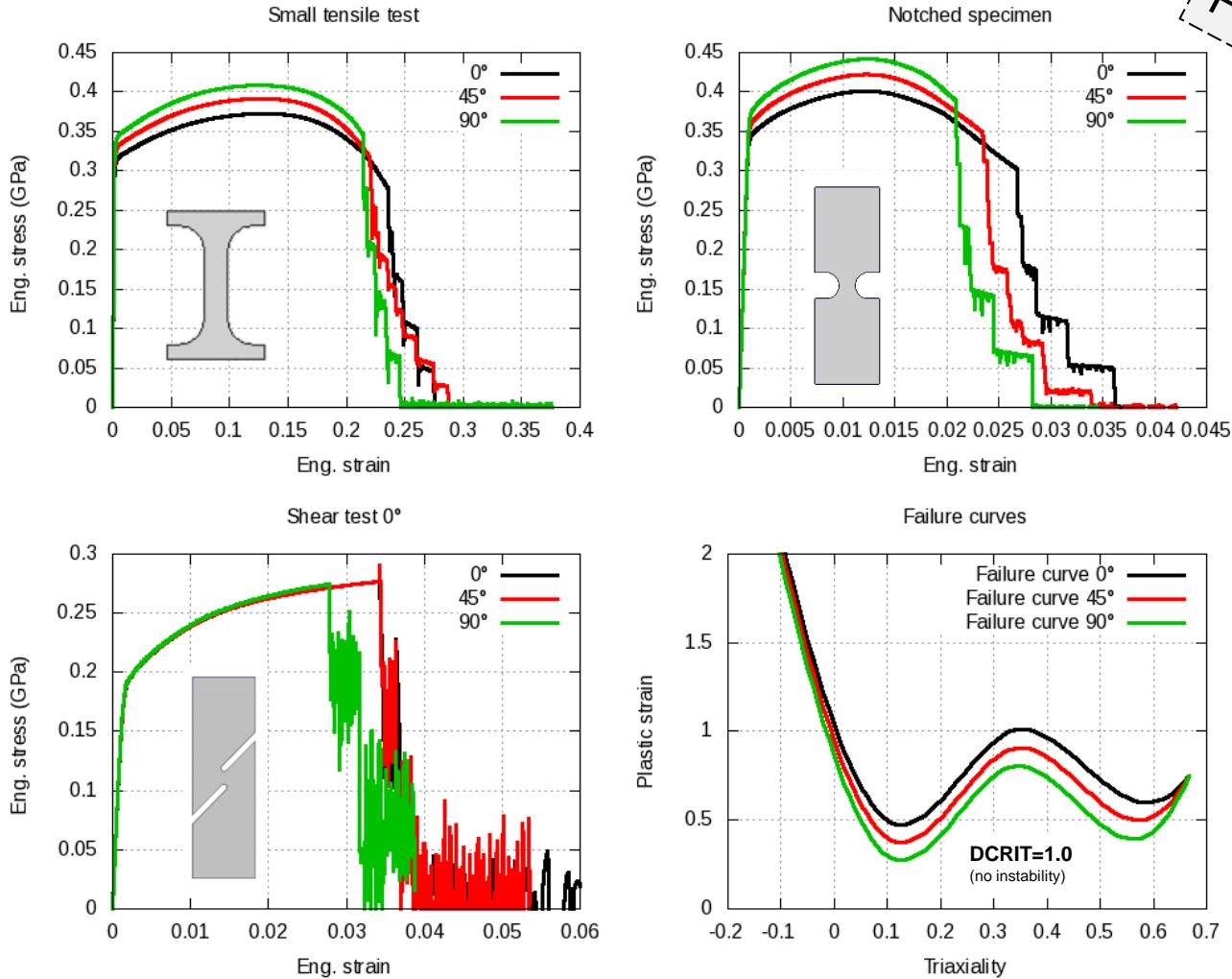
Aluminium

(orthotropic behaviour)

Material modeling in LS-DYNA

Anisotropic plasticity (*MAT_036, HR=7)

Anisotropic damage (*MAT_ADD_GENERALIZED_DAMAGE)

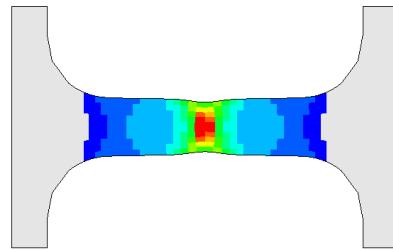
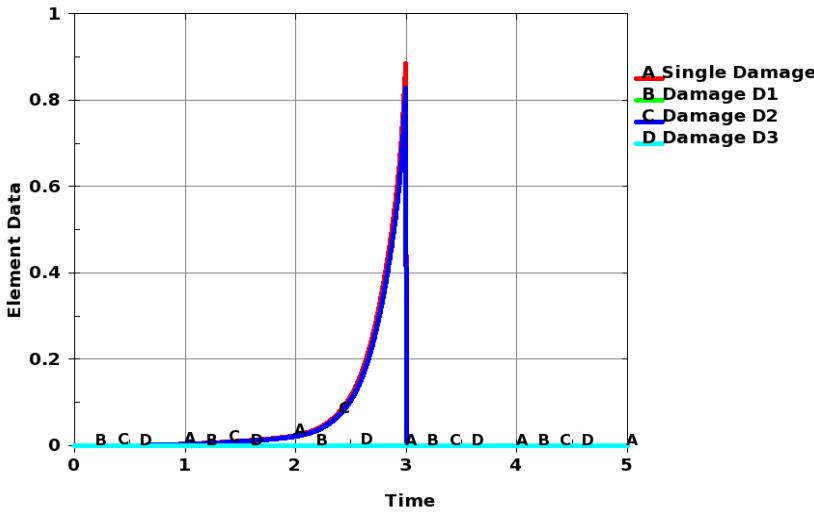


Material modeling in LS-DYNA

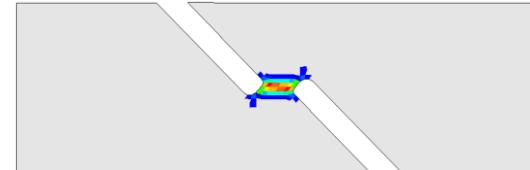
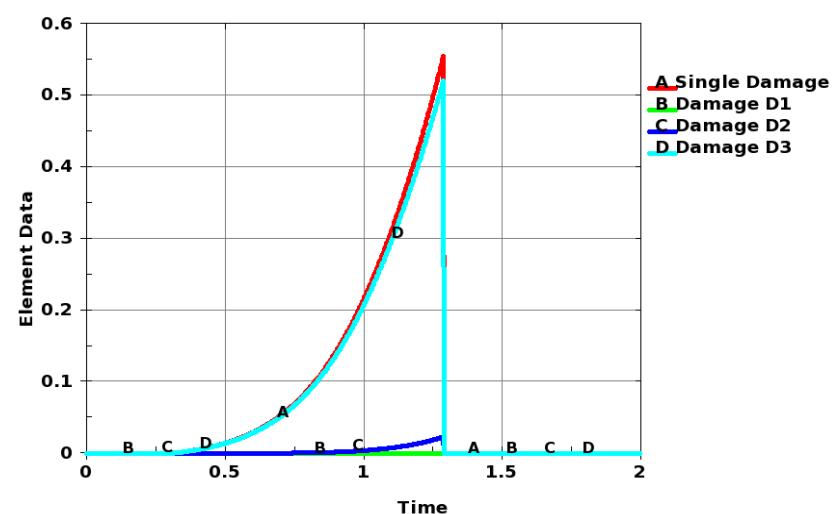
Evolution of damage in different directions

$$D_{n+1} = D_n + \sqrt{\frac{\Delta D_{00}^2 + \Delta D_{90}^2 + \Delta D_{45}^2}{(\Delta \varepsilon_{00}^{ep})^2 + (\Delta \varepsilon_{90}^{ep})^2 + (\Delta \varepsilon_{45}^{ep})^2} \Delta \varepsilon_p^2}$$

Tensile test in 90°

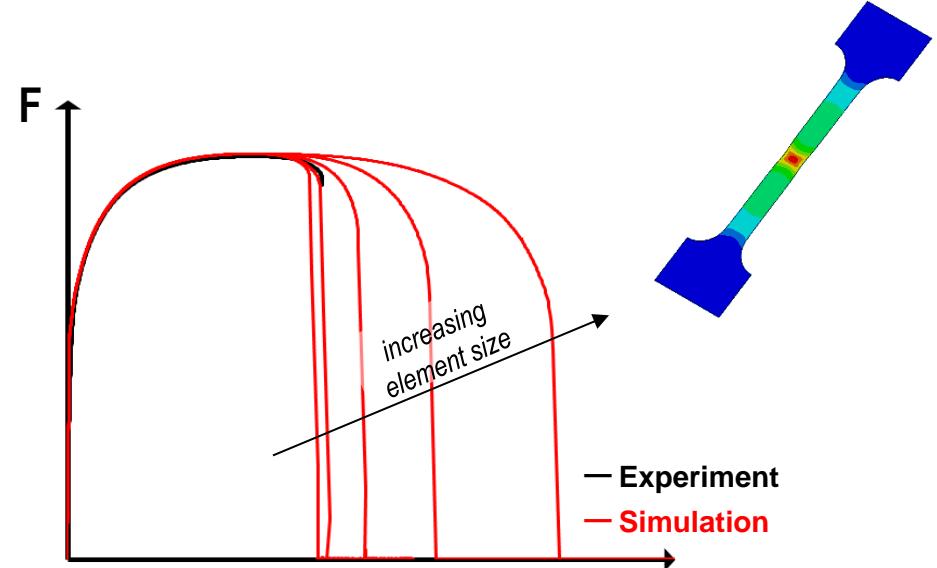
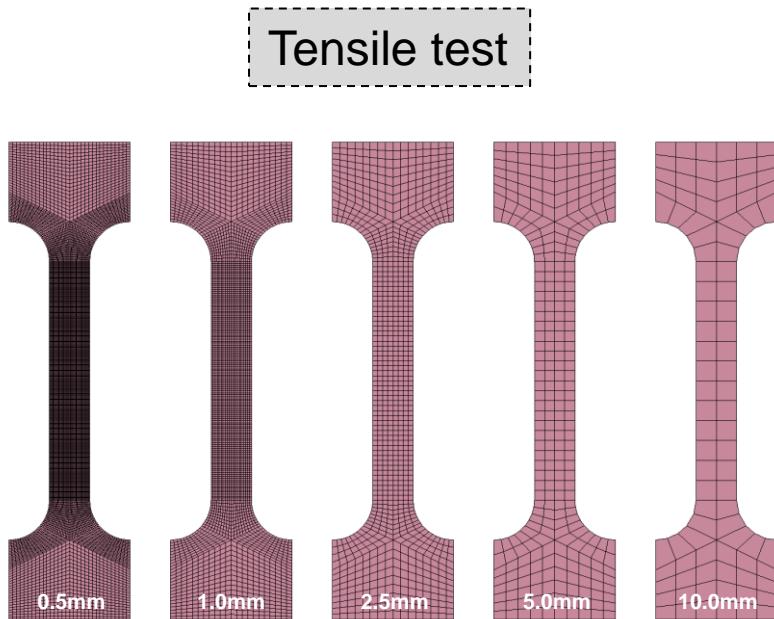


Shear test in 45°



Material modeling in LS-DYNA

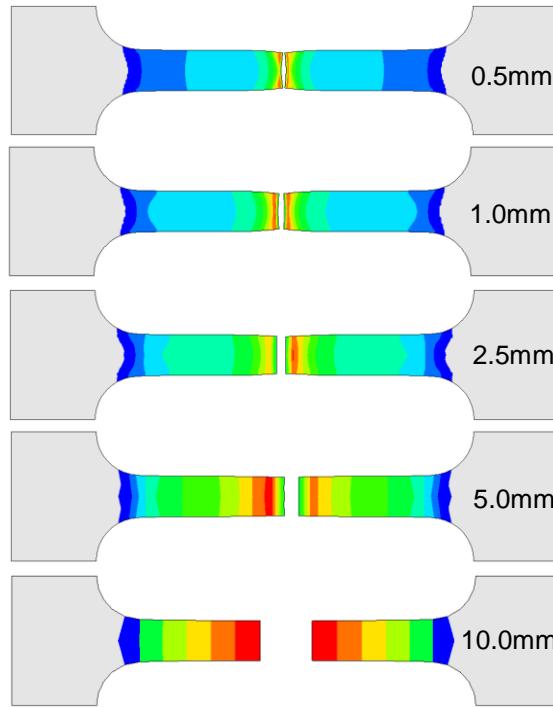
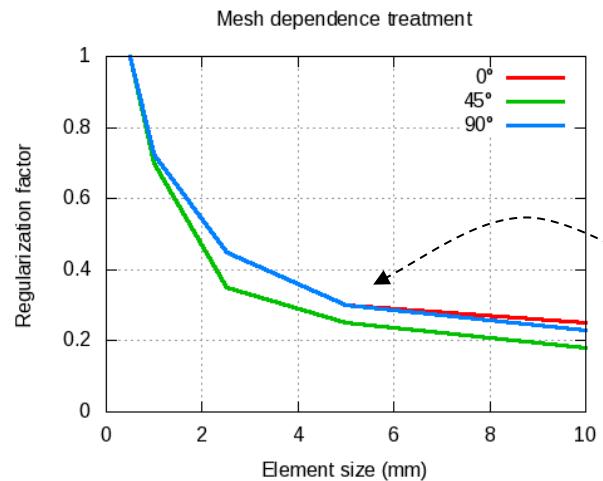
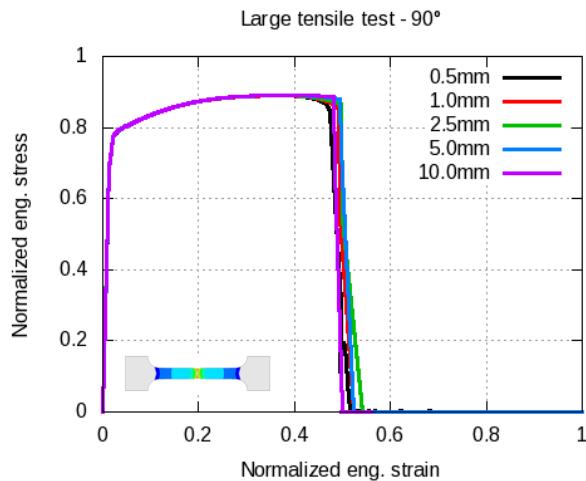
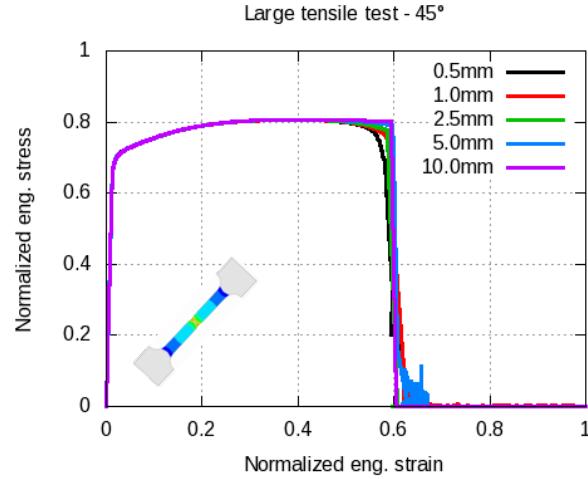
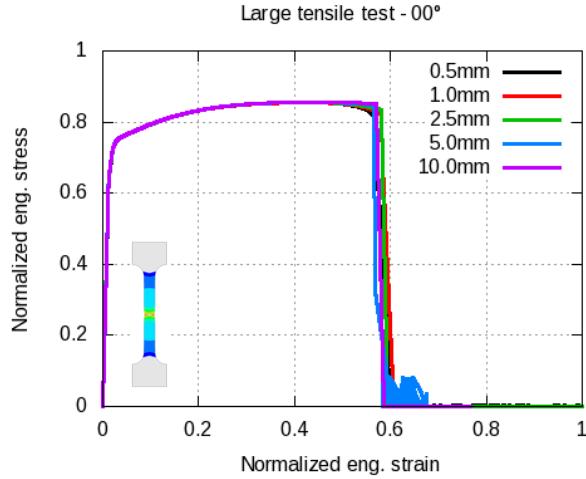
Spurious mesh dependence - if nothing is done to prevent these effects:



Material modeling in LS-DYNA

*MAT_036 + *MAT_ADD_GENERALIZED_DAMAGE

Treatment of the mesh dependence

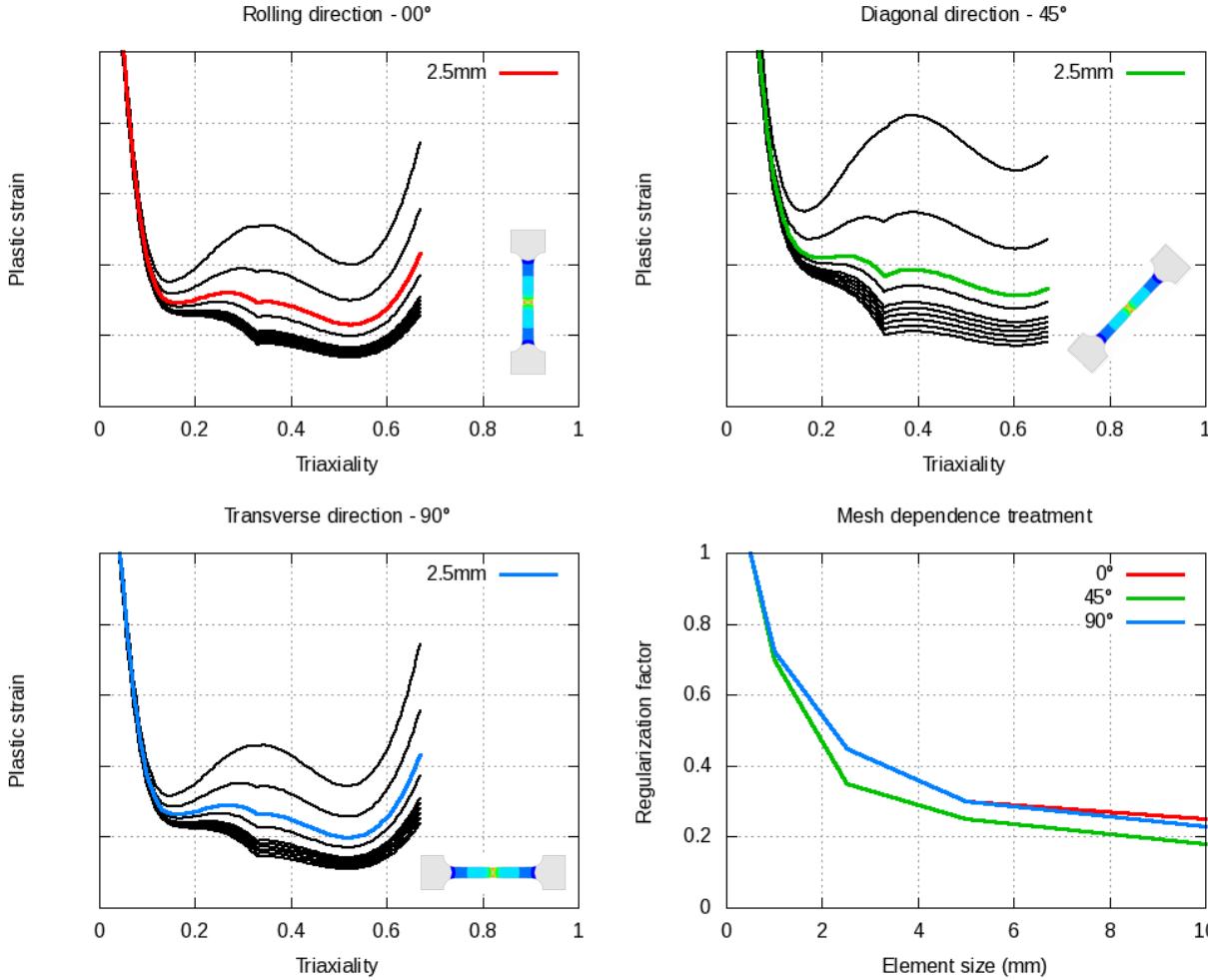


Regularization depends
on the orientation

Material modeling in LS-DYNA

*MAT_036 + *MAT_ADD_GENERALIZED_DAMAGE

Treatment of the mesh dependence – influence of the triaxiality



Regularization also depends on the stress state! The flags SHRF and BIAXF can be defined in different directions



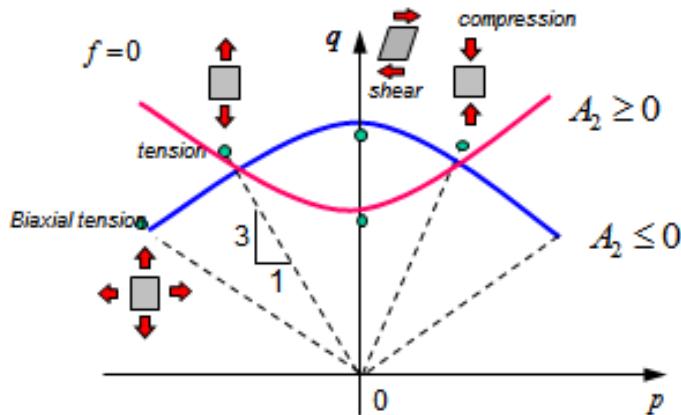
FICTITIOUS DATA

Polymere

(volumetric/deviatoric behaviour)

Material modeling in LS-DYNA

Isotropic plasticity with SAMP-1 (*MAT_187) including viscoelasticity if necessary

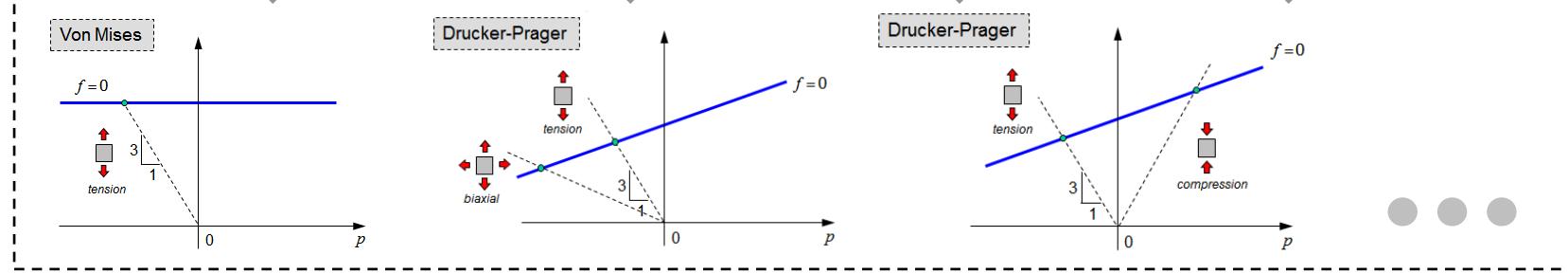
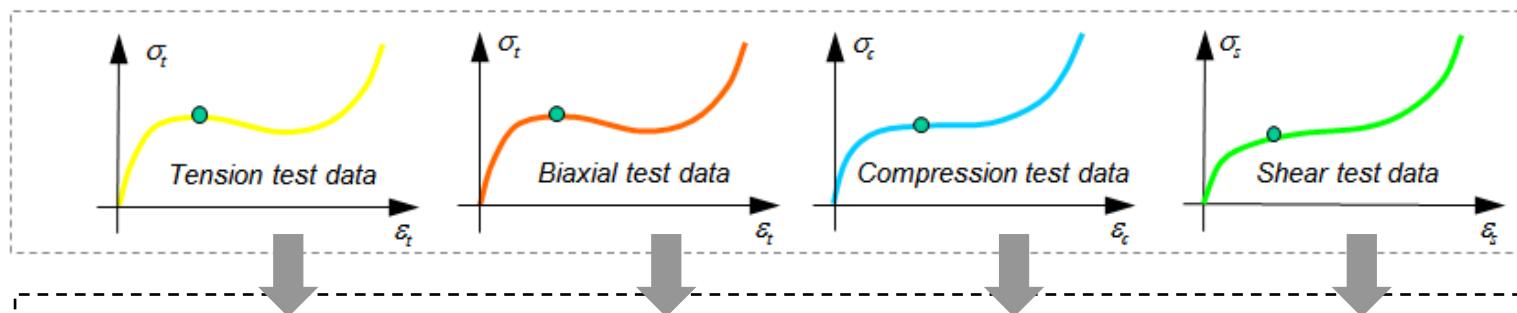


Yield surface:

$$f(p, \sigma_{vm}, \bar{\epsilon}^{pl}) = \sigma_{vm}^2 - A_0 - A_1 p - A_2 p^2 \leq 0$$

Condition for convexity :

$$A_2 \leq 0 \Leftrightarrow \sigma_s \geq \frac{\sqrt{\sigma_t \sigma_c}}{\sqrt{3}}$$



*MAT_ADD_GENERALIZED_DAMAGE

History variables (check in d3hsp) of constitutive plasticity model:

e.g., *MAT_187

- 1** tlam_o + dlam
- 2** Eqstrtc
- 3** Eqstrs
- 4** Eqstrb
- 5** Damage
- 6** Eqdc
- 7** Dfail
- 8** deps(1)
- 9** deps(2)
- 10** deps(3)
- 11** Eqdum
- 12** Eqsp
- 13** Triaxfadeinit
- 14** dacritf

Material modeling in LS-DYNA

Isotropic plasticity (*MAT_187)

Volumetric/deviatoric damage (*MAT_ADD_GENERALIZED_DAMAGE)

- SAMP has been used as plasticity model, calibrated for PC ABS
- eGISSMO in MAT_ADD_GENERALIZED_DAMAGE is used for damage with PDDT=2 and HISV1=0 (deviatoric straining) and HIS2=6 (volumetric straining)

```
*MAT_SAMP-1_TITLE
PC ABS
$      MID      RO      BULK      SHEAR      EMOD      NUE      RBCFAC
      1      1.0E-6      0.0      0.0      2.2      0.4      1      0
$      LCID_T    LCID_C    LCID_S    LCID_B    RNUEP    LCID_P    INCDAM
      100
$      LCID_D    EPFAIL   DEPRPT   LCID_TRI   LCID_LC
      0          0.0      0          0
$      MAXITER   MIPS      INCFAIL   ICONV     ASAFA    IPRINT   NHISV
      0          20       0          0          0       0.0
$-----1-----2-----3-----4-----5-----6-----7-----8
*MAT_ADD_GENERALIZED_DAMAGE
$      pid      idam    dmgtyp    refsz    numfip      PDDT      nhis
      1          1          1          1          1          2          2
$      his1      his2    his3      iflg1    iflg2    iflg3
      0          6          0          0          0          0
$      dam11     dam22    dam33    dam44    dam55    dam66
$      dam12     dam21    dam24    dam42    dam14    dam41
```

Material modeling in LS-DYNA

Isotropic plasticity (*MAT_187)

Volumetric/deviatoric damage (*MAT_ADD_GENERALIZED_DAMAGE)

- SAMP has been used as plasticity model, calibrated for PC ABS
- eGISSMO in MAT_ADD_GENERALIZED_DAMAGE is used for damage with PDDT=2 and HISV1=0 (deviatoric straining) and HIS2=6 (volumetric straining)

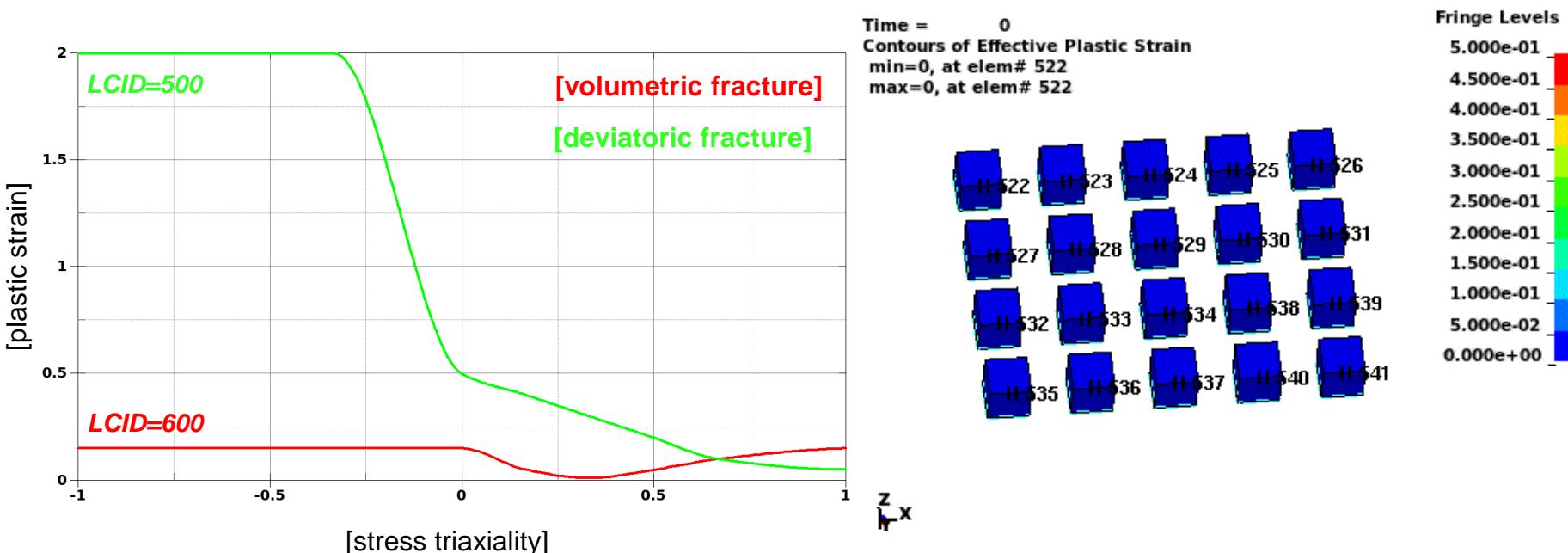
```
$ MAXITER      MIPS          INCFAIL      ICONV      ASAFT      IPRINT      NHISV
      0           20            0             0           0           0.0
$-----1-----2-----3-----4-----5-----6-----7-----8
*MAT_ADD_GENERALIZED_DAMAGE
$     pid      idam      dmgtyp      refsz      numfip
      1         1          1
$     his1      his2      his3      iflg1      iflg2      iflg3
      0         6
$     dam11     dam22     dam33     dam44     dam55     dam66
$     dam12     dam21     dam24     dam42     dam14     dam41
$     lcsdg     ecrit     dmgexp      dcrit      fadexp      lcregd
      500      -500       2.0
$     lcsrs     shrf      biaxf
$     lcsdg     ecrit     dmgexp      dcrit      fadexp      lcregd
      600      -600       2.0
$     lcsrs     shrf      biaxf
```

Material modeling in LS-DYNA

Isotropic plasticity (*MAT_187)

Volumetric/deviatoric damage (*MAT_ADD_GENERALIZED_DAMAGE)

- The classical multiaxial (numerical) test for one element has been modified for 3D elements
- SAMP has been used as plasticity model, calibrated for PC ABS
- eGISSMO in MAT_ADD_GENERALIZED_DAMAGE is used for damage with PDDT=2 and HISV1=0 (deviatoric straining) and HIS2=6 (volumetric straining)

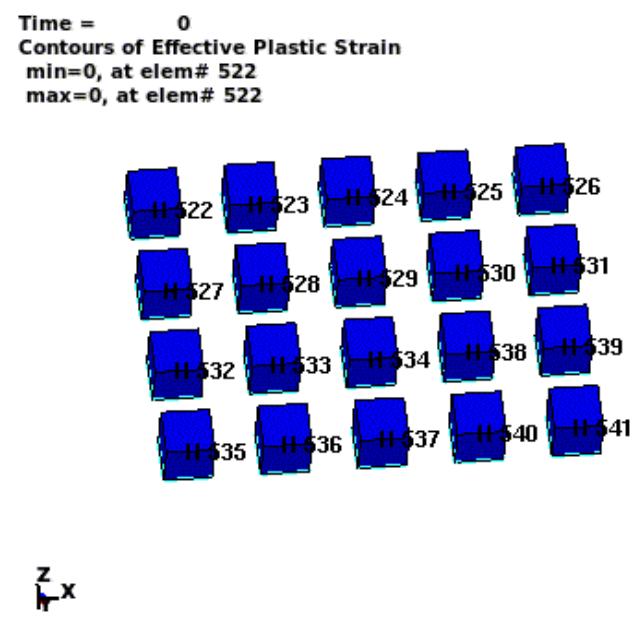
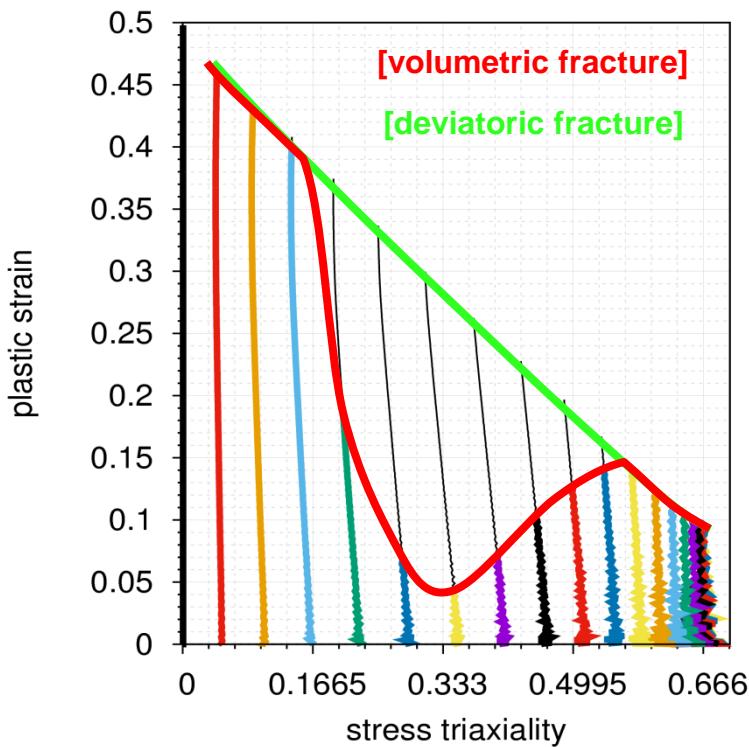


Material modeling in LS-DYNA

Isotropic plasticity (*MAT_187)

Volumetric/deviatoric damage (*MAT_ADD_GENERALIZED_DAMAGE)

- The classical multiaxial test for one element has been modified for 3D elements
- SAMP has been used as plasticity model
- eGISSMO in MAT_ADD_GENERALIZED_DAMAGE is used for damage with PDDT=2 and HISV1=0 (deviatoric straining) and HIS2=6 (volumetric straining)



Conclusions

Final remarks

- A new feature was implemented in **LS-DYNA version R9**
- *MAT_ADD_GENERALIZED_DAMAGE / eGISSMO is a highly flexible damage/failure model that can consider orthotropic damage but also damage due to different contributions (e.g., deviatoric and volumetric)
- In case of orthotropic damage, especial components of the plastic strain tensor are evaluated. These are the drivers for the damage accumulation in three material directions
- A reasonable description of orthotropic plasticity is crucial for accurate plastic strains and, therefore, for an accurate failure prediction
- *MAT_036's extended formulation (HR=7) seems to be a good choice for orthotropic elasto-plasticity but one should pay attention to the shape of the final yield surface
- *MAT_187 can be used with eGISSMO to split deviatoric and volumetric fracture behaviour (crazing). Larger applications on component level are on the way.

FIN