ON THE DEVELOPMENT OF THE NEW GENERALIZED ORTHOTROPIC DAMAGE AND FRACTURE MODEL eGISSMO

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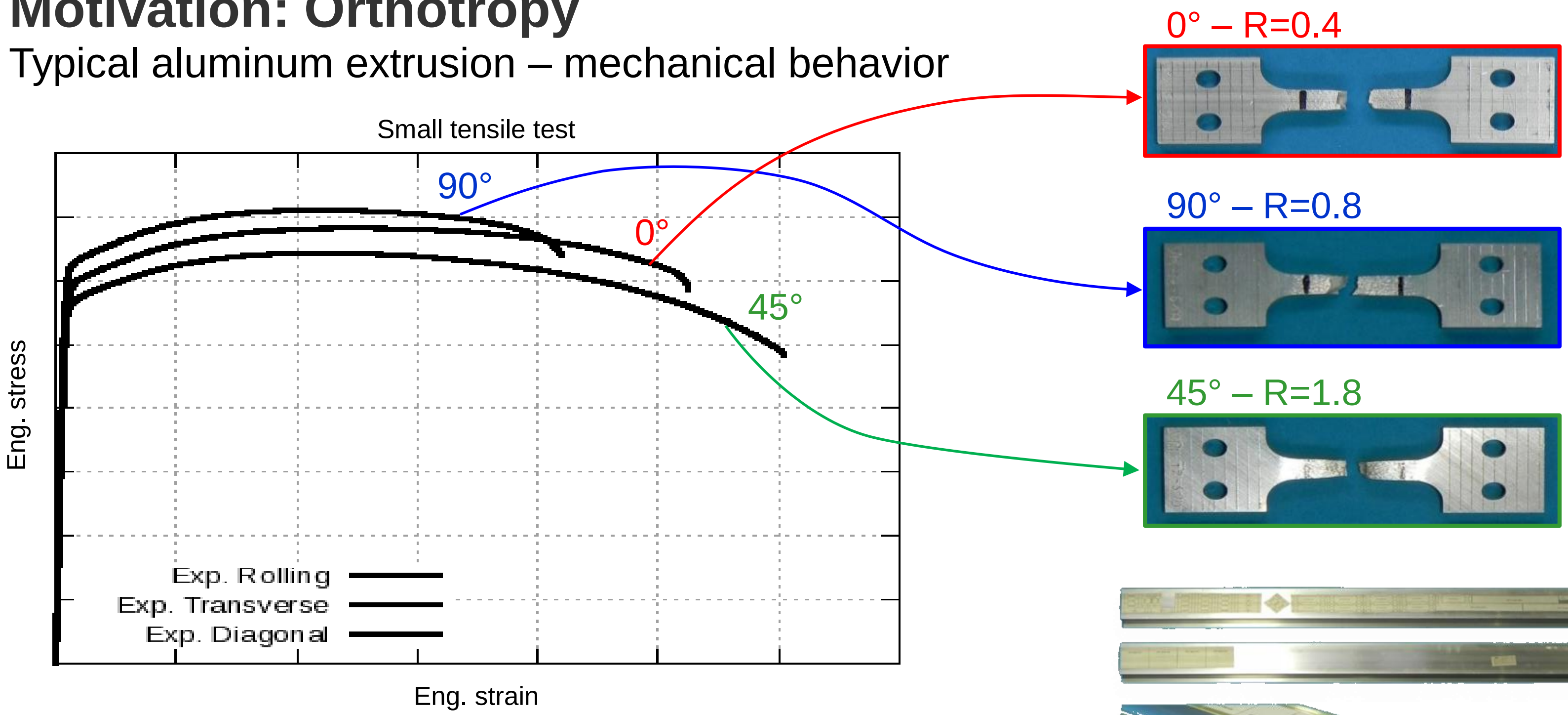
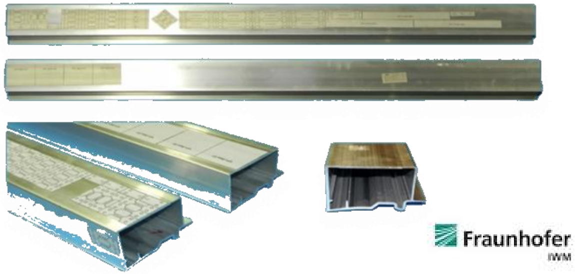
Motivation: Orthotropy

Typical aluminum extrusion – mechanical behavior





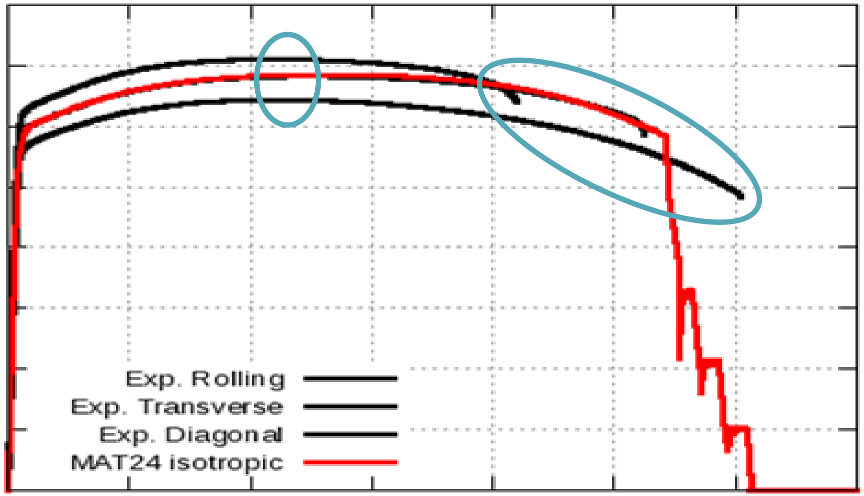
➢ Stress and failure can be direction-dependent

Motivation: Orthotropy

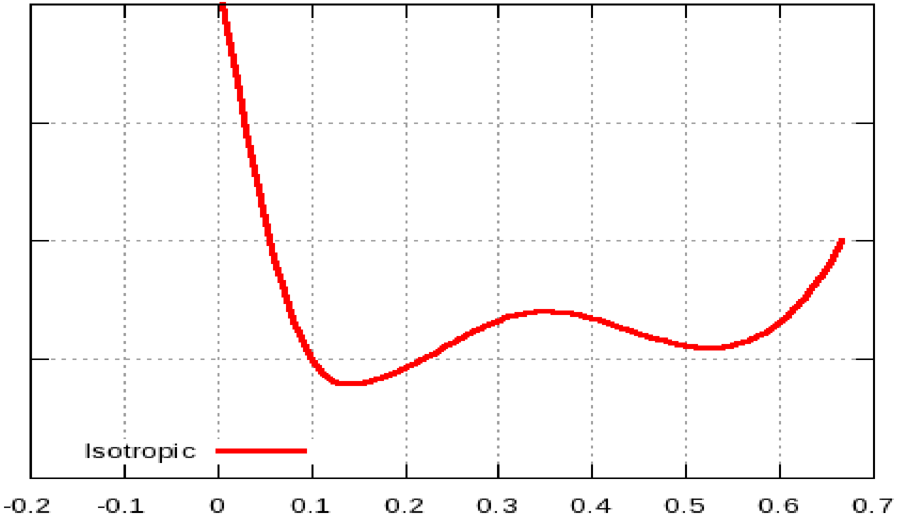
Limitations of isotropic material and failure models (e.g., ***MAT_024 + GISSMO**)

Small tensile test

Eng. stress



Eng. strain



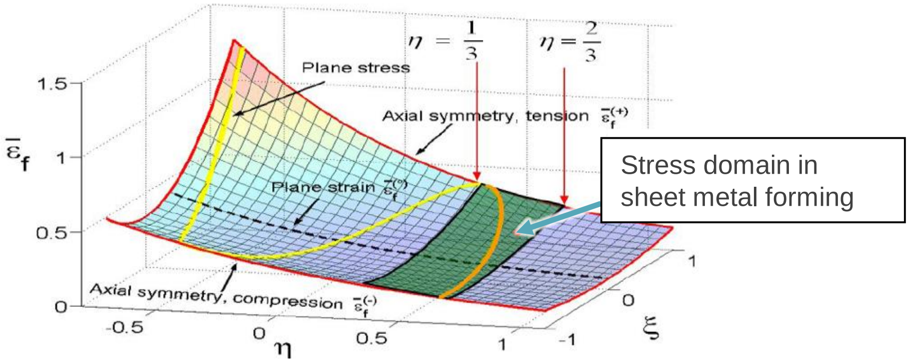
Triaxiality

- ➢ Different stress levels and fracture strains cannot be captured with isotropic plasticity and isotropic damage/failure models

Damage and failure with isotropic GISSMO

GISSMO

Failure criterion in planes stress and 3D stress states

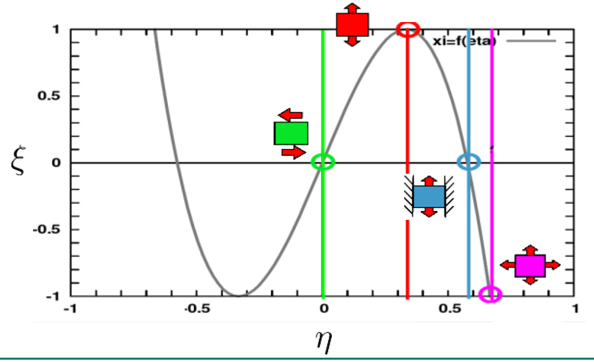


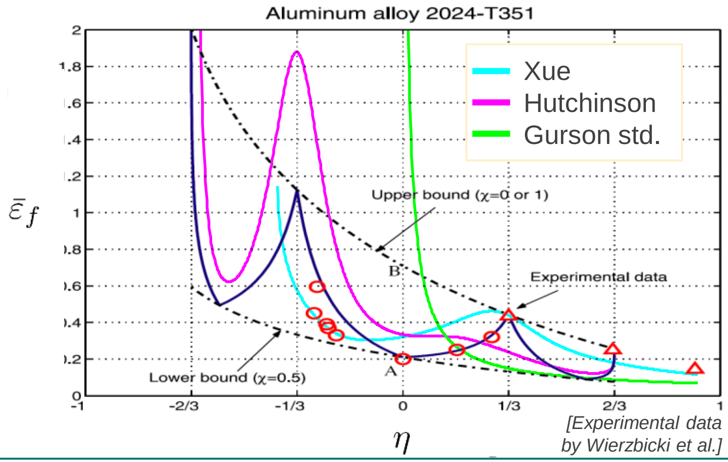
[Source: Wierzbicki et al.]

Parameter definition

$$\eta = \frac{\sigma_m}{\sigma_{vM}} = \frac{I_1}{\sigma_{vM}}$$

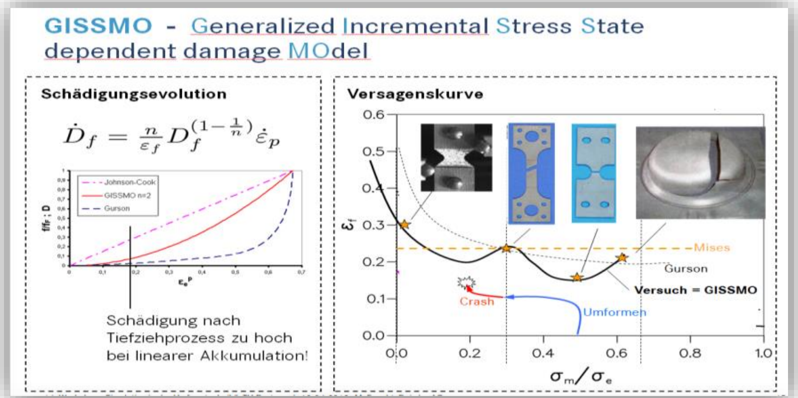
$$\xi = \frac{27}{2}\frac{J_3}{(\sigma_{vM})^3} \quad \text{with} \quad J_3 = s_1 s_2 s_3$$

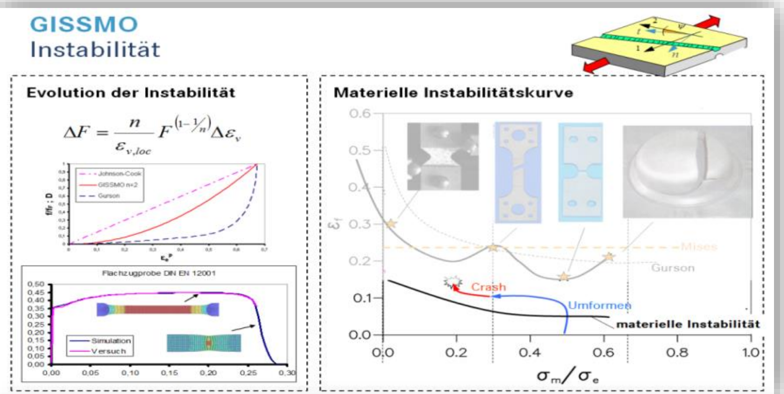


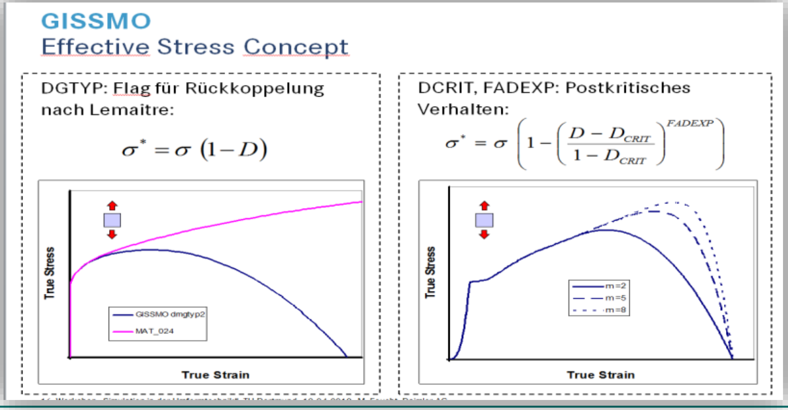


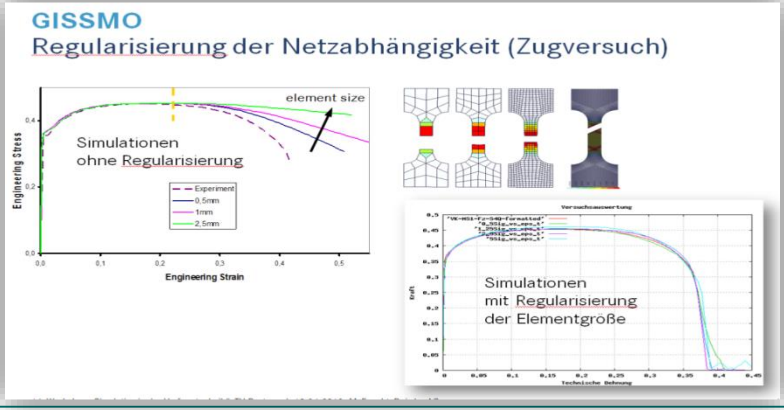
[Experimental data by Wierzbicki et al.]

GISSMO – A quick overview









Modular Concept

Plasticity model and isotropic damage model: GISSMO

Plasticity

$$\dot{\boldsymbol{\sigma}}^{\mathit{eff}} = \mathbf{C}(\dot{\boldsymbol{\varepsilon}} - \dot{\boldsymbol{\varepsilon}}_p)$$

$$\dot{\boldsymbol{\varepsilon}}_p = \dot{\lambda}\frac{\partial g(\boldsymbol{\sigma}^{\mathit{eff}})}{\partial \boldsymbol{\sigma}^{\mathit{eff}}}$$

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

$$f(\boldsymbol{\sigma}^{\mathit{eff}}, \mathbf{q}) \leq 0\,, \quad \dot{\lambda} \geq 0$$

$$f(\boldsymbol{\sigma}^{\mathit{eff}}) = \text{ von Mises, Hill, ...}$$

$$g(\boldsymbol{\sigma}^{\mathit{eff}}) = f(\boldsymbol{\sigma}^{\mathit{eff}})$$

$$\boldsymbol{\sigma}^{\mathit{eff}}\,, \quad \dot{\varepsilon}_p$$

Damage

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

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

$$\dot{D} = nD^{\left(1-\frac{1}{n}\right)}\frac{\dot{\varepsilon}_p}{\varepsilon_{fail}(\eta, \xi, l_c, \dot{\varepsilon}_p)}$$

$$F = \int \dot{F}\,\mathrm{d}t \leq 1 \quad \Rightarrow \quad D_{crit} := D$$

$$D = \int \dot{D}\,\mathrm{d}t \leq 1$$

Damage and failure with eGISSMO

Modular Concept: Toolbox

Plasticity model and anisotropic damage model: eGISSMO

plastic strain tensor is estimated:

$$\dot{\boldsymbol{\varepsilon}}_p = \frac{\dot{\varepsilon}^p_{eff}}{\dot{\varepsilon}_{eff}}\left(\dot{\boldsymbol{\varepsilon}} - \frac{\dot{\varepsilon}_{vol}}{3}\boldsymbol{\delta}\right)$$

Plasticity

$$\dot{\boldsymbol{\sigma}}^{eff} = \mathbf{C}(\dot{\boldsymbol{\varepsilon}} - \dot{\boldsymbol{\varepsilon}}_p)$$

$$\dot{\boldsymbol{\varepsilon}}_p = \dot{\lambda}\frac{\partial g(\boldsymbol{\sigma}^{eff})}{\partial \boldsymbol{\sigma}^{eff}}$$

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

$$f(\boldsymbol{\sigma}^{eff}, \mathbf{q}) \leq 0\,, \quad \dot{\lambda} \geq 0$$

$$f(\boldsymbol{\sigma}^{eff}) = \text{ Barlat, Hill, ...}$$

$$g(\boldsymbol{\sigma}^{eff}) = f(\boldsymbol{\sigma}^{eff})$$

$$\boldsymbol{\sigma}^{eff}\,,\quad \dot{\varepsilon}_p,\quad \dot{\boldsymbol{\varepsilon}}\,,\quad \text{HIS}$$

Damage

$$\boldsymbol{\sigma} = \mathbf{M}^{-1}\,\boldsymbol{\sigma}^{eff}$$

$$\text{with}\quad \mathbf{M}^{-1} = \begin{bmatrix} \widetilde{D}_{11} & \widetilde{D}_{12} & \widetilde{D}_{13} & 0 & 0 & 0 \\ \widetilde{D}_{21} & \widetilde{D}_{22} & \widetilde{D}_{23} & 0 & 0 & 0 \\ \widetilde{D}_{31} & \widetilde{D}_{32} & \widetilde{D}_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & \widetilde{D}_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & \widetilde{D}_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & \widetilde{D}_{66} \end{bmatrix} \quad \text{where}\quad \widetilde{D}_{ij} = \widetilde{D}_{ij}(D_1, D_2, D_3)$$

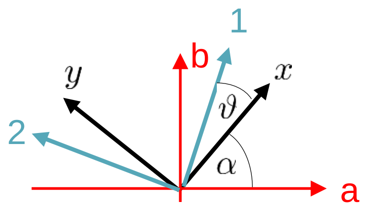
$$\dot{D}_1 = n_1 D_1^{\left(1-\frac{1}{n_1}\right)}\frac{\dot{\varepsilon}_1^{eq}}{\varepsilon_1^f(\eta,\xi)} \qquad \dot{\varepsilon}_1^{eq} = f_1(\dot{\varepsilon}^p_{xx}, \dot{\varepsilon}^p_{yy}, \dot{\varepsilon}^p_{zz}, \dot{\varepsilon}^p_{xy}, \dot{\varepsilon}^p_{yz}, \dot{\varepsilon}^p_{xz}) \quad \text{or} \quad \text{HIS1}$$

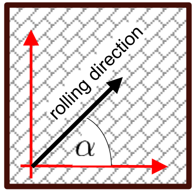
$$\dot{D}_2 = n_2 D_2^{\left(1-\frac{1}{n_2}\right)}\frac{\dot{\varepsilon}_2^{eq}}{\varepsilon_2^f(\eta,\xi)} \qquad \dot{\varepsilon}_2^{eq} = f_2(\dot{\varepsilon}^p_{xx}, \dot{\varepsilon}^p_{yy}, \dot{\varepsilon}^p_{zz}, \dot{\varepsilon}^p_{xy}, \dot{\varepsilon}^p_{yz}, \dot{\varepsilon}^p_{xz}) \quad \text{or} \quad \text{HIS2}$$

$$\dot{D}_3 = n_3 D_3^{\left(1-\frac{1}{n_3}\right)}\frac{\dot{\varepsilon}_3^{eq}}{\varepsilon_3^f(\eta,\xi)} \qquad \dot{\varepsilon}_3^{eq} = f_3(\dot{\varepsilon}^p_{xx}, \dot{\varepsilon}^p_{yy}, \dot{\varepsilon}^p_{zz}, \dot{\varepsilon}^p_{xy}, \dot{\varepsilon}^p_{yz}, \dot{\varepsilon}^p_{xz}) \quad \text{or} \quad \text{HIS3}$$

Setting up coordinate system for plane stress

- Element coordinate system: a-b
- Material direction=rolling/extrusion direction= **x-y**
- Principal strains are denoted 1-2





$$(\dot\varepsilon^p_{xx},\ \dot\varepsilon^p_{yy},\ \dot\varepsilon^p_{xy}) \quad \Rightarrow \quad \left(\dot\varepsilon^p_1,\ b=\frac{\dot\varepsilon^p_2}{\dot\varepsilon^p_1},\ \vartheta\right)$$

$$\begin{pmatrix} \dot\varepsilon^p_{xx} & \dot\varepsilon^p_{xy} \\ \dot\varepsilon^p_{xy} & \dot\varepsilon^p_{yy} \end{pmatrix} = \dot\varepsilon^p_1 \begin{pmatrix} \cos^2\vartheta + b\sin^2\vartheta & (1-b)\sin\vartheta\cos\vartheta \\ (1-b)\sin\vartheta\cos\vartheta & \sin^2\vartheta + b\cos^2\vartheta \end{pmatrix}$$

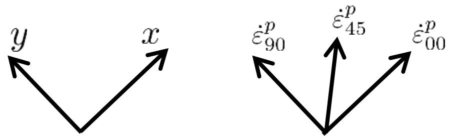
$$\begin{pmatrix} \dot\varepsilon^p_{xx} & \dot\varepsilon^p_{xy} \\ \dot\varepsilon^p_{xy} & \dot\varepsilon^p_{yy} \end{pmatrix} = \dot\varepsilon^p_{00} \begin{pmatrix} 1 & 0 \\ 0 & b \end{pmatrix} + \dot\varepsilon^p_{90} \begin{pmatrix} b & 0 \\ 0 & 1 \end{pmatrix} + \frac{\dot\varepsilon^p_{45}}{2}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

$$\dot\varepsilon^{eq}_{00} := 2\,|\dot\varepsilon^p_{00}|\,\sqrt{\frac{1}{3}(1+b+b^2)} := 2\,|\dot\varepsilon^p_1 \langle \cos^2\vartheta - |\cos\vartheta\sin\vartheta| \rangle|\,\sqrt{\frac{1}{3}(1+b+b^2)}$$

$$\dot\varepsilon^{eq}_{90} := 2\,|\dot\varepsilon^p_{90}|\,\sqrt{\frac{1}{3}(1+b+b^2)} := 2\,|\dot\varepsilon^p_1 \langle \sin^2\vartheta - |\cos\vartheta\sin\vartheta| \rangle|\,\sqrt{\frac{1}{3}(1+b+b^2)}$$

$$\dot\varepsilon^{eq}_{45} := 2\,|\dot\varepsilon^p_{45}|\,\sqrt{\frac{1}{3}(1+b+b^2)} := 2\,|\dot\varepsilon^p_1\, 2\,|\cos\vartheta\sin\vartheta||\,\sqrt{\frac{1}{3}(1+b+b^2)}$$

Damage accumulation in material coordinate system:



Damage accumulation:

$$D_{00} = \int \dot D_{00}\,\mathrm{d}t \qquad \dot D_{00} = n_{00} D_{00}^{\left(1-\frac{1}{n_{00}}\right)} \frac{\dot\varepsilon^{eq}_{00}}{\varepsilon^f_{00}}$$

$$D_{90} = \int \dot D_{90}\,\mathrm{d}t \qquad \dot D_{90} = n_{90} D_{90}^{\left(1-\frac{1}{n_{90}}\right)} \frac{\dot\varepsilon^{eq}_{90}}{\varepsilon^f_{90}}$$

$$D_{45} = \int \dot D_{45}\,\mathrm{d}t \qquad \dot D_{45} = n_{45} D_{45}^{\left(1-\frac{1}{n_{45}}\right)} \frac{\dot\varepsilon^{eq}_{45}}{\varepsilon^f_{45}}$$

Orthotropic/isotropic plasticity with orthotropic damage

[DuBois, Erhart, Haufe, Feucht]

plastic strain tensor is estimated:

$$\dot{\boldsymbol{\varepsilon}}_p = \frac{\dot{\varepsilon}^p_{eff}}{\dot{\varepsilon}_{eff}}\left(\dot{\boldsymbol{\varepsilon}} - \frac{\dot{\varepsilon}_{vol}}{3}\boldsymbol{\delta}\right)$$

Plasticity

$$\dot{\boldsymbol{\sigma}}^{\mathit{eff}} = \mathbf{C}(\dot{\boldsymbol{\varepsilon}} - \dot{\boldsymbol{\varepsilon}}_p)$$

$$\dot{\boldsymbol{\varepsilon}}_p = \dot{\lambda}\frac{\partial g(\boldsymbol{\sigma}^{\mathit{eff}})}{\partial \boldsymbol{\sigma}^{\mathit{eff}}}$$

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

$$f(\boldsymbol{\sigma}^{\mathit{eff}}, \mathbf{q}) \leq 0\,, \quad \dot{\lambda} \geq 0$$

$$f(\boldsymbol{\sigma}^{\mathit{eff}}) = \text{ Barlat, Hill, ...}$$

$$g(\boldsymbol{\sigma}^{\mathit{eff}}) = f(\boldsymbol{\sigma}^{\mathit{eff}})$$

$$\boldsymbol{\sigma}^{\mathit{eff}}, \dot{\varepsilon}_p, \dot{\boldsymbol{\varepsilon}}$$

Material coordinate system:

$$\text{“}x - y\text{”} \rightarrow \text{“}0° - 90°\text{”}$$

Damage

$$\boldsymbol{\sigma} = \mathbf{M}\boldsymbol{\sigma}^{\mathit{eff}} \quad \rightarrow \quad \begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz=0} \\ \sigma_{xy} \\ \sigma_{yz} \\ \sigma_{xz} \end{bmatrix} = \begin{bmatrix} 1-\widetilde{D}_{00} & 0 & 0 & 0 & 0 & 0 \\ 0 & 1-\widetilde{D}_{90} & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1-\widetilde{D}_{45} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \sigma^{\mathit{eff}}_{xx} \\ \sigma^{\mathit{eff}}_{yy} \\ \sigma^{\mathit{eff}}_{zz=0} \\ \sigma^{\mathit{eff}}_{xy} \\ \sigma^{\mathit{eff}}_{yz} \\ \sigma^{\mathit{eff}}_{xz} \end{bmatrix}$$

$$\dot{D}_{00} = n_{00} D_{00}^{\left(1-\frac{1}{n_{00}}\right)} \frac{\dot{\varepsilon}^{eq}_{00}}{\varepsilon^f_{00}(\eta)} \qquad \text{with} \qquad \widetilde{D}_i = \left(\frac{D_{(i)} - D^{crit}_{(i)}}{1 - D^{crit}_{(i)}}\right)^{m_i}$$

$$\dot{D}_{90} = n_{90} D_{90}^{\left(1-\frac{1}{n_{90}}\right)} \frac{\dot{\varepsilon}^{eq}_{90}}{\varepsilon^f_{90}(\eta)}$$

$$\dot{D}_{45} = n_{45} D_{45}^{\left(1-\frac{1}{n_{45}}\right)} \frac{\dot{\varepsilon}^{eq}_{45}}{\varepsilon^f_{45}(\eta)}$$

$$\dot{\varepsilon}^{eq}_{00} = 2\left|\dot{\varepsilon}^p_1 \left\langle \cos^2\vartheta - |\cos\vartheta \sin\vartheta| \right\rangle\right| \sqrt{\tfrac{1}{3}(b^2 + b + 1)}$$

$$\dot{\varepsilon}^{eq}_{90} = 2\left|\dot{\varepsilon}^p_1 \left\langle \sin^2\vartheta - |\cos\vartheta \sin\vartheta| \right\rangle\right| \sqrt{\tfrac{1}{3}(b^2 + b + 1)}$$

$$\dot{\varepsilon}^{eq}_{45} = 2\left|\dot{\varepsilon}^p_1 \, 2\,|\cos\vartheta \sin\vartheta|\right| \sqrt{\tfrac{1}{3}(b^2 + b + 1)}$$

$$\text{either} \quad \max(D_{00}, D_{90}, D_{45}) \leq 1 \quad \text{with} \quad D_i = \int \dot{D}_i \, \mathrm{d}t$$

$$\text{or} \quad D = \int \dot{D} \, \mathrm{d}t \leq 1 \quad \text{with} \quad \dot{D} = \dot{\varepsilon}_p \sqrt{\frac{\dot{D}^2_{00} + \dot{D}^2_{90} + \dot{D}^2_{45}}{(\dot{\varepsilon}^{eq}_{00})^2 + (\dot{\varepsilon}^{eq}_{90})^2 + (\dot{\varepsilon}^{eq}_{45})^2}}$$

(both) according to IFLG3

Orthotropic damage in plane stress *[DuBois et al.]*

IFLG3=0

Gissmo 00°

$$\dot{\varepsilon}^{eq}_{00} := 2\left|\dot{\varepsilon}^{p}_{1}\left\langle \cos^2\vartheta - |\cos\vartheta\sin\vartheta|\right\rangle\right|\sqrt{\tfrac{1}{3}(b^2+b+1)}$$

$$\dot{F}_{00} = n_{00}F_{00}^{\left(1-\frac{1}{n_{00}}\right)}\frac{\dot{\varepsilon}^{eq}_{00}}{\varepsilon^{crit}_{00}(\eta)}\,; \quad F_{00} = \int \Delta F_{00} \leq 1 \quad \rightarrow \quad D^{crit}_{00} := D_{00}$$

$$\dot{D}_{00} = n_{00}D_{00}^{\left(1-\frac{1}{n_{00}}\right)}\frac{\dot{\varepsilon}^{eq}_{00}}{\varepsilon^{f}_{00}(\eta, l_c, \dot{\varepsilon}^{eq}_{00})}\,; \quad D_{00} = \int \Delta D_{00} \leq 1\,; \quad \widetilde{D}_{00} = \left(\frac{D_{00}-D^{crit}_{00}}{1-D^{crit}_{00}}\right)^{m_{00}}$$

Gissmo 90°

$$\dot{\varepsilon}^{eq}_{90} := 2\left|\dot{\varepsilon}^{p}_{1}\left\langle \sin^2\vartheta - |\cos\vartheta\sin\vartheta|\right\rangle\right|\sqrt{\tfrac{1}{3}(b^2+b+1)}$$

$$\dot{F}_{90} = n_{90}F_{90}^{\left(1-\frac{1}{n_{90}}\right)}\frac{\dot{\varepsilon}^{eq}_{90}}{\varepsilon^{crit}_{90}(\eta)}\,; \quad F_{90} = \int \Delta F_{90} \leq 1 \quad \rightarrow \quad D^{crit}_{90} := D_{90}$$

$$\dot{D}_{90} = n_{90}D_{90}^{\left(1-\frac{1}{n_{90}}\right)}\frac{\dot{\varepsilon}^{eq}_{90}}{\varepsilon^{f}_{90}(\eta, l_c, \dot{\varepsilon}^{eq}_{90})}\,; \quad D_{90} = \int \Delta D_{90} \leq 1\,; \quad \widetilde{D}_{90} = \left(\frac{D_{90}-D^{crit}_{90}}{1-D^{crit}_{90}}\right)^{m_{90}}$$

Gissmo 45°

$$\dot{\varepsilon}^{eq}_{45} := 2\left|\dot{\varepsilon}^{p}_{1}\, 2\,|\cos\vartheta\sin\vartheta|\right|\sqrt{\tfrac{1}{3}(b^2+b+1)}$$

$$\dot{F}_{45} = n_{45}F_{45}^{\left(1-\frac{1}{n_{45}}\right)}\frac{\dot{\varepsilon}^{eq}_{45}}{\varepsilon^{crit}_{45}(\eta)}\,; \quad F_{45} = \int \Delta F_{45} \leq 1 \quad \rightarrow \quad D^{crit}_{45} := D_{45}$$

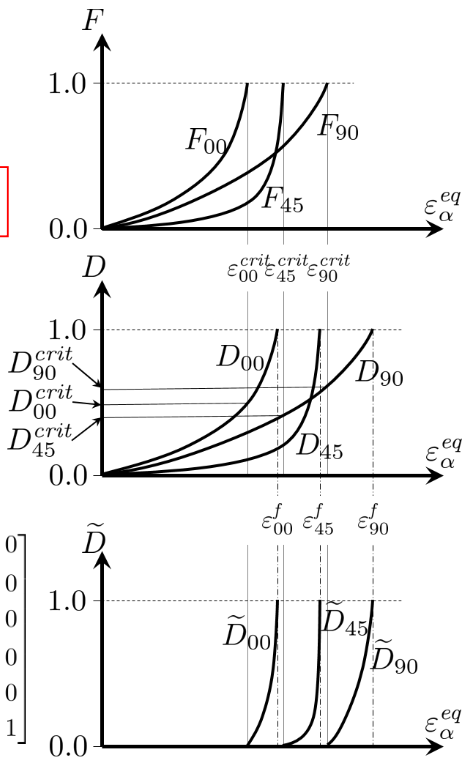
$$\dot{D}_{45} = n_{45}D_{45}^{\left(1-\frac{1}{n_{45}}\right)}\frac{\dot{\varepsilon}^{eq}_{45}}{\varepsilon^{f}_{45}(\eta, l_c, \dot{\varepsilon}^{eq}_{45})}\,; \quad D_{45} = \int \Delta D_{45} \leq 1\,; \quad \widetilde{D}_{45} = \left(\frac{D_{45}-D^{crit}_{45}}{1-D^{crit}_{45}}\right)^{m_{45}}$$

$$\max(D_{00}, D_{90}, D_{45}) \leq 1$$

$$\boldsymbol{\sigma} = \mathbf{M}^{-1}\boldsymbol{\sigma}^{eff}$$

$$\mathbf{M}^{-1} = \begin{bmatrix} 1-\widetilde{D}_{00} & 0 & 0 & 0 & 0 & 0 \\ 0 & 1-\widetilde{D}_{90} & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1-\widetilde{D}_{45} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Example for $\eta = \text{const.}$



Orthotropic damage in plane stress *[DuBois et al.]*

IFLG3=1

Gissmo 00°

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

$$\dot{F}_{00} = n_{00} F_{00}^{\left(1-\frac{1}{n_{00}}\right)} \frac{\dot{\varepsilon}_{00}^{eq}}{\varepsilon_{00}^{crit}(\eta)}$$

$$\dot{D}_{00} = n_{00} D_{00}^{\left(1-\frac{1}{n_{00}}\right)} \frac{\dot{\varepsilon}_{00}^{eq}}{\varepsilon_{00}^{f}(\eta, l_c, \dot{\varepsilon}_{00}^{eq})}\,; \quad D_{00} = \int \Delta D_{00}\,; \quad \widetilde{D}_{00} = \left(\frac{D - D^{crit}}{1 - D^{crit}}\right)^{m_{00}}$$

Gissmo 90°

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

$$\dot{F}_{90} = n_{90} F_{90}^{\left(1-\frac{1}{n_{90}}\right)} \frac{\dot{\varepsilon}_{90}^{eq}}{\varepsilon_{90}^{crit}(\eta)}$$

$$\dot{D}_{90} = n_{90} D_{90}^{\left(1-\frac{1}{n_{00}}\right)} \frac{\dot{\varepsilon}_{90}^{eq}}{\varepsilon_{90}^{f}(\eta, l_c, \dot{\varepsilon}_{90}^{eq})}\,; \quad D_{90} = \int \Delta D_{90}\,; \quad \widetilde{D}_{90} = \left(\frac{D - D^{crit}}{1 - D^{crit}}\right)^{m_{90}}$$

Gissmo 45°

$$\dot{\varepsilon}_{45}^{eq} := 2\,\left|\dot{\varepsilon}_1^p\, 2\,|\cos\vartheta \sin\vartheta|\right| \sqrt{\tfrac{1}{3}(b^2+b+1)}$$

$$\dot{F}_{45} = n_{45} F_{45}^{\left(1-\frac{1}{n_{45}}\right)} \frac{\dot{\varepsilon}_{45}^{eq}}{\varepsilon_{45}^{crit}(\eta)}$$

$$\dot{D}_{45} = n_{45} D_{45}^{\left(1-\frac{1}{n_{45}}\right)} \frac{\dot{\varepsilon}_{45}^{eq}}{\varepsilon_{45}^{f}(\eta, l_c, \dot{\varepsilon}_{45}^{eq})}\,; \quad D_{45} = \int \Delta D_{45}\,; \quad \widetilde{D}_{45} = \left(\frac{D - D^{crit}}{1 - D^{crit}}\right)^{m_{45}}$$

$$\dot{F} = \dot{\varepsilon}_p \sqrt{\frac{\dot{F}_{00}^2 + \dot{F}_{90}^2 + \dot{F}_{45}^2}{(\dot{\varepsilon}_{00}^{eq})^2 + (\dot{\varepsilon}_{90}^{eq})^2 + (\dot{\varepsilon}_{45}^{eq})^2}}$$

$$\rightarrow \qquad F = \int \dot{F}\,\mathrm{d}t \leq 1 \;\rightarrow\; D^{crit} := D$$

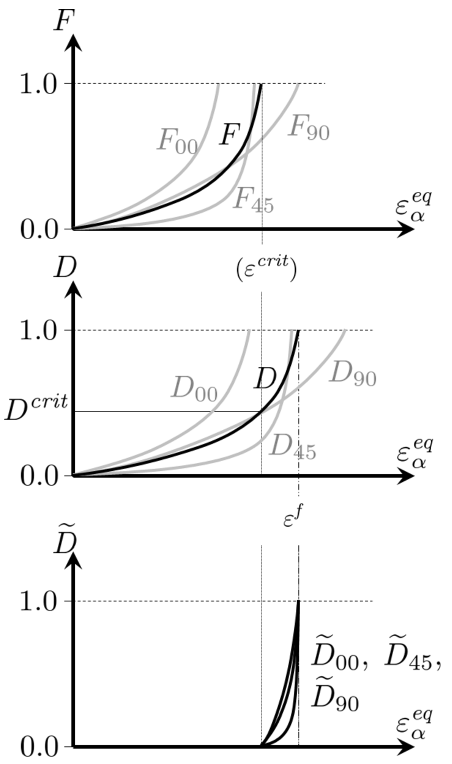
$$\dot{D} = \dot{\varepsilon}_p \sqrt{\frac{\dot{D}_{00}^2 + \dot{D}_{90}^2 + \dot{D}_{45}^2}{(\dot{\varepsilon}_{00}^{eq})^2 + (\dot{\varepsilon}_{90}^{eq})^2 + (\dot{\varepsilon}_{45}^{eq})^2}}$$

$$\rightarrow \qquad D = \int \dot{D}\,\mathrm{d}t \leq 1$$

$$\boldsymbol{\sigma} = \mathbf{M}^{-1} \boldsymbol{\sigma}^{eff}$$

$$\mathbf{M}^{-1} = \begin{bmatrix} 1-\widetilde{D}_{00} & 0 & 0 & 0 & 0 & 0 \\ 0 & 1-\widetilde{D}_{90} & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1-\widetilde{D}_{45} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Example for $\eta = \text{const.}$

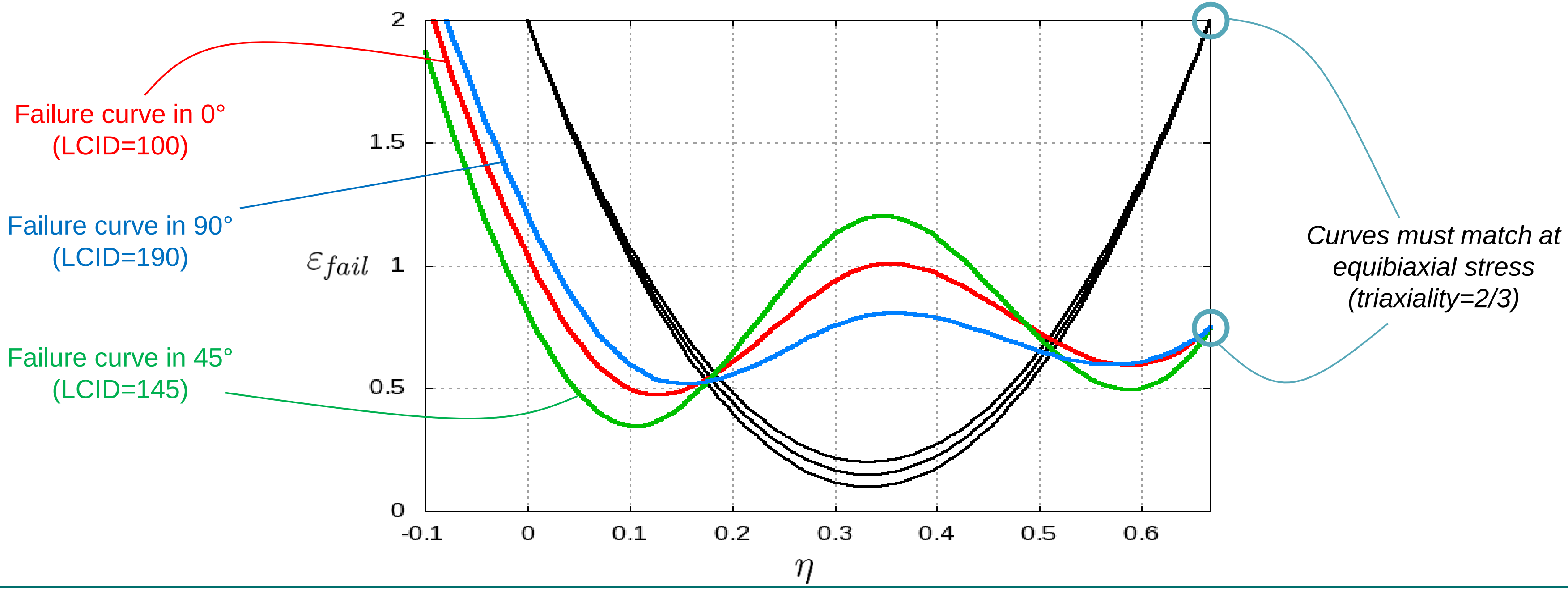


Application

eGISSMO in LS-DYNA

Orthotropic damage through ***MAT_ADD_GENERALIZED_DAMAGE** (eGISSMO)

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



eGISSMO in LS-DYNA

Orthotropic damage through *MAT_ADD_GENERALIZED_DAMAGE (eGISSMO)

IDAM=1 → GISSMO is used for damage accumulation

DTYP=1 → element failure occurs at D=1.0

```
*MAT_ADD_GENERALIZED_DAMAGE
$      mid      idam      dtyp     refsz    numfip                pddt      nhis
        10         1         1                                                 3
$     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

$    lcsdg     ecrit    dmgexp     dcrit    fadexp    lcregd
       100      -200       2.0                 2.5       400
$    lcsrs      shrf     biaxf
                 1.0       0.0
$    lcsdg     ecrit    dmgexp     dcrit    fadexp    lcregd
       190      -290       2.0                 2.5       490
$    lcsrs      shrf     biaxf
                 1.0       0.0
$    lcsdg     ecrit    dmgexp     dcrit    fadexp    lcregd
       145      -245       2.0                 2.5       445
$    lcsrs      shrf     biaxf
                 1.0       0.0
```

Number of history variables for the accumulation of damage

define functions for the damage tensor

Rolling/Extrusion Direction (0°)

Transverse Direction (90°)

Diagonal Direction (45°)

Usual GISSMO definitions but now in three directions (0°, 90°, 45°)

eGISSMO in LS-DYNA

Orthotropic damage through *MAT_ADD_GENERALIZED_DAMAGE (eGISSMO)

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

```
*MAT_ADD_GENERALIZED_DAMAGE
$       mid      idam      dtyp     refsz    numfip                pddt      nhis
         10         1         1                                              3
$      his1      his2      his3     iflg1     iflg2     iflg3
                                        2         1         1
...
```

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.

eGISSMO in LS-DYNA

Orthotropic damage through *MAT_ADD_GENERALIZED_DAMAGE (eGISSMO)

IFLG1=2, IFLG2=1

```
*MAT_ADD_GENERALIZED_DAMAGE
$      mid      idam      dtyp     refsz    numfip                pddt      nhis
        10         1         1                                                3
$     his1      his2      his3     iflg1     iflg2     iflg3
                                       2         1         1
...
```

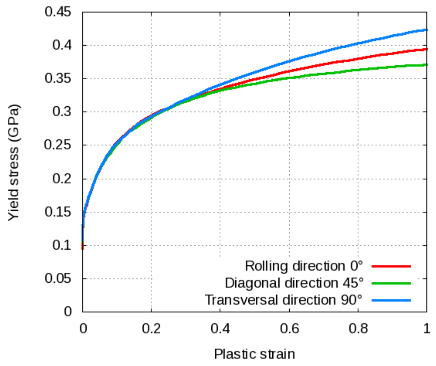
	Predefined functions	Instability	Damage
0°	$\Delta\varepsilon_{00}^{eq} = 2\,\lvert\Delta\varepsilon_1^p\rvert\,\langle\cos^2\vartheta - \lvert\cos\vartheta\sin\vartheta\rvert\rangle\sqrt{\frac{1}{3}(1+b+b^2)}$	$\Delta F_{00} = n_{00} F_{00}^{\left(1-\frac{1}{n_{00}}\right)} \frac{\Delta\varepsilon_{00}^{eq}}{\varepsilon_{00}^{crit}(\eta)}$	$\Delta D_{00} = n_{00} D_{00}^{\left(1-\frac{1}{n_{00}}\right)} \frac{\Delta\varepsilon_{00}^{eq}}{\varepsilon_{00}^{f}(\eta)}$
90°	$\Delta\varepsilon_{90}^{eq} = 2\,\lvert\Delta\varepsilon_1^p\rvert\,\langle\sin^2\vartheta - \lvert\cos\vartheta\sin\vartheta\rvert\rangle\sqrt{\frac{1}{3}(1+b+b^2)}$	$\Delta F_{90} = n_{90} F_{90}^{\left(1-\frac{1}{n_{90}}\right)} \frac{\Delta\varepsilon_{90}^{eq}}{\varepsilon_{90}^{crit}(\eta)}$	$\Delta D_{90} = n_{90} D_{90}^{\left(1-\frac{1}{n_{90}}\right)} \frac{\Delta\varepsilon_{90}^{eq}}{\varepsilon_{90}^{f}(\eta)}$
45°	$\Delta\varepsilon_{45}^{eq} = 4\,\lvert\Delta\varepsilon_1^p\rvert\,\lvert\cos\vartheta\sin\vartheta\rvert\sqrt{\frac{1}{3}(1+b+b^2)}$	$\Delta F_{45} = n_{45} F_{45}^{\left(1-\frac{1}{n_{45}}\right)} \frac{\Delta\varepsilon_{45}^{eq}}{\varepsilon_{45}^{crit}(\eta)}$	$\Delta D_{45} = n_{45} D_{45}^{\left(1-\frac{1}{n_{45}}\right)} \frac{\Delta\varepsilon_{45}^{eq}}{\varepsilon_{45}^{f}(\eta)}$

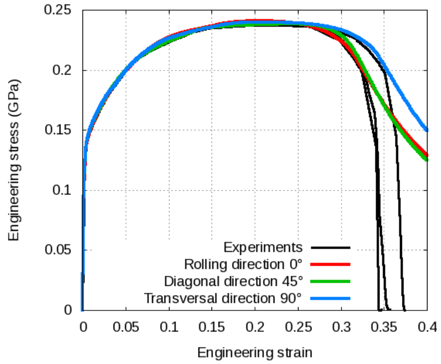
Example

Material modeling in LS-DYNA

Aluminum sheet (*MAT_036E, no failure)

Strain fields prior to failure

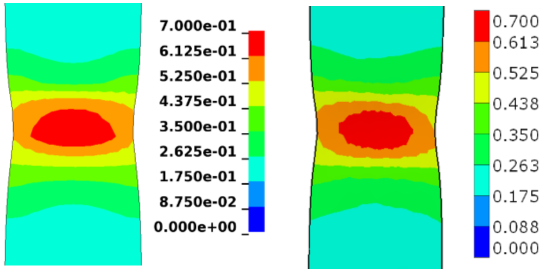




Rolling direction 0°

Simulation

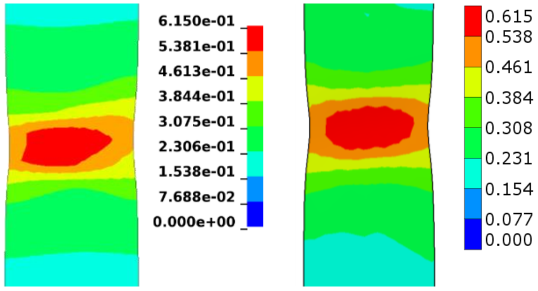
Experiment



Diagonal direction 45°

Simulation

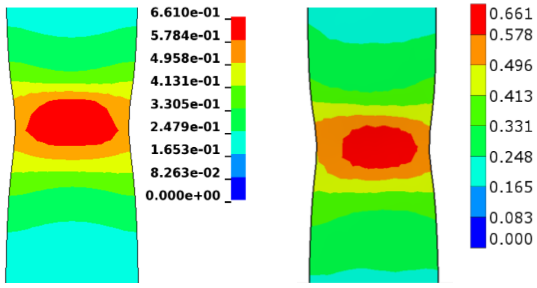
Experiment



Transversal direction 90°

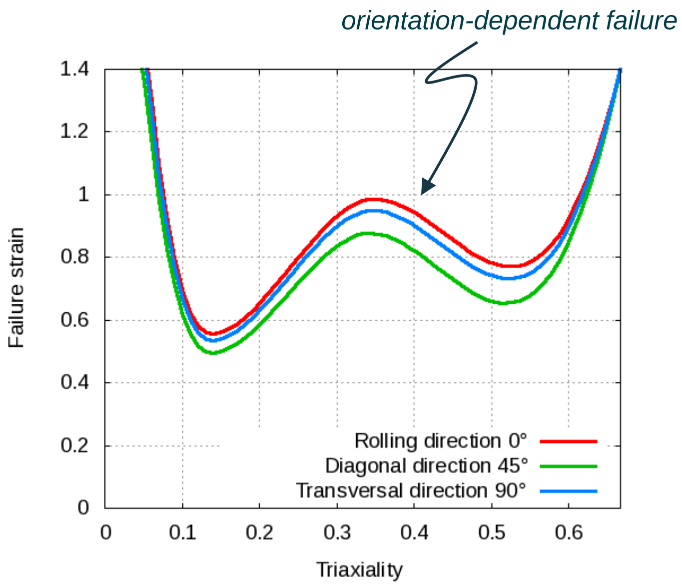
Simulation

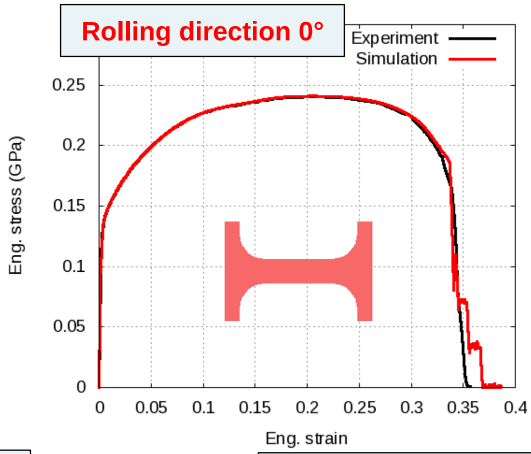
Experiment

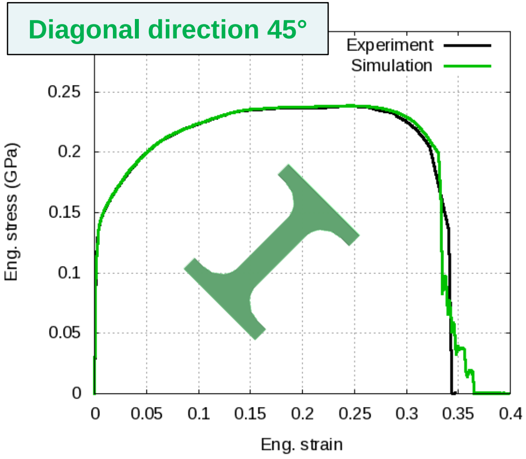


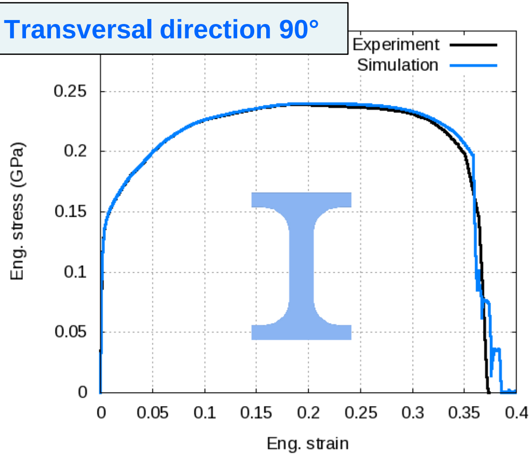
Material modeling in LS-DYNA

Aluminum sheet (*MAT_036E + eGISSMO)









Final remarks

- A reasonable description of orthotropic plasticity is crucial for accurate plastic strains and, therefore, for an accurate failure prediction.

- In case of orthotropic damage, special components of the plastic strain tensor are evaluated.
  These are the drivers for the damage accumulation in three material directions.

- *MAT_ADD_GENERALIZED_DAMAGE / eGISSMO is a highly flexible damage/failure model that can consider orthotropic damage, among other things.

- eGISSMO may also consider damage due to other contributions (e.g., deviatoric and volumetric splitting).
  Consider a mighty constitutive toolbox!

- eGISSMO is available since **LS-DYNA version R9.**

eGISSMO

Give it a chance!
We will support you.