A Generalized Damage and Failure Formulation for SAMP

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Simulation of Failure in Shell-like Structures

- Very high and ultra high strength steels may exhibit reduced ductility
- Plastic trim panels fail during side impact
- Possibility of failure during crash events needs to be considered in numerical simulations
- The technology of simulating failure is still in it‘s infancy

Aspects of Failure Simulation

- Mesh: should be fine enough to capture localization arising before failure
- Discretization : simply connected part must be separated into multiply connected part, many possibilities :
  - Lagrangian with element erosion
  - ALE with FSI
  - Meshless methods (SPH, EFG)
  - MMALE

Aspects of Failure Simulation

- Regularization: each softening problem is inherently mesh dependent, no material and/or failure law is meaningful unless it is regularized
- Damage and failure law: verification and validation process is needed to calibrate a damage and/or failure law to physical experiments

Aspects of Failure Simulation

- Consideration of deformation history: stress/strain path during manufacturing may influence failure during crash event
- Physical material data are needed up to failure, true hardening data beyond necking strain can only be obtained through reverse engineering

Today‘s Presentation

- Simulation of failure has many aspects
- Today we only compare failure and damage models implemented in LS-DYNA
- It should be emphasized that all failure and damage models will in practice need to be regularized

Failure and Damage Models

- Failure model: when a failure variable reaches a critical value, rupture (fracture) will occur
- Damage model: material strength and/or material stiffness are reduced in function of a damage variable
- Remark: in most damage models the damage variable serves as a failure variable simultaneously

Part I
Failure Models

Failure Models in LS-DYNA

- Compare some elementary failure models that are implemented in LS-DYNA
- Focus on deformation based criteria
- Some of the models considered are available for shell elements only
- We are interested in thin panels
- Plane state of stress can be assumed

Failure Models in LS-DYNA

	FAILURE CRITERION(S)	Dependency of		
		Load path	Strain rate	State of stress
MAT_24	$\varepsilon_p \leq \varepsilon_{pf}$	yes	no	no
MAT_123	$\varepsilon_p \leq \varepsilon_{pf}$ $\varepsilon_1 \leq \varepsilon_{1f}$ $\varepsilon_3 \leq \varepsilon_{3f}$	yes no no	no no no	no no no
MAT_15	$d = \int \frac{d\varepsilon_p}{d_1 + d_2 e^{d_3 \frac{p}{\sigma_{vm}}}} \leq 1$	yes	yes	yes

Failure Models in LS-DYNA

	FAILURE CRITERION(S)	Dependency of		
		Load path	Strain rate	State of stress
MAT_39	$\varepsilon_1 \leq \varepsilon_{1fld}(\varepsilon_2)$	no	no	yes
MAT_89	$\varepsilon_1 \leq \varepsilon_{1f}(\ln \dot{\varepsilon})$	no	yes	no
MAT_15	$d = \int \frac{d\varepsilon_p}{d_1\left(1 + d_4 \ln \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)} \leq 1$ $VP = 0 \Rightarrow \dot{\varepsilon} = \dot{\varepsilon}_{eff}$ $VP = 1 \Rightarrow \dot{\varepsilon} = \dot{\varepsilon}_p$	yes	yes	yes

Failure Models in LS-DYNA

- As failure criteria we can distinguish:
  - Principal strain
  - Thinning
  - Equivalent plastic strain
  - Forming Limit Diagram (FLD)
  - Johnson-Cook
- With or without rate dependency

Comparison of Failure Models

- Perform a detailed comparison of failure criteria for the following case :
  - Plane stress : $\sigma_3 = 0$
  - Small elastic deformations : $\varepsilon_1 \approx \varepsilon_{p1}$, $\varepsilon_2 \approx \varepsilon_{p2}$
  - Isochoric plasticity : $\varepsilon_3 \approx \varepsilon_{p3} = -\varepsilon_{p1} - \varepsilon_{p2}$
  - Proportional loading : $\sigma_2 = a\sigma_1$, $\varepsilon_{p2} = b\varepsilon_{p1}$ $\quad a = \dfrac{1+2b}{2+b}$

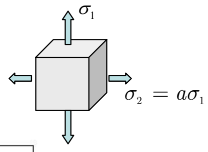
Triaxiality: Invariant Characterization of the Plane State of Stress

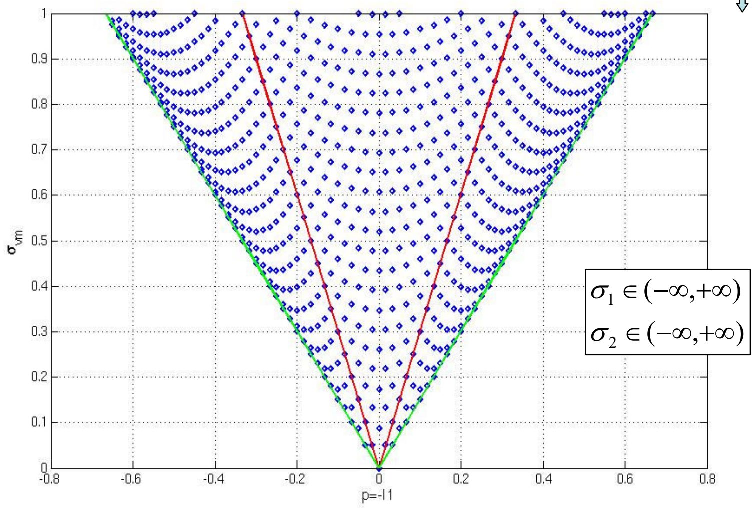
$$\sigma_2 = a\sigma_1$$
$$\varepsilon_{p2} = b\varepsilon_{p1}$$
$$a = \frac{1+2b}{2+b}$$

$$\varepsilon_p = \sqrt{\frac{4}{3}\varepsilon_{p1}^2\left(1+b^2+b\right)}$$
$$\sigma_{vm} = \sqrt{\sigma_1^2\left(1+a^2-a\right)}$$
$$\frac{p}{\sigma_{vm}} = -\frac{1+a}{3\sqrt{1+a^2-a}}$$

Plane Stress

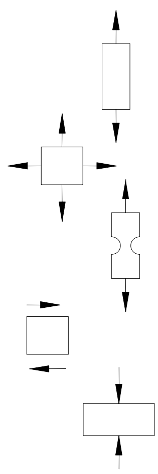
lower bound: $\sigma_{vm} = \pm\frac{3}{2}p$ (biaxial tension)



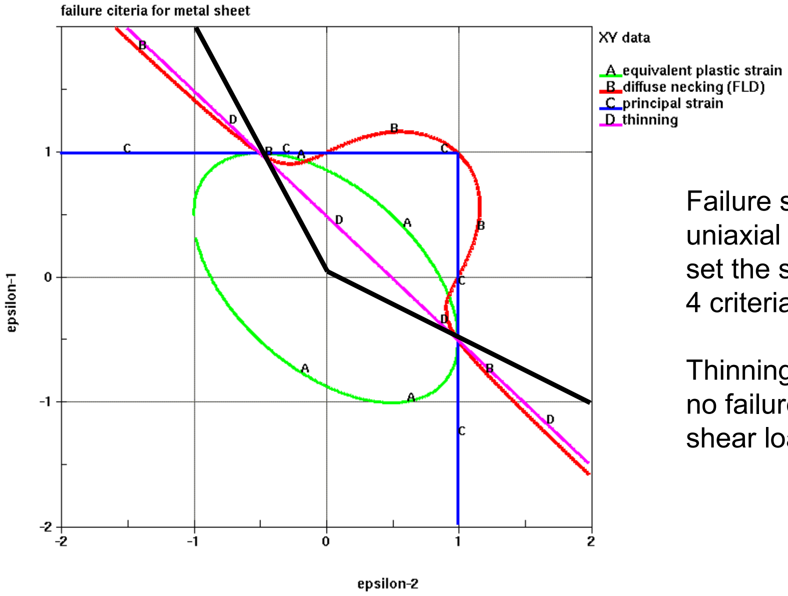


Typical Proportional Stress/Strain Paths

	$a = \frac{\sigma_2}{\sigma_1}$	$b = \frac{\varepsilon_{p2}}{\varepsilon_{p1}}$	$\frac{p}{\sigma_{vm}}$
Uniaxial stress Tension	**0**	**-0.5**	**-0.3333**
Biaxial stress	**1**	**1**	**-0.6666**
Uniaxial tension laterally confined	**0.5**	**0**	**-0.57735** $= -\frac{1}{\sqrt{3}}$
Pure shear	**-1**	**-1**	**0**
Uniaxial stress Compression	∞	**-2**	**0.3333**



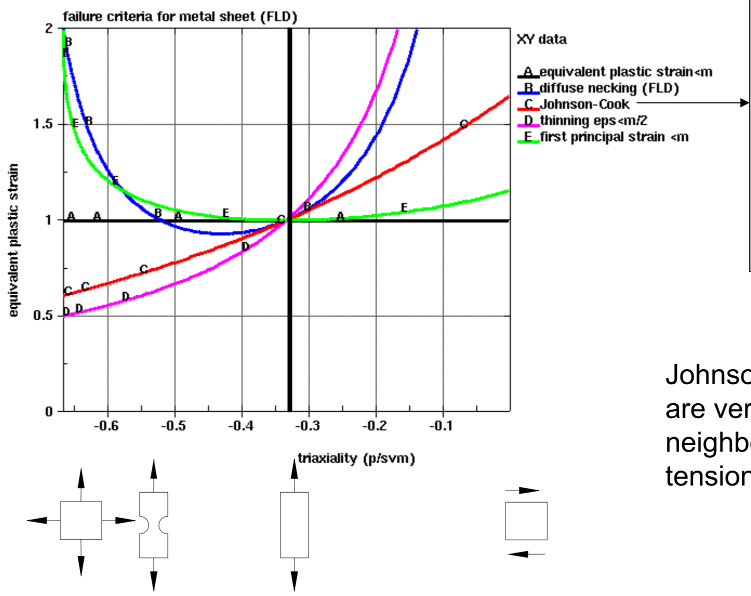
Comparison of Failure Models in the Plane of Principal Strain



Failure strain under uniaxial tension is set the same in all 4 criteria

Thinning and FLD predict no failure under pure shear loading

Comparison to the Johnson-Cook Criterion (Hancock-McKenzie)



$$\varepsilon_{pf} = d_1 + d_2 e^{d_3 \frac{p}{\sigma_{vm}}}$$

$$d_1 = 0$$

$$d_3 = \frac{3}{2}$$

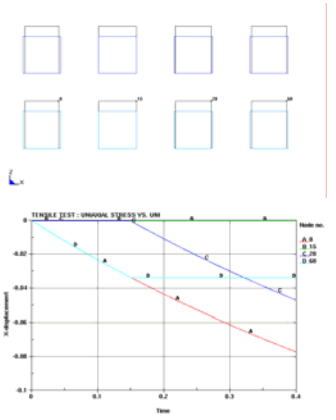
$$d_2 = \varepsilon_{1f} e^{-\frac{1}{2}}$$

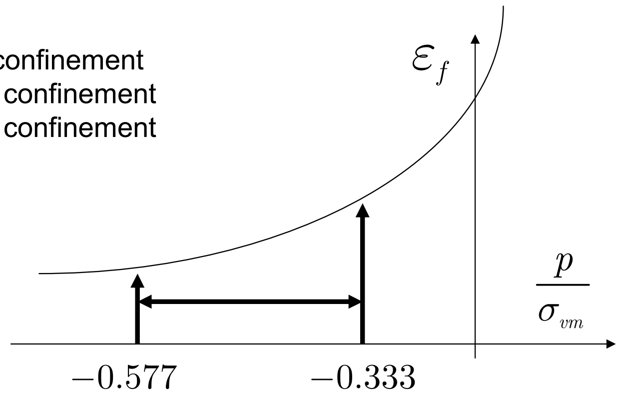
Johnson-Cook and FLD are very close in the neighborhood of uniaxial tension

Non-Proportional Loading

Compare 4 load paths :

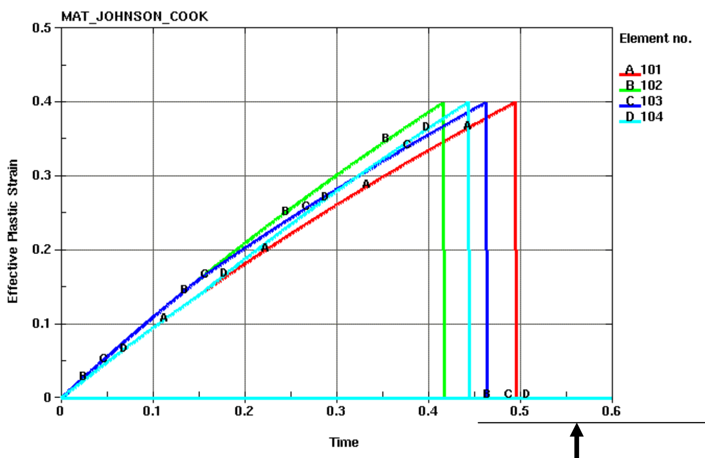
- uniaxial tension
- uniaxial tension with lateral confinement
- uniaxial tension with/without confinement
- uniaxial tension without/with confinement





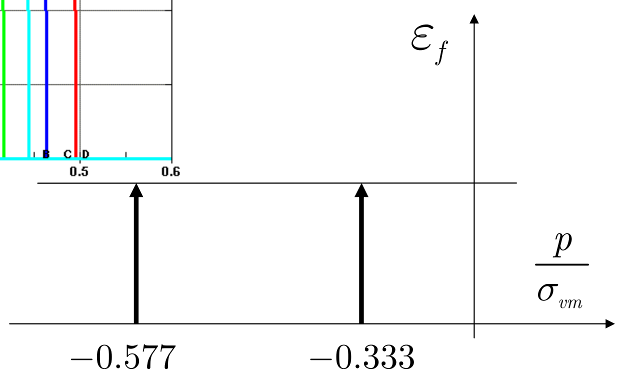
Triaxiality is no longer constant over the stress-strain path if lateral constraint is imposed or lifted

Non-Proportional Loading Criterion without Triaxiality

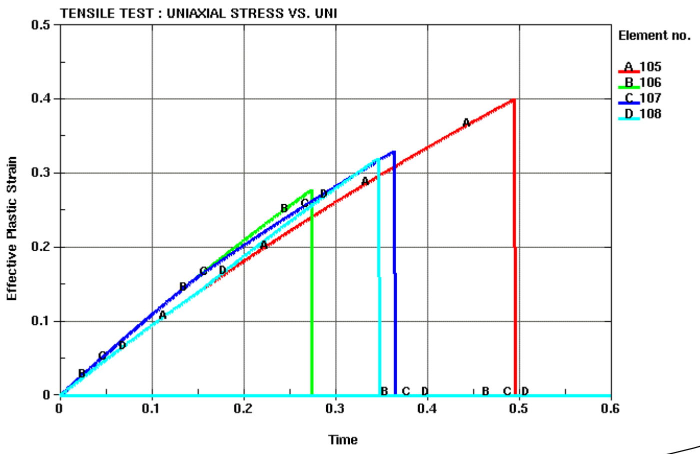


$$\varepsilon_f = d_1 = 0.4$$

$$d = \int \frac{\dot{\varepsilon}_p}{\varepsilon_f} dt \le 1 \Rightarrow \varepsilon_p \le \varepsilon_f$$

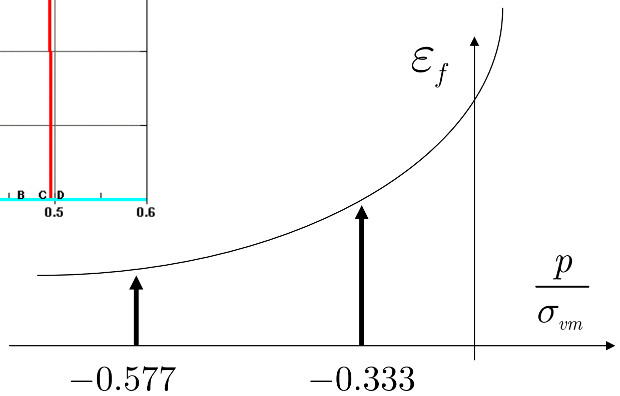


Non-Proportional Loading Criterion with Triaxiality

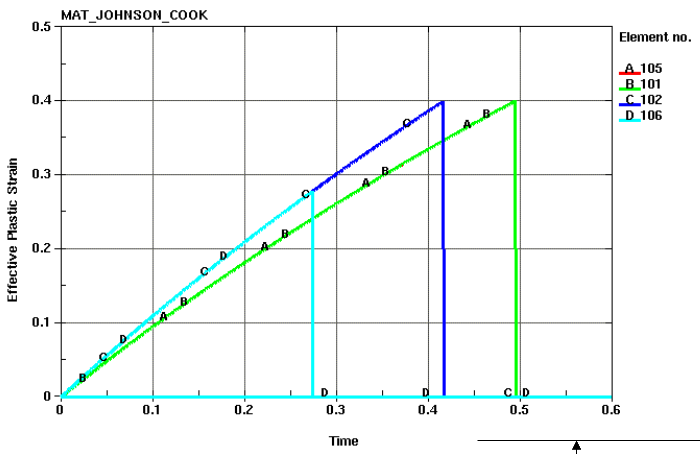


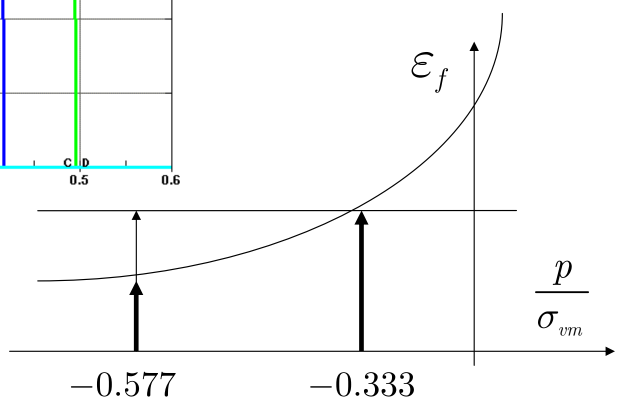
$$\varepsilon_f = d_1 + d_2 e^{d_3 \frac{p}{\sigma_{vm}}} = 0.66 e^{1.5 \frac{p}{\sigma_{vm}}}$$

$$d = \int \frac{\dot{\varepsilon}_p}{\varepsilon_f} dt \le 1 \overset{\frac{p}{\sigma_{vm}} = cte}{\Longrightarrow} \varepsilon_p \le \varepsilon_f$$

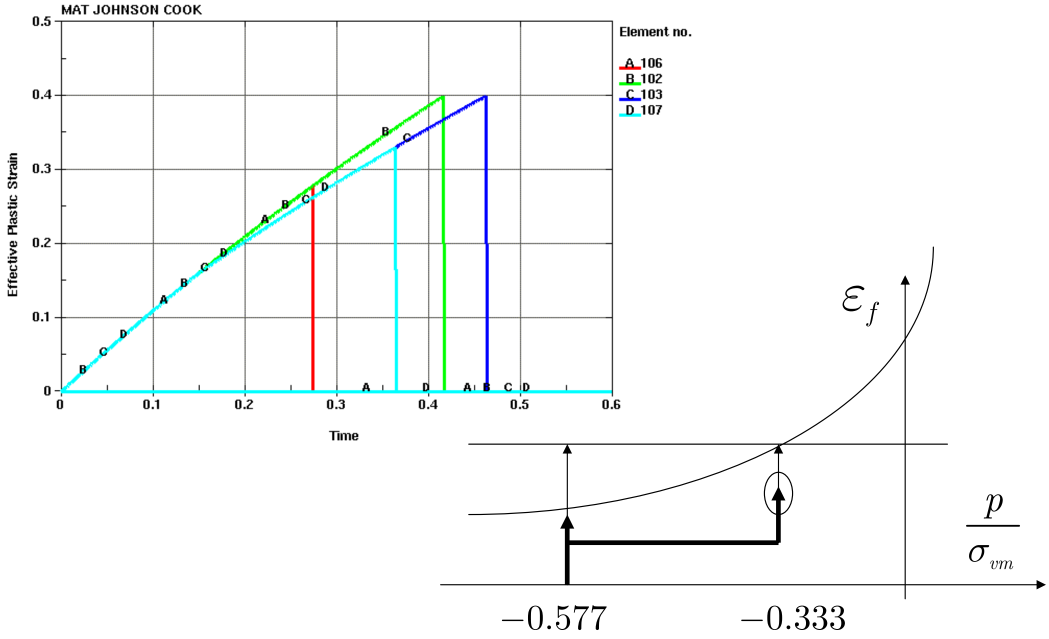


Direct Comparison: Uniaxial Tension with/without Confinement

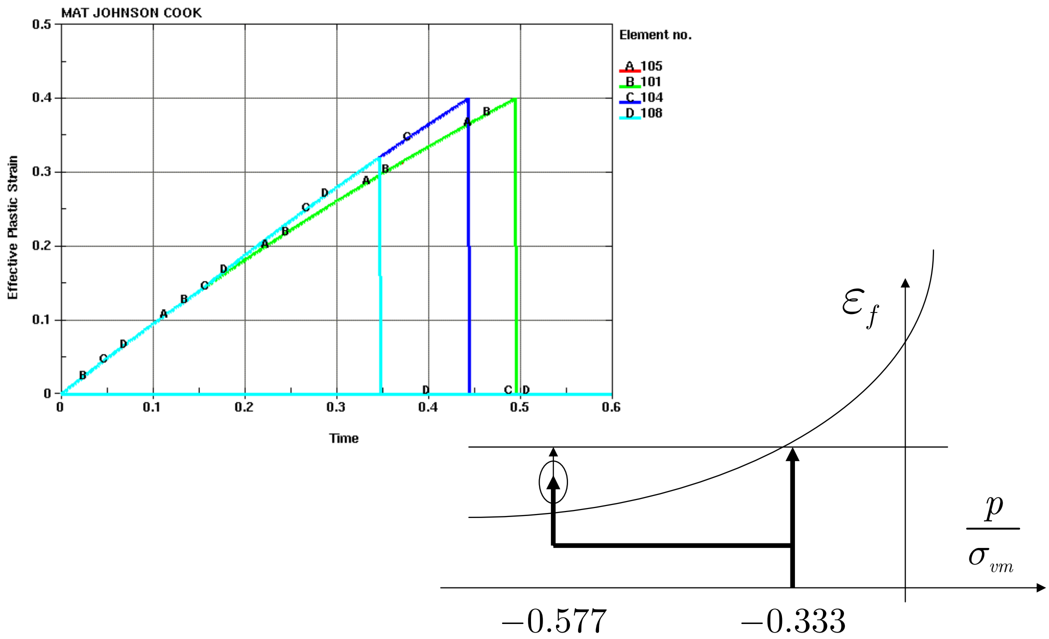




Direct Comparison: Lateral Confinement lifted or not at 15ms



Direct Comparison: Lateral Confinement applied or not at 15ms



General failure criterion

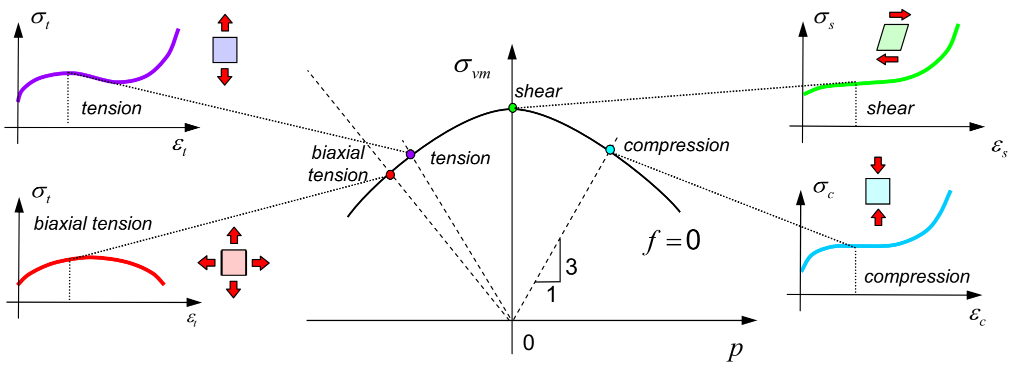
Evolution law for failure variable
$$d = \int \frac{d\varepsilon_p}{f\left(\frac{p}{\sigma_{vm}}\right) g(\dot{\varepsilon})}$$

Failure criterion
$$d \leq d_c$$

For proportional loading at constant strain rate :
$$d = \frac{\int d\varepsilon_p}{f\left(\frac{p}{\sigma_{vm}}\right) g(\dot{\varepsilon})} = \frac{\varepsilon_p}{f\left(\frac{p}{\sigma_{vm}}\right) g(\dot{\varepsilon})}$$

$$d \leq d_c \Rightarrow \varepsilon_p \leq \varepsilon_{pf} = d_c f\left(\frac{p}{\sigma_{vm}}\right) g(\dot{\varepsilon})$$

SAMP - Reminder



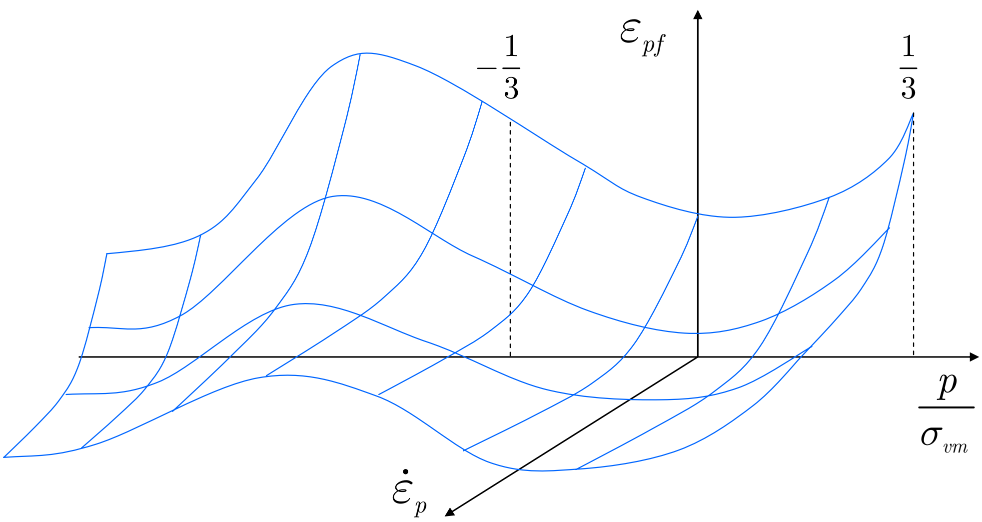
Implemented as MAT-SAMP-1 (MAT187) in LS-DYNA 9.71
All hardening curves are tabulated as known from MAT24

In what follows, the failure criteria added to SAMP are discussed

The Failure Model(s) in SAMP

- All dependencies (strain rate and state of stress) are tabulated
- In a mathematical sense, a tabulated curve is the most general form of a continuous function in the Euclidian manifold – so why settle for less?
- The SAMP failure criterion can be considered a tabulated generalization of the Johnson-Cook criterion

Tabulated Input



$$\varepsilon_{pf} = D_c\left(\dot{\varepsilon}_p\right) \cdot LCID\_TRI\left(\frac{p}{\sigma_{vm}}\right)$$

The Failure Model(s) in SAMP

LCID_D	DC	EQFAIL	LCID_TRI	failure variable
0	>0 ε_{pf}	>0	none	ε_p
0	0 ∞	>0	none	ε_p
0	<0 $g\left(\dot{\varepsilon}_p\right)$	>0	$f\left(\frac{p}{\sigma_{vm}}\right)$	ε_p
0	<0 $g\left(\dot{\varepsilon}_p\right)$	<0	$f\left(\frac{p}{\sigma_{vm}}\right)$	$\int \frac{d\varepsilon_p}{gf}$

SAMP Implementations : Total (old) Formulation : EQFAIL>0

$$d = \int d\varepsilon_p = \varepsilon_p \le \varepsilon_{pf}\left(\dot{\varepsilon}_p\right) f\left(\frac{p}{\sigma_{vm}}\right) = d_c$$

failure variable is the equivalent plastic strain

critical damage equals the equivalent plastic strain at failure and depends upon the strain rate and the state of stress

this formulation will be equivalent to EQFAIL<0 iff
- the loading is proportional

or
- the failure plastic strain is a constant

SAMP Implementations : Incremental Formulation : EQFAIL<0

$$f\left(-\frac{1}{3}\right) = 1$$

critical damage is a constant and is computed internally

$$d = \int \frac{\varepsilon_{pf}(0) f\left(-\frac{1}{3}\right)}{\varepsilon_{pf}(\dot{\varepsilon}_p) f\left(\frac{p}{\sigma_{vm}}\right)} d\varepsilon_p \leq \varepsilon_{pf}(0) f\left(-\frac{1}{3}\right) = \varepsilon_{pf}(0) = d_c$$

for quasi-static uniaxial tension the failure variable is equal to the equivalent plastic strain:

$$d = \int \frac{\varepsilon_{pf}(0) f\left(-\frac{1}{3}\right)}{\varepsilon_{pf}(\dot{\varepsilon}_p) f\left(\frac{p}{\sigma_{vm}}\right)} d\varepsilon_p = \int d\varepsilon_p = \varepsilon_p \leq \varepsilon_{pf}(0) f\left(-\frac{1}{3}\right) = d_c$$

The Failure Model(s) in SAMP

The Johnson-Cook failure criterion is recovered if:

$$LCID\_D = 0$$

$$LCID\_TRI > 0 \Rightarrow f\left(\frac{p}{\sigma_{vm}}\right) = \frac{d_1 + d_2 e^{d_3 \frac{p}{\sigma_{vm}}}}{d_1 + d_2 e^{-d_3 \frac{1}{3}}}$$

$$DC < 0 \Rightarrow g(\dot{\varepsilon}) = \left(d_1 + d_2 e^{-d_3 \frac{1}{3}}\right)\left(1 + d_4 \ln \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)$$

$$EQFAIL < 0$$

Verification: Comparison SAMP/JC

	failure strain	failure criterion
JC	$d_1 + d_2 e^{d_3 \frac{p}{\sigma_{vm}}} = 0.66 e^{1.5 \frac{p}{\sigma_{vm}}}$	$\int \frac{d\varepsilon_p}{\varepsilon_f} \leq 1$
SAMP total EQFAIL=0.01	$g(\dot{\varepsilon}) f\left(\frac{p}{\sigma_{vm}}\right)$	$\varepsilon_p \leq \varepsilon_f$
SAMP incremental EQFAIL=-0.01	$g(\dot{\varepsilon}) f\left(\frac{p}{\sigma_{vm}}\right)$	$\int \frac{g(0) d\varepsilon_p}{fg} \leq g(0)$

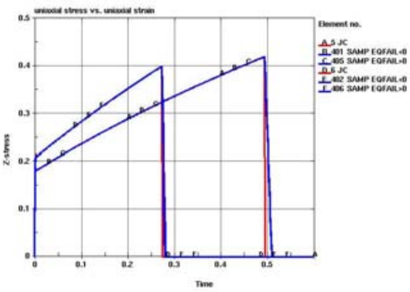
$$DC < 0$$

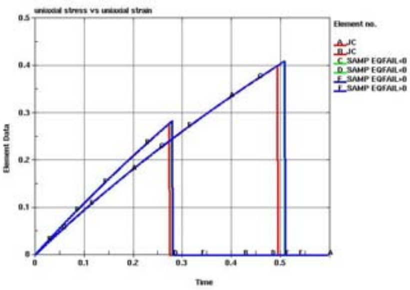
$$g(\dot{\varepsilon}) = 0.66 e^{-1.5\frac{1}{3}}$$

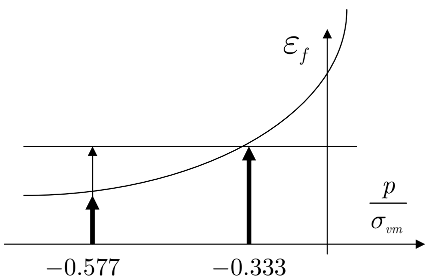
$$LCID\_TRI > 0$$

$$f\left(\frac{p}{\sigma_{vm}}\right) = \frac{0.66 e^{1.5 \frac{p}{\sigma_{vm}}}}{0.66 e^{-1.5\frac{1}{3}}}$$

Proportional Loading
Uniaxial Tension with/without Lateral Confinement

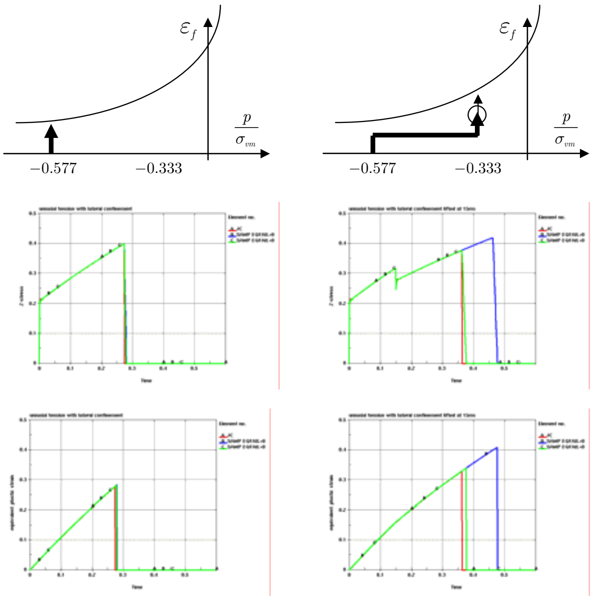






All 3 models yield identical results if the loading is proportional

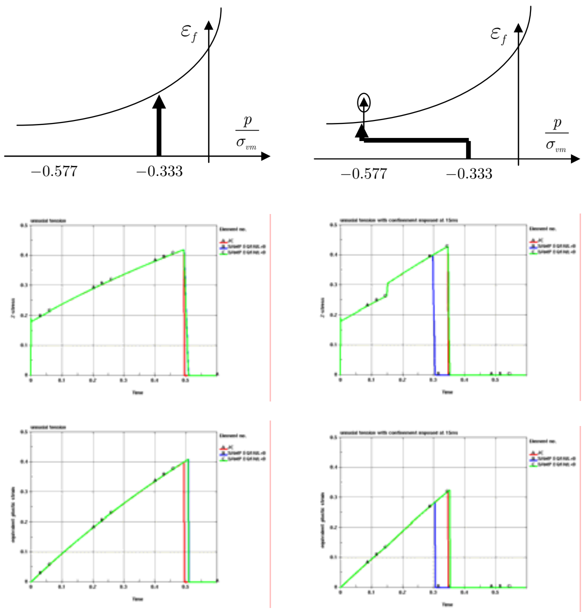
Non-Proportional Loading
Uniaxial Tension, Lateral Confinement Lifted or not at 15ms



The total formulation predicts a higher rupture strain than the incremental formulation

Rupture strain is determined by the unconfined state if the total formulation is used

Non-Proportional Loading
Uniaxial Tension, Lateral Confinement Imposed or not at 15ms



The total formulation predicts a lower rupture strain than the incremental formulation

Rupture strain is determined by the confined state if the total formulation is used

Conclusions (Failure)

- Tabulated failure formulation has been added to the SAMP material model
- Encapsulates many previously implemented formulations (as long as the failure variable depends on plastic strain)
- Failure variable can be total or incremental (accumulated)
- Considerable flexibility to fit experiments
- Presented failure model will be implemented in MAT_187 next

Part II
Damage Models

Principles of Damage

- Damage allows fitting of the unloading path, cyclic loading paths and load paths with strain softening
- a damage variable (d or f) quantifies the part of the material cross section that no longer transmits forces (cracks or pores)
- only isotropic damage considered at this time
- Elastic damage effects material stiffness (reduction of elastic moduli)
- Ductile damage effects material strength (reduction of yield stress) or both material strength and material stiffness

Elastic Damage: Effective Cross Section and Effective Stress

$$A_0$$

Undeformed cross section

$$A$$

deformed or current cross section

$$A_{eff} = A(1-d)$$

effective cross section

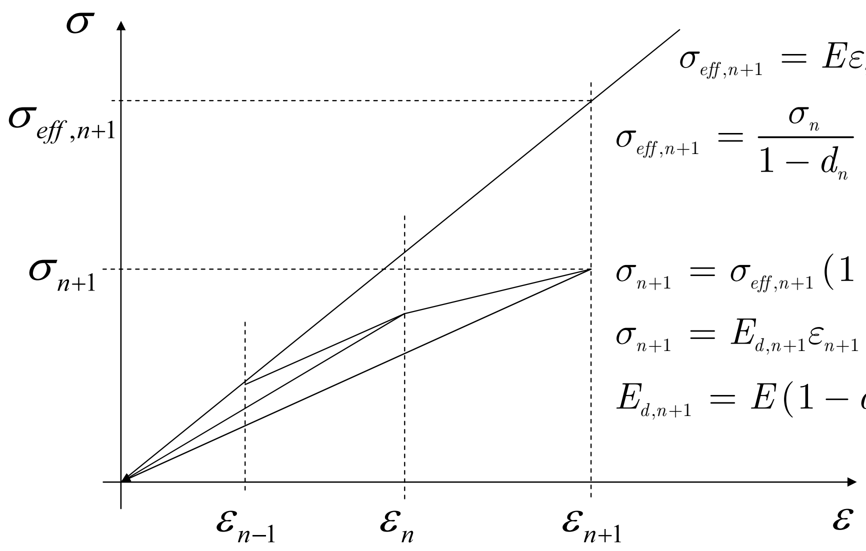
$$\sigma = \frac{f}{A}$$

true stress relates to true cross section

$$\sigma_{eff} = \frac{f}{A_{eff}} = \frac{\sigma}{1-d}$$

effective stress relates to effective cross section (undamaged material)

Elastic Damage: Damaged Modulus



$$\sigma_{eff,n+1} = E\varepsilon_{n+1}$$

$$\sigma_{eff,n+1} = \frac{\sigma_n}{1-d_n} + E(\varepsilon_{n+1} - \varepsilon_n)$$

$$\sigma_{n+1} = \sigma_{eff,n+1}(1-d_{n+1})$$

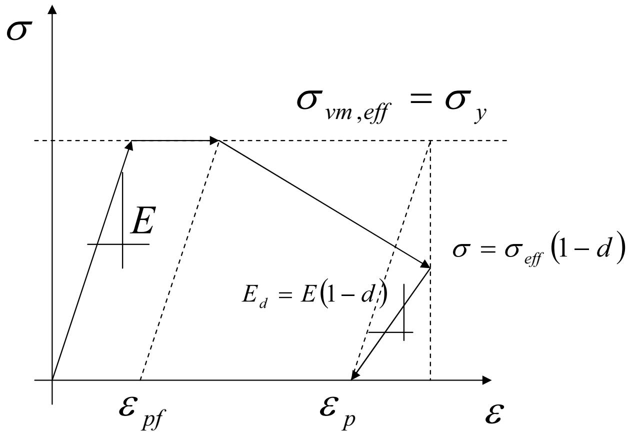
$$\sigma_{n+1} = E_{d,n+1}\varepsilon_{n+1}$$

$$E_{d,n+1} = E(1-d_{n+1})$$

Ductile Damage

	effective geometry	effective stress	damaged modulus
strain equivalence	$A = A_{eff}(1-d)$	$\sigma = \sigma_{eff}(1-d)$	$E_d = E(1-d)$
energy equivalence	$V = V_{eff}(1-f)$	$\sigma = \sigma_{eff}(1-f)\frac{\dot{\varepsilon}_{p,eff}}{\dot{\varepsilon}_p}$	$E_d = E$
general	$A = A_{eff}(1-d)$ $V = V_{eff}(1-f)$	$\sigma = \sigma_{eff}(1-f)\frac{\dot{\varepsilon}_{p,eff}}{\dot{\varepsilon}_p}$	$E_d = E(1-d)$

Ductile Damage: Strain Equivalence

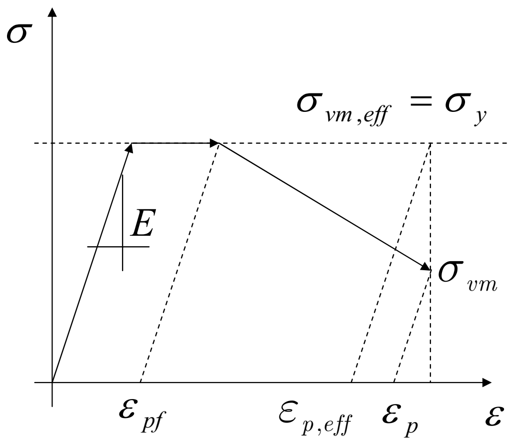


$$\sigma_{vm} = (1-d)\,\sigma_{vm,eff}$$
$$E_d = (1-d)\,E$$

$$\varepsilon_{p,eff} = \varepsilon - \frac{\sigma_{vm,eff}}{E}$$
$$\varepsilon_p = \varepsilon - \frac{\sigma_{vm}}{E_d}$$
$$\varepsilon_p = \varepsilon_{p.eff}$$

Ductile Damage: Energy Equivalence

$$\sigma_{vm}\dot{\varepsilon}_p = (1-f)\,\sigma_{vm,eff}\,\dot{\varepsilon}_{p,eff}$$
$$E_d = E$$



$$\dot{\varepsilon}_{p,eff} = \dot{\varepsilon} - \frac{\dot{\sigma}_{vm,eff}}{E}$$
$$\dot{\varepsilon}_p = \dot{\varepsilon} - \frac{\dot{\sigma}_{vm}}{E}$$
$$\dot{\varepsilon}_p = \frac{\left(1 - \frac{\dot{\sigma}_{vm}}{E\dot{\varepsilon}}\right)}{\left(1 - \frac{\dot{\sigma}_{vm,eff}}{E\dot{\varepsilon}}\right)}\dot{\varepsilon}_{p,eff}$$

Data Preparation

- Material input consists of rate dependent hardening curves based on the undamaged material (effective yield stress values)
- Additionally the damage evolution must be defined, theoretical models and tabulated models (based on a damage curve) exist
- Failure plastic strain corresponds to the first point of the damage curve
- Rupture plastic strain corresponds to the point on the damage curve where d attains a critical value (<1), this critical value must be defined additionally

Damage Models in LS-DYNA

- Compare some elementary damage models that are implemented in LS-DYNA
- Only isotropic damage will be taken into account
- Only ductile damage models will be considered
- Some models (MAT_081) are implemented for shell elements only

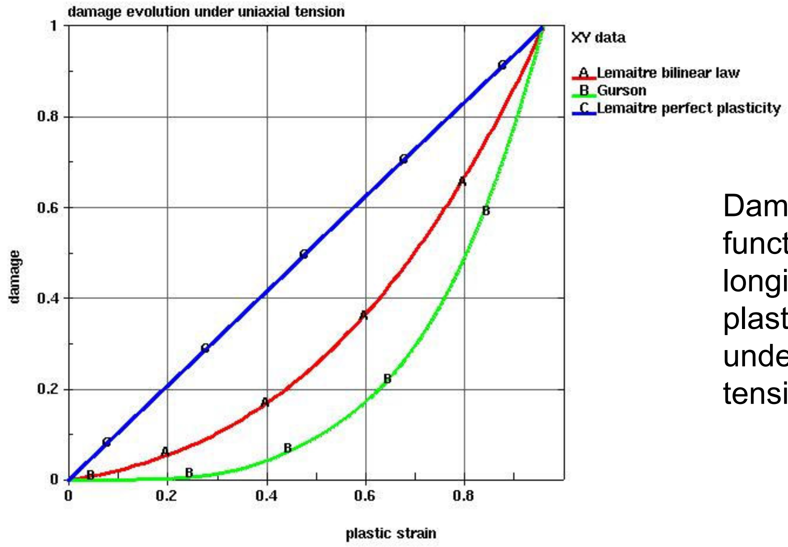
Damage Models in LS-DYNA

	DAMAGE EVOLUTION	Path dependent	Non-proportional loading
MAT_81	$d = d(\varepsilon_p)$	yes	no
MAT_81	$d = \int_{\varepsilon_{pd}}^{\varepsilon_p} d_c \frac{d\varepsilon_p}{\varepsilon_{pr} - \varepsilon_{pd}}$	yes	no
MAT_105	$d = \int_{\varepsilon_{pd}}^{\varepsilon_p} \frac{\sigma_{vm}^2 \left(\frac{2}{3}(1+\nu) + 3(1-2\nu)\left(\frac{\sigma_H}{\sigma_{vm}}\right)^2 \right)}{2E(1-d)^2 S} d\varepsilon_p$	yes	yes

Damage Models in LS-DYNA

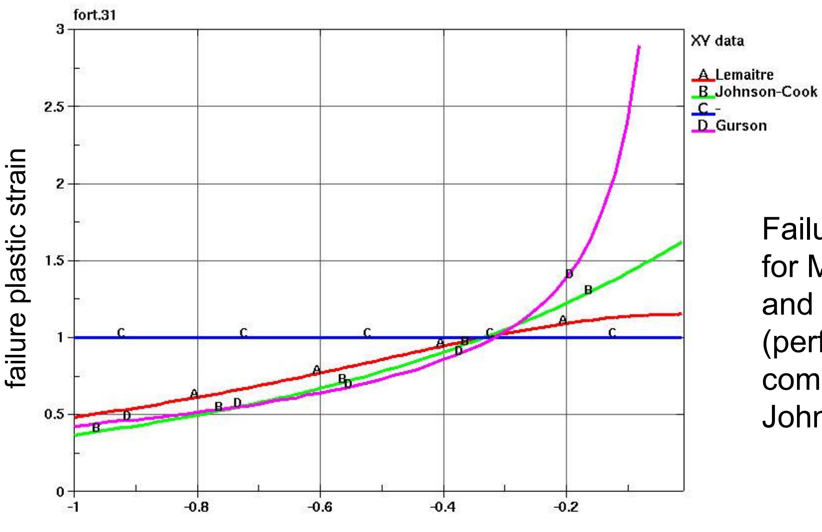
	Damage Evolution	Path dependent	Non-proportional loading
MAT_187	$d = d(\varepsilon_p)$ $d \le d_c$	yes	no/yes
MAT_120	$f = f_0 + \int (1-d)\dot{\varepsilon}_{vp} + \int \frac{f_N}{s_N\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{\varepsilon_p - \varepsilon_N}{s_N}\right)^2} \dot{\varepsilon}_p$ $f^* = \begin{cases} f & f \le f_c \\ f_c + \frac{\frac{1}{q_1} - f_c}{f_F - f_c}(f - f_c) & f > f_c \end{cases}$ $d := q_1 f^*(f_F) \le d_c = 1$	yes	yes

Damage Models in LS-DYNA



Damage in function of longitudinal plastic strain under uniaxial tension

Damage Models in LS-DYNA



Failure plastic strain for MAT_81 and MAT_105 (perfect plasticity), compared to Johnson-Cook

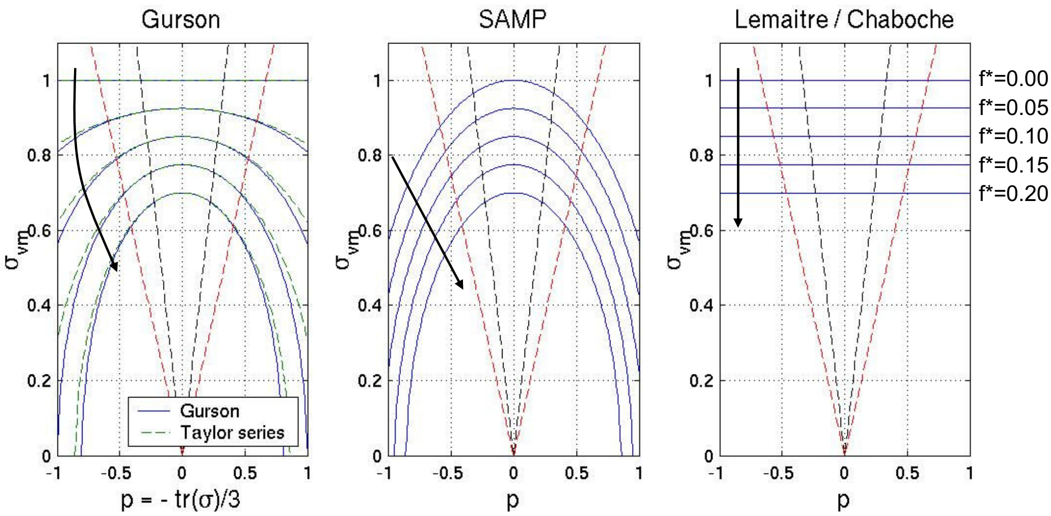
Damage Models in LS-DYNA

	Damaged yield function
MAT_81 Mat_105	$\Phi = \frac{\sigma_{vm}}{(1-d)} - \sigma_{y,eff}\left(\varepsilon_{p,eff}\right)$ $\Phi = \sigma_{vm}^2 - (1-d)^2\,\sigma_{y,eff}^2\left(\varepsilon_{p,eff}\right)$
MAT_120	$\Phi = \frac{\sigma_{vm}^2}{\sigma_{y,eff}^2} + 2q_1 f^* \cosh\left(\frac{q_2(-3p)}{2\sigma_{y,eff}}\right) - 1 - q_1^2 f^{*2}$ $\cosh x \approx 1 + \frac{x^2}{2}$ $\Phi = \sigma_{vm}^2 + q_1 f^* q_2^2 \frac{9}{4} p^2 - (1 - q_1 f^*)^2\,\sigma_{y,eff}^2$

Damage Models in LS-DYNA

	Damaged yield function
MAT_187	$\Phi = \sigma_{vm}^2 - A_2 p^2 - (1-d)A_1 p - (1-d)^2 A_0$
MAT_120	$\Phi = \sigma_{vm}^2 + q_1 f^* q_2^2 \frac{9}{4} p^2 - (1 - q_1 f^*)^2\,\sigma_{y,eff}^2$ $\Phi = \sigma_{vm}^2 + d q_2^2 \frac{9}{4} p^2 - (1-d)^2\,\sigma_{y,eff}^2$ $A_0 = \sigma_{y,eff}^2 \quad A_1 = 0$ $A_2 = -d q_2^2 \frac{9}{4} = -q_1 f^* q_2^2 \frac{9}{4} \neq const$

Damage Models in LS-DYNA



Evolution of the yield surface in function of damage in invariant plane

The Damage Model(s) in SAMP

- All dependencies are tabulated
- Damage curve as a function of equivalent plastic strain allows to fit experimentally determined unloading moduli at different values of plastic deformation
- Damage curve is combined with a hardening curve giving effective yield stress in function of effective equivalent plastic strain
- For LCID_D>0 effective stress values are provided by the user in the hardening curve
- For LCID_D<0 true stress values are provided by the user in the hardening curve and the conversion to effective values is done automatically in the code

Damage Model in SAMP

Evolution law for damage variable and failure variable :

$$d = \int \frac{\partial d}{\partial \varepsilon_p^t} \frac{d\left(\varepsilon_{pf}^t(0)\right)}{d\left(\varepsilon_{pf}^t(\dot{\varepsilon}_p^t)\, f\left(\frac{p}{\sigma_{vm}}\right)\right)} d\varepsilon_p^t \qquad f\left(-\frac{1}{3}\right) = 1$$

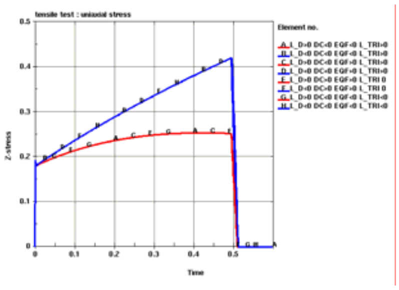
For quasistatic uniaxial tension :

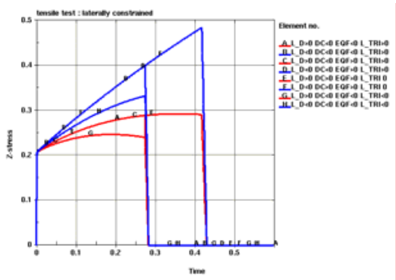
$$d = \int \frac{\partial d}{\partial \varepsilon_p^t} \frac{d\left(\varepsilon_{pf}^t(0)\right)}{d\left(\varepsilon_{pf}^t(0)\, f\left(-\frac{1}{3}\right)\right)} d\varepsilon_p^t = d\left(\varepsilon_p^t\right)$$

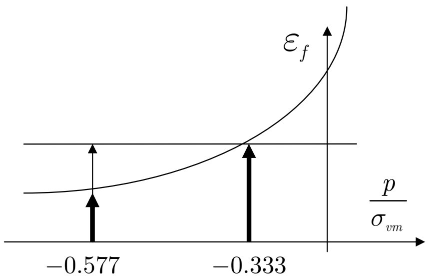
Damage Model(s) in SAMP

EQFAIL	damage	failure
>0	$d = d(\varepsilon_p^t)$	$d = d(\varepsilon_p^t) \le d_c$
>0	$d = d(\varepsilon_p^t)$	$d = d(\varepsilon_p^t) \le d_c(\dot{\varepsilon}_p^t)\, f\left(\frac{p}{\sigma_{vm}}\right)$
<0	$d = d(\varepsilon_p^t)$	$d = \int \frac{d\left(\varepsilon_{pf}^t(0)\right)}{d\left(\varepsilon_{pf}^t(\dot{\varepsilon}_p^t)\, f\left(\frac{p}{\sigma_{vm}}\right)\right)} \frac{\partial d}{\partial \varepsilon_p^t} d\varepsilon_p^t \le d\left(\varepsilon_{pf}^t(0)\right)$
<0	$d = \int \frac{d\left(\varepsilon_{pf}^t(0)\right)}{d\left(\varepsilon_{pf}^t(\dot{\varepsilon}_p^t)\, f\left(\frac{p}{\sigma_{vm}}\right)\right)} \frac{\partial d}{\partial \varepsilon_p^t} d\varepsilon_p^t$	$d = \int \frac{d\left(\varepsilon_{pf}^t(0)\right)}{d\left(\varepsilon_{pf}^t(\dot{\varepsilon}_p^t)\, f\left(\frac{p}{\sigma_{vm}}\right)\right)} \frac{\partial d}{\partial \varepsilon_p^t} d\varepsilon_p^t \le d\left(\varepsilon_{pf}^t(0)\right)$

Verification: Proportional Loading Uniaxial Tension with/without Confinement



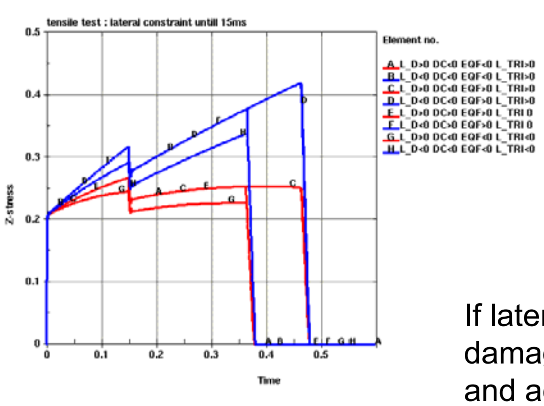


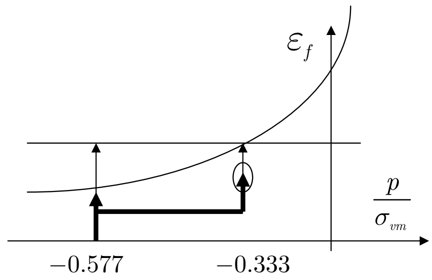


All 4 models yield identical results under uniaxial tension

If lateral motion is confined, accumulated damage (LC_TRI<0) yields lower stress and accumulated failure (EQFAIL<0) gives lower rupture strain

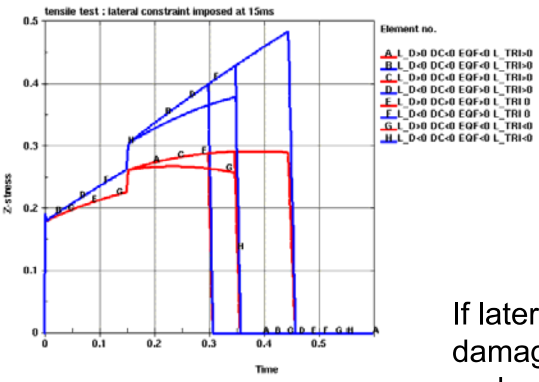
Verification for Non-Proportional Loading: Uniaxial Tension, Confinement lifted at 15ms

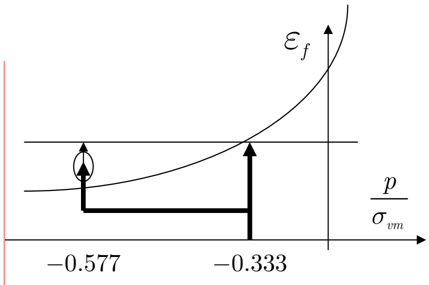




If lateral motion is confined, accumulated damage (LC_TRI<0) yields lower stress and accumulated failure (EQFAIL<0) gives lower rupture strain

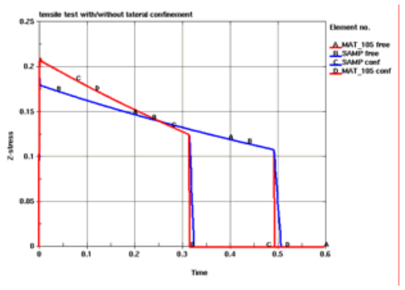
Verification for Non-Proportional Loading: Uniaxial Tension, Confinement applied at 15ms

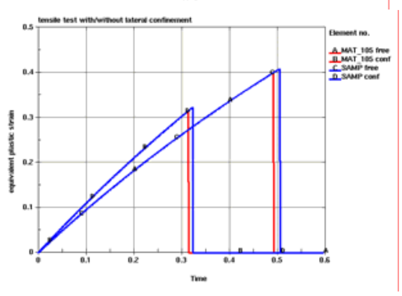


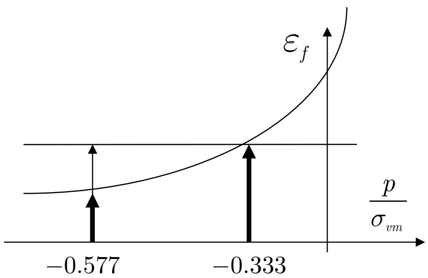


If lateral motion is confined, accumulated damage (LC_TRI<0) yields lower stress and accumulated failure (EQFAIL<0) gives lower rupture strain

Verification : Proportional Loading Comparison SAMP-MAT_105



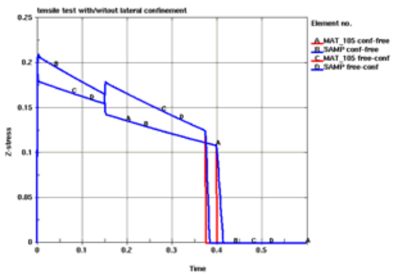


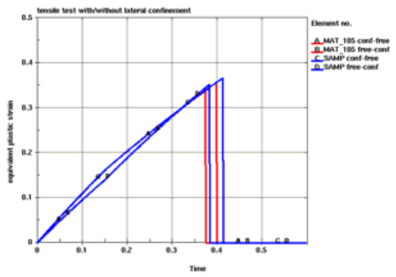


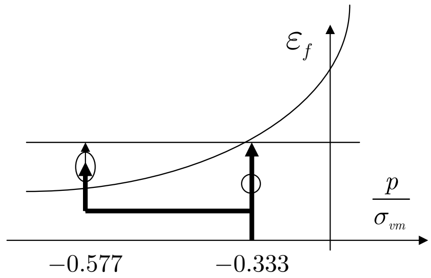
SAMP gives identical results to the damage/failure model of Lemaitre

only difference is in the fade-out

Verification for Non-Proportional Loading : Comparison SAMP-MAT_105



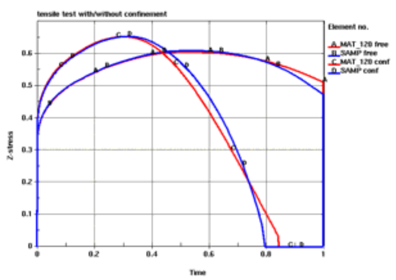


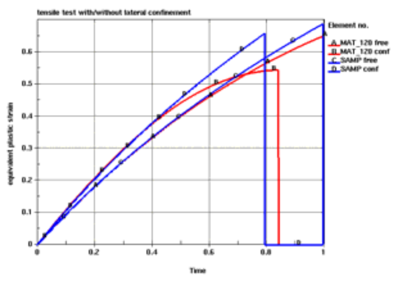


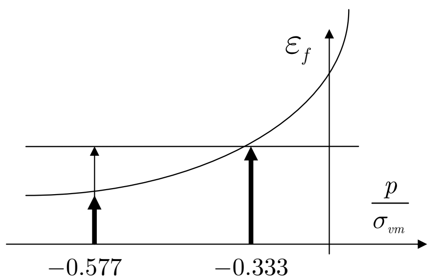
SAMP gives identical results to the damage/failure model of Lemaitre

only difference is in the fade-out

Verification : Proportional Loading Comparison SAMP-MAT_120

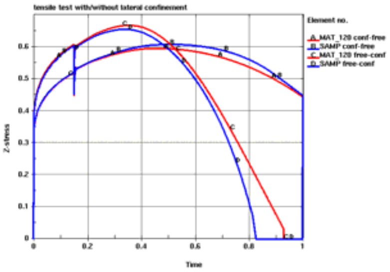


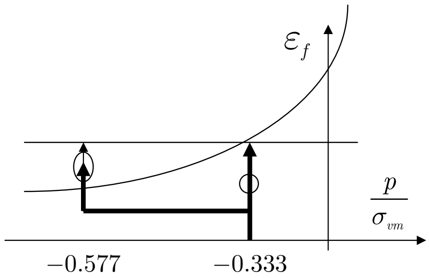


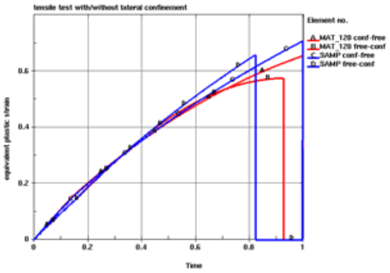


SAMP gives good approximation to the damage/failure model of Gurson

Verification for Non-Proportional Loading: Comparison SAMP-MAT_120







SAMP gives good approximation to the damage/failure model of Gurson

Conclusions (Damage)

- A generalized damage formulation has been implemented for SAMP
- Input is fully tabulated
- Existing damage models can largely be recovered (Lemaitre, Chaboche, Gurson among others)
- Considerable flexibility to fit experimental data from tests with unloading or failure
- Will be implemented in MAT_187 next