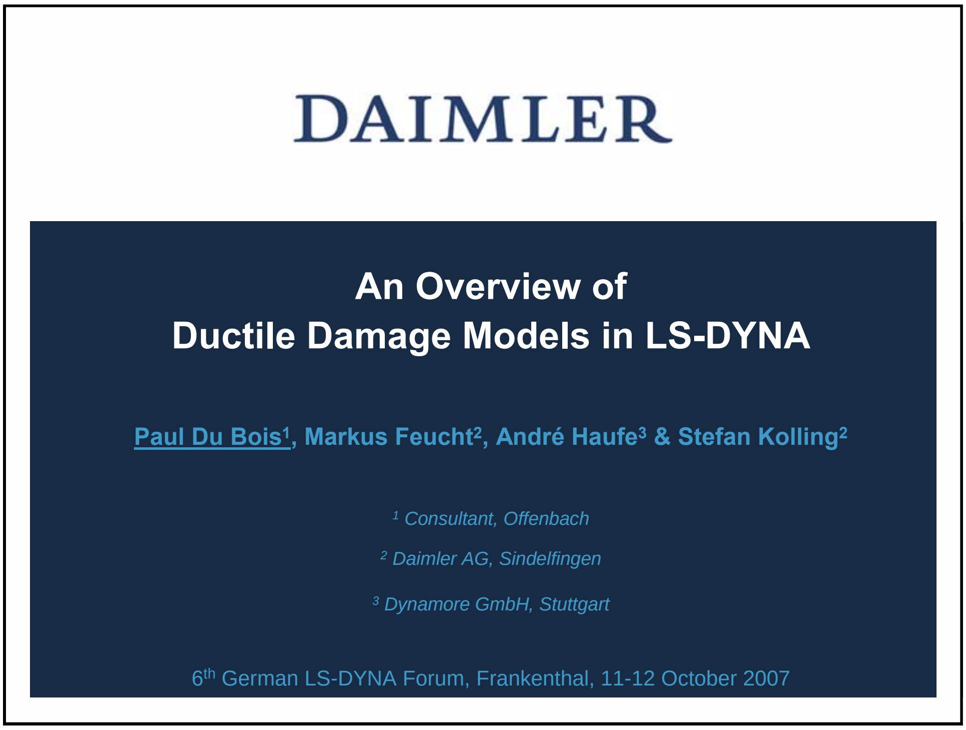

An Overview of Ductile Damage Models in LS-DYNA

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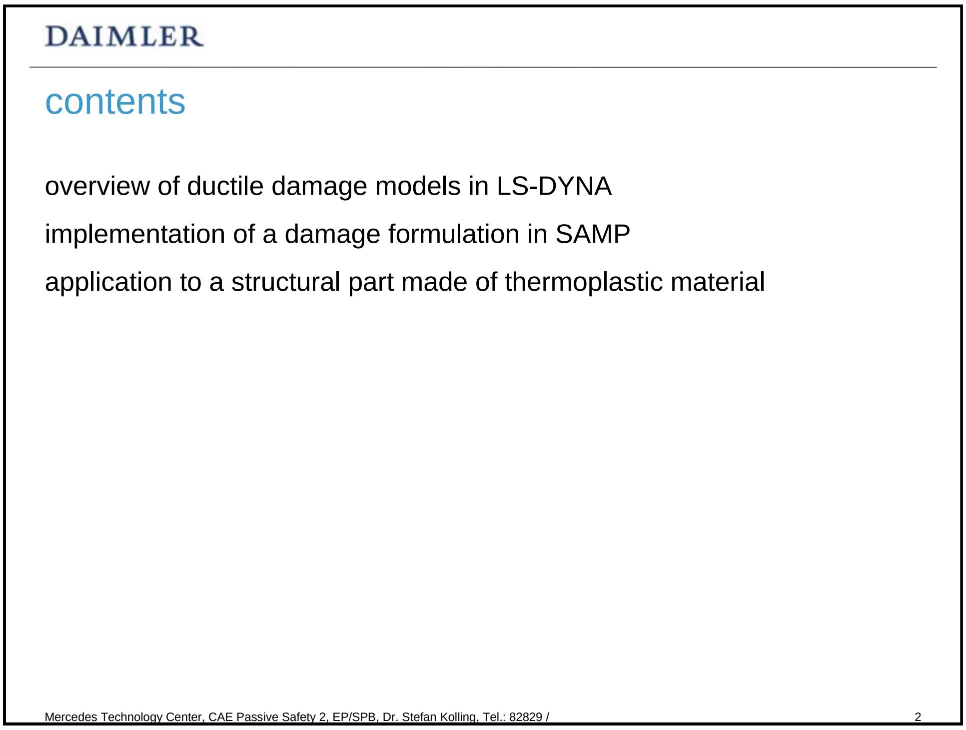
6th German LS-DYNA Forum, Frankenthal, 11-12 October 2007

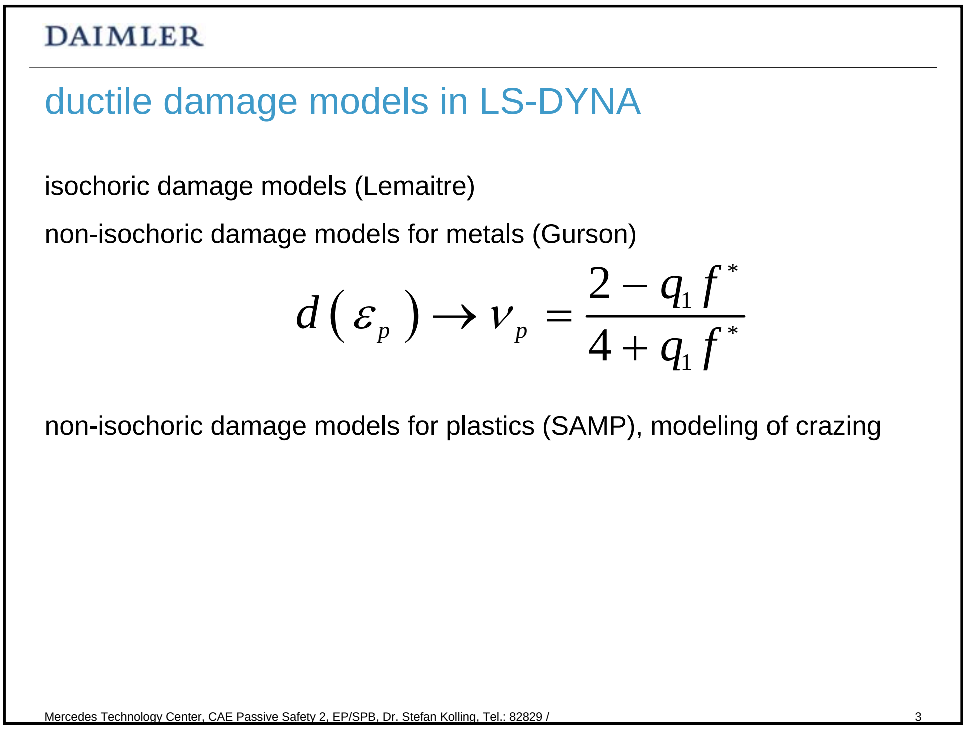


contents

overview of ductile damage models in LS-DYNA

implementation of a damage formulation in SAMP

application to a structural part made of thermoplastic material



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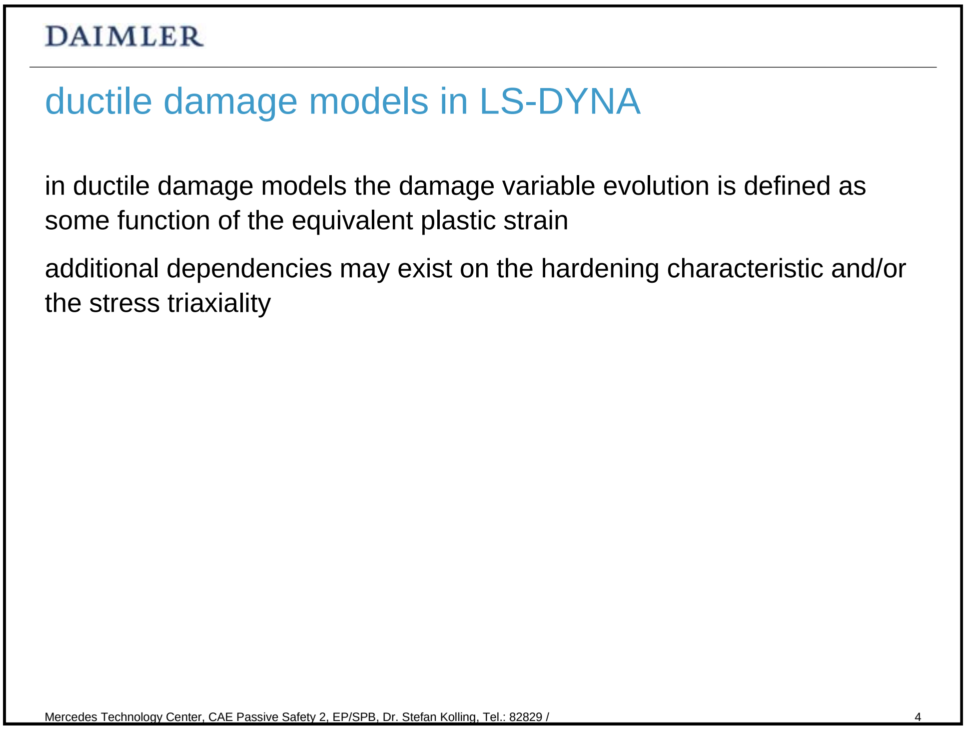
ductile damage models in LS-DYNA

isochoric damage models (Lemaitre)

non-isochoric damage models for metals (Gurson)

$$d\left(\varepsilon_p\right) \rightarrow \nu_p = \frac{2 - q_1 f^*}{4 + q_1 f^*}$$

non-isochoric damage models for plastics (SAMP), modeling of crazing



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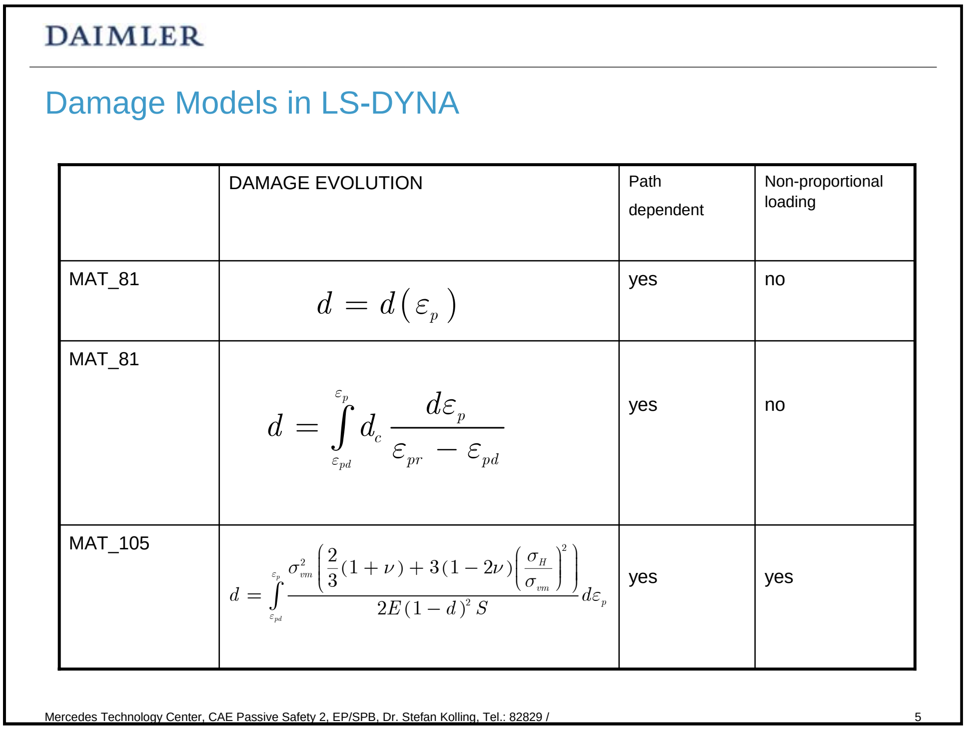
ductile damage models in LS-DYNA

in ductile damage models the damage variable evolution is defined as some function of the equivalent plastic strain

additional dependencies may exist on the hardening characteristic and/or the stress triaxiality



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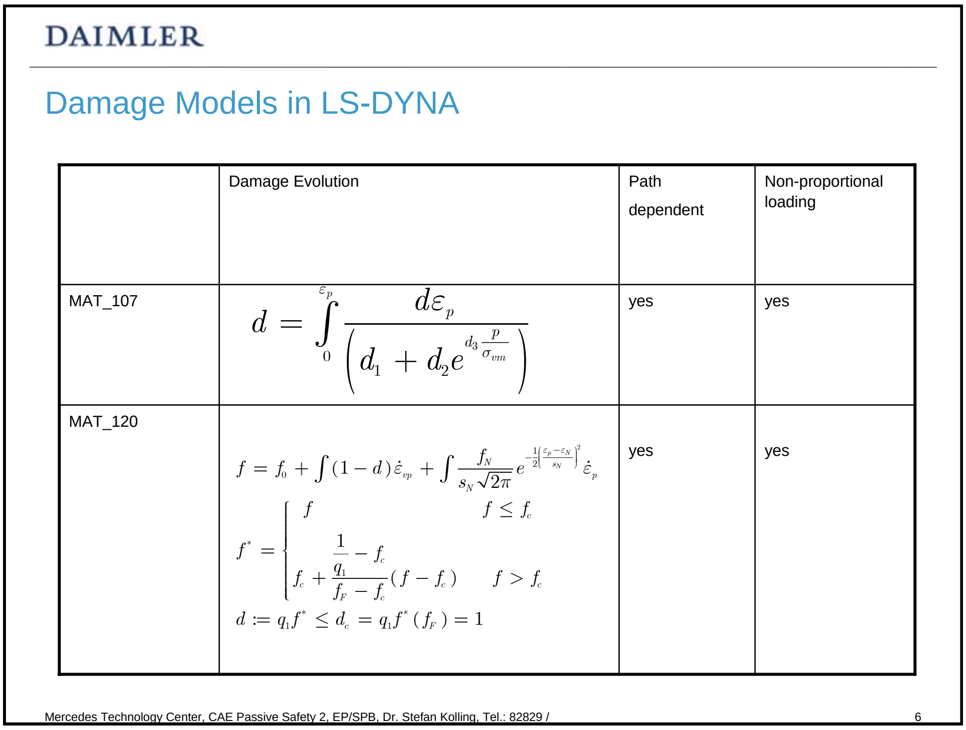
Damage Models in LS-DYNA

	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



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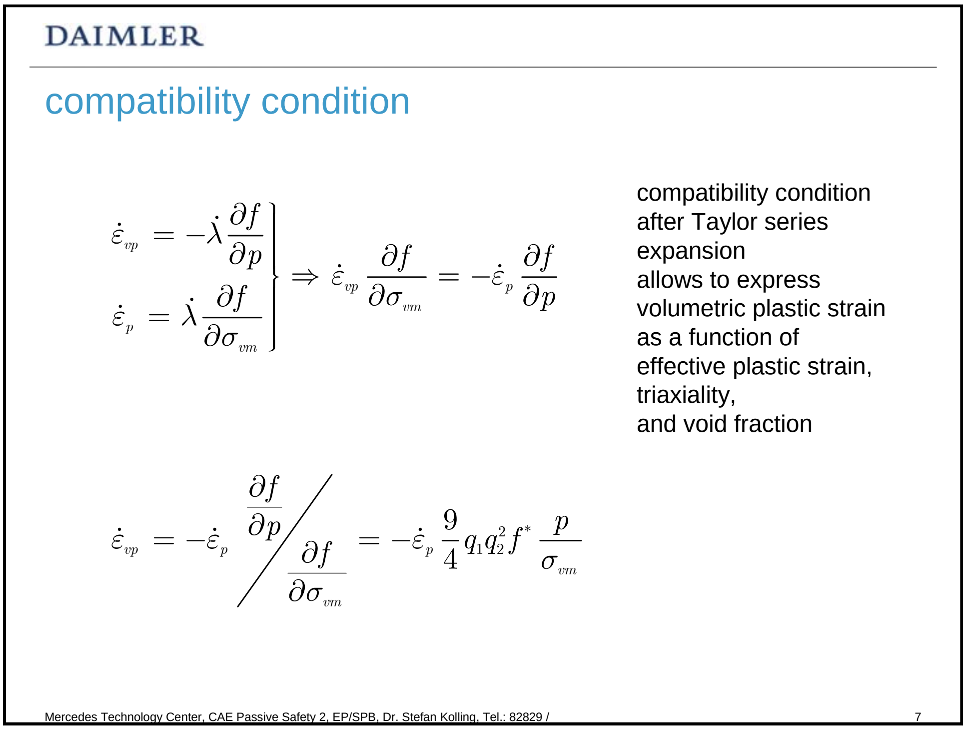
Damage Models in LS-DYNA

	Damage Evolution	Path dependent	Non-proportional loading
MAT_107	$d = \int_0^{\varepsilon_p} \frac{d\varepsilon_p}{\left(d_1 + d_2 e^{d_3 \frac{p}{\sigma_{vm}}}\right)}$	yes	yes
MAT_120	$f = f_0 + \int (1-d)\dot{\varepsilon}_{vp} + \int \frac{f_N}{s_N\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{\varepsilon_p - \varepsilon_N}{s_N}\right)^2} \dot{\varepsilon}_p$ $f^* = \begin{cases} f & f \le f_c \\ f_c + \frac{\frac{1}{q_1} - f_c}{f_F - f_c}(f - f_c) & f > f_c \end{cases}$ $d := q_1 f^* \le d_c = q_1 f^*(f_F) = 1$	yes	yes



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compatibility condition

$$\left.\begin{aligned}\dot{\varepsilon}_{vp} &= -\dot{\lambda}\frac{\partial f}{\partial p}\\ \dot{\varepsilon}_{p} &= \dot{\lambda}\frac{\partial f}{\partial \sigma_{vm}}\end{aligned}\right\} \Rightarrow \dot{\varepsilon}_{vp}\frac{\partial f}{\partial \sigma_{vm}} = -\dot{\varepsilon}_{p}\frac{\partial f}{\partial p}$$

compatibility condition
after Taylor series
expansion
allows to express
volumetric plastic strain
as a function of
effective plastic strain,
triaxiality,
and void fraction

$$\dot{\varepsilon}_{vp} = -\dot{\varepsilon}_{p}\left.\frac{\partial f}{\partial p}\middle/\frac{\partial f}{\partial \sigma_{vm}}\right. = -\dot{\varepsilon}_{p}\frac{9}{4}q_1 q_2^2 f^* \frac{p}{\sigma_{vm}}$$

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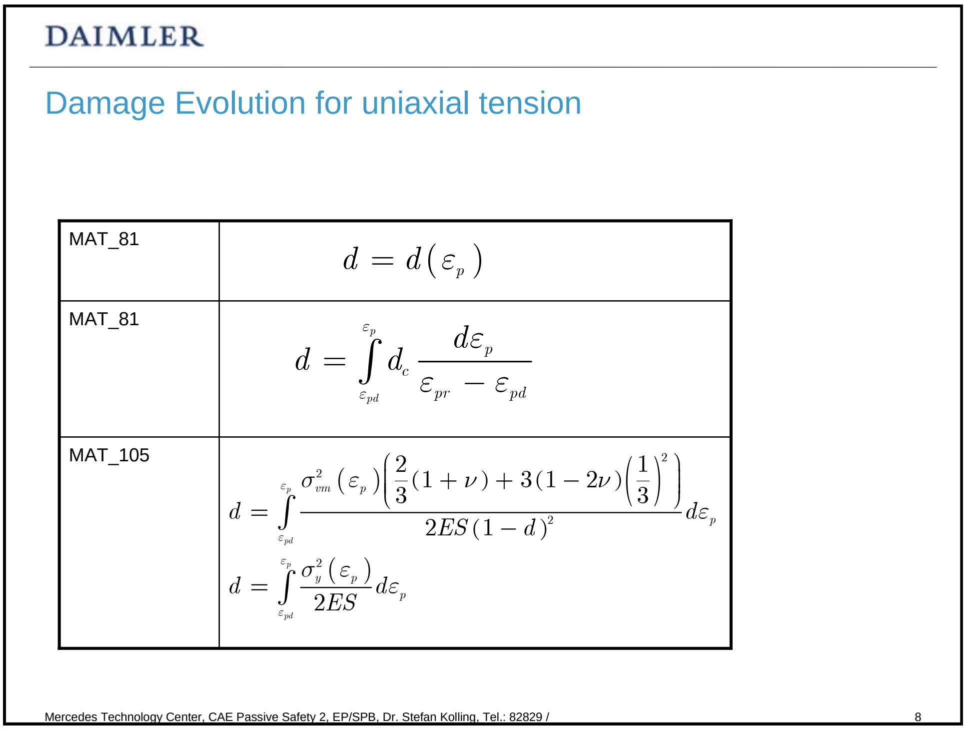

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Damage Evolution for uniaxial tension

MAT_81	$d = d(\varepsilon_p)$
MAT_81	$d = \int_{\varepsilon_{pd}}^{\varepsilon_p} d_c \frac{d\varepsilon_p}{\varepsilon_{pr} - \varepsilon_{pd}}$
MAT_105	$d = \int_{\varepsilon_{pd}}^{\varepsilon_p} \frac{\sigma_{vm}^2(\varepsilon_p)\left(\frac{2}{3}(1+\nu) + 3(1-2\nu)\left(\frac{1}{3}\right)^2\right)}{2ES(1-d)^2} d\varepsilon_p$ $d = \int_{\varepsilon_{pd}}^{\varepsilon_p} \frac{\sigma_y^2(\varepsilon_p)}{2ES} d\varepsilon_p$

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Damage Evolution for uniaxial tension

MAT_107	$d = \frac{1}{\left(d_1 + d_2 e^{-d_3 \frac{1}{3}}\right)} \int_0^{\varepsilon_p} d\varepsilon_p$
MAT_120	$f \approx f_0 + \int -(1-f) q_1 f^* q_2^2 \frac{9}{4} \frac{p}{\sigma_{vm}} \dot{\varepsilon}_p + \int \frac{f_N}{s_N \sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{\varepsilon_p - \varepsilon_N}{s_N}\right)^2} \dot{\varepsilon}_p$ $f^* = \begin{cases} f & f \le f_c \\ f_c + \frac{\frac{1}{q_1} - f_c}{f_F - f_c}(f - f_c) & f > f_c \end{cases}$ $d = q_1 f^* \le 1$

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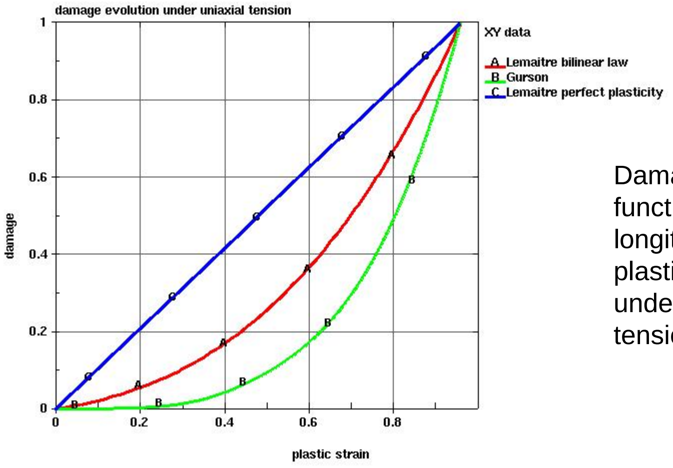
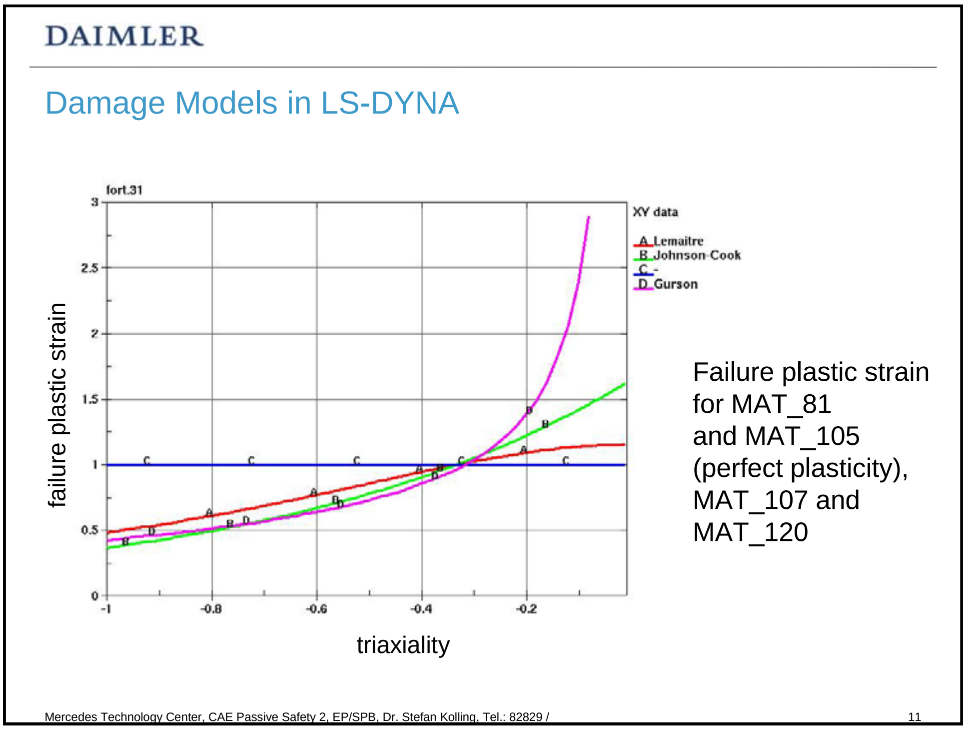
Damage Evolution for uniaxial tension



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),
MAT_107 and
MAT_120

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SAMP damage model

$$\varepsilon_{pf} = DC(\dot{\varepsilon}_{pt})\, LCID\_TRI\left(\frac{p}{\sigma_{vm}}\right) LCID\_LC(l_c)$$

$$\varepsilon_{ptf0} = DC(0)$$

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

$$LCID\_LC(l_{c0}) = 1$$

User defines the plastic strain at failure as a function of plastic strain rate, stress triaxiality and characteristic element length using up to 3 loadcurves

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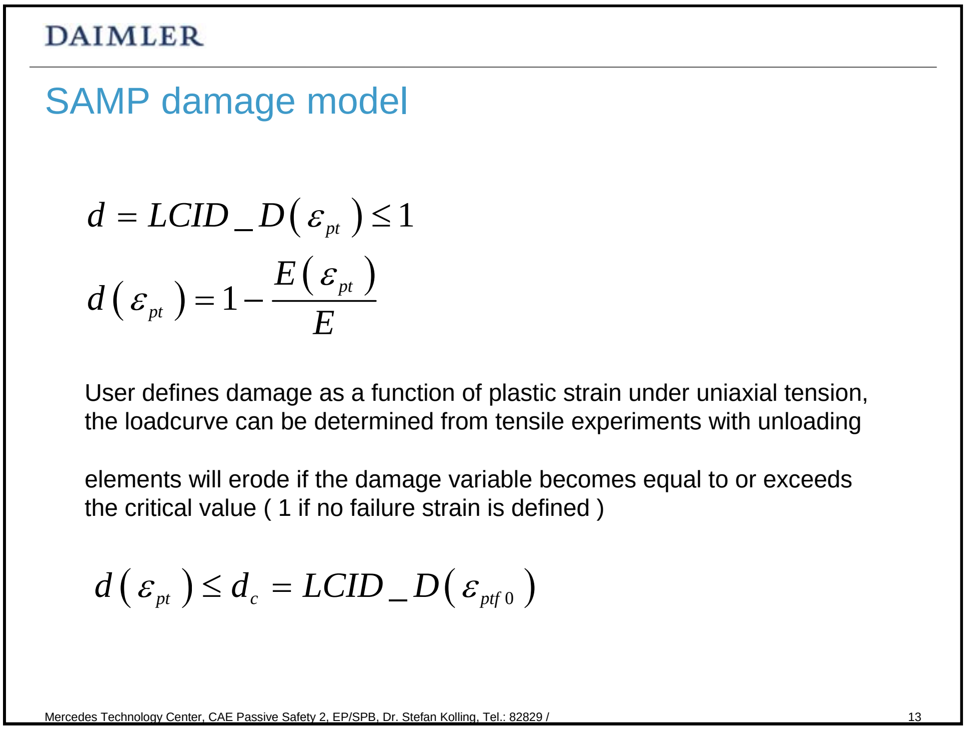


SAMP damage model

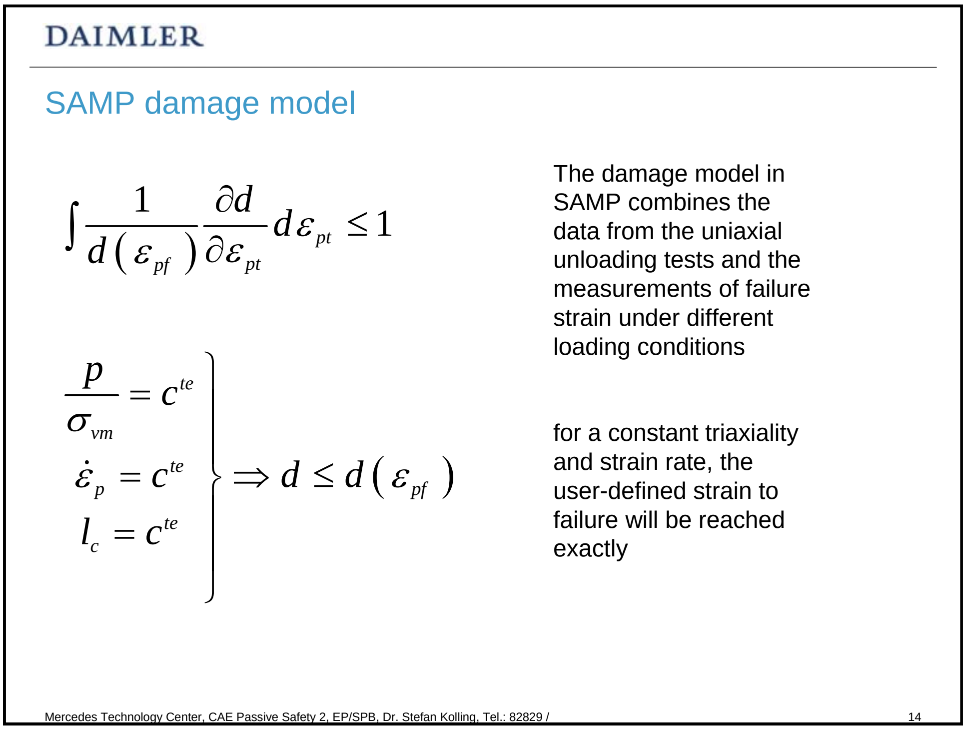
$$d = LCID\_D(\varepsilon_{pt}) \le 1$$

$$d(\varepsilon_{pt}) = 1 - \frac{E(\varepsilon_{pt})}{E}$$

User defines damage as a function of plastic strain under uniaxial tension, the loadcurve can be determined from tensile experiments with unloading

elements will erode if the damage variable becomes equal to or exceeds the critical value (1 if no failure strain is defined)

$$d(\varepsilon_{pt}) \le d_c = LCID\_D(\varepsilon_{ptf0})$$



SAMP damage model

$$\int \frac{1}{d(\varepsilon_{pf})} \frac{\partial d}{\partial \varepsilon_{pt}} d\varepsilon_{pt} \le 1$$

The damage model in SAMP combines the data from the uniaxial unloading tests and the measurements of failure strain under different loading conditions

$$\left.\begin{array}{l} \dfrac{p}{\sigma_{vm}} = c^{te} \\ \dot{\varepsilon}_p = c^{te} \\ l_c = c^{te} \end{array}\right\} \Rightarrow d \le d(\varepsilon_{pf})$$

for a constant triaxiality and strain rate, the user-defined strain to failure will be reached exactly

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SAMP damage model

SAMP allows to emulate most other damage models by using adequate load curves

in MAT_120 volumetric plastic strain will occur as a consequence of the damage model

in SAMP the plastic Poisson ratio is defined as an extra load curve which directly defines the plastic flow surface

single element tests illustrate the equivalence of different approaches

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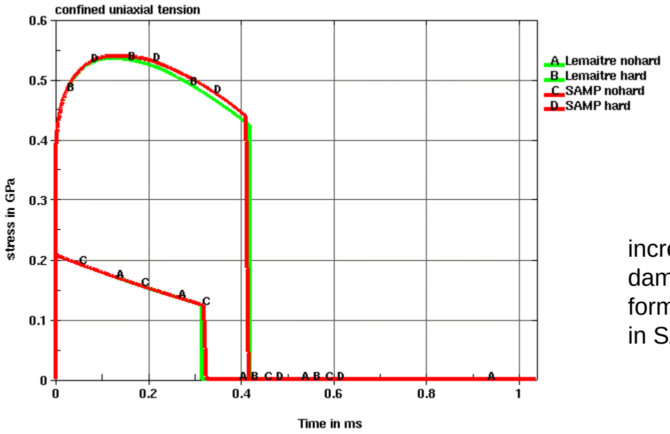
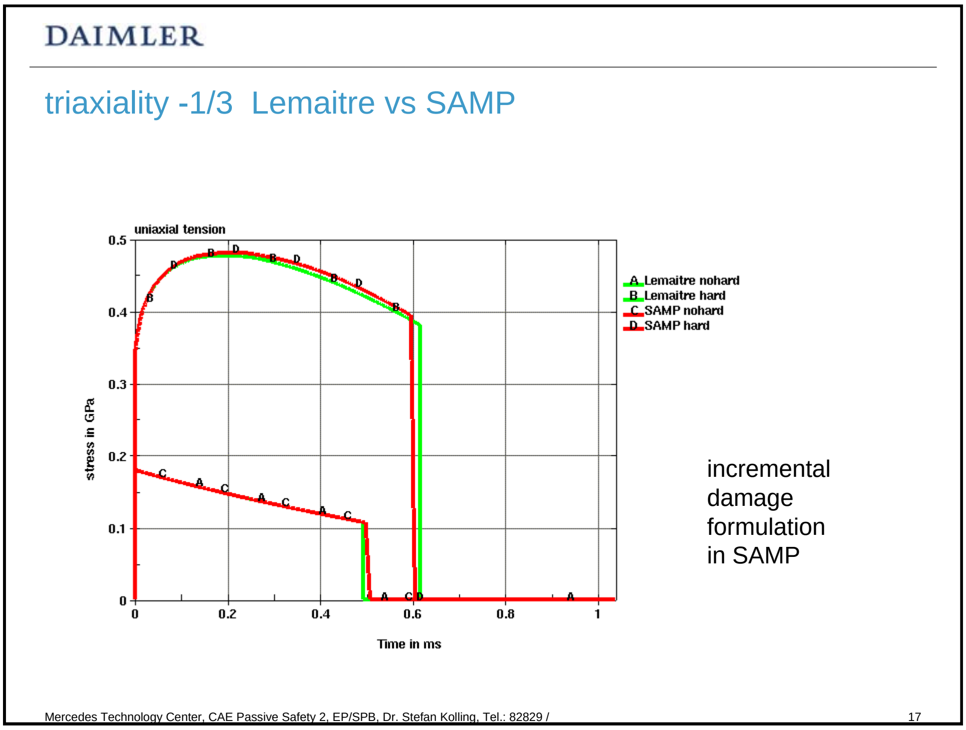
triaxiality -1/sqrt(3) Lemaitre vs SAMP



incremental damage formulation in SAMP



triaxiality -1/3 Lemaitre vs SAMP

incremental
damage
formulation
in SAMP

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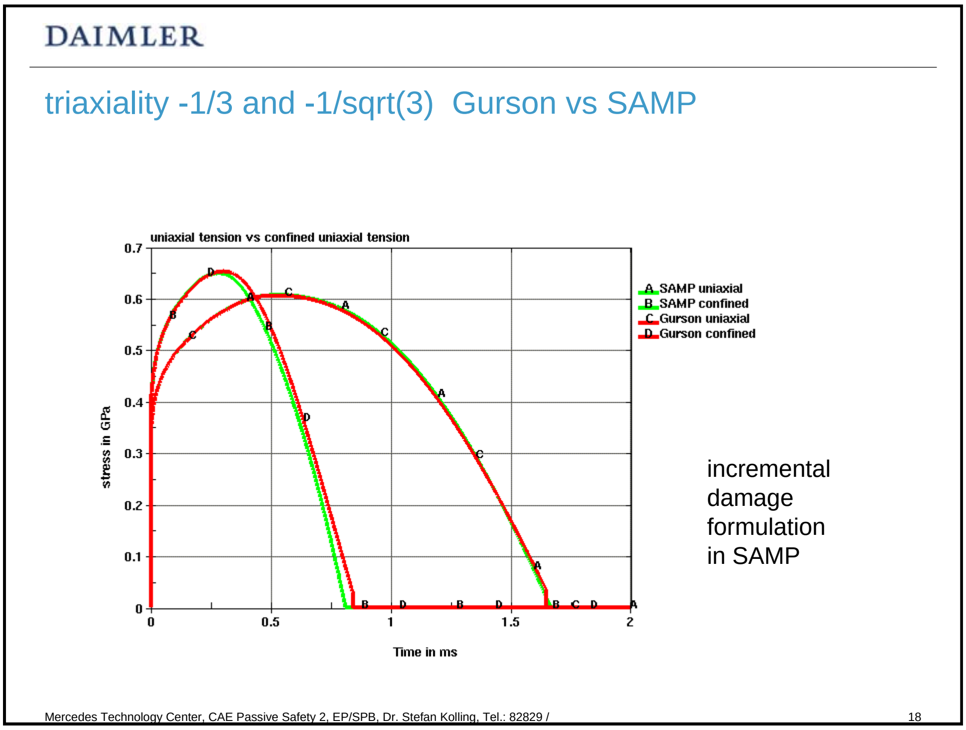

triaxiality -1/3 and -1/sqrt(3) Gurson vs SAMP

incremental
damage
formulation
in SAMP

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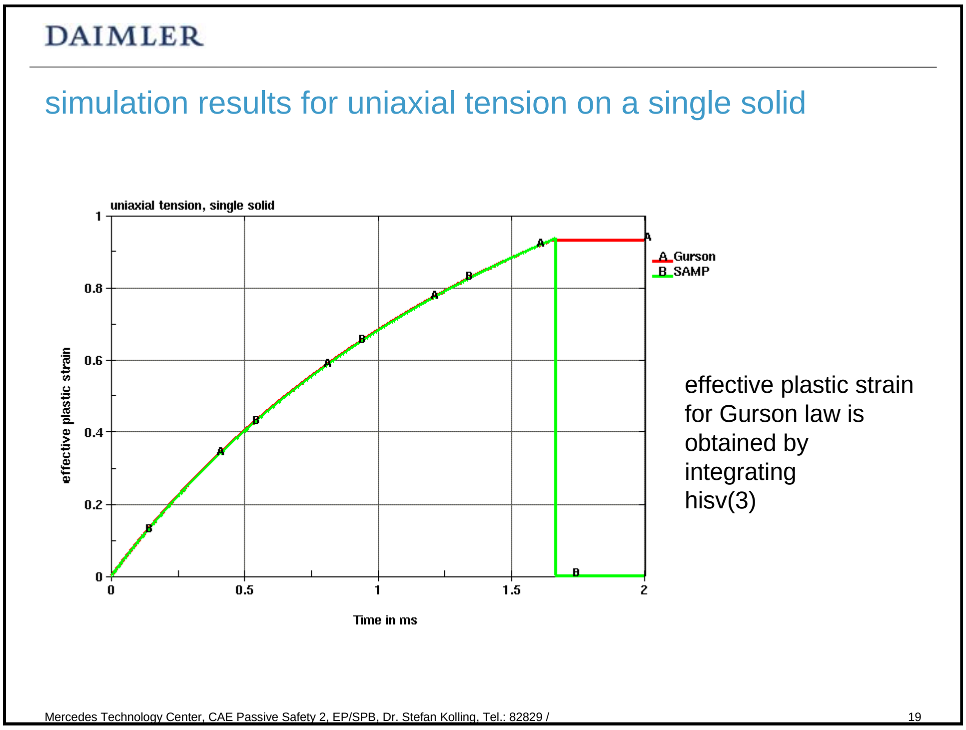

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simulation results for uniaxial tension on a single solid

effective plastic strain for Gurson law is obtained by integrating hisv(3)

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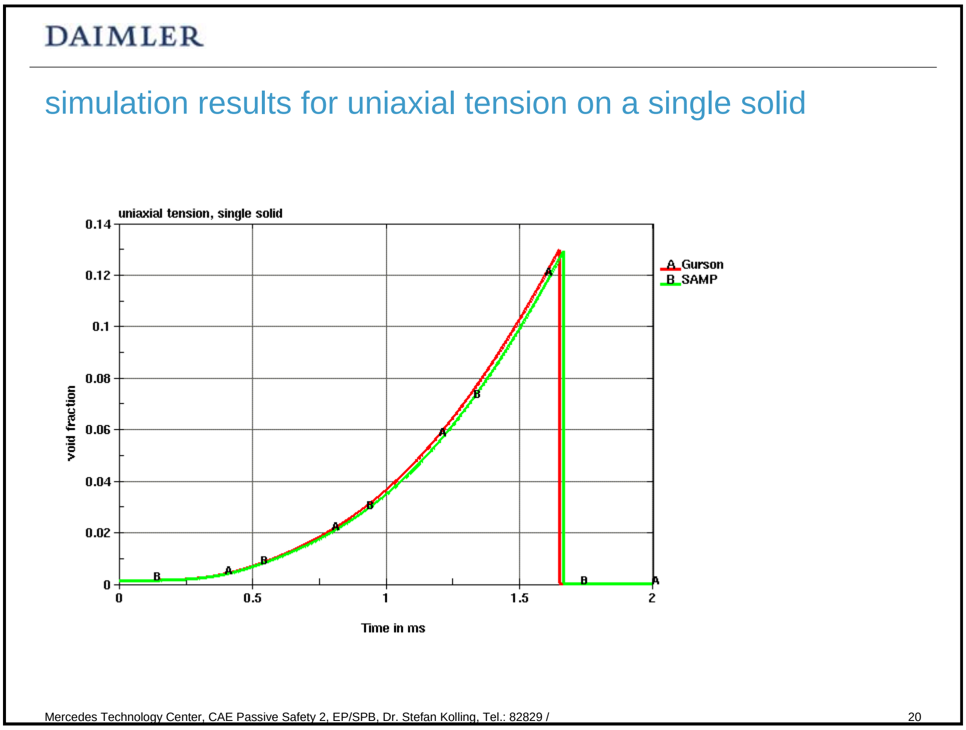

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simulation results for uniaxial tension on a single solid

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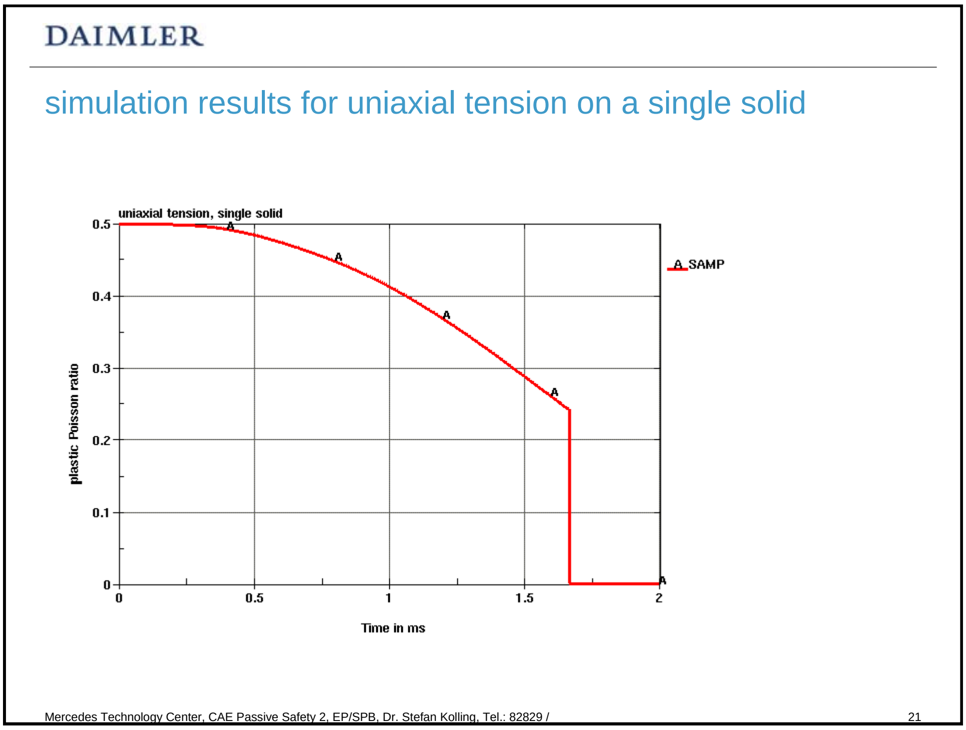

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simulation results for uniaxial tension on a single solid

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thermoplastics

bending strength of a plastic panel is higher then predicted by elasto-plastic properties derived from uniaxial tensile test

due to high compressive strength :

$$\sigma_c(\lambda) > \sigma_t(\lambda)$$

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thermoplastics

decreasing unloading modulus with increasing equivalent plastic strain

a load curve giving damage evolution for uniaxial tensile conditions can be derived from testing with unloading :

$$d\left(\varepsilon_p\right) = 1 - \frac{E\left(\varepsilon_p\right)}{E}$$

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thermoplastics

white zones indicate craze deformations in zones of localisation (caused by reduced biaxial strength)

crazing corresponds to permanent positive volumetric strain

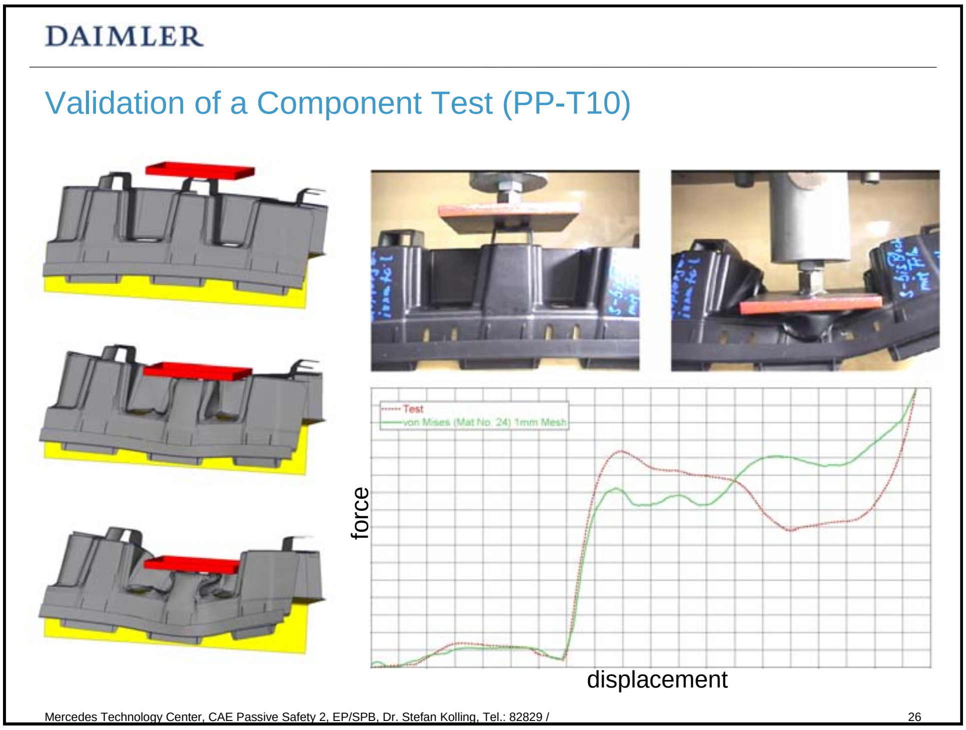
$$\nu_p\left(\lambda\right) < \frac{1}{2} \qquad \sigma_b\left(\lambda\right) < \sigma_t\left(\lambda\right)$$

thermoplastics

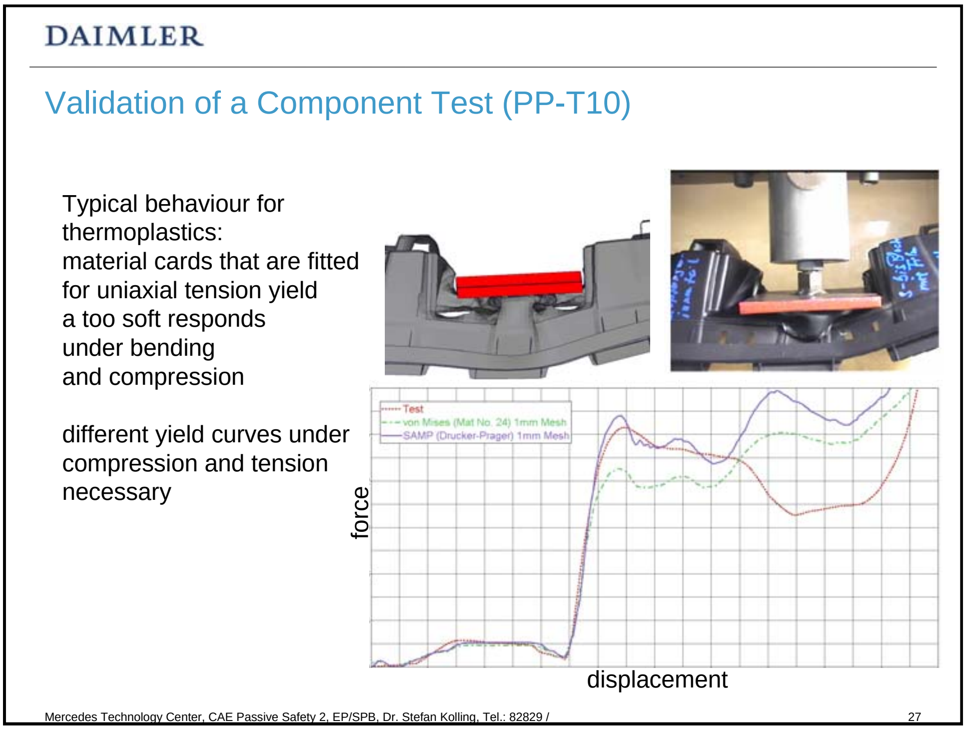
plastic strain at failure depends upon strain rate and state of stress

separable as a first approximation

$$\varepsilon_{pf} = f\left(\dot{\varepsilon}_p\right) g\left(\frac{p}{\sigma_{vm}}\right)$$



Validation of a Component Test (PP-T10)



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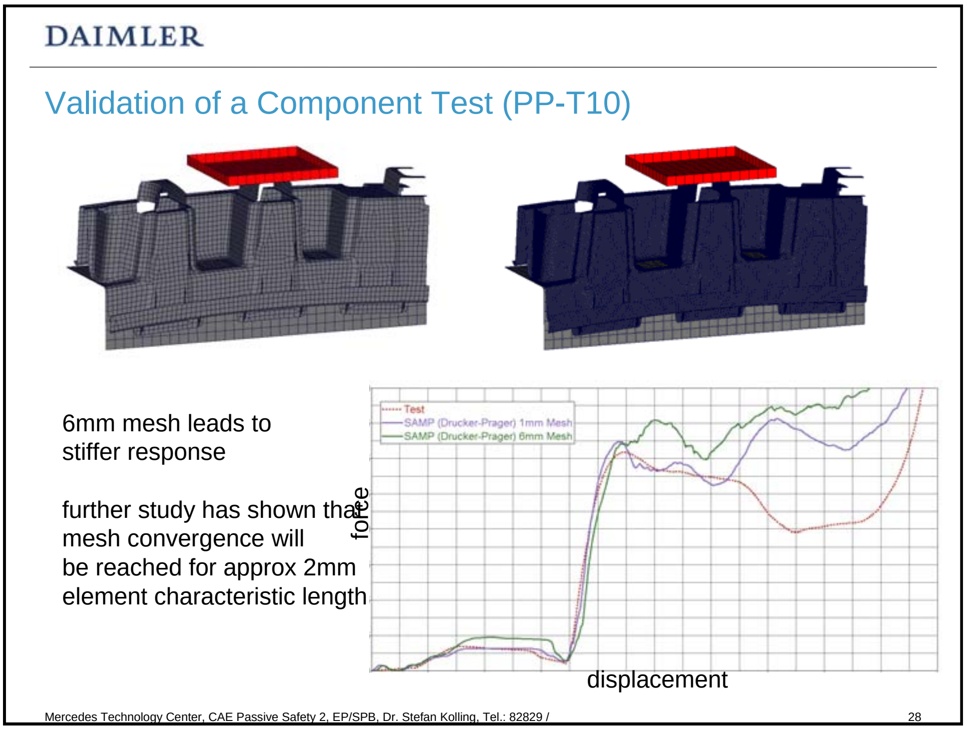
Validation of a Component Test (PP-T10)

Typical behaviour for thermoplastics:
material cards that are fitted for uniaxial tension yield a too soft responds under bending and compression

different yield curves under compression and tension necessary



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Validation of a Component Test (PP-T10)

6mm mesh leads to stiffer response

further study has shown that mesh convergence will be reached for approx 2mm element characteristic length

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Simulation of Crazing

plastic Poisson’s ratio decreases with increasing plastic strain

plastic incompressibility under compression

reduced biaxial strength

damage evolution

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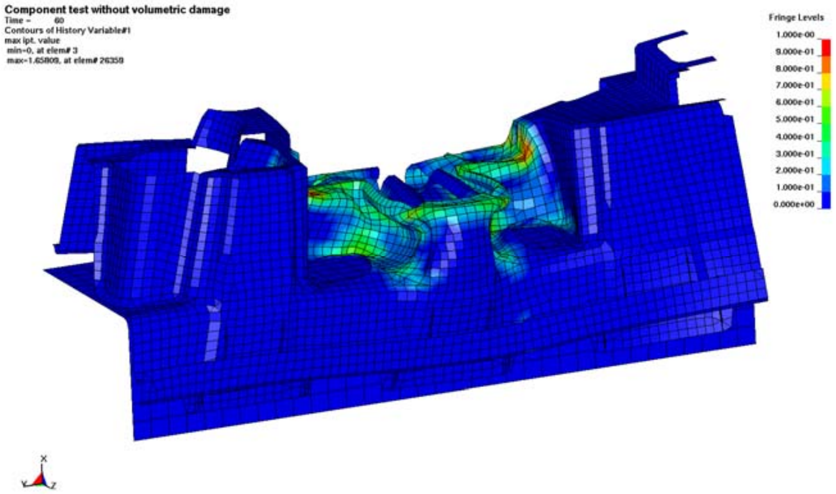
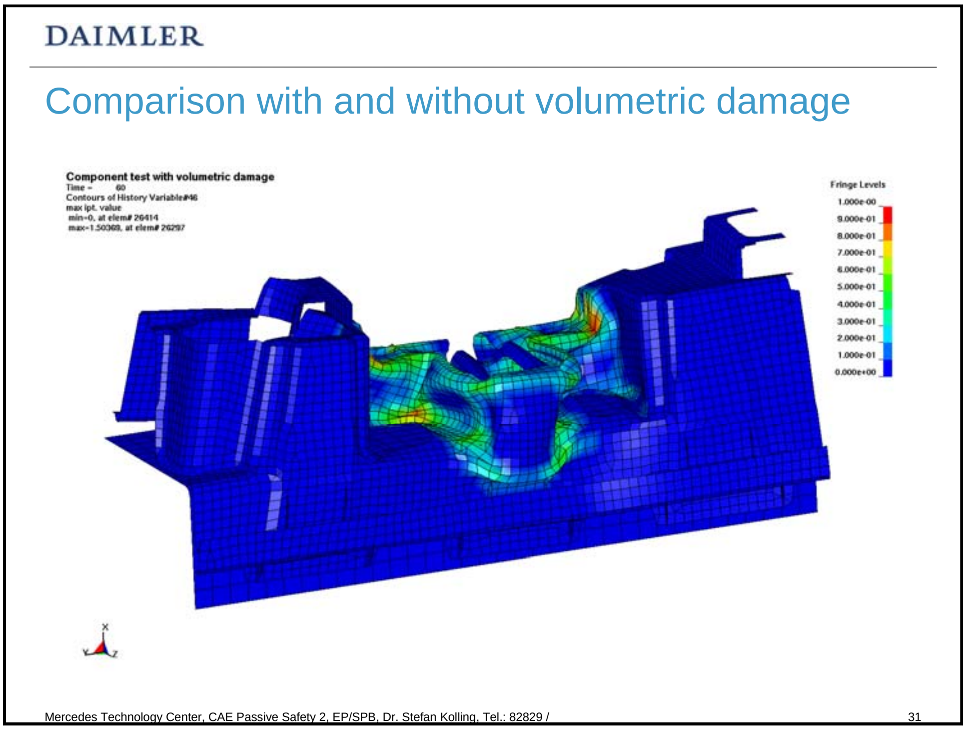
Comparison with and without volumetric damage





Comparison with and without volumetric damage

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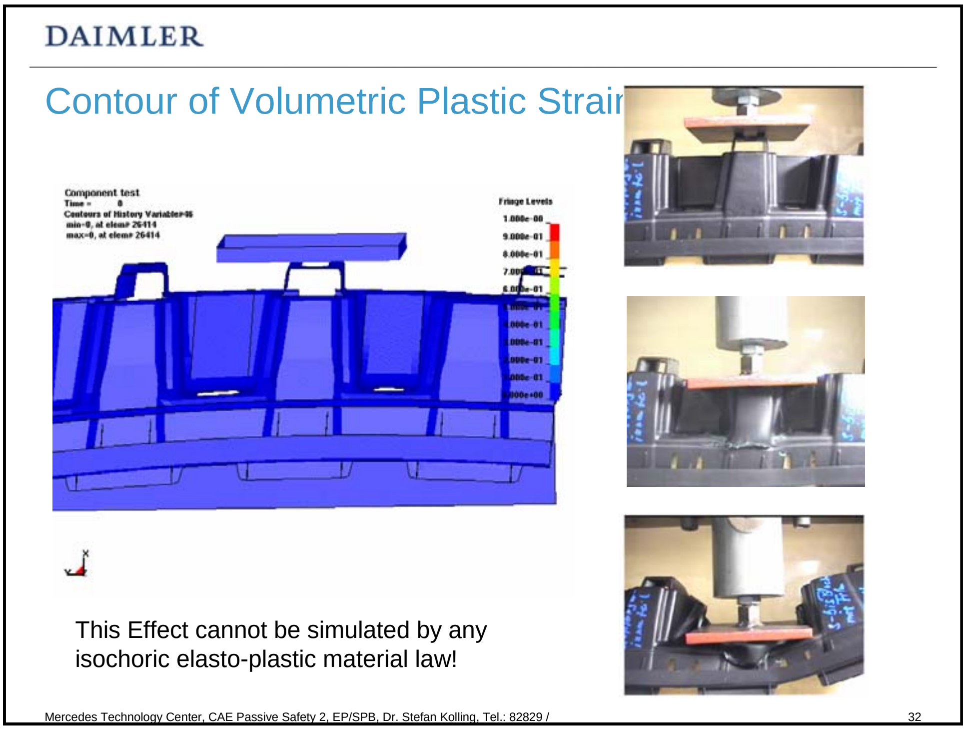

Contour of Volumetric Plastic Strain

This Effect cannot be simulated by any isochoric elasto-plastic material law!

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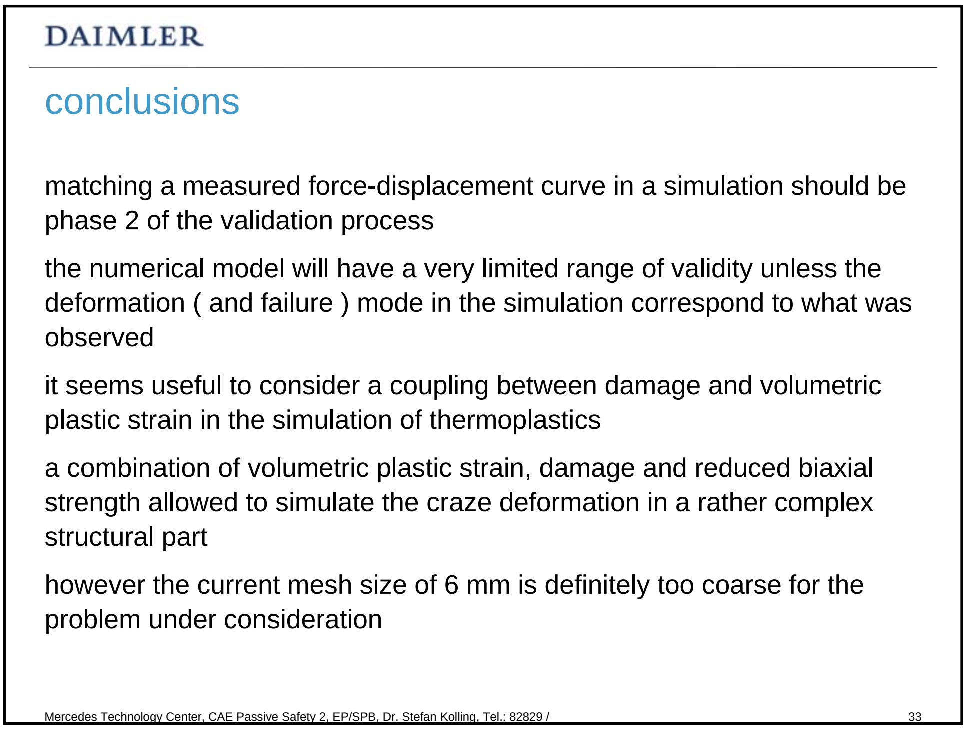

conclusions

matching a measured force-displacement curve in a simulation should be phase 2 of the validation process

the numerical model will have a very limited range of validity unless the deformation (and failure) mode in the simulation correspond to what was observed

it seems useful to consider a coupling between damage and volumetric plastic strain in the simulation of thermoplastics

a combination of volumetric plastic strain, damage and reduced biaxial strength allowed to simulate the craze deformation in a rather complex structural part

however the current mesh size of 6 mm is definitely too coarse for the problem under consideration