DaimlerChrysler

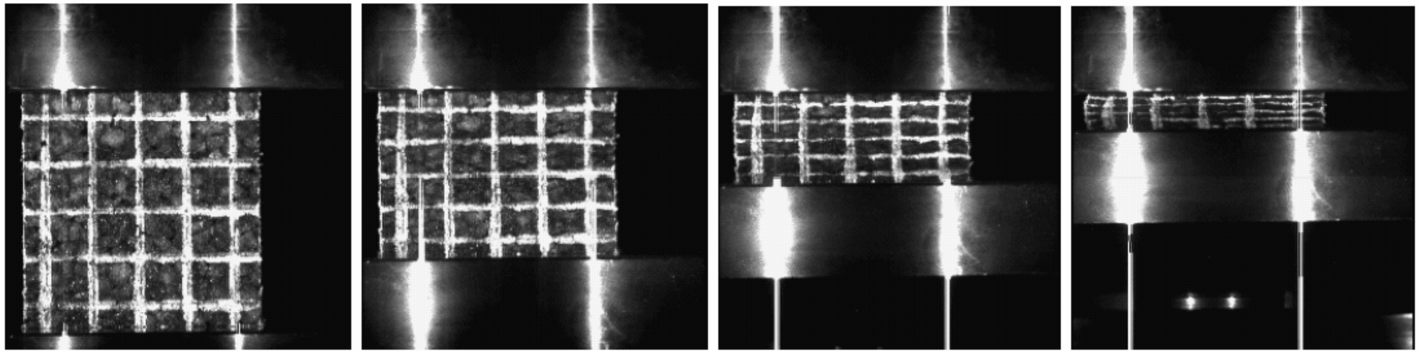
Stefan Kolling & Markus Feucht
MTC Sindelfingen

Constitutive Models for Foams in Crashworthiness Analysis - a State-of-the-Art Review

Workshop *Simulation von Schaumstoffen mit stark nichtlinearem Verhalten*, Hohenwart 15.-16.9.2005

Introduction

- What are foams?
  - Material scientist: any material manufactured by some expansion process
  - (Crash-) Numericist: a material with a Poisson coefficient close to zero



EPP
RG20

  - Both definitions coincide only for low density foams, roughly below 200g/l
  - High density (>200g/l) structural foams are not foams in the numerical sense since they exhibit a non-negligible Poisson effect
- In what follows: polymeric foams are considered only

Constraints in crashworthiness analysis

- Used: explicit finite element method (LS-DYNA)
- Time step determined by element size and material tangent
- Material model determines computation time !
- Results have to be generated very fast due to development process
- Time-consuming parameter identification not acceptable

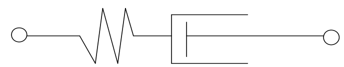
Further limitations

- Accuracy
  - Global density variations
  - local density variations (gradients in the part)
  - skin formation in cold formed parts (not in cut parts)
  - influence of the microstructure, mainly in parts with small dimensions
- Simulation problems
  - Dynamic test results on soft polyurethanes (seatfoams) are dependent on size and shape of the sample, due to the open cell structure and air outflow
  - theory of porous media needed
  - or tests on samples that are roughly the size of the part of interest

Subdivision according to their mechanical behaviour

- Elastic foams
  - Hyperelastic-viscous behaviour (MAT_57/73/83...)

$$\sigma_i = \frac{1}{\lambda_j \lambda_k} \frac{\partial W}{\partial \lambda_i} = \frac{1}{\lambda_j \lambda_k} \tau_i(\lambda_i) \qquad W = \int \tau \, d\lambda \qquad \left(+ \right.$$



$$\left. \right)$$

- Crushable foams
  - Visco-elastic-visco-plastic behaviour (not available yet)
  - Strain rate independent plasticity $f(\sigma_{ij}) \leq 0$ anisotropic (MAT_142)
  - Strain rate dependent plasticity $f(\sigma_{vm}, p) \leq 0$ isotropic (MAT_075)
  - Elasto-visco-plasticity $f(\sigma_{vm}, p, \dot{\varepsilon}^p) \leq 0$ isotropic (SAMP)

Elastic foams

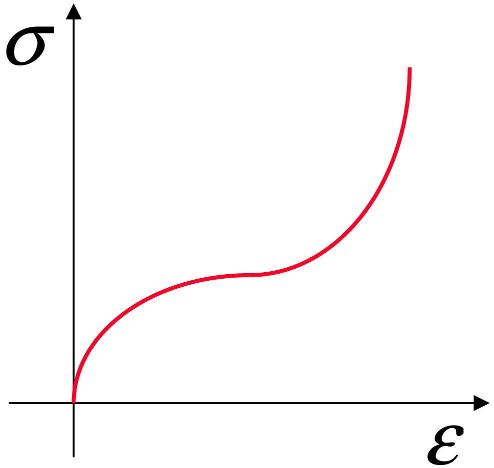
- Hyperelastic viscous material behaviour
  - Poisson‘s ratio = 0 (=> principle stresses uncoupled)
  - Hill-functional + viscous terms formulated in principal stress space

$$\sigma_i = \frac{1}{\lambda_j \lambda_k} \frac{\partial W}{\partial \lambda_i} = \frac{1}{\lambda_j \lambda_k} \tau_i(\lambda_i) \qquad W = \int \tau d\lambda$$

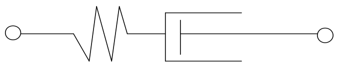
  - Input of stress-strain curves at different strain-rates desirable
- Important applications:
  - bumper foam
  - seat and padding
  - pedestrian protection: leg impactor (Conforfoam)

Material laws for elastic foams (no Poisson effect)

hyperelastic-visco-elastic

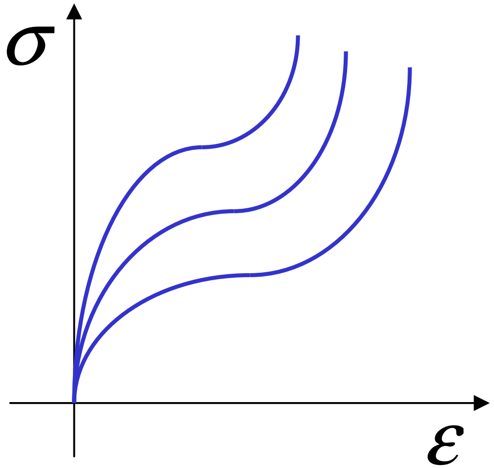


+



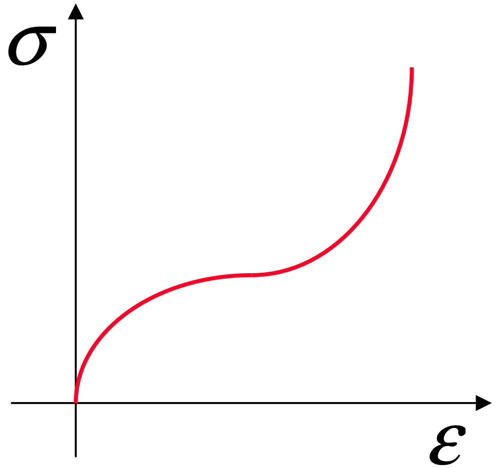
MAT_57
MAT_LOW_DENSITY_FOAM

strainrate dependent hyperelastic

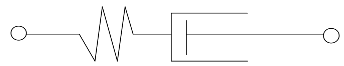


MAT_83
MAT_FU-CHANG_FOAM

hyperelastic-visco-elastic



+



MAT_62
MAT_LOW_DENSITY_FOAM

Material law for elastic foams (with Poisson effect)

- Implemented as MAT_SIMPLIFIED_RUBBER/FOAM in 2004 (Kolling/DuBois/Feng)
- Uses Hill instead of Ogden functional (incompressible case):

$$W = \sum_{j=1}^{m} \frac{C_j}{b_j} \left[\lambda_1^{b_j} + \lambda_2^{b_j} + \lambda_3^{b_j} - 3 + \frac{1}{n}\left(J^{-nb_j} - 1 \right) \right]$$

where C_j b_j and n are material constants and $J = \lambda_1 \lambda_2 \lambda_3$

The nominal stresses (force per unit undeformed area) are $i = 1,2,3$

$$S_i = \frac{1}{\lambda_i} \sum_{j=1}^{m} C_j \left[\lambda_1^{b_j} - J^{-nb_j} \right]$$

for uniaxial tension:

$$n = \frac{-\log \lambda_3}{2 \log \lambda_3 + \log \lambda_1} \qquad \to \quad S_1(\lambda_1) = \frac{1}{\lambda_1} \sum_{j=1}^{m} C_j \left[\lambda_1^{b_j} - \lambda_1^{\frac{-nb_j}{2n+1}} \right]$$

Material law for elastic foams (with Poisson effect)

let $$f(\lambda) = \sum_{j=1}^{m} C_j \lambda^{b_j}$$

$$\Rightarrow \quad \lambda_1^{\left(\frac{-n}{2n+1}\right)^k} S_1\left(\lambda_1^{\left(\frac{-n}{2n+1}\right)^k}\right) = f\left(\lambda_1^{\left(\frac{-n}{2n+1}\right)^k}\right) - f\left(\lambda_1^{\left(\frac{-n}{2n+1}\right)^{2k}}\right), \quad k = 1,2,3,\ldots$$

$$\Rightarrow \quad f(\lambda_1) = \lambda_1 S_1(\lambda_1) + \lambda_1^{\frac{-n}{2n+1}} S_1\left(\lambda_1^{\frac{-n}{2n+1}}\right) + \lambda_1^{\left(\frac{-n}{2n+1}\right)^2} S_1\left(\lambda_1^{\left(\frac{-n}{2n+1}\right)^2}\right) + \ldots.$$

The function $f(\lambda)$ is determined and $$S_i = \frac{1}{\lambda_i}\left[f(\lambda_i) - f(J^{-n}) \right], \quad i = 1,2,3$$

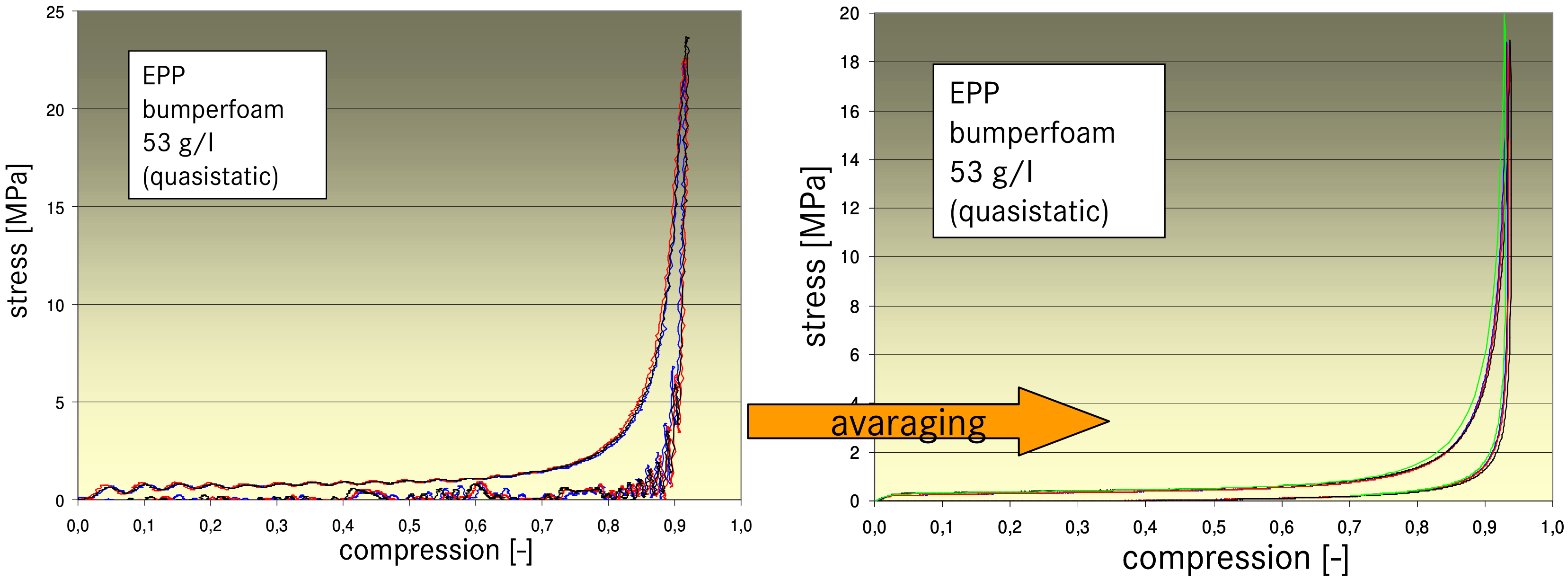
- Load curves directly inputted in material card
- Extension due to elastic damage is realized in Mat183 (for rubber first) (Kolling/Du Bois/Benson) => simulation of hysteresis by dissipation

Material laws for elastic foams in LS-DYNA

No.	keyword	formulation	input
38	MAT_BLATZ_KO_FOAM	hyperel., $\upsilon = 0.25$	1 parameter
57	MAT_LOW_DENSITY_FOAM	hyperel. + viscoel.	LC+parameter
62	MAT_VISCOUS_FOAM	hyperel. + viscoel. υ variable	parameter
73	MAT_LOW_DENSITY_VISCOUS_FOAM	hyperel. + 6 viscoel. dampers	LC parameter
83	MAT_FU-CHANG_FOAM	hyperel.+strain-rate	LC/ table
177	MAT_HILL_FOAM	hyperel., υ variable	LC
178	MAT_VISCOELASTIC_HILL_FOAM	= 177 + viscoel	LC + parameter
179	MAT_LOW_DENSITY _SYNTETIC_FOAM	hyperel. pseudo-damage	LC LC
180	MAT_LOW_DENSITY _SYNTETIC_FOAM_ORTHO	no damage orthog- onal load direction	LC
181	MAT_SIMPLIFIED_RUBBER/FOAM _(WITH_FAILURE)	hyperel.+strain-rate υ variable	LC/ table

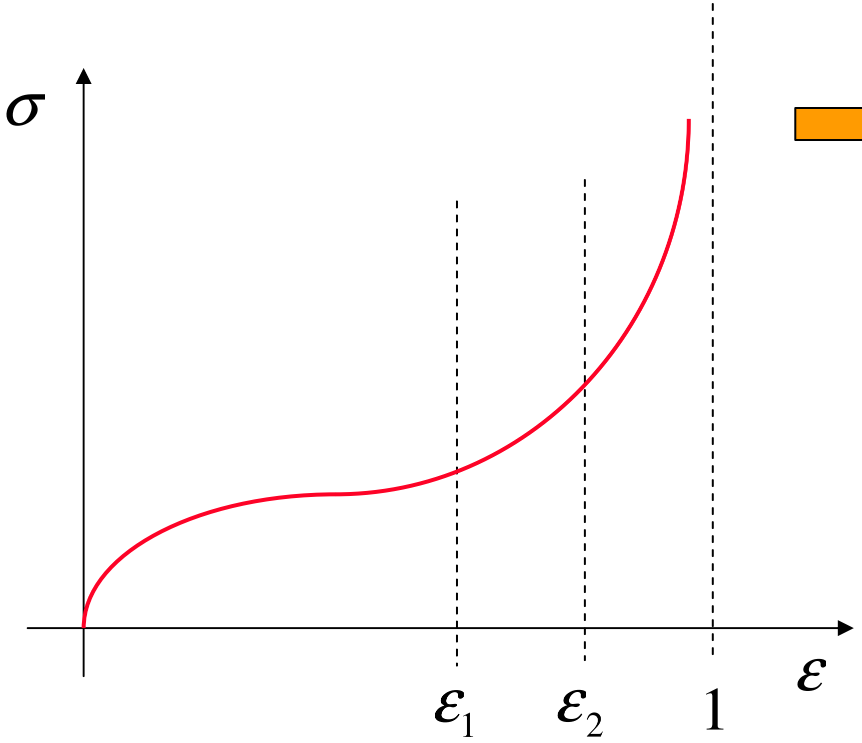
Material laws for elastic foams

- Material 83 is the most frequently used industrial solution for the simulation of elastic foams: bumperfoam and seatfoam
- main reason is user-friendliness: no parameters need to be fitted, test curves are (almost) directly inputted



Material laws for elastic foams

- If extrapolation of test curves is necessary:
  - We use a hyperbolic function of order n
  - Extrapolation exponent n is fitted to have a continuous transition



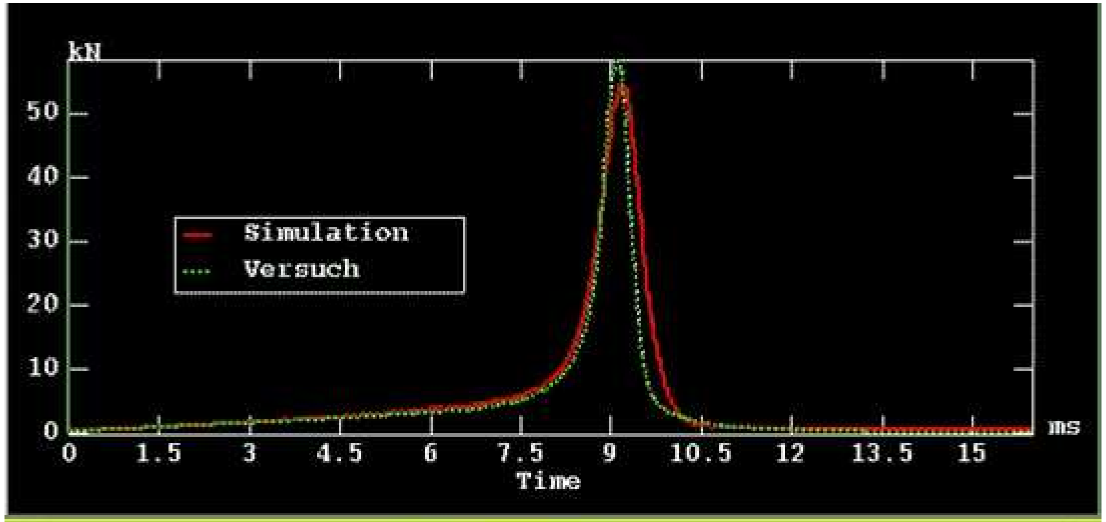
$$\sigma_{n+1} = \sigma_n + \left.\frac{\partial \sigma}{\partial \varepsilon}\right|_{\varepsilon_1} \left(\frac{1-\varepsilon_1}{1-\varepsilon_n}\right)^n \Delta\varepsilon$$

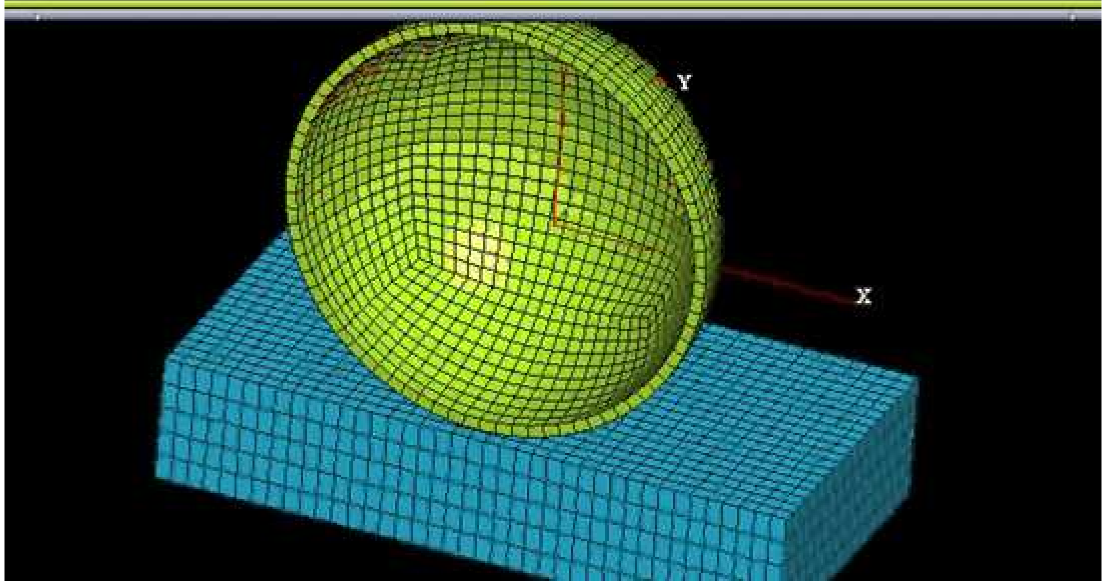
$$\varepsilon_n > \varepsilon_1$$

$$n = \frac{\ln\left(\dfrac{\sigma_2 - \sigma_1}{\left.\dfrac{\partial \sigma}{\partial \varepsilon}\right|_{\varepsilon_1} \Delta\varepsilon}\right)}{\ln\left(\dfrac{1-\varepsilon_1}{1-\varepsilon_2}\right)}, \quad \varepsilon_2 > \varepsilon_1$$

Example: PU-Foam

- Extremely high compression up to 98%
- Stability problems
- Time step size!
- Contact problems
- Sharp impactors cause deformation gradients in foam parts
- Lagrangean finite elements cannot follow the corresponding deformed shapes unlimitedly
- EFG methods (v970) may present an alternative



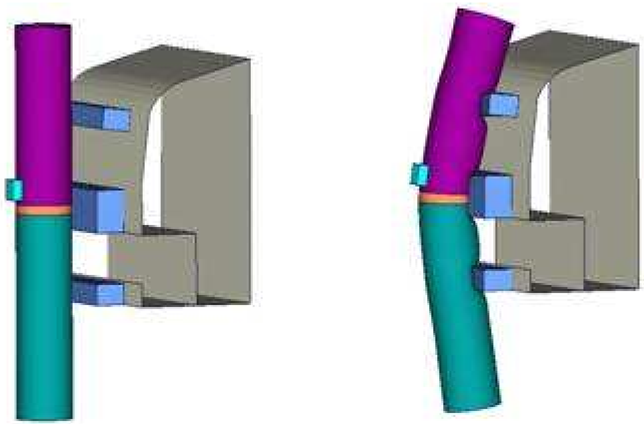


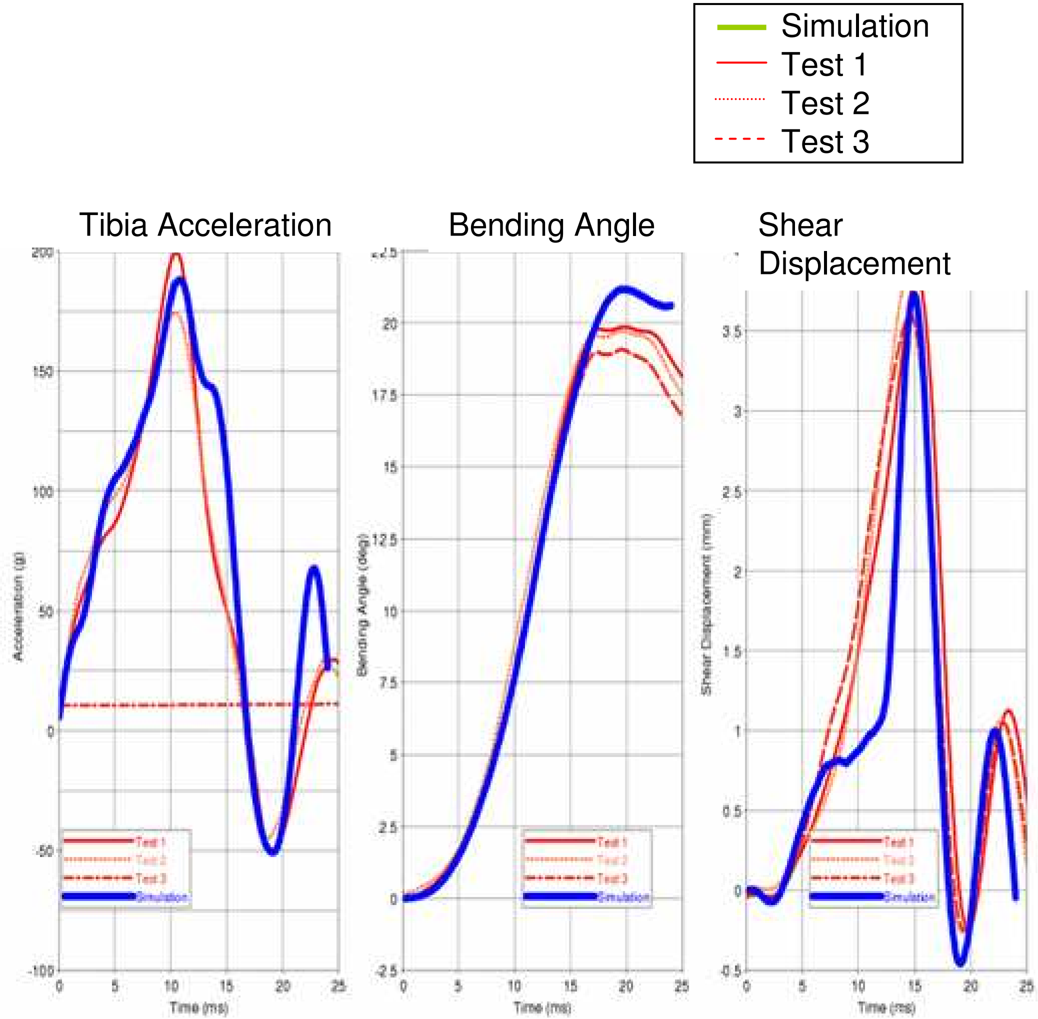
Example: Conforfoam, leg-impact

Validation test

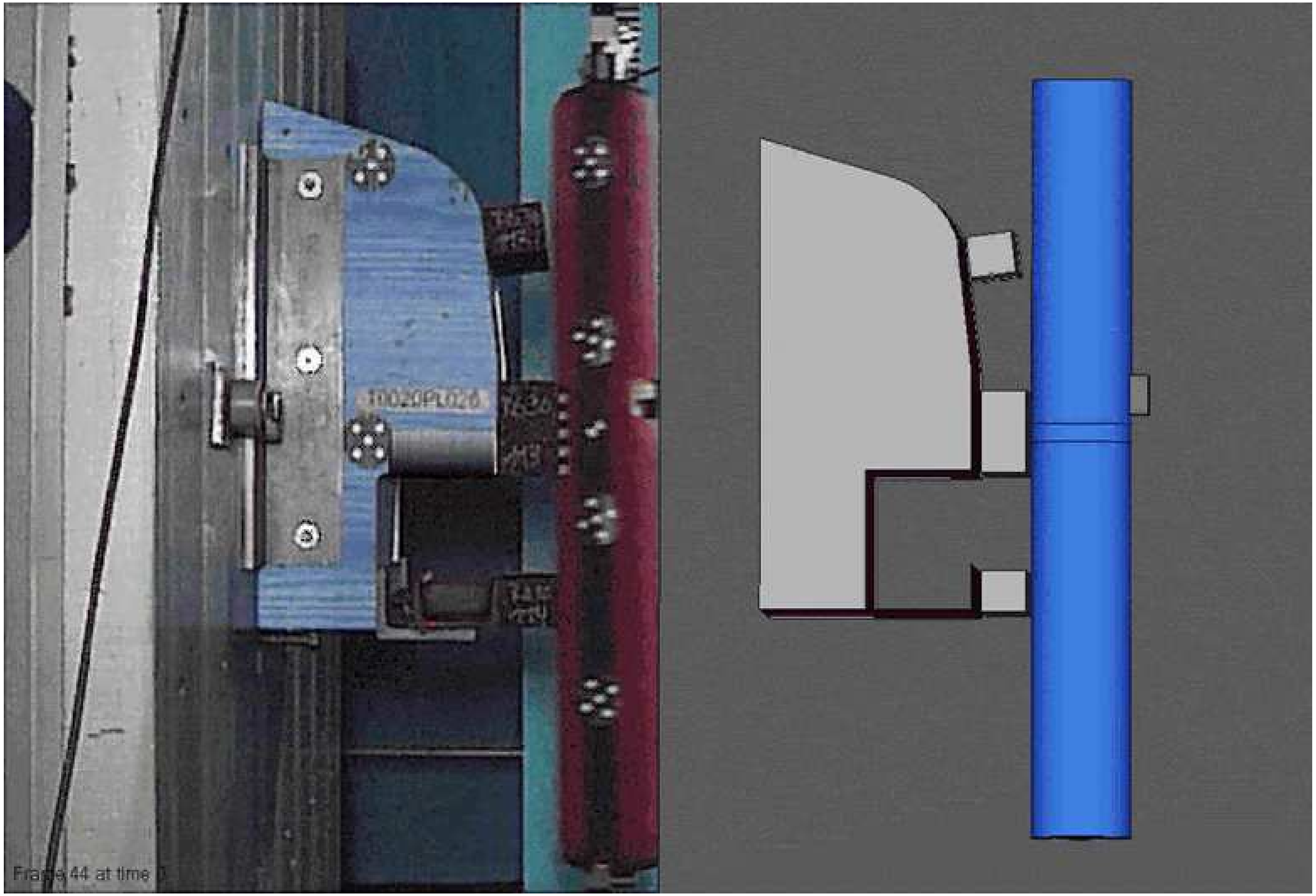
Impact velocity 35/40 km/h

Variation in vertical positions

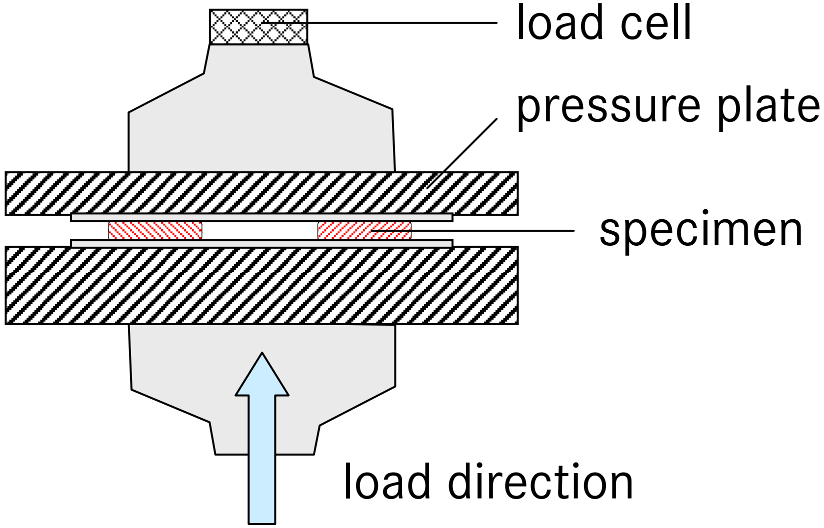




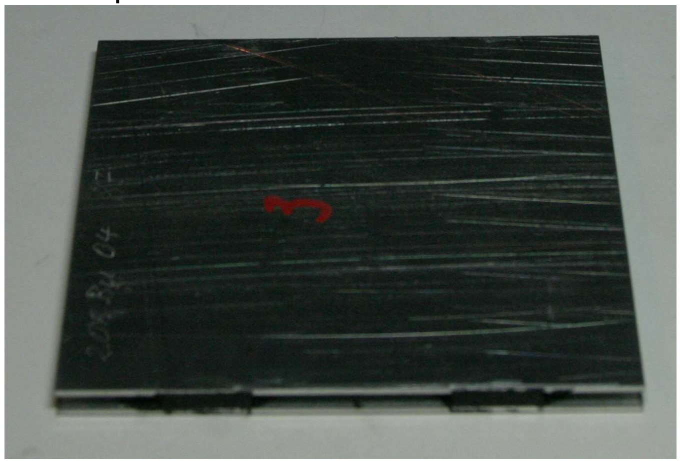
Leg-impact: test configuration for validation



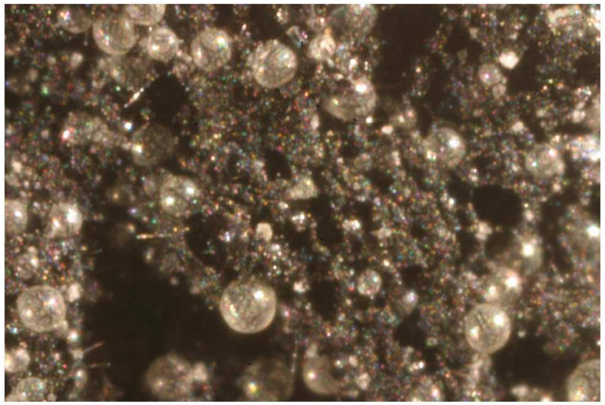
Example: Adhesive EFBond (rubber foam)



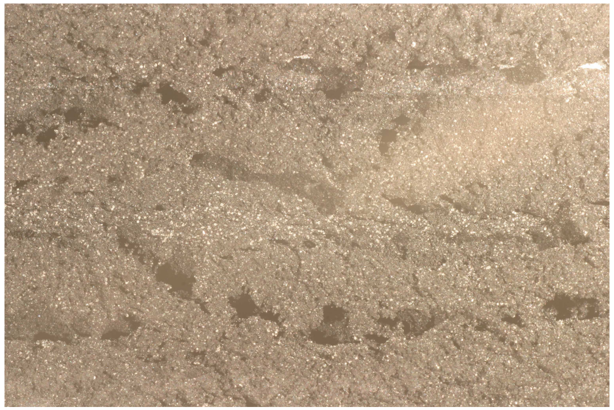
test specimen



Microstructure, 1.7x22.5mm

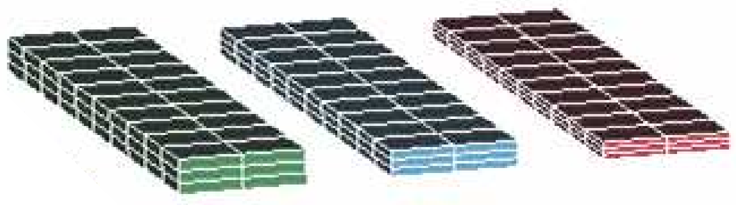


compression

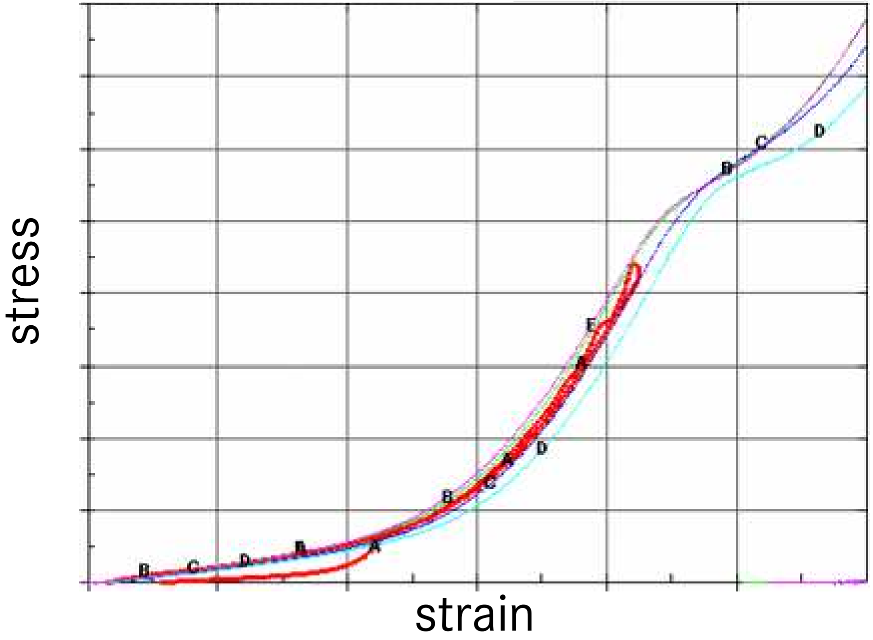


Adhesive EFBond

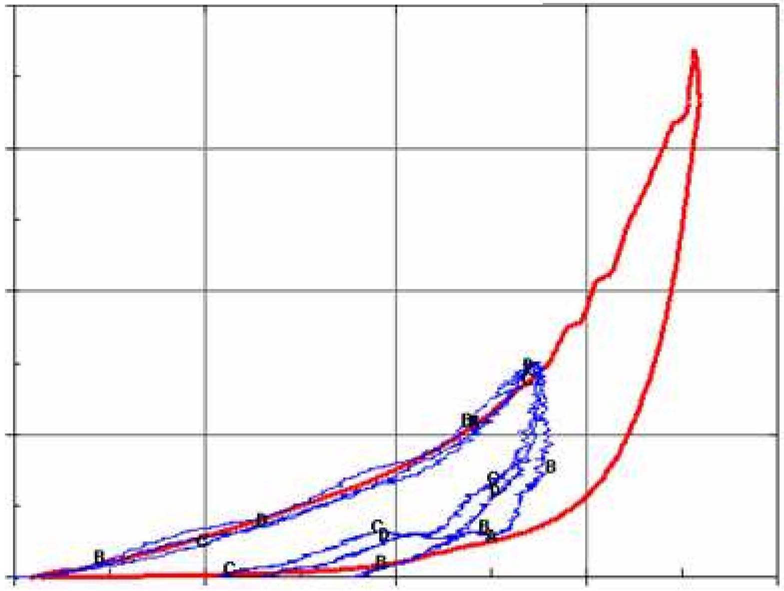
- l=100mm, b=15mm and t=2/3/4 mm
- volume elements: min l = 0.67mm
- timestep = 6.8 10^{-6} s



quasi static loading



dynamic loading: 800/s



Plastic foams

- Structural and crushable foams
- Material model: SAMP
  - not only valid for thermoplastics
  - It covers metals as well
  - Also suitable for
    - Adhesives (if you have a glue how to model)
    - Structural foams
    - Crushable foams
- Example: validation of a high-strength, low-density, expandable epoxy polymer (Terocore by CORE Products) using a single material input card of SAMP

Material laws for crushable foams in LS-DYNA

No.	keyword	formulation	input
5,14	MAT_SOIL_AND_FOAM	isotropic, el-pl	parameter
26,126	MAT_HONEYCOMB	anisotropic, el-pl	LC
53	MAT_CLOSED_CELL_FOAM	isotropic, el-pl	LC
63,163	MAT_CRUSHABLE_FOAM	isotropic, el-pl υ variable	LC / table
75	MAT_BILKHU/DUBOIS_FOAM	isotropic, el-pl strain-rate	LC parameter
142	MAT_TRANSVERSELY_ANISO TROPIC_CRUSHABLE_FOAM	anisotropic el-pl	LC
144	MAT_PITZER_CRUSHABLE _FOAM	isotropic, el-pl υ variable	LC + strain-rate parameter
user	MAT_SAMP	isotropic, el-pl υ variable	LC / table

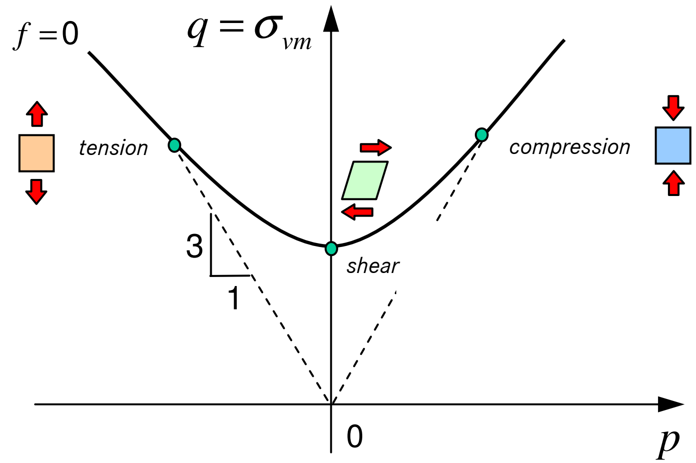
SAMP: A Semi-Analytical Model for Polymers

In co-operation with André Haufe (Dynamore) & Paul Du Bois (Consultant)

$$f = q^2 - A_0 - A_1 p - A_2 p^2$$

$$A_0 = 3\sigma_s^2 \qquad A_1 = 9\left(\sigma_s^2 \frac{\sigma_c - \sigma_t}{\sigma_c \sigma_t}\right)$$

$$A_2 = 9\left(\frac{\sigma_t \sigma_c - 3\sigma_s^2}{\sigma_t \sigma_c}\right)$$



plastic potential:

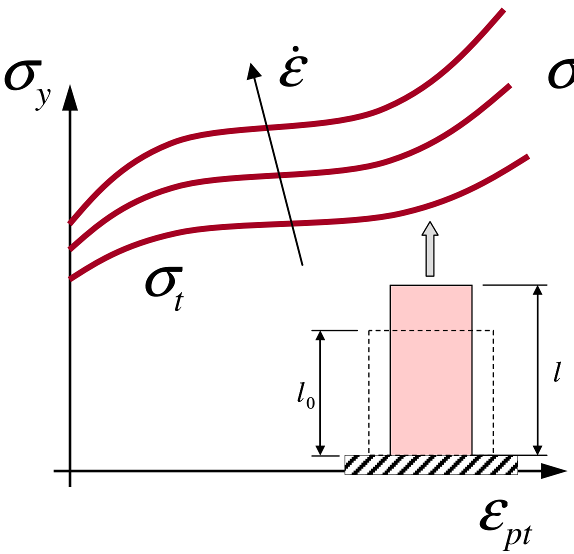
C[1]-continuous yield surface

$$g = \begin{cases} q^2 - A_0 - A_1 p - A_2 p^2 & \text{associated} \\ \sqrt{q^2 + \alpha p^2} & \text{non-associated} \end{cases}$$

flow parameter correlates to plastic Poisson's ratio: $\alpha \propto \upsilon_p = \frac{9 - 2\alpha}{18 + 2\alpha} \leq 0.5$

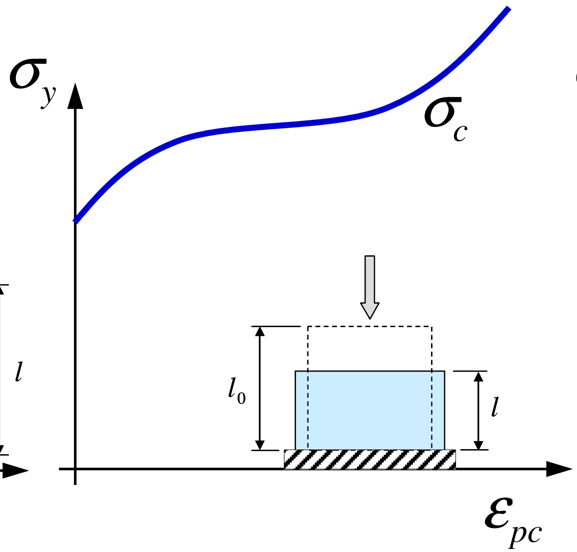
SAMP – A Semi-Analytical Model for Polymers

- Hardening curves: tabulated data



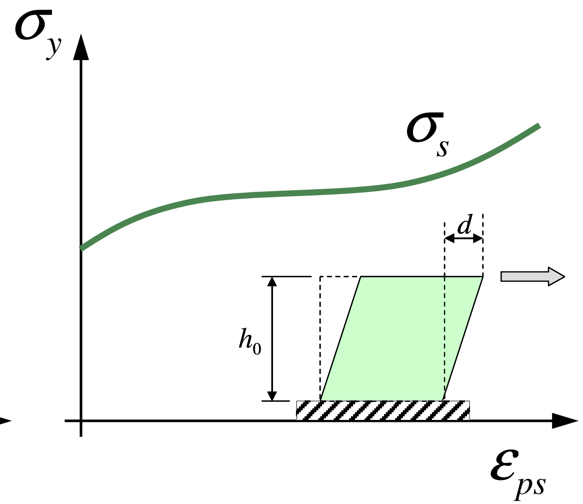
tensile hardening curve from tensile test at different strain rates

$$\varepsilon_{pt} = \varepsilon_t - \frac{\sigma_t}{E}, \quad \varepsilon_t = \ln\frac{l}{l_0}$$



compressive hardening curve from compression test

$$\varepsilon_{pc} = \varepsilon_c - \frac{\sigma_c}{E}, \quad \varepsilon_c = -\ln\frac{l}{l_0}$$



shear hardening curve from shear test

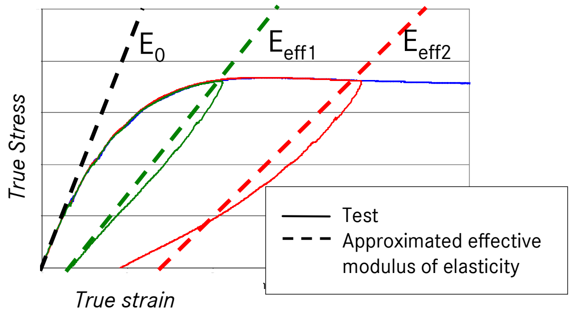
$$\varepsilon_{ps} = \varepsilon_s - \frac{\sigma_s}{2G}, \quad \varepsilon_s = \frac{1}{2}\int \frac{\partial \dot{x}}{\partial y}\, dt = \frac{1}{2}\frac{d}{h_0}$$

difficult !

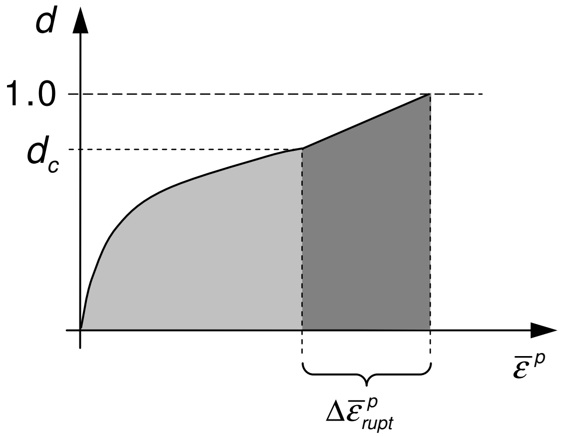
SAMP: Ductile damage and failure

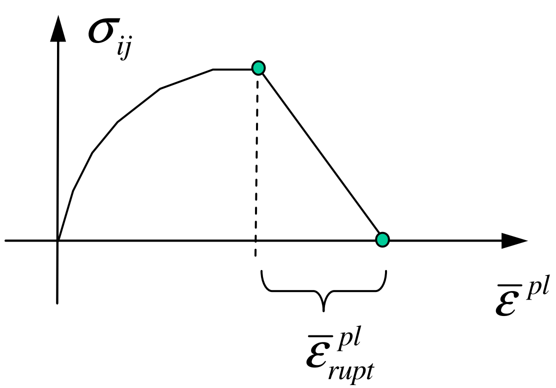
Damage for elastic unloading is defined by a load curve $\chi(\bar{\varepsilon}^{pl}) = [0,1]$

$$\boldsymbol{\sigma}_{eff} = \boldsymbol{\sigma}_{pl} \cdot \left(1 - \chi(\bar{\varepsilon}^{pl})\right)$$



Failure onset defined by the parameter d_c, further fading of the element defined by $\Delta\bar{\varepsilon}^{p}_{rupt}$

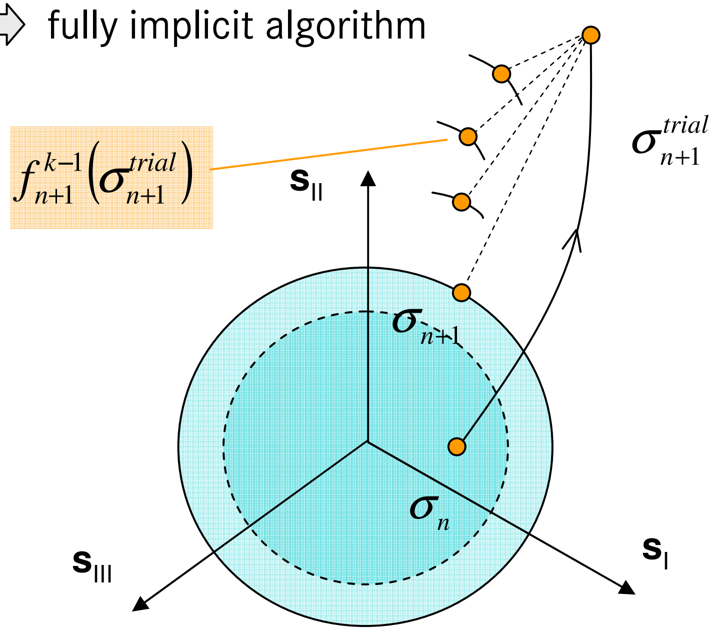




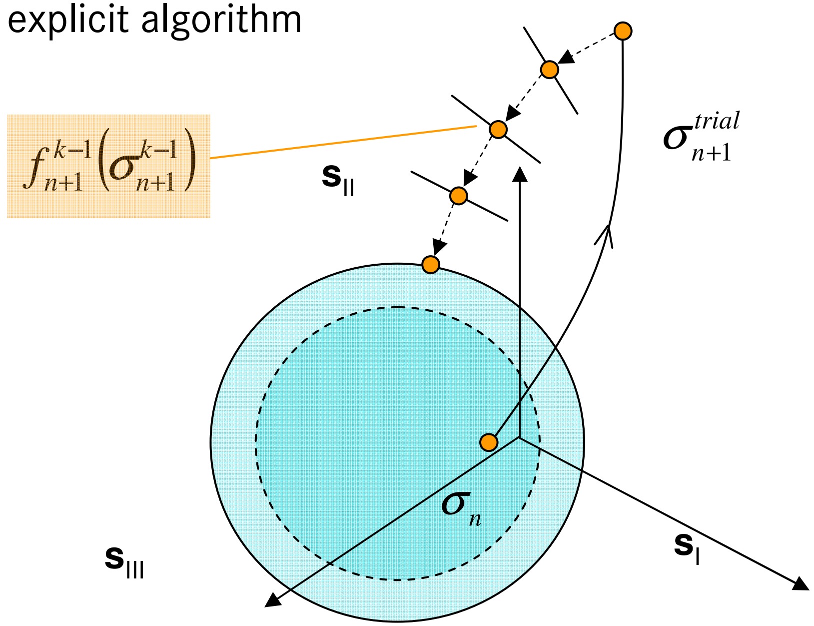
Stress update algorithms : NEWTON-iteration

Backward Euler return mapping or general closest-point-projection or radial return

fully implicit algorithm



explicit algorithm

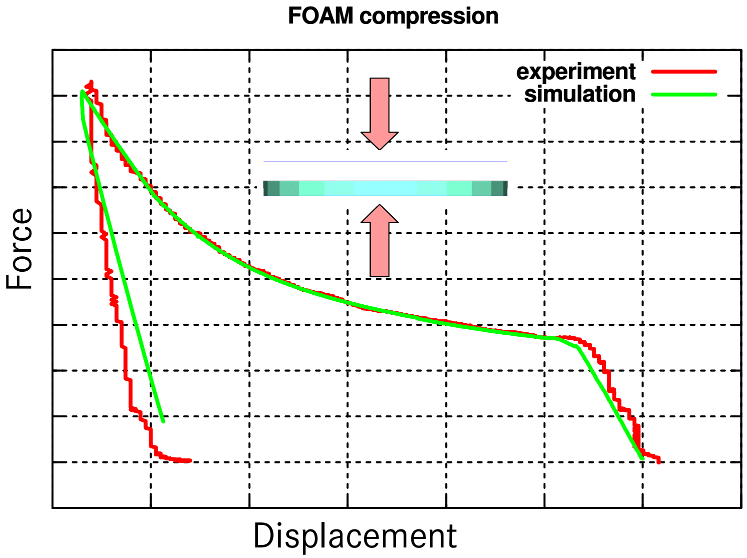


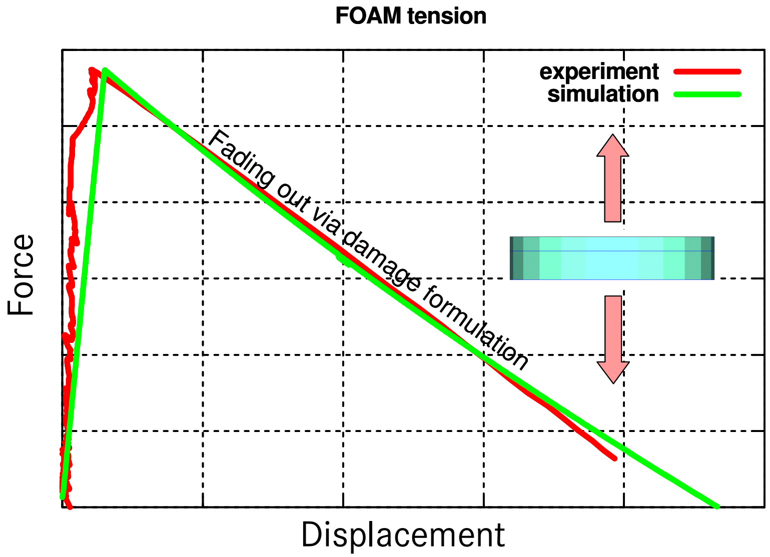
linearization around the elastic trail state :

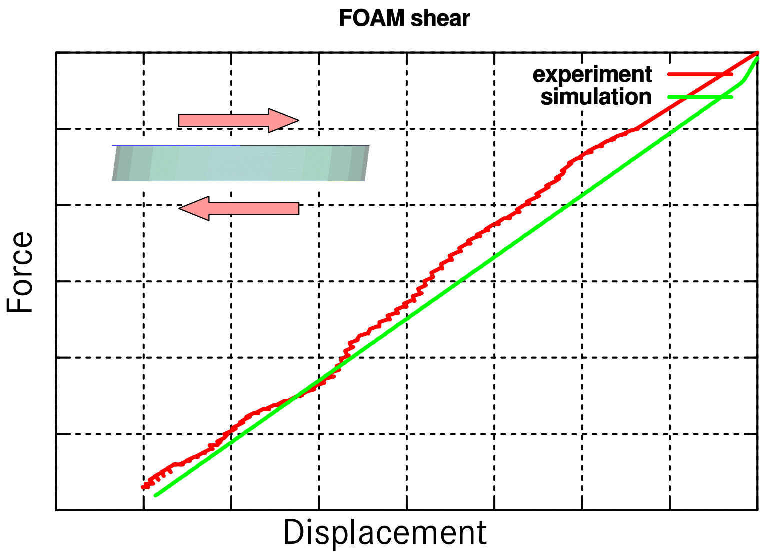
$$f_{n+1}^{k} = f_{n+1}^{k-1} + \frac{\partial f}{\partial \Delta\lambda} d(\Delta\lambda)^{k-1} = 0$$

$$\Delta\lambda^{k} = \Delta\lambda^{k-1} + d(\Delta\lambda)^{k-1} = \Delta\lambda^{k-1} - \frac{f_{n+1}^{k-1}}{\dfrac{\partial f}{\partial \Delta\lambda}}$$

Materialvalidierung mit SAMP





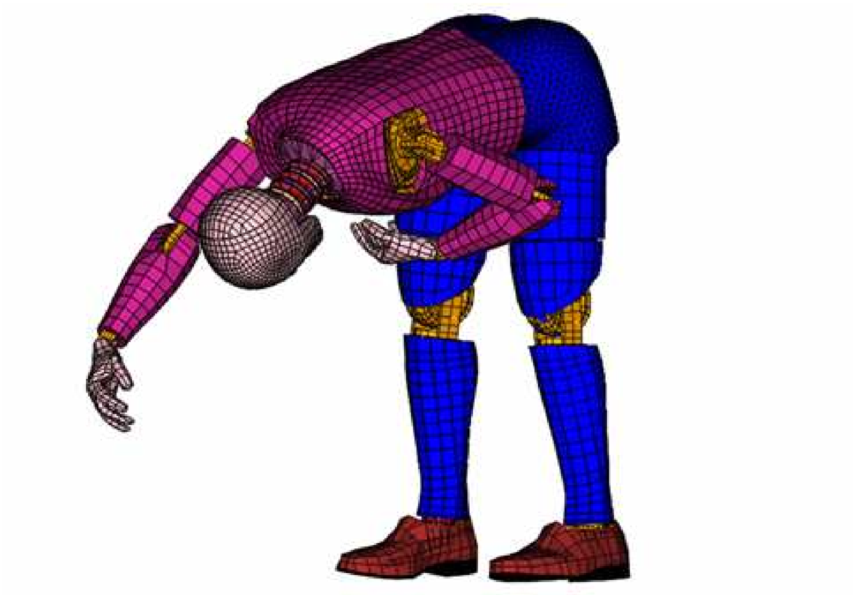


DAIMLERCHRYSLER

Conclusions and outlook

- Elastic foams
  - Popular material law based on strain rate dependent hyperelasticity (kind of pseudo viscosity): FU_CHANG_FOAM
  - Stress-strain curves as input directly from test data
  - Real viscosity and elastic rebound are the biggest stumbling blocks in that kind of formulation
- Crushable foams
  - Material laws for crushable foams available (even anisotropic)
  - SAMP as an alternative considering different behaviour under tension, compression, shear and biaxial loading
  - Anisotropic extension for SAMP desirable

Thanks for your attention!



Acknowledgement:

The experimental testing of EPP has been performed by T. Gerster, EMI

The experimental testing of EFBOND has been performed by H. Nahme, EMI

Experimental testing of Terocore by G. Schmich, CORE Products

The presentation was highly supported by A. Haufe (Dynamore) & Paul Du Bois