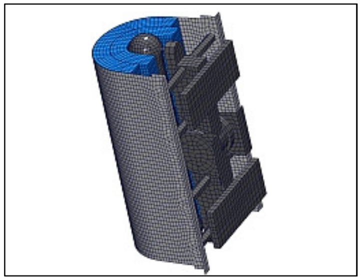
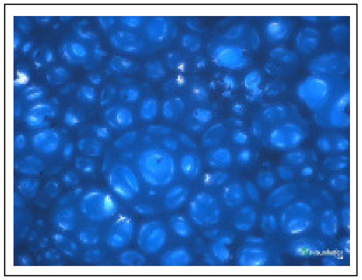
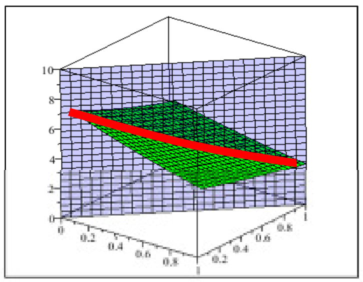
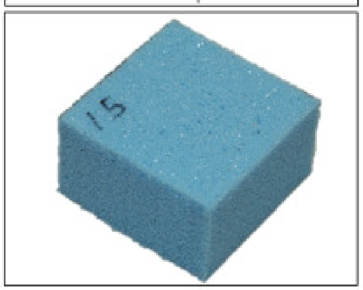








Nonlinear viscoelastic modeling of foams

Veronika Effinger[1], Paul DuBois[2]
Markus Feucht[3], André Haufe[1], Manfred Bischoff[4]

[1]Dynamore GmbH, Stuttgart, Germany
[2]Consultant, Offenbach, Germany
[3]Daimler AG, Sindelfingen, Germany
[4]Institute of Structural Mechanics, University of Stuttgart, Germany

13th LS-Dyna Forum 2014
Bamberg, Germany

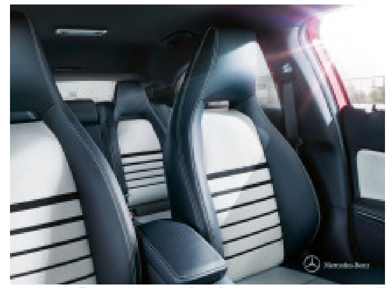
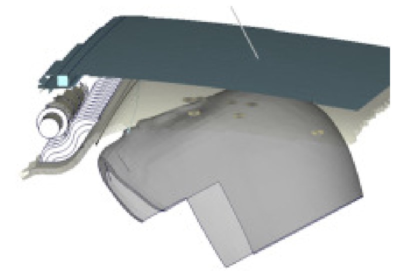
Outline

- Motivation
- State of the art in LS-DYNA®
- Nonlinear viscoelasticity for foams
- Modeling of Confor® foam
- Summary
- Literature

Motivation

- Polymer materials and passive safety

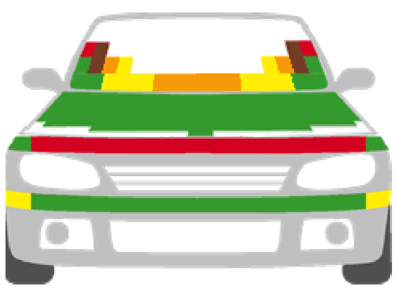


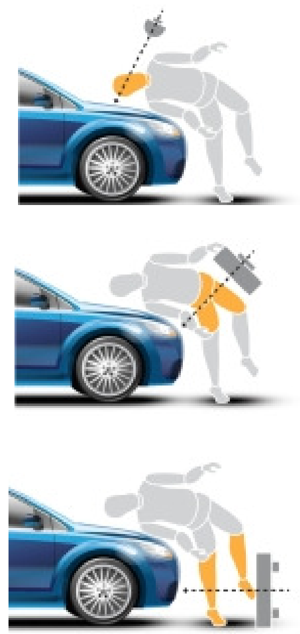



[www.daimler.com]

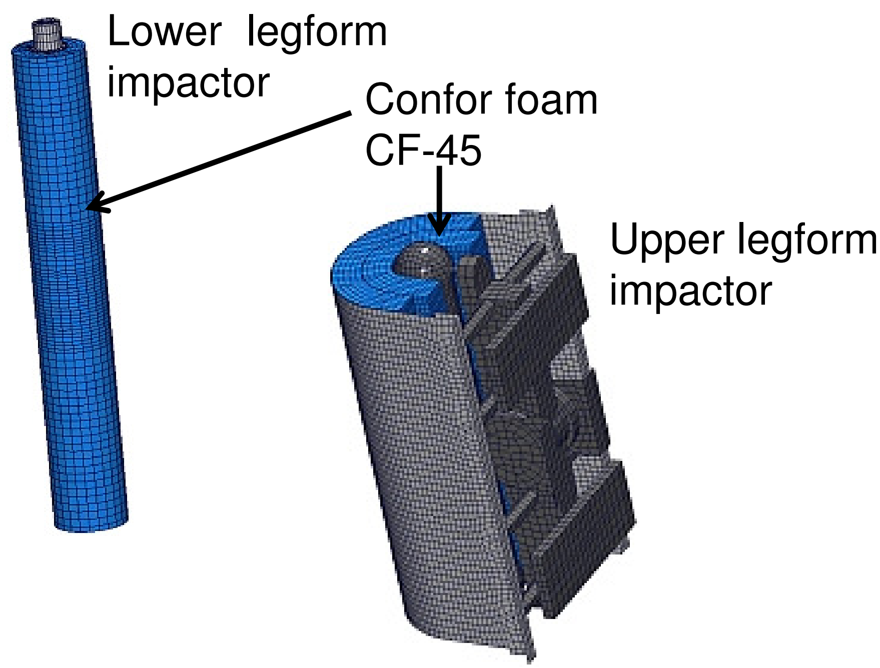
- Pedestrian protection

Euro NCAP
safety rating





[www.euroncap.org]



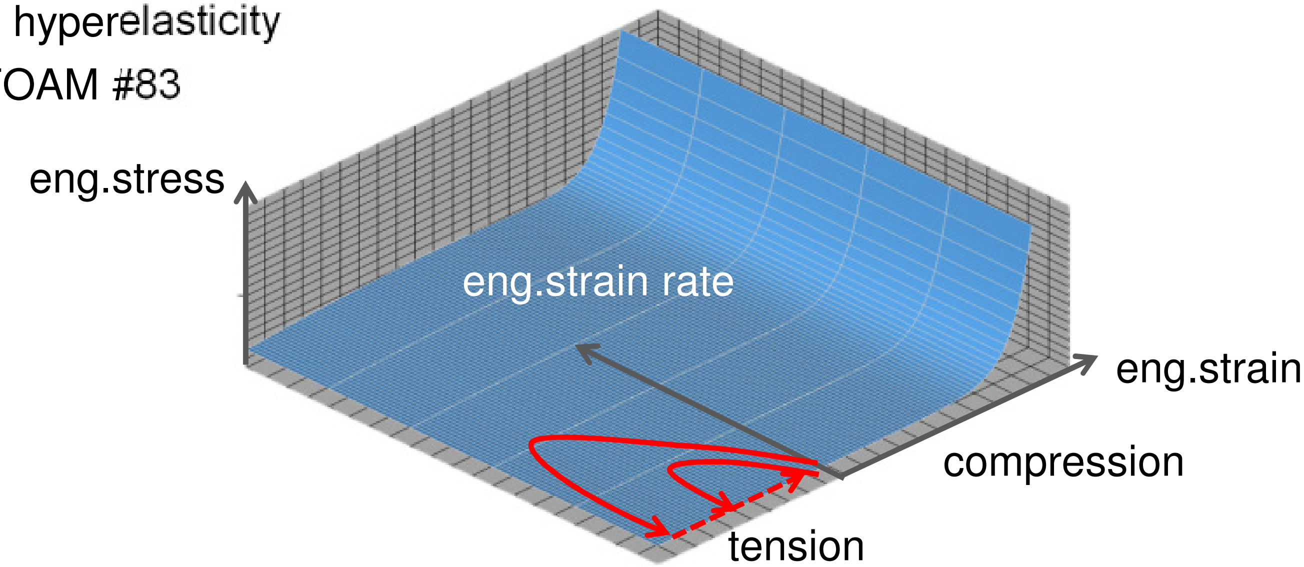
Outline

- Motivation
- **State of the art in LS-DYNA®**
- Nonlinear viscoelasticity for foams
- Modeling of Confor® foam
- Summary

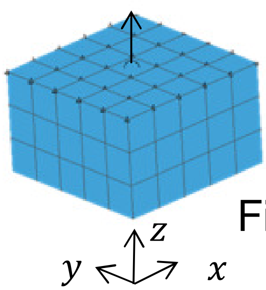
State of the art in LS-DYNA®

- Strain rate dependent hyperelasticity
  *MAT_FU_CHANG_FOAM #83

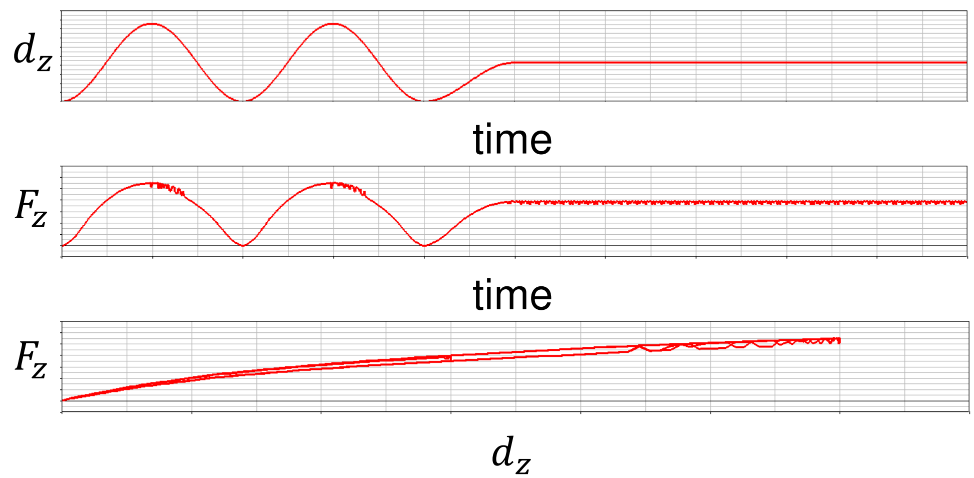
Without damage



Time-dependent displacement d_z of the upper surface



Fixed lower surface

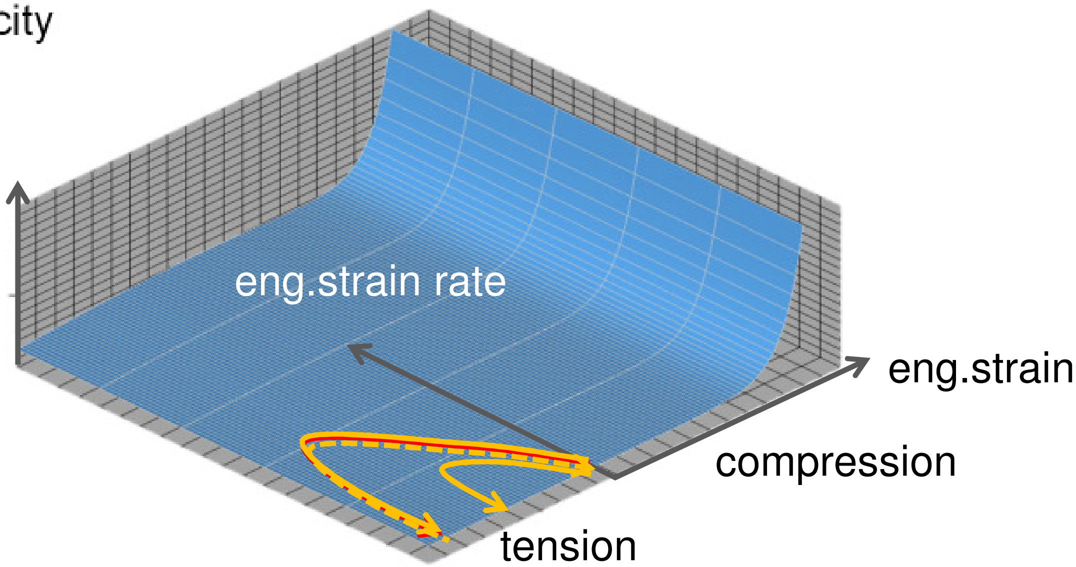


State of the art in LS-DYNA®

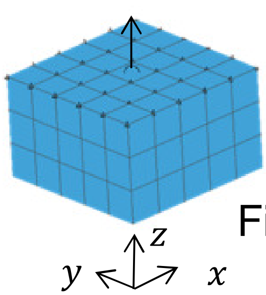
- Strain rate dependent hyperelasticity
  *MAT_FU_CHANG_FOAM #83

With damage

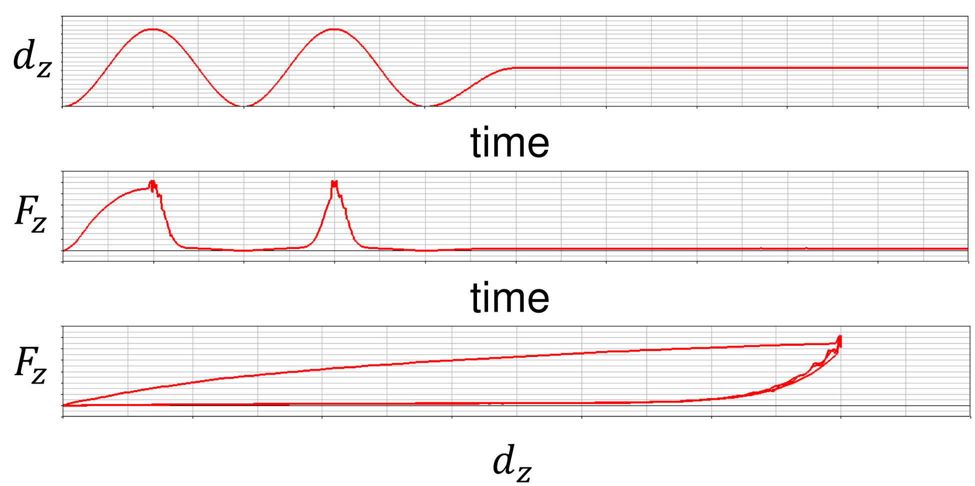
$$\sigma_i = \sigma_i(1-d)$$
$$d = (1-HU)\left(1-\left(\frac{W_{cur}}{W_{max}}\right)^{SHAPE}\right)$$



Time-dependent displacement d_z of the upper surface



Fixed lower surface



State of the art in LS-DYNA®

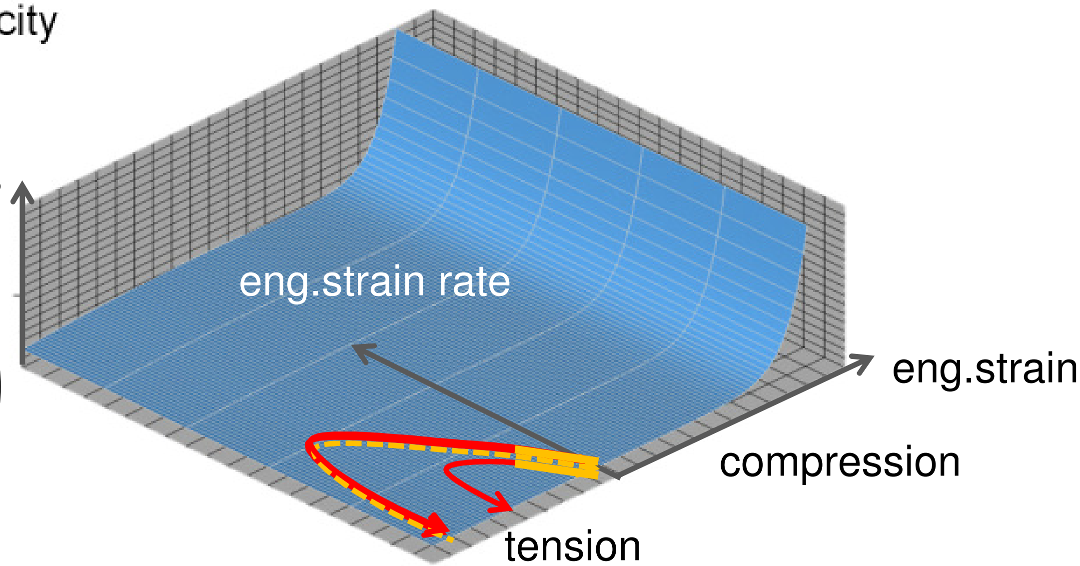
- Strain rate dependent hyperelasticity
  *MAT_FU_CHANG_FOAM #83

With damage decay

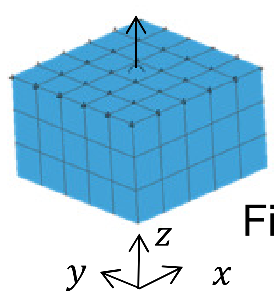
$$\sigma_i = \sigma_i(1-d)$$

$$d = (1-HU)\left(1-\left(\frac{W_{cur}}{W_{max}}\right)^{SHAPE}\right)$$

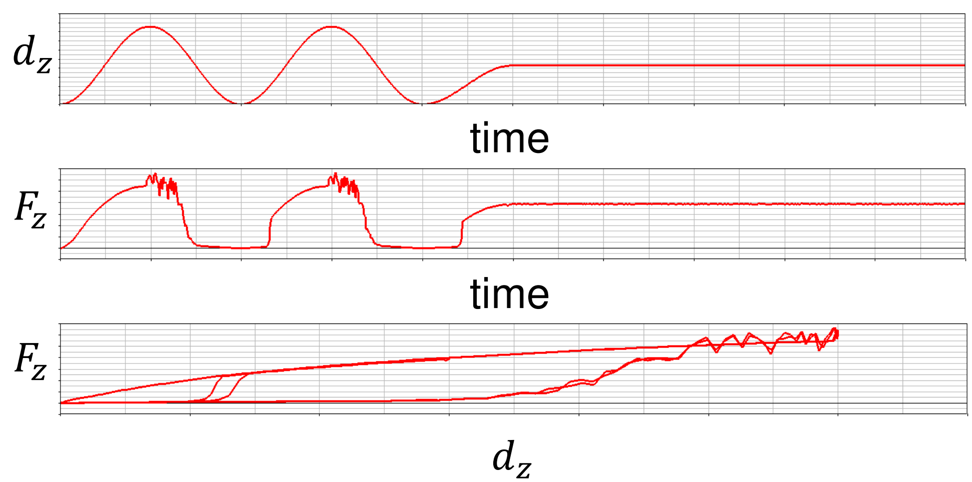
$$W_{max} = W_{max}e^{-BETAT\cdot time}$$



Time-dependent displacement d_z of the upper surface



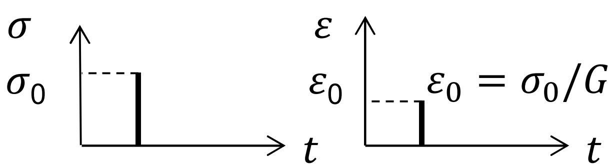
Fixed lower surface



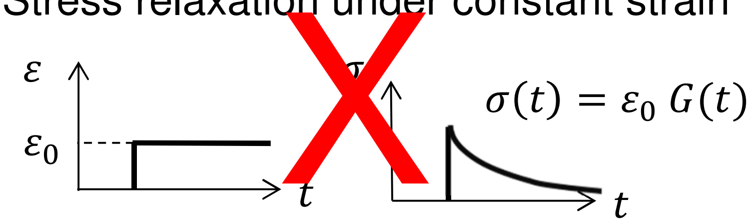
State of the art in LS-DYNA®

- Characteristic properties of viscoelastic solids

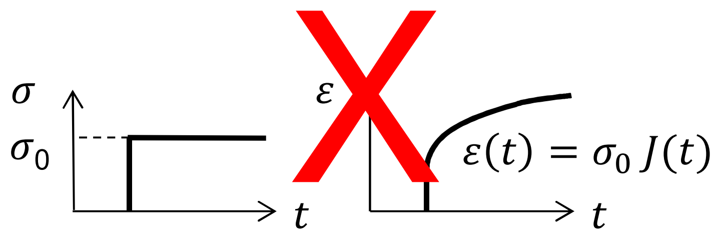
Instantaneous elasticity



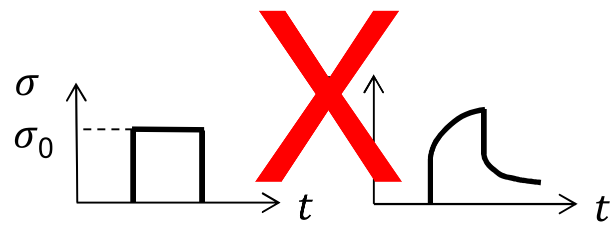
Stress relaxation under constant strain



Creep under constant stress



Instantaneous and delayed recovery



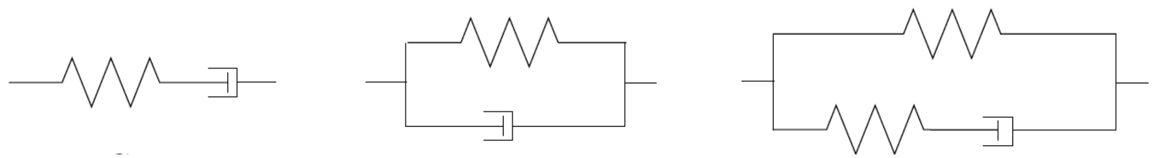
Strain rate dependent hyperelasticity with damage formulation *MAT_083

State of the art in LS-DYNA®

- Linear viscoelastic material models based on rheological models

  Material models: 6, 61, 76, 86, 134, 164, 234, 276,…

Maxwell-Element | Kelvin-Voigt-Element | Standard Linear Solid



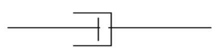
Generalized Maxwell element of linear viscoelasticity

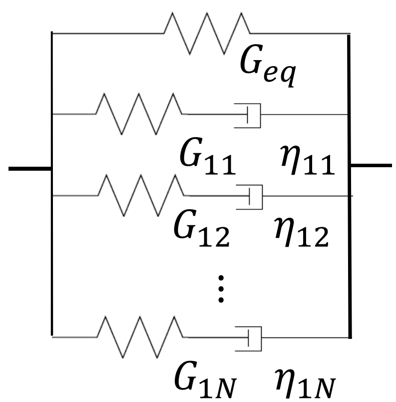
Hooke‘s law

$$\sigma(t) = G\varepsilon(t)$$

Newton‘s law

$$\sigma(t) = \eta \frac{\partial\varepsilon(t)}{\partial t}$$





Prony series

$$\tilde{R}_1(t) = G_{eq} + \sum_{i=1}^{N} G_{1i} e^{-\beta_{1i} t}$$

$$\beta_{1i} = \eta_{1i}/G_{1i}$$

$$\sigma(t) = \int_0^t \tilde{R}_1(t-u) \frac{\partial\varepsilon(u)}{\partial u} du$$

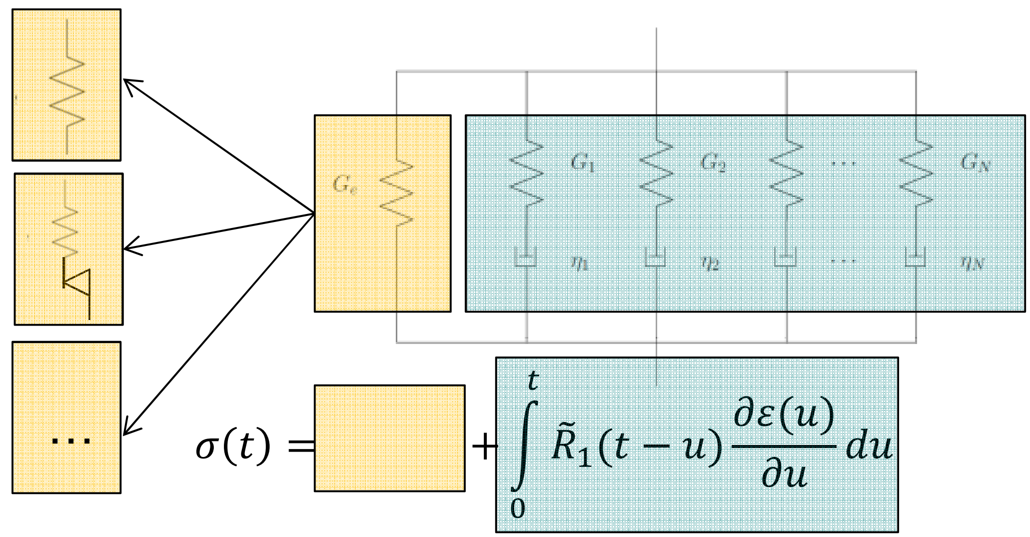
State of the art in LS-DYNA®

- Linear viscoelastic overstress and equilibrium material model

Nonlinear spring
e. g. hyperelasticity

Friction element
e. g. Elasto-Plasticity

Viscoplasticity,
Damage, Failure,…



$$\sigma(t) = \square + \int_0^t \tilde{R}_1(t-u)\frac{\partial\varepsilon(u)}{\partial u}\,du$$

Material models: Hyperelasticity, (Visco-) Plasticity, …
57, 73, 77, 87, 91, 124, 127, 129, 155, 158,175, 178,…

State of the art in LS-DYNA®

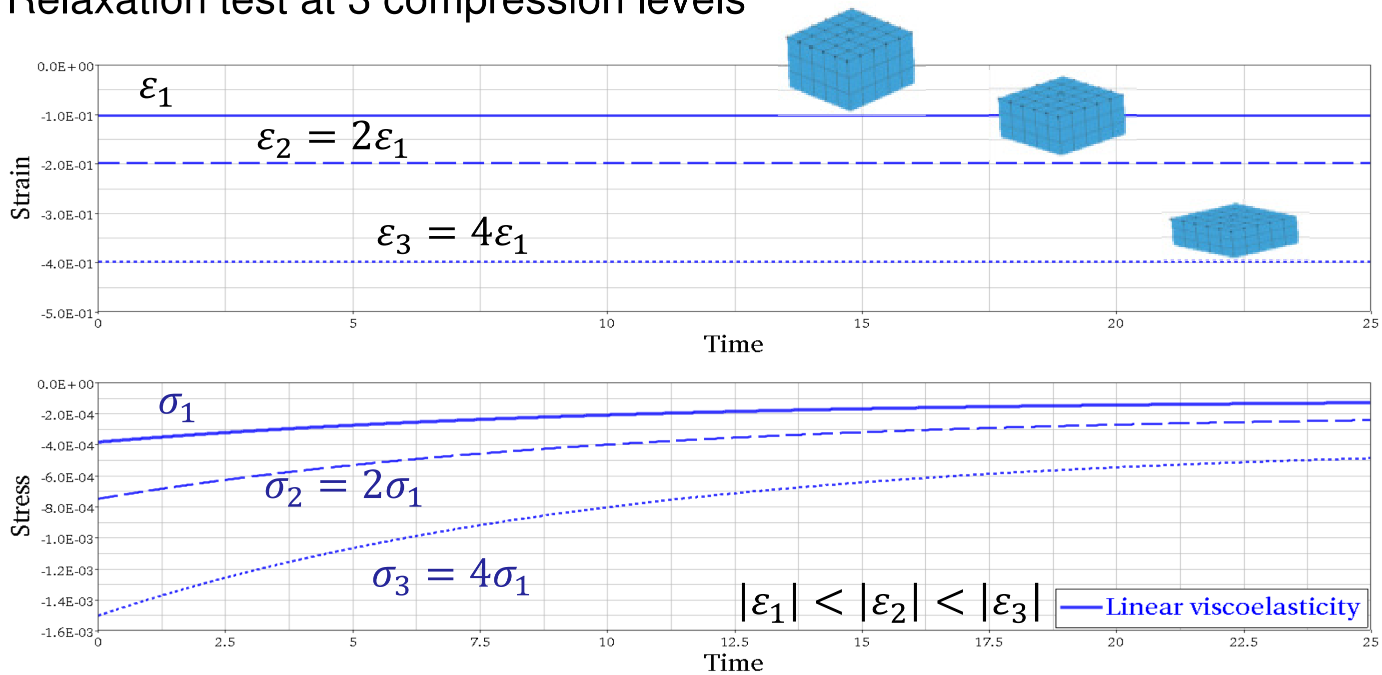
- Linear viscoelasticity for simple, homogeneous and non-aging materials

$$\sigma(t) = \mathcal{F}_{u=0}^{t}(\varepsilon(t-u))$$

- Stress-Strain Linearity

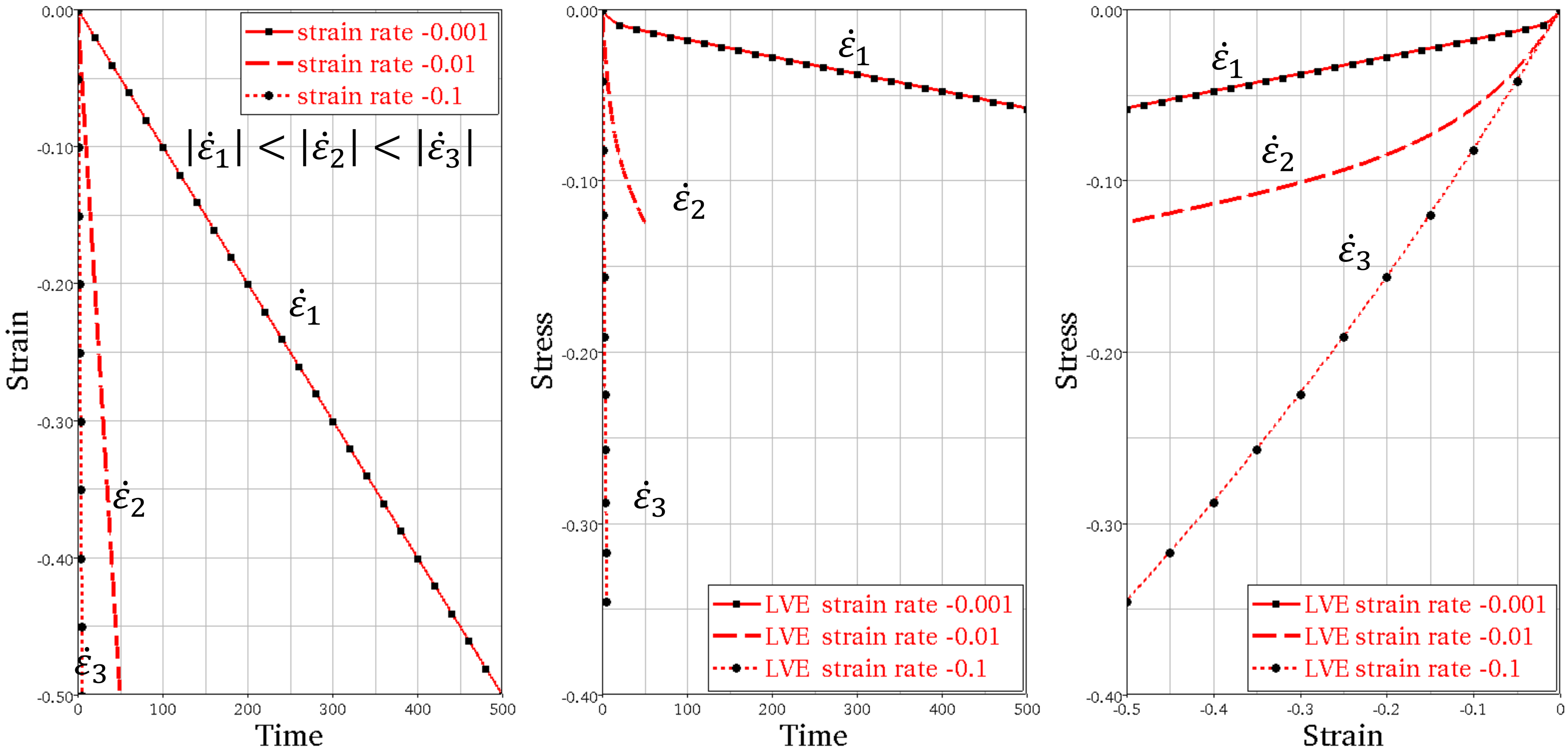
$$\mathcal{F}_{u=0}^{t}\big(\boldsymbol{\alpha}\varepsilon(t-u)\big) = \boldsymbol{\alpha}\mathcal{F}_{u=0}^{t}\big(\varepsilon(t-u)\big) = \boldsymbol{\alpha}\sigma(t)$$

- Relaxation test at 3 compression levels



State of the art in LS-DYNA®

- Linear viscoelasticity: constant strain rate excitation



$$\varepsilon_1(t) = \dot{\varepsilon_1} t$$

$$\varepsilon_2(t) = \alpha \dot{\varepsilon_1} t$$

$$\sigma_1(t)$$

$$\sigma_2(t) = \alpha \sigma_1(t)$$

Outline

- Motivation
- State of the art in LS-DYNA®
- **Nonlinear viscoelasticity for foams**
- Modeling of Confor® foam
- Summary

Nonlinear viscoelasticity for foams

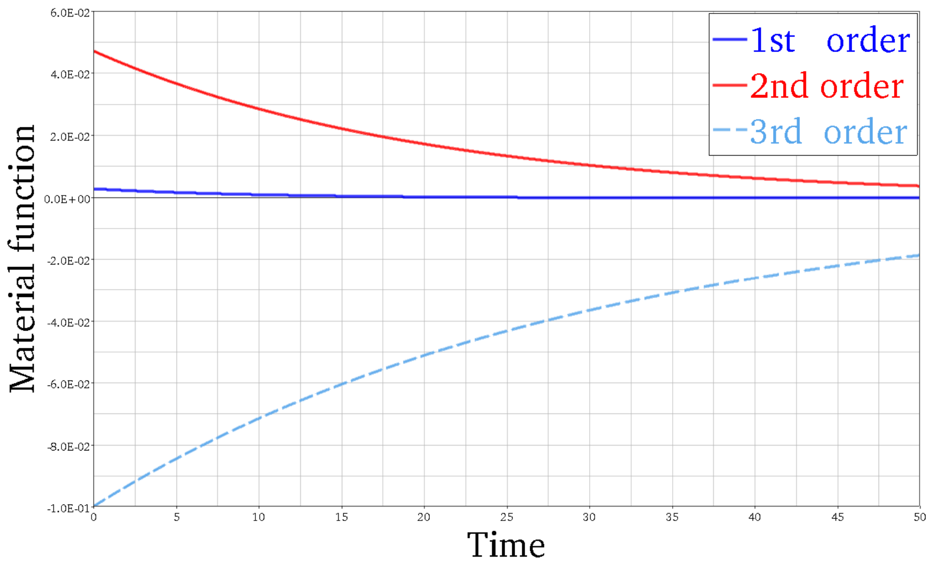
- Green-Rivlin model for isotropic foams

$$\boldsymbol{S}(t) = \int_0^t \tilde{R}_1(t-u_1)\,\dot{\boldsymbol{E}}(u_1)du_1 + \left[\int_0^t \tilde{R}_2(t-u_1)\dot{\boldsymbol{E}}(u_1)du_1\right]^2 + \left[\int_0^t \tilde{R}_3(t-u_1)\dot{\boldsymbol{E}}(u_1)du_1\right]^3 + \left[\int_0^t \tilde{R}_4(t-u_1)\dot{\boldsymbol{E}}(u_1)du_1\right]^4 + \left[\int_0^t \tilde{R}_5(t-u_1)\dot{\boldsymbol{E}}(u_1)du_1\right]^5$$

Prony series up to 5th order

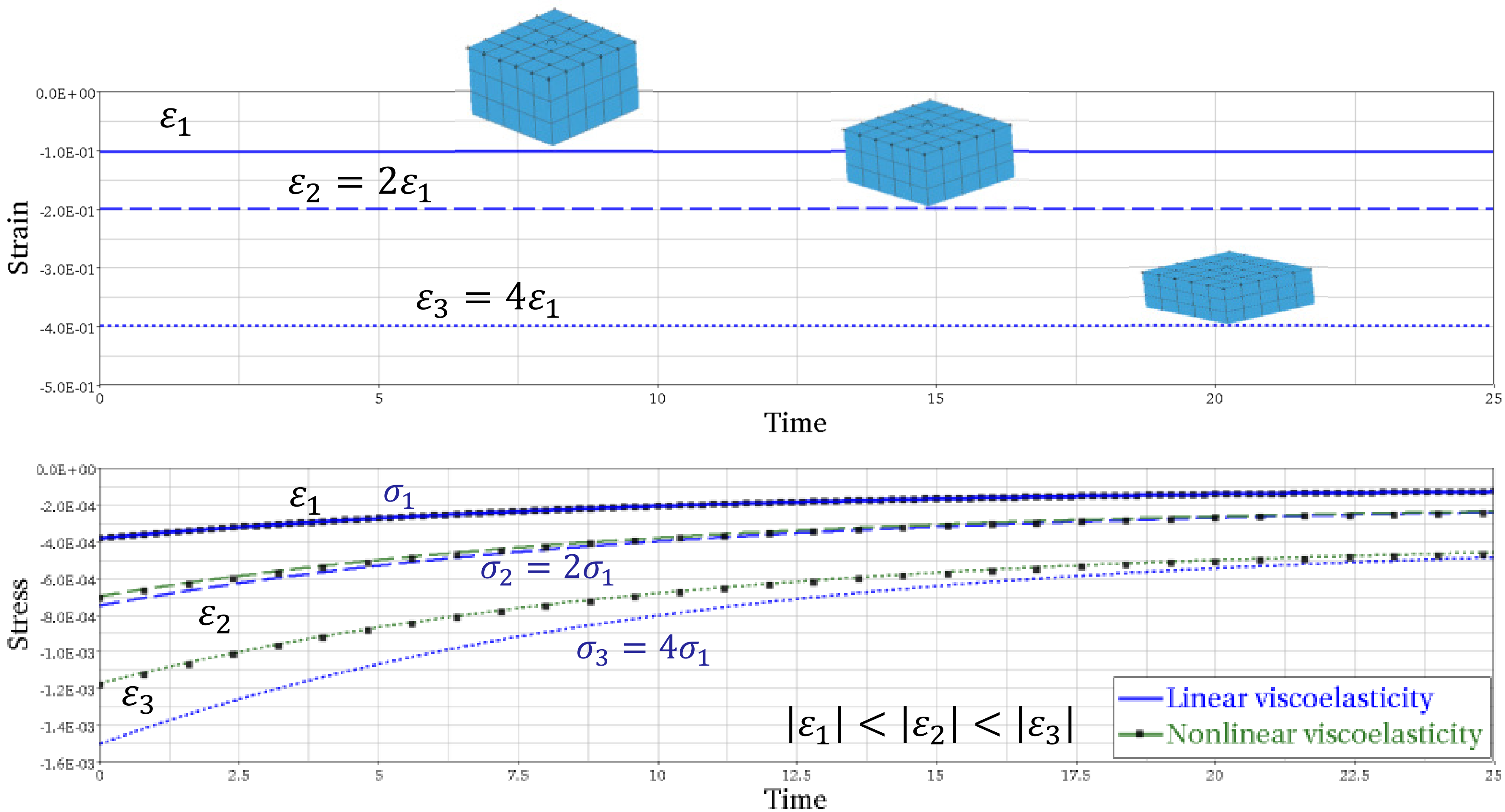
$$\tilde{R}_j(t) = \sum_{i=1}^{N} G_{ji} e^{-\beta_{ji} t}$$

$$[\tilde{R}_j(t)] = \sqrt[j]{N/m^2}$$



Nonlinear viscoelasticity for foams

- Relaxation test at 3 compression level: Saturation

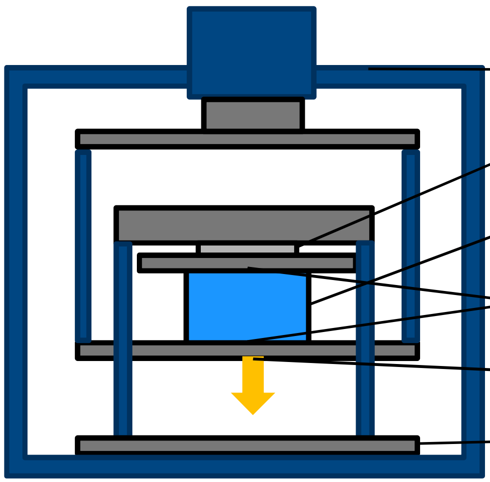


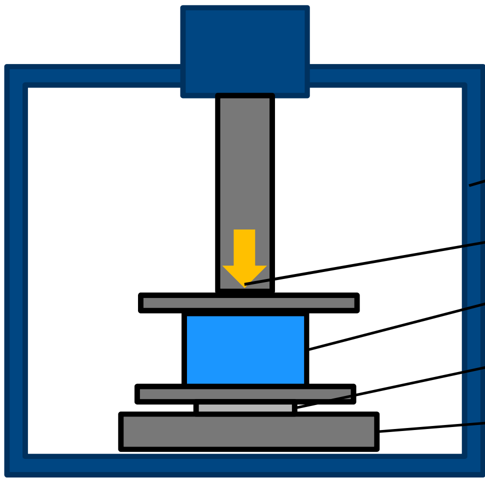
Outline

- Motivation
- State of the art in LS-DYNA®
- Nonlinear viscoelasticity for foams
- **Modeling of Confor® foam**
- Summary

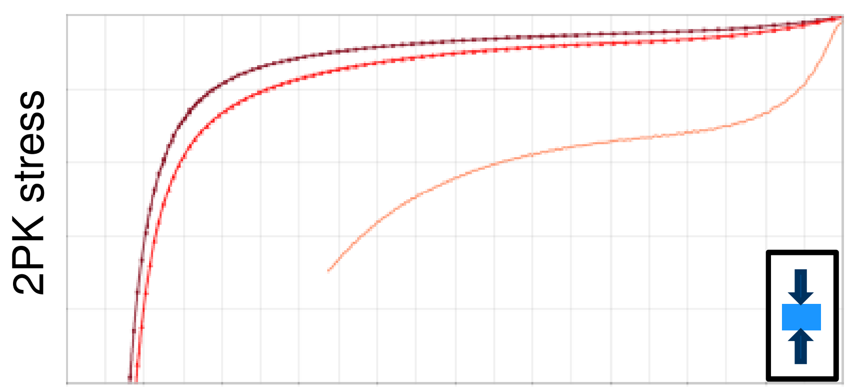
Modeling of Confor® foam

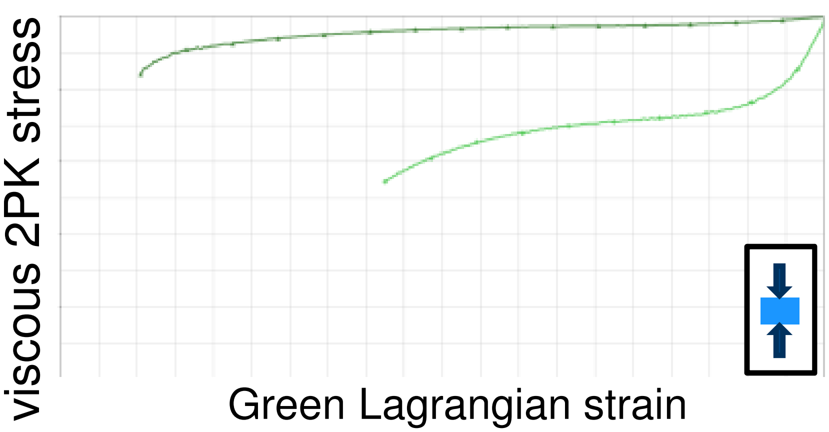
- Testing in uniaxial tension and compression load





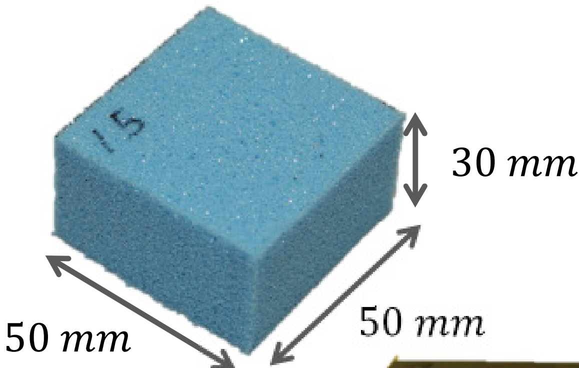
Viscous stress = Dynamic testing - Quasistatic testing

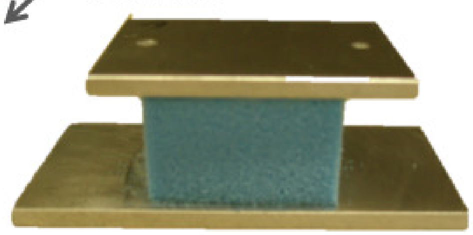




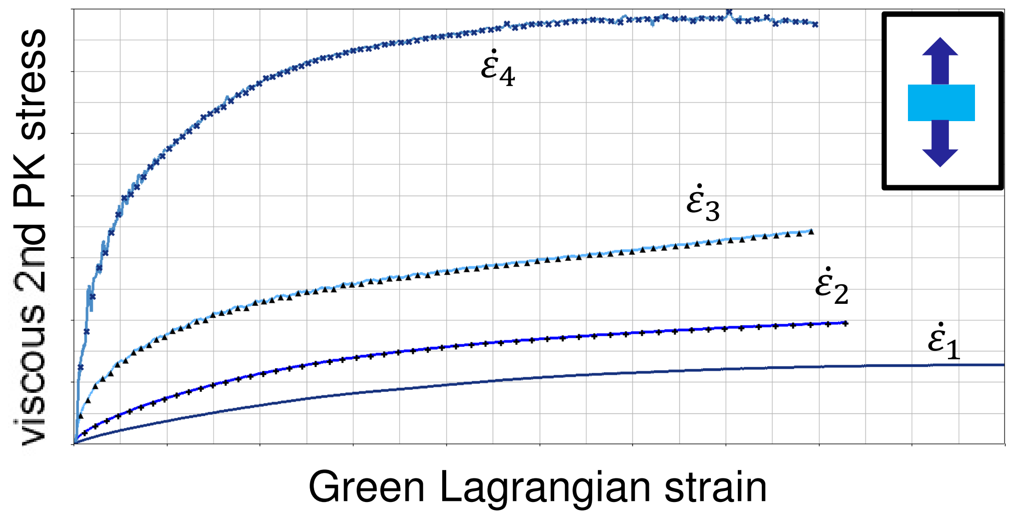
Modeling of Confor® foam

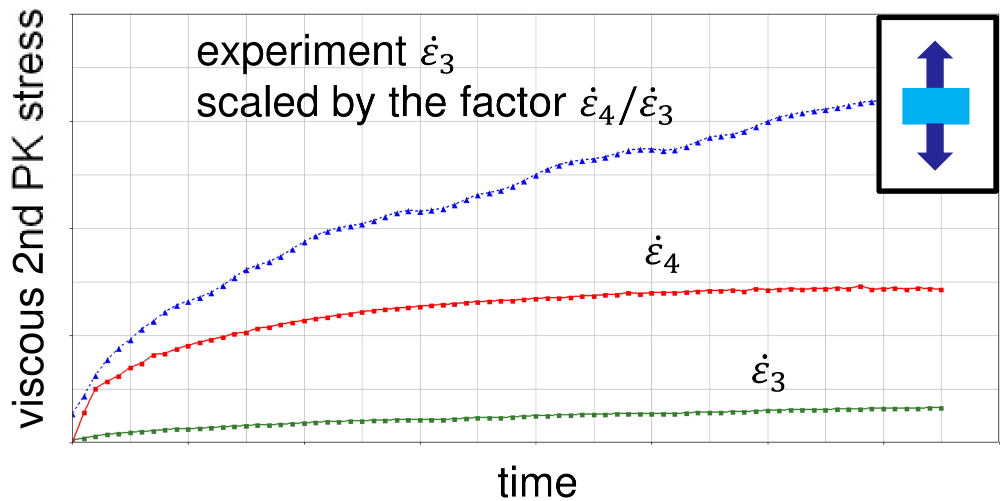
- Nonlinear viscoelastic properties





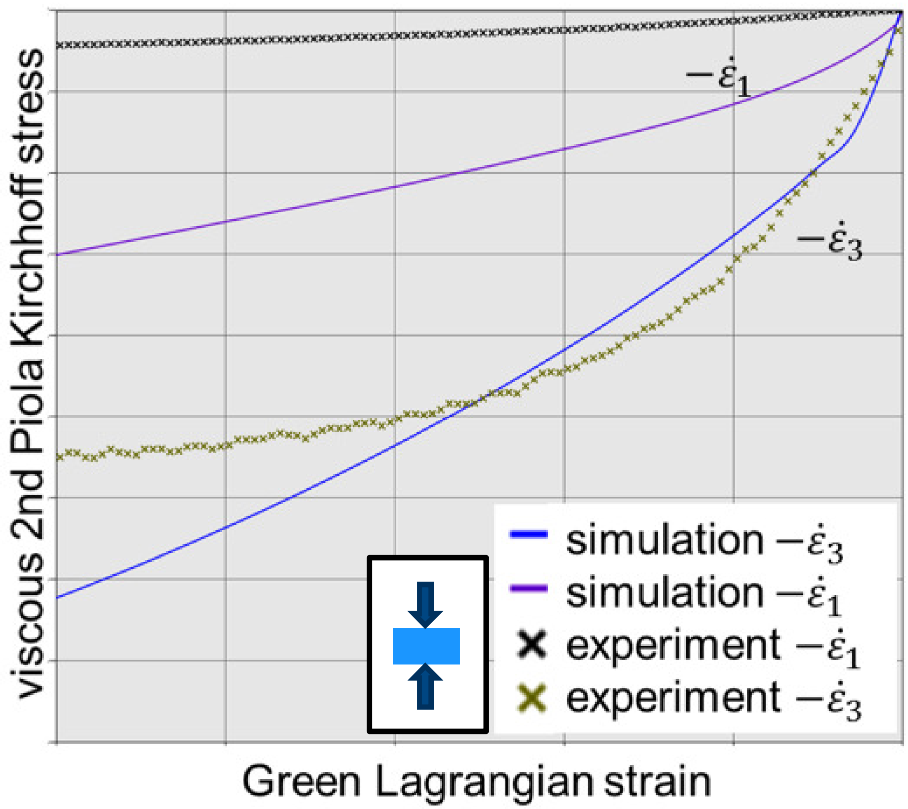
Fraunhofer
EMI

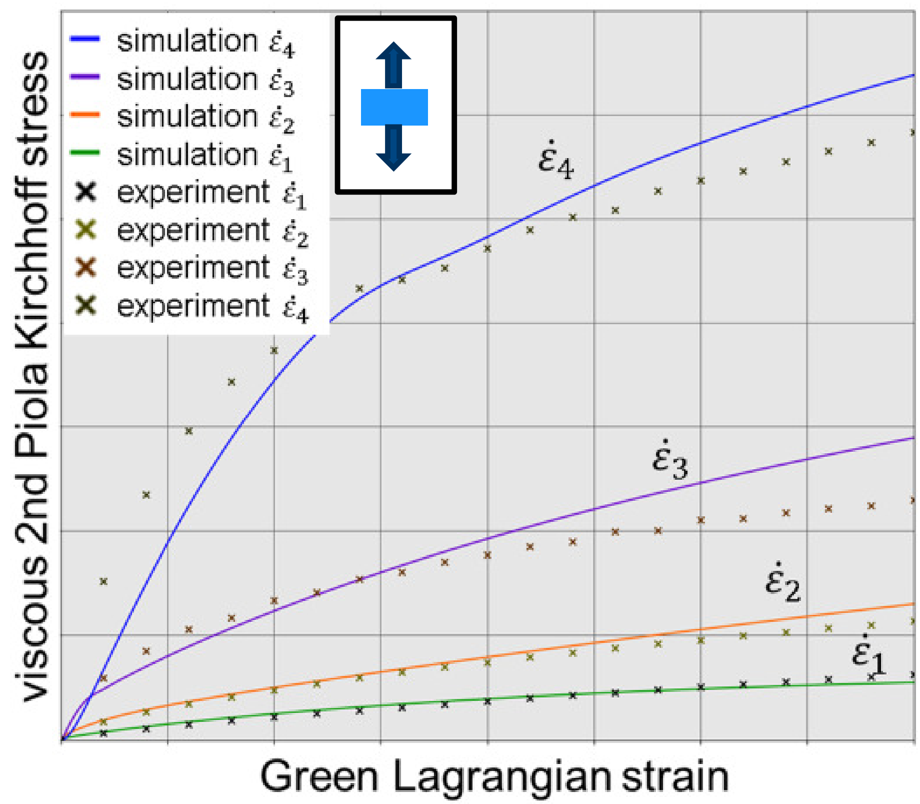




Modeling of Confor® foam

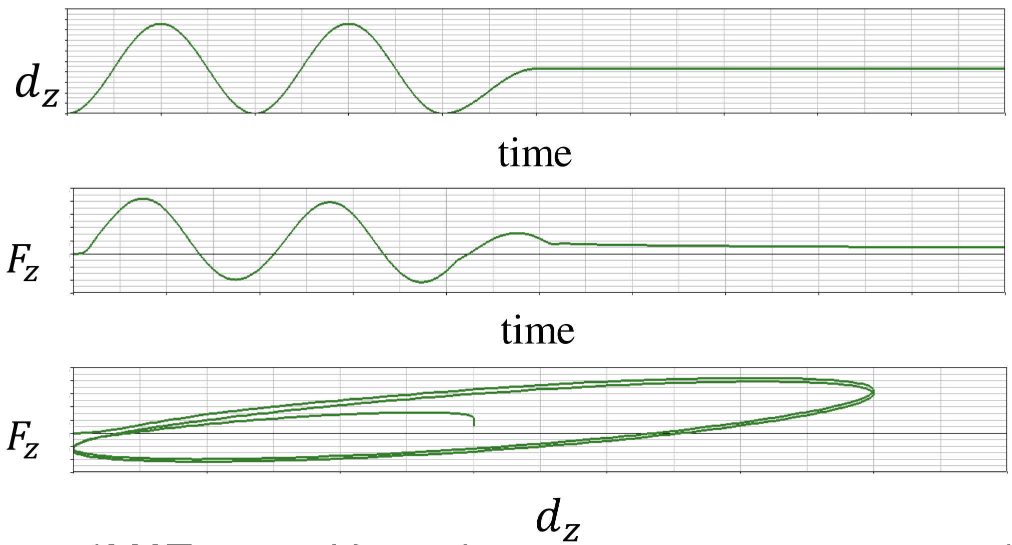
- Parameter identification up to 20% GL strain



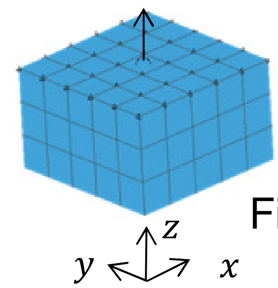


Modeling of Confor® foam

- Green-Rivlin model for foams

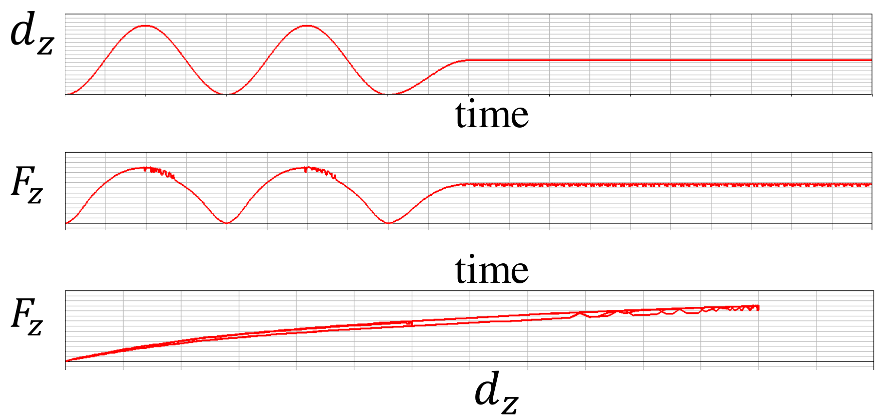


Time-dependent displacement d_z of the upper surface

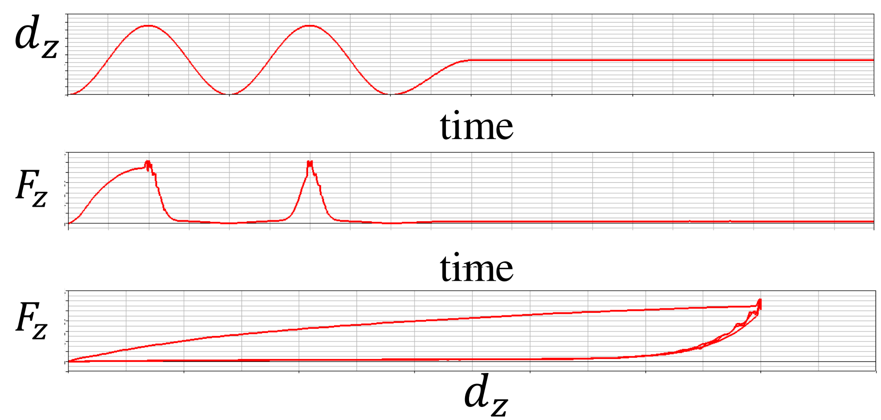


Fixed lower surface

- *MAT_083 without damage



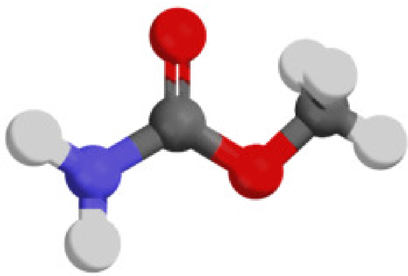
- *MAT_083 with damage



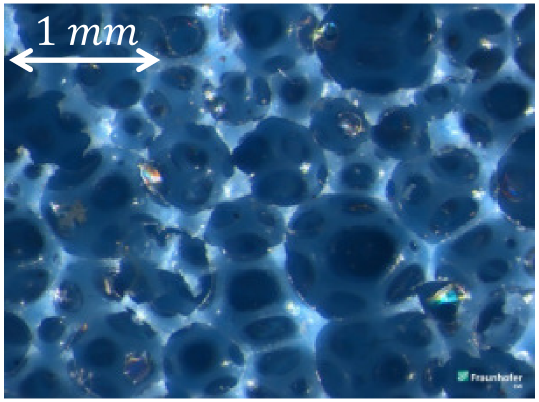
Modeling of Confor® foam

- Continuum approach to open-cell foams

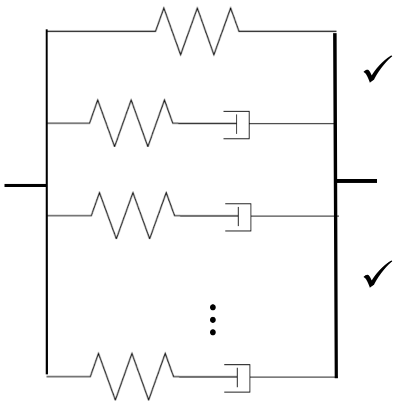
Material



Foam structure



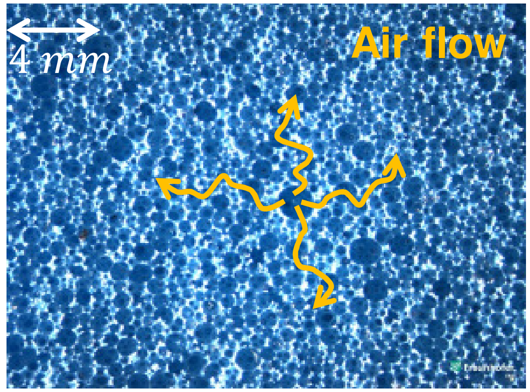
Sample size



✓ Equilibrium material response: asymmetric behaviour under compression and tension

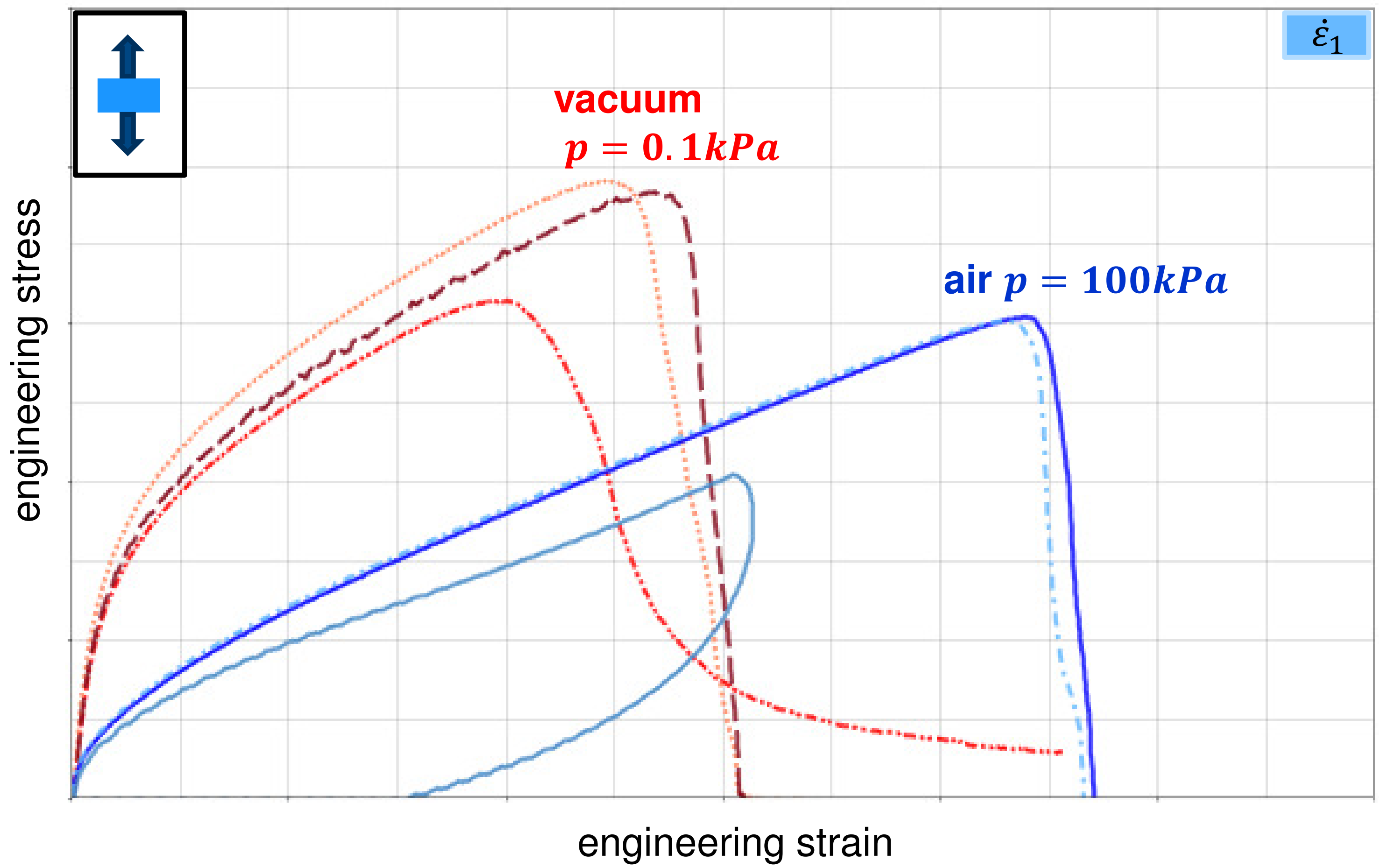
✓ Non-equilibrium material response: nonlinear viscoelasticity

Porous media: gas solid interaction



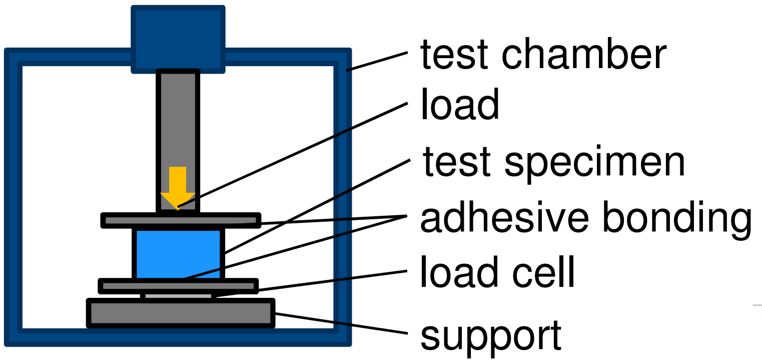
Modeling of Confor® foam

- Testing in air and vacuum



Modeling of Confor® foam

- Dynamic Mechanical Analysis (DMA): Glass transition temperature



Precompression: 30% eng. Strain

$$d_0 = 0.1mm, f = 10\ 1/s$$

Enforced displacement

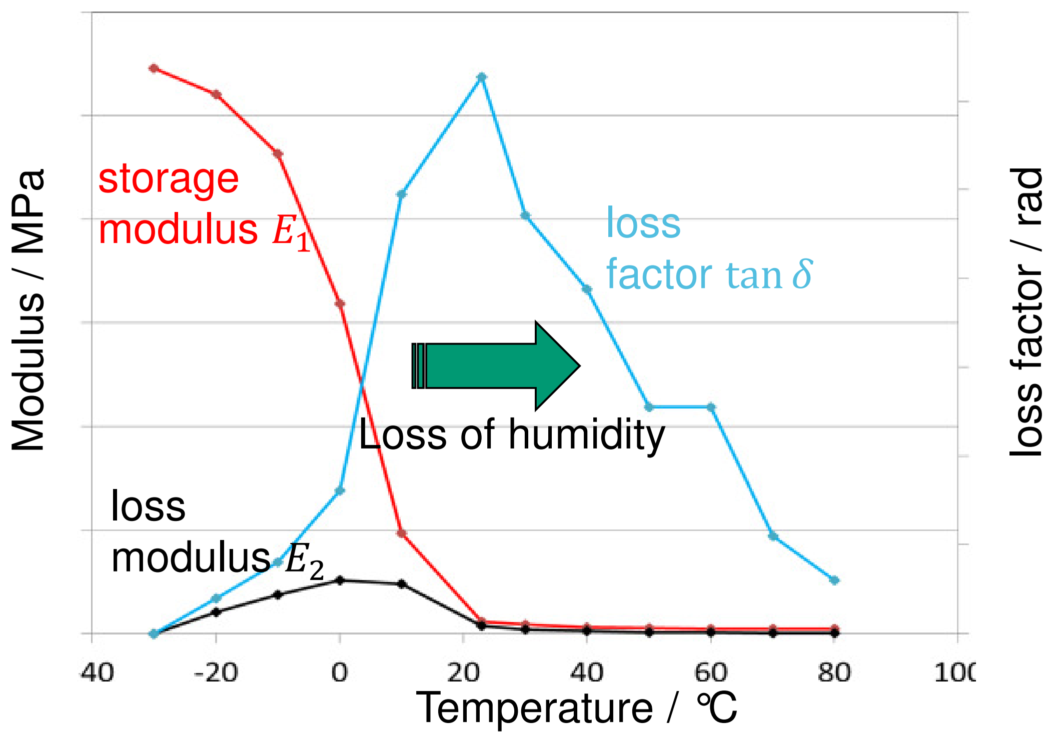
$$d = d_0 \sin(\omega t)$$

Force measurement

$$\frac{F}{A_0} = \frac{F_0}{A_0}\sin(\omega t + \delta) = |E^*|\varepsilon_0 \sin(\omega t + \delta)$$

Complex modulus

$$E^* = |E^*|e^{i\delta} = (E_1 + iE_2)$$



Outline

- Motivation
- State of the art in LS-DYNA®
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- **Summary**

Summary

- State of the art modeling without viscoelasticity
- Limits of linear viscoelasticity
- Improvement with nonlinear viscoelastic constitutive equation for foams
- Further research on parameter identification
- No separation of viscoelasticity and air flow with vacuum testing for Confor foam

Literature

- Effinger, V. et. al.: “Nonlinear Viscoelastic Modeling for Foams”, 13th International LS-DYNA Users Conference Detroit, 2014

  http://www.dynalook.com/13th-international-ls-dyna-conference/constitutive-modeling/nonlinear-viscoelastic-modeling-for-foams