Material Models of Polymers for Crash Simulation

An overview with focus on the dynamic test setup Impetus by 4a engineering

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Dynamore Infotag "Impetus", 30.11.2009

Laboratory of Mechanics - Equipment

- Hardware / Software
  - Clusters of Xeon, Intel Dual-Core and Quad-Core, 8CPUs parallel
  - FE Packages: LS-Dyna, Radioss, Nastran
  - Pre and Postprocessor: Hyperworks, LS-PrePost
- Experimental Setups
  - Quasi-static tensile and compression tester by Instron
  - Dynamic testing system “4a Impetus II”, movable devices for compression and bending tests, range of velocities: 500-4500mm/s
  - Dynamic test setup for impact tests on windshields
  - Drop tower

Outline

- Parameter based Input vs. Tabulated Input
- Rubberlike Materials
  - Finite Elasticity
  - Blatz-Ko Rubber (Mat_7)
  - Simplified Rubber (Mat_181)
- Foams
  - Fu Chang Foam (Mat_83)
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- Plastics
  - Piecewise Linear Plasticity Mat_24
  - Schmachtenberg / Johnson Cook

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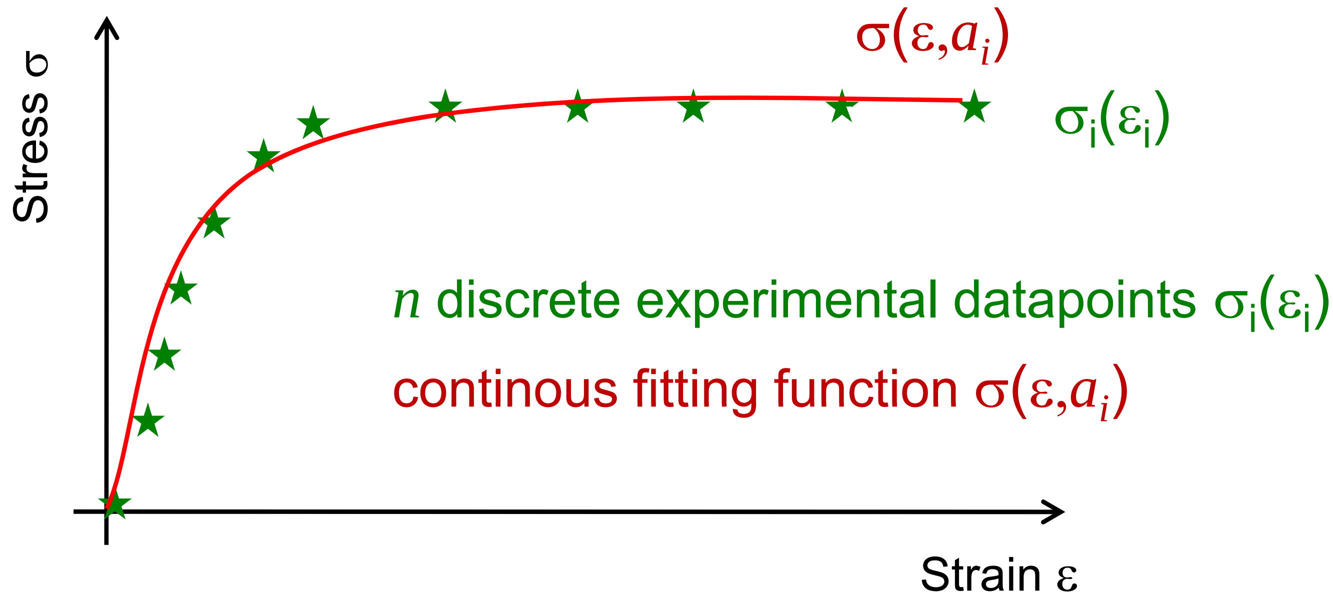
Parameter based Input versus Tabulated Input

- Input of stress-strain relations in a tabulated way are very popular in commercial crash-codes
- The (more or less) direct input of experimental data obtained by tensile tests is the major benefit of those approaches
- This advantage fails in the validation and verification process where the stress-strain-curves have to be fitted to experimental results
- Parameter based stress-strain relations have therefore a huge advantage in reverse engineering (fitting of parameters, e.g. by LS-OPT, instead of the entire stress-strain-datapoints)

Parameter based Input versus Tabulated Input

- Parametrized Formulation



- Usually via suitable ansatz $\sigma(\varepsilon,a_i)$ in dependence of the material under consideration, where a_i are material parameters

Parameter based Input versus Tabulated Input

- Parameters may then be identified, e.g. by least square fit:

$$S(a_i) := \sum_{k=1}^{n} \left[\sigma_k(\varepsilon_k) - \sigma(\varepsilon, a_i)\right]^2 \rightarrow MIN$$

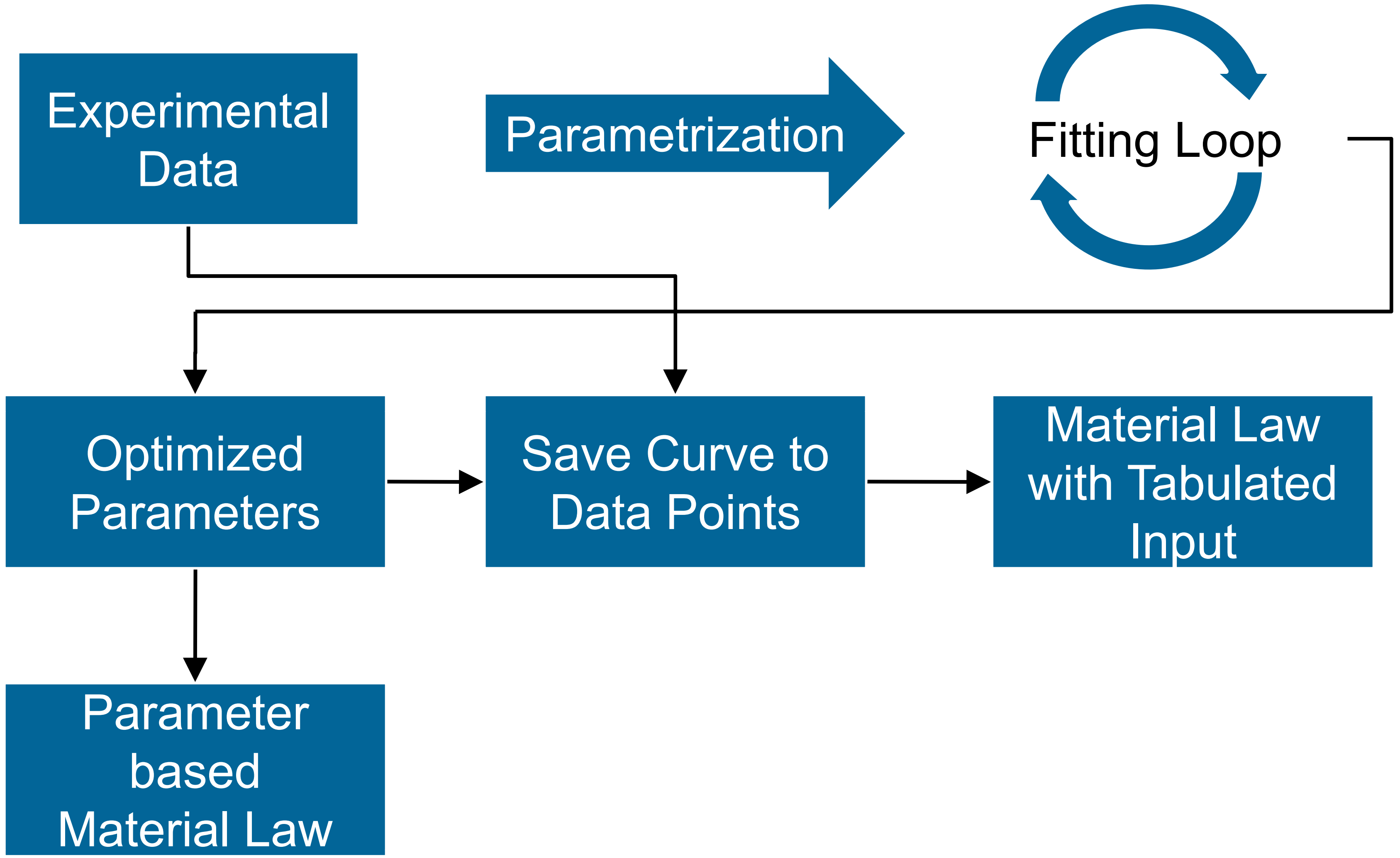
$$\Rightarrow \quad \partial_{a_1} S(a_1) = \partial_{a_2} S(a_2) = \ldots = \partial_{a_n} S(a_n) = 0$$

which leads to a nonlinear system of equations in general

- Alternatively LS-OPT can also be used

Parameter based Input versus Tabulated Input

- Procedures of Material Card Generation



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Hyperelasticity

Right Cauchy-Green Tensor $\mathbf{C} = \mathbf{F}^T \mathbf{F}$ with $\mathbf{F} = Grad\,\mathbf{x}$

2. PK: $\mathbf{S} = 2\dfrac{\partial W}{\partial \mathbf{C}}$ → Cauchy stress tensor $\sigma = \dfrac{1}{J}\mathbf{F}\mathbf{S}\mathbf{F}^T$ $\quad J = \det \mathbf{F}$

Strain energy density in terms of invariants: $W = \hat{W}(I_C, II_C, III_C)$

$$I_C = 1 : \mathbf{C} = \mathrm{tr}\,\mathbf{C}, \quad II_C = \frac{1}{2}\left(I_C^2 - \mathbf{C} : \mathbf{C}\right), \quad III_C = \det \mathbf{C}$$

Derivative:

$$\mathbf{S} = 2\frac{\partial W}{\partial I_C}\mathbf{1} + 2\frac{\partial W}{\partial II_C}\left(I_C\mathbf{1} - \mathbf{C}\right) + 2\frac{\partial W}{\partial III_C} III_C \mathbf{C}^{-1}$$

Rubber Laws in LS-DYNA

Law	
7	MAT_BLATZ-KO_RUBBER
27	MAT_ MOONEY-RIVLIN_RUBBER
31 77	MAT_FRAZER-NASH_RUBBER MAT_GENERALIZED_RUBBER
77	MAT_OGDEN_RUBBER
181	MAT_SIMPLIFIED_RUBBER

One-Parameter Law: Blatz-Ko Energy Function

- General form for polyurethane foam rubbers (1962):

$$W = \frac{G}{2}\left[I_1 + \frac{1}{\alpha}\left(I_3^{-\alpha} - 1\right) - 3\right] + \frac{G}{2}(1-\beta)\left[\frac{I_2}{I_3} + \frac{1}{\alpha}\left(I_3^{\alpha} - 1\right) - 3\right]$$

$$\alpha = \frac{\nu}{1-2\nu}$$

- Implemented as material law no. 7 in LS-DYNA:

$$\beta = 1, \quad \nu = 0.463$$

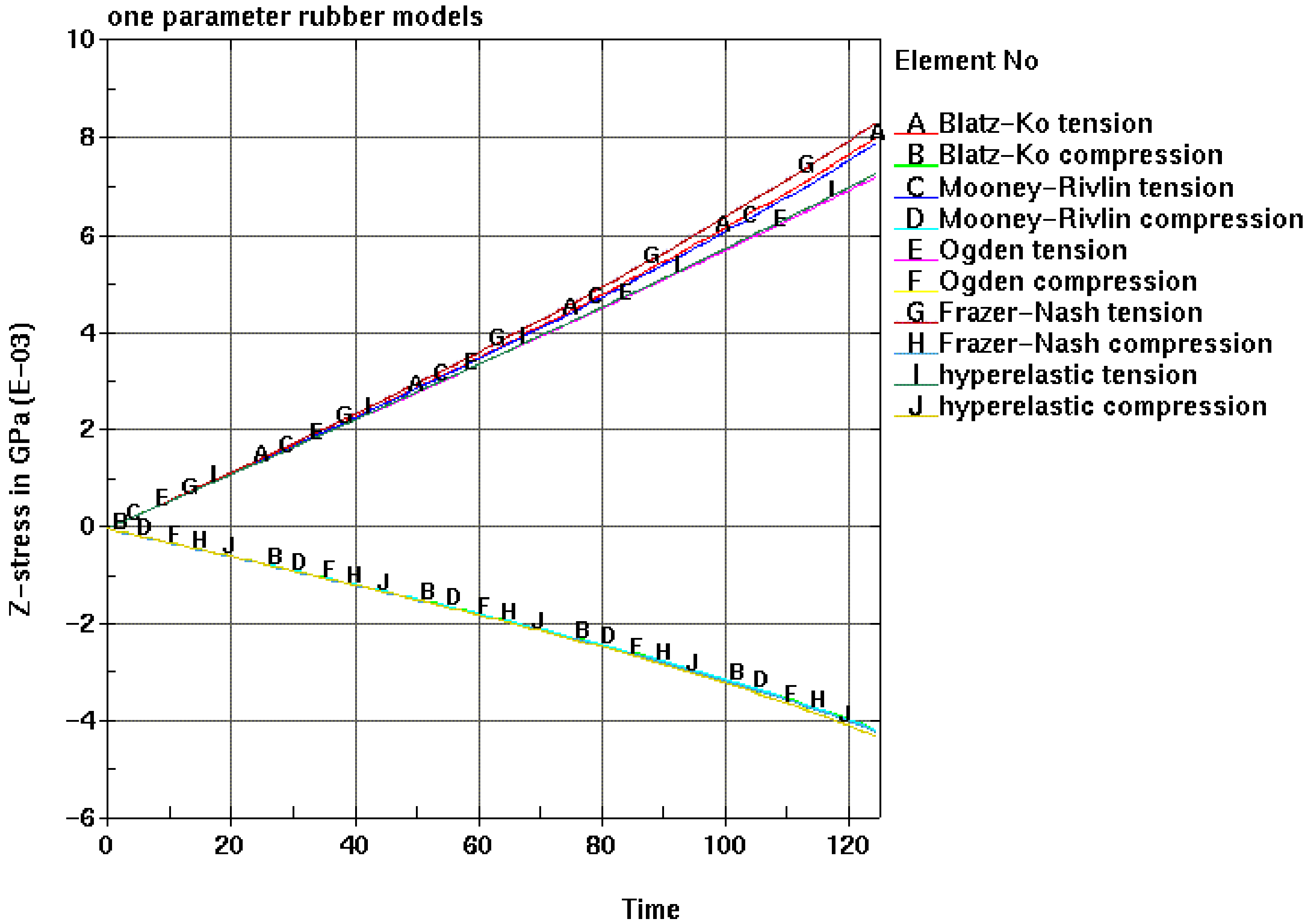
$$W = \frac{G}{2}\left[I_1 - 3 + \frac{1}{\alpha}\left(I_3^{-\alpha} - 1\right)\right] \Rightarrow \sigma = G\left(\frac{1}{J}\mathrm{FF}^{\mathrm{T}} - J^{-2\alpha-1}\delta\right)$$

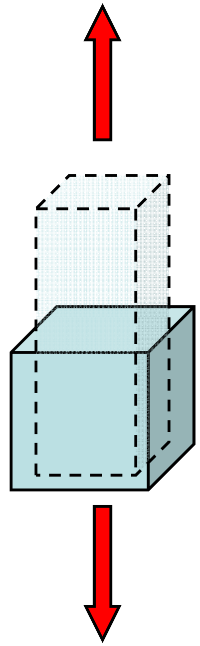
$$\alpha = \frac{\nu}{1-2\nu} \Rightarrow -2\alpha - 1 = -2\frac{\nu}{1-2\nu} - 1 = \frac{-1}{1-2\nu}$$

Equivalent One-Parameter Models

7	27	77 Ogden	31	77
G	$A = \frac{G}{2}$	$\mu_1 = G$ $\alpha_1 = 2$	$C100 = \frac{G}{2}$	$C10 = \frac{G}{2}$

Equivalent One-Parameter Models





Limitations of Low Order Models

- Fitting of a higher curvature in the stress-strain curve for large deformations will not work
- Optimization software will not help
- Multiple parameter models, e.g. Ogden's energy function (Mat_77) allow for fitting stress-strain curves with higher curvature

$$W = \sum_{i=1}^{3} \sum_{j=1}^{n} \frac{\mu_j}{\alpha_j} \left(\lambda_i^{*\alpha_j} - 1 \right) + K \left(J - 1 - \ln J \right)$$

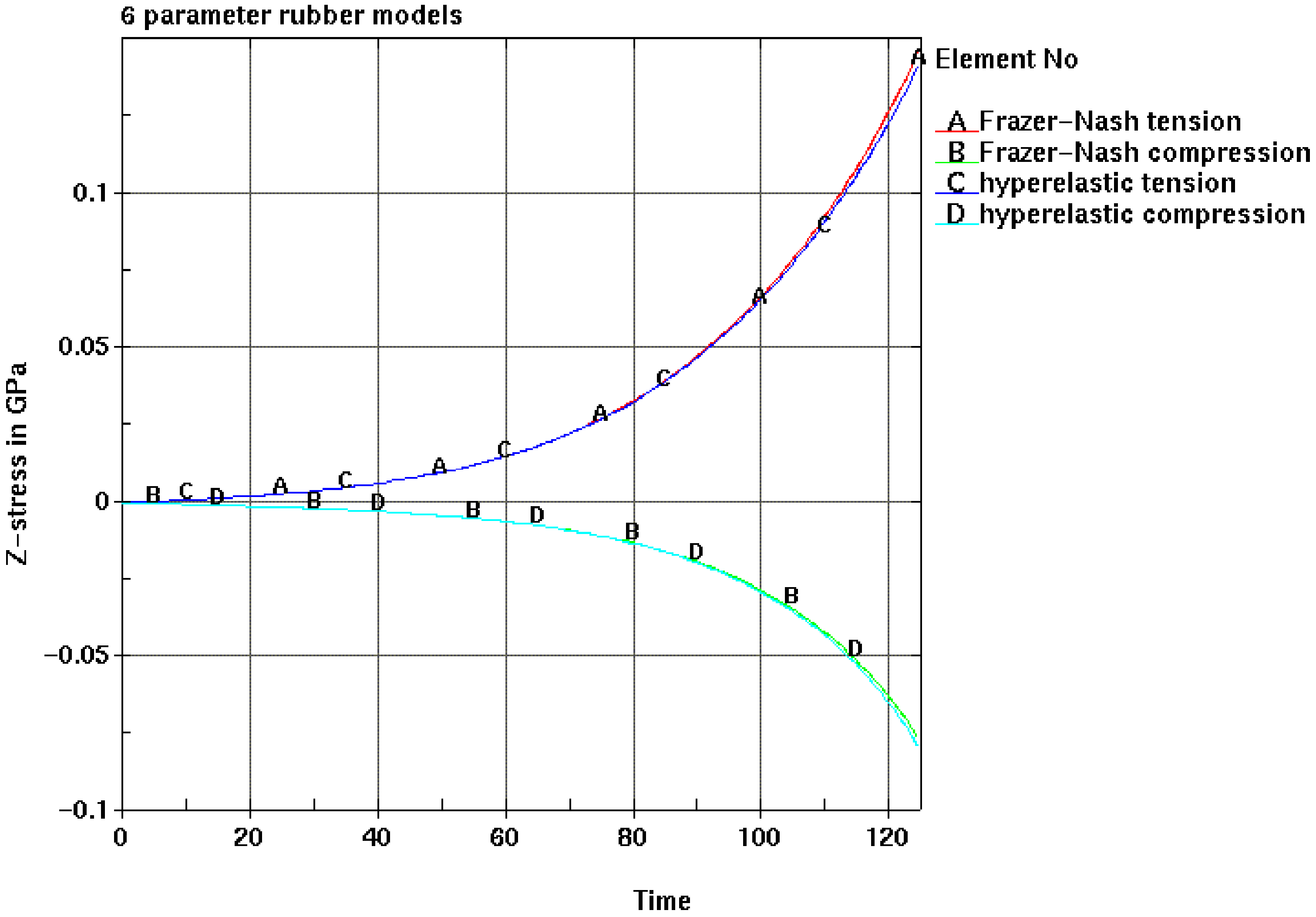
$$J = \lambda_1 \lambda_2 \lambda_3 , \quad \lambda_i^* = \lambda_i J^{-1/3} = \frac{\lambda_i}{J^{1/3}}$$

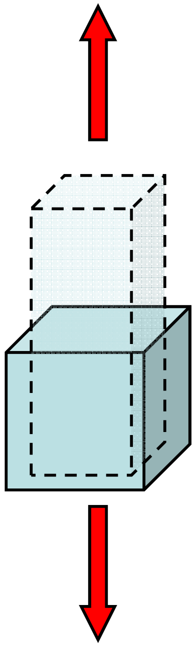
- Tabulated version available in MAT_SIMPLIFIED_RUBBER

Equivalent Multiple-Parameter Models

31		77
C100	I_1	C10
C200	I_1^2	C20
C300	I_1^3	C30
C400	I_1^4	
C110	$I_1 I_2$	C11
C210	$I_1^2 I_2$	
C010	I_2	C01
C020	I_2^2	C02

Equivalent Multiple-Parameter Models





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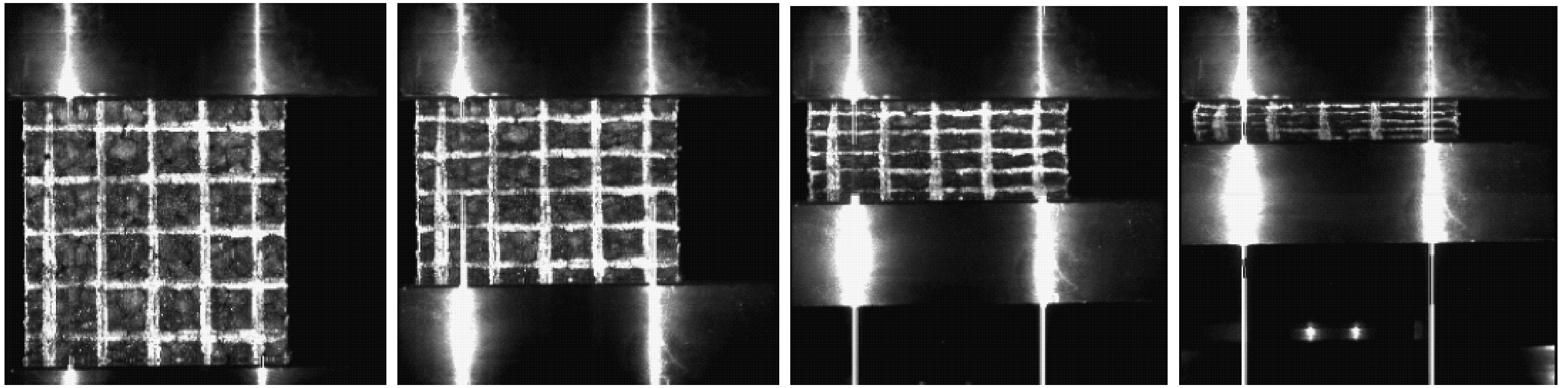
Introduction - What are Foams?

- Material scientist: any material manufactured by some expansion process
- (Crash-) Numericist: a material with Poisson's ratio close to zero



EPP
RG20

- Both definitions coincide only for low density foams, roughly below 200g/l
- High density (>200g/l) structural foams exhibit a non-negligible Poisson effect

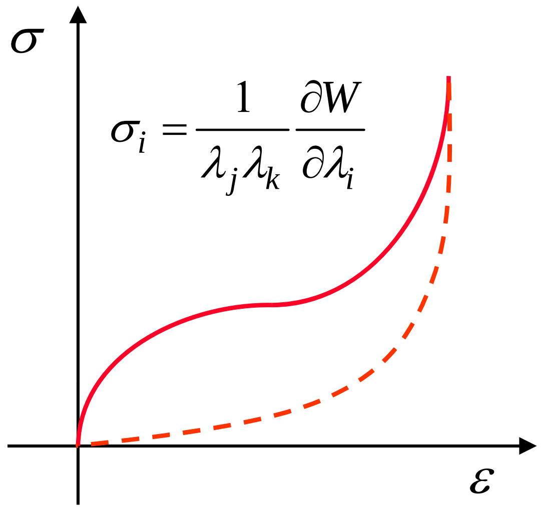
Material Laws for Elastic Foams in LS-DYNA

No.	keyword	formulation	input
38	MAT_BLATZ_KO_FOAM	hyperel., ν = 0.25	1 parameter
57	MAT_LOW_DENSITY_FOAM	hyperel. + viscoel.	LC + parameter
62	MAT_VISCOUS_FOAM	hyperel. + viscoel. ν 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., ν 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
181 183	MAT_SIMPLIFIED_RUBBER/FOAM _(WITH_FAILURE) / _WITH_DAMAGE	hyperel. + strain-rate ν variable	LC/ table

Material Laws for Elastic Foams (no Poisson Effect)

strainrate dependent hyperelastic

visco-hyperelastic



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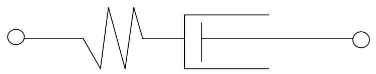

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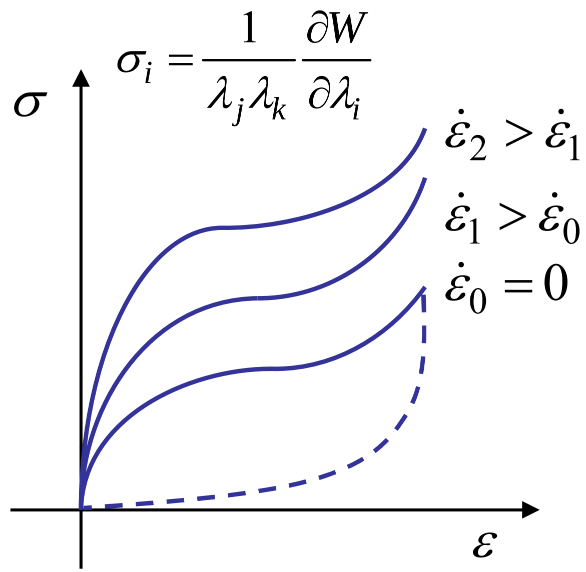
elastic damage



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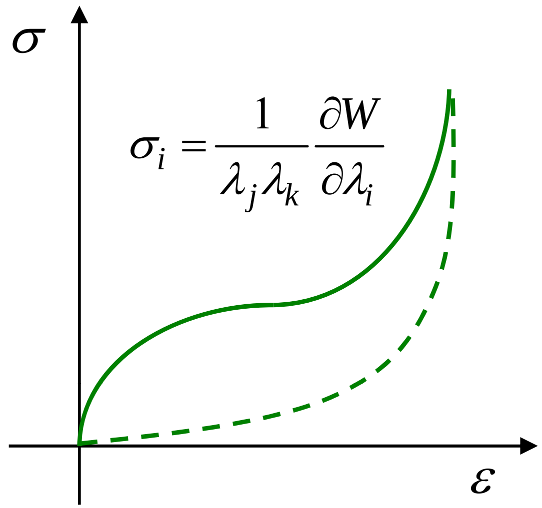
elastic damage

visco-hyperelastic



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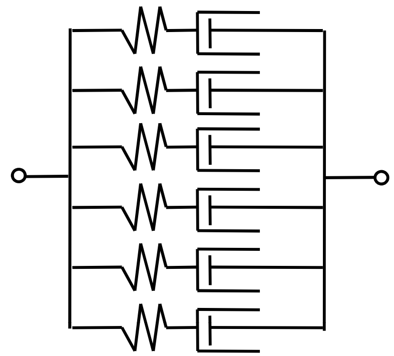

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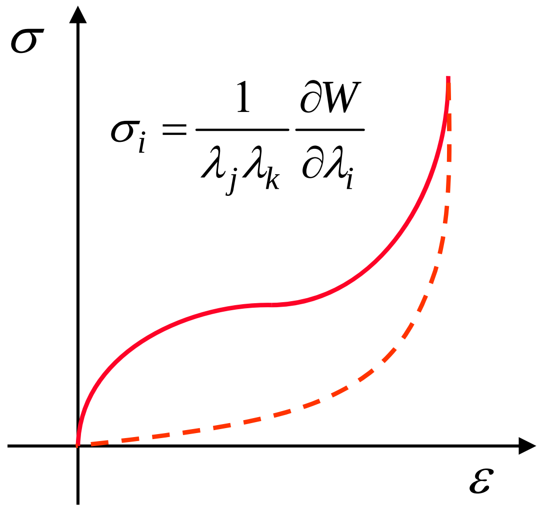
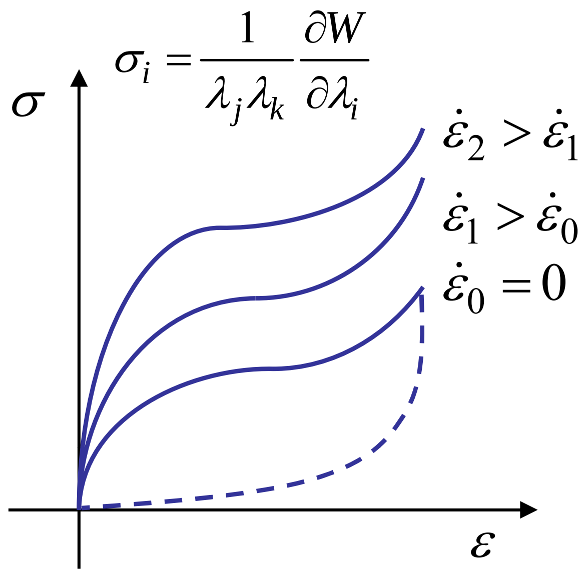
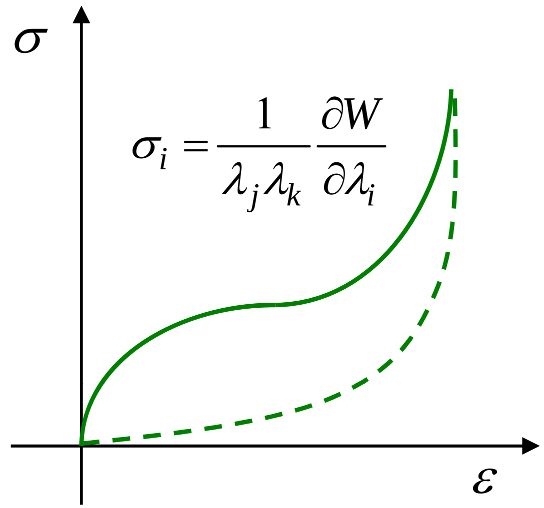
strainrate dependent hyperelastic

visco-hyperelastic





visco-hyperelastic



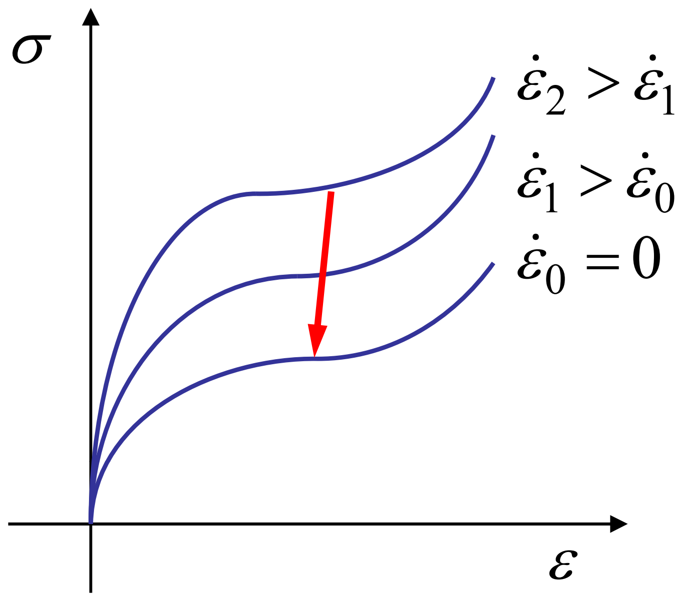
MAT_83
MAT_FU-CHANG_FOAM

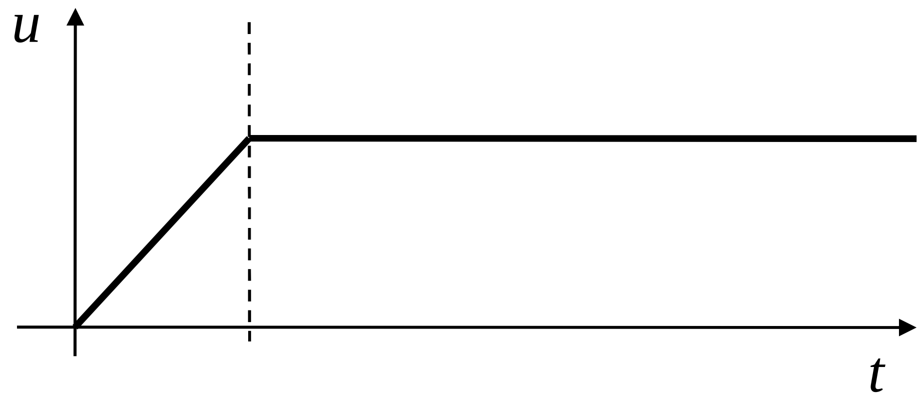
MAT_57
MAT_LOW_DENSITY_FOAM

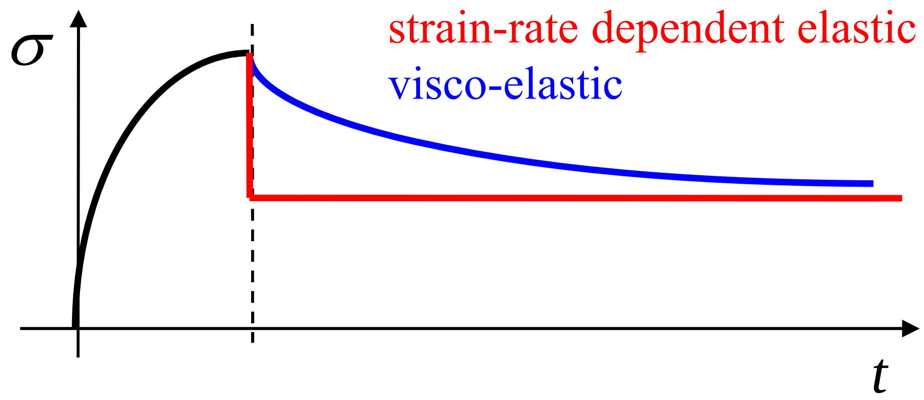
MAT_62
MAT_LOW_DENSITY_FOAM

Rate-Dependent Hyperelasticity versus Visco-Elasticity

Relaxation Test







- rate-independent unloading
- numerically stable
- unrealistic, potential problem for foams with high damping (e.g. confor foam)

MAT_83
MAT_73

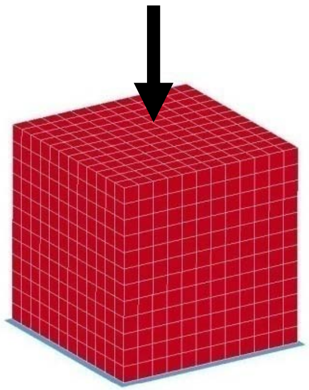
Complete Input-Data: Unloading

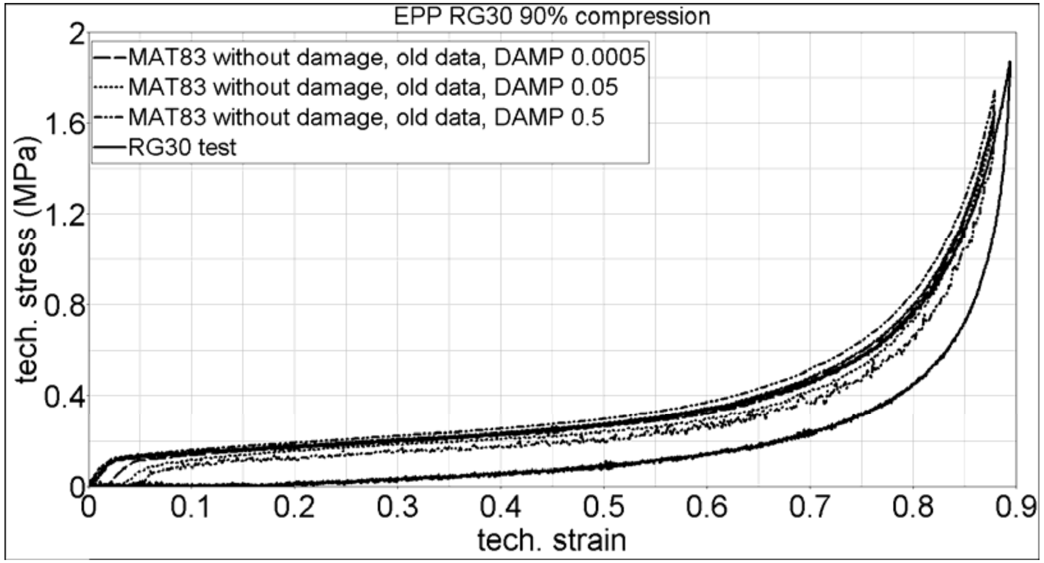
- Define an additional curve for unloading (strain rate zero in TABLE), this should correspond to the quasistatic unloading path
- Unloading always follows the curve with lowest strain rate and is detected by

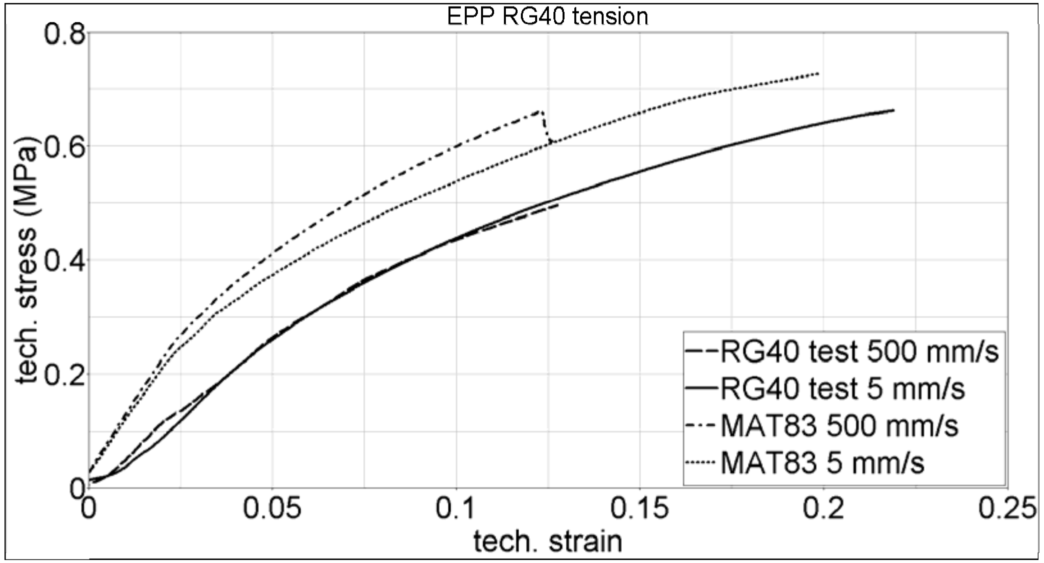
$$\varepsilon_i \cdot \dot{\varepsilon}_i \begin{cases} \leq 0 & \rightarrow \textit{ unloading: strain rate is set to zero} \\ > 0 & \rightarrow \textit{ loading: strain rate dependence} \end{cases}$$

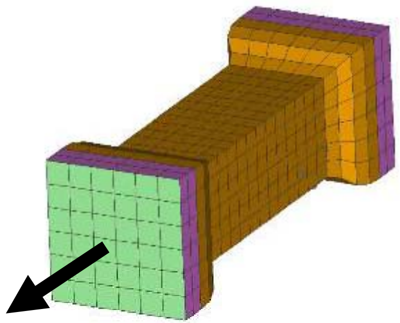
- This may lead to numerical problems that can be avoided by an elastic damage formulation
- Furthermore, no rate dependency upon unloading

Some Validation Tests – How Accurate is MAT_83?

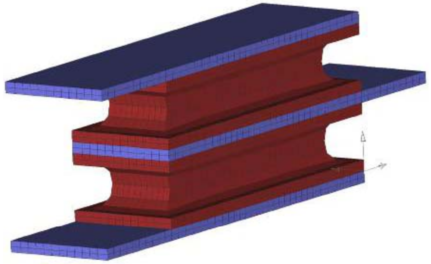


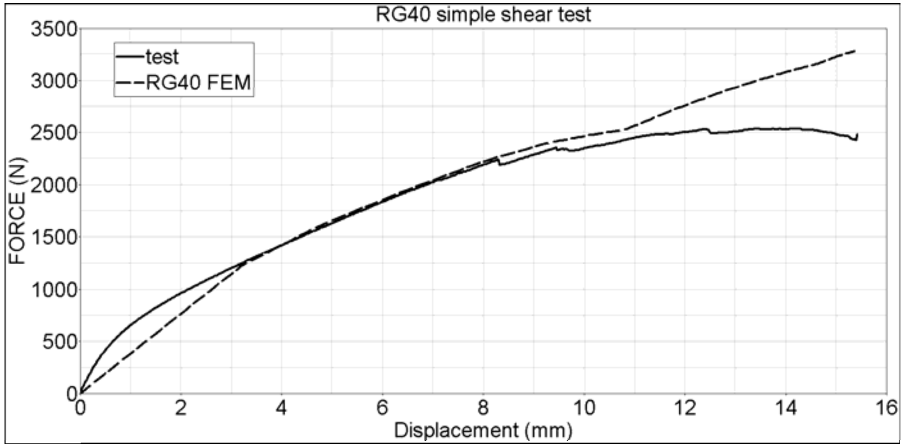


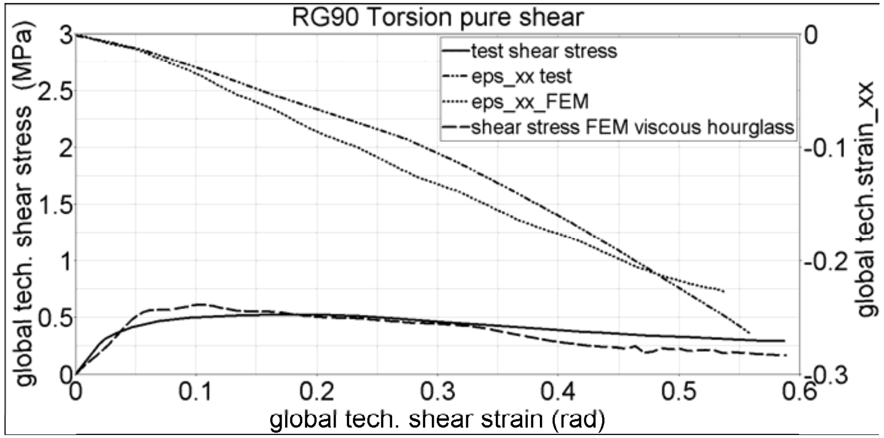


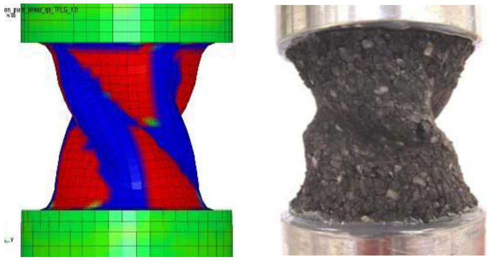


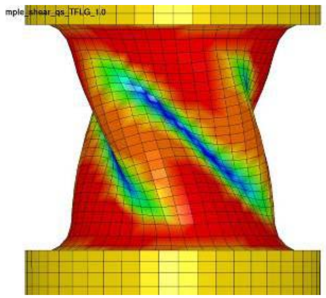
Some Validation Tests – How Accurate is MAT_83?

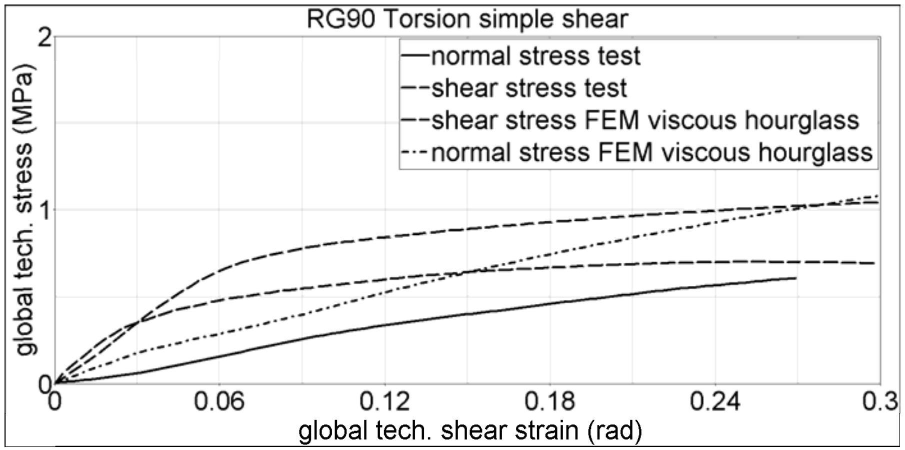






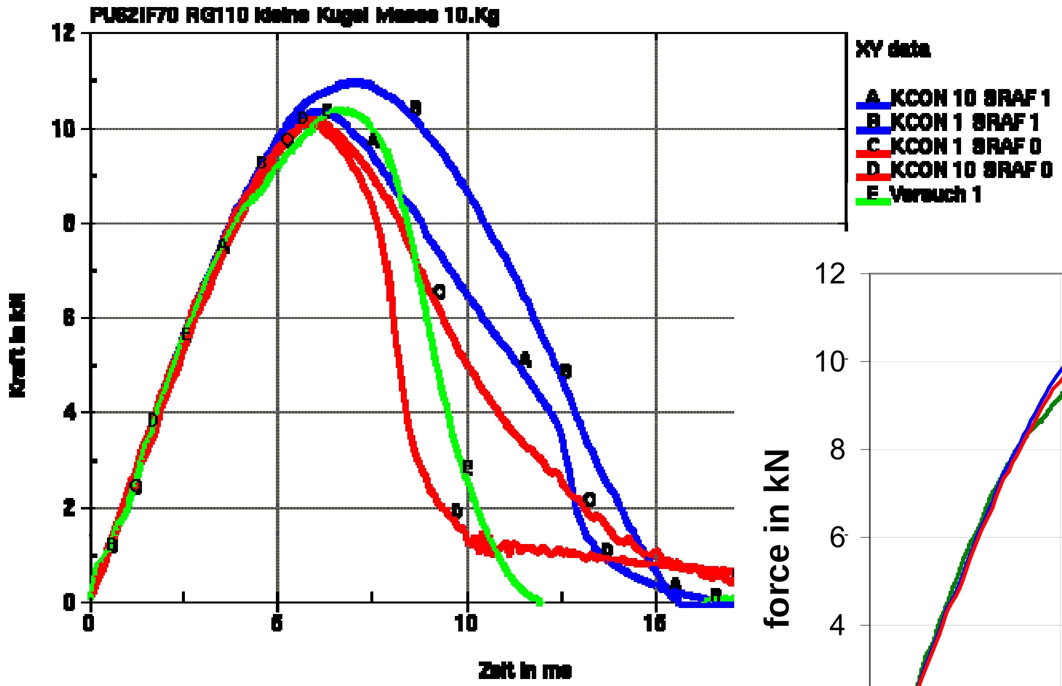


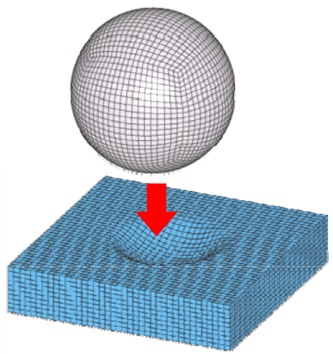


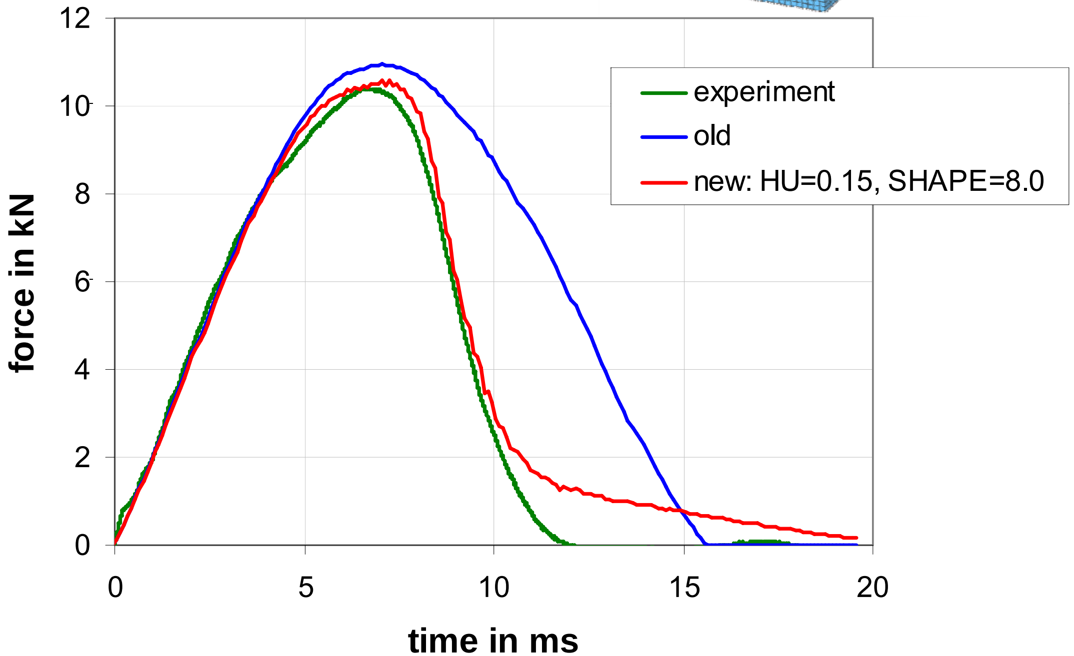


Some Validation Tests – How Accurate is MAT_83?

- Damage formulation a further improvement and can also be identified during the Impetus/LS-OPT procedure!







Material Law for Elastic Foams with Poisson Effect

- Uses Hill instead of Ogden functional (incompressible case, rubber):

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

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

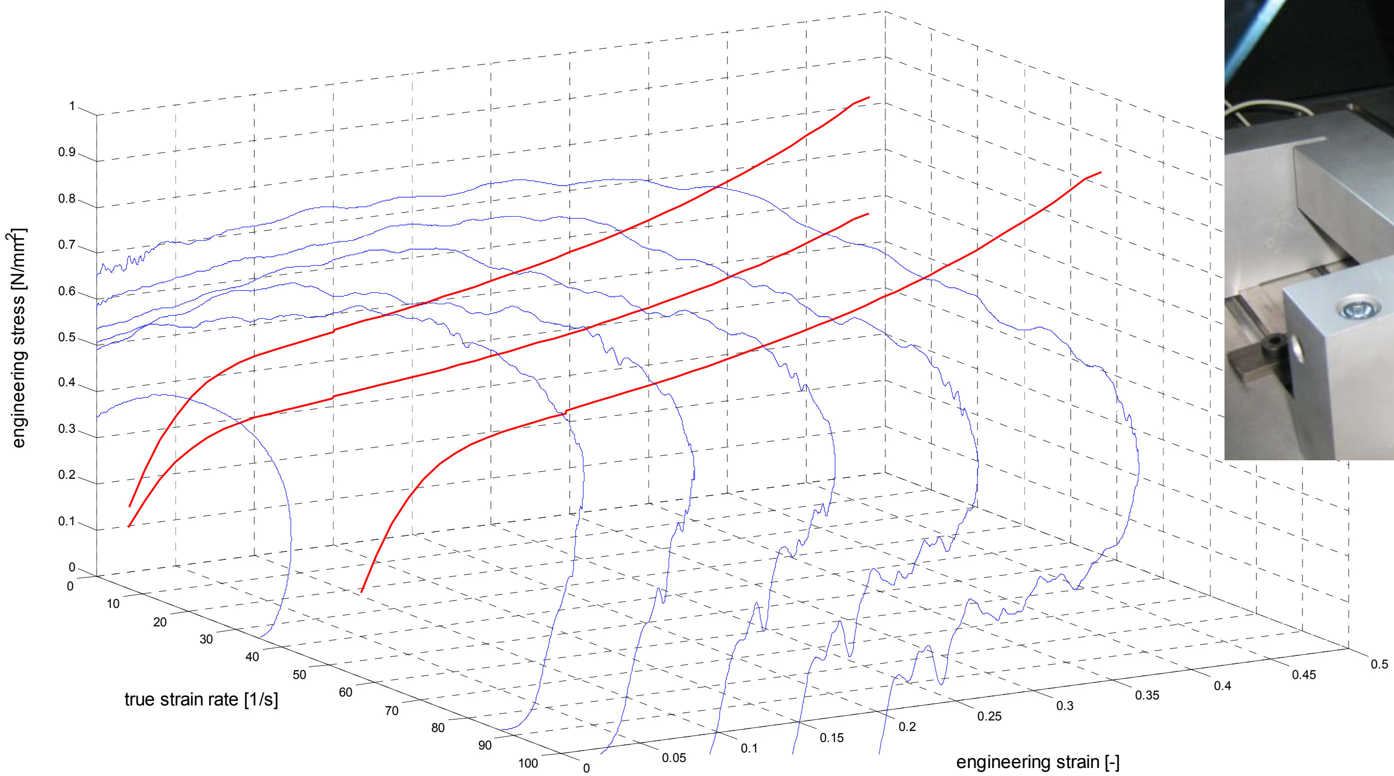
The nominal stresses (force per unit undeformed area) are

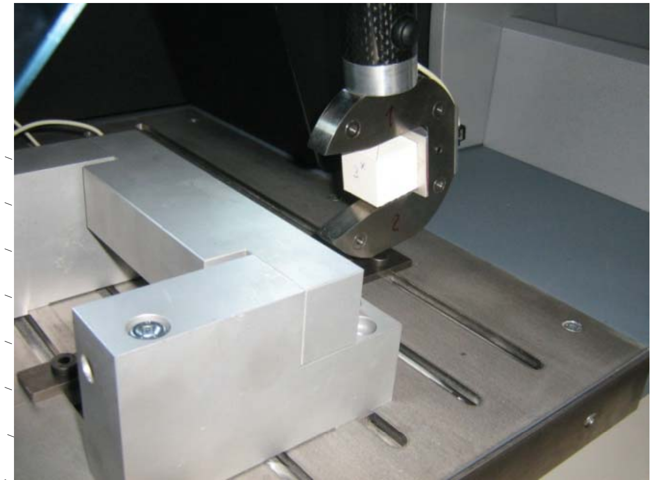
$$S_i = \frac{1}{\lambda_i} \sum_{j=1}^{m} C_j \left[\lambda_1^{b_j} - J^{-nb_j} \right] \qquad i = 1,2,3$$

- Allows for a fully tabulated input implemented as MAT_SIMPLIFIED_RUBBER/FOAM in 2004

Example: Rubberlike Foam for Sensomotoric Inlays

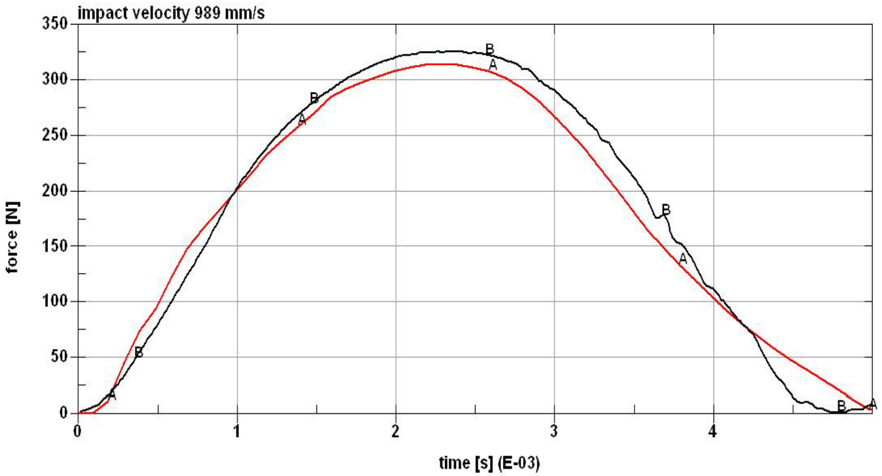
- In pendulum impact tests (Impetus) stress can be plotted as a function of strain and the strain rate: $\sigma = \sigma\left(\varepsilon, \dot{\varepsilon}\right)$
- A fitted surface leads then to stress-strain relations for tabulated input
- Neuronal network in LS-OPT works similar

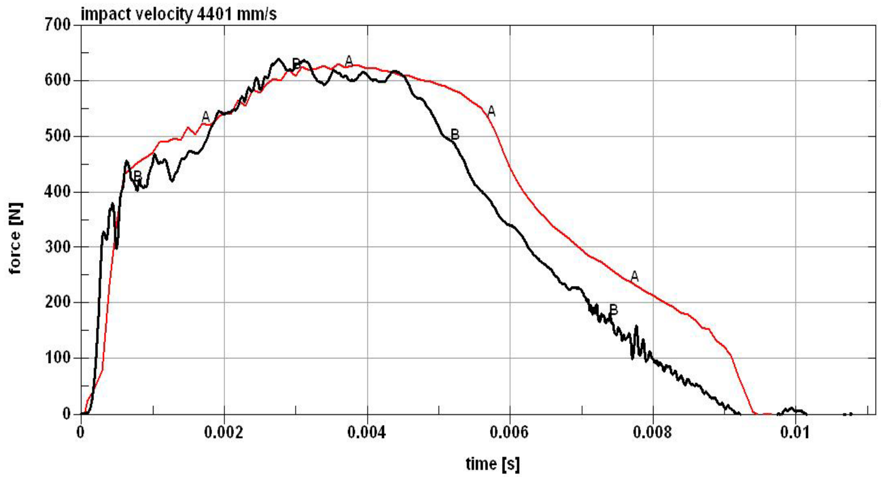




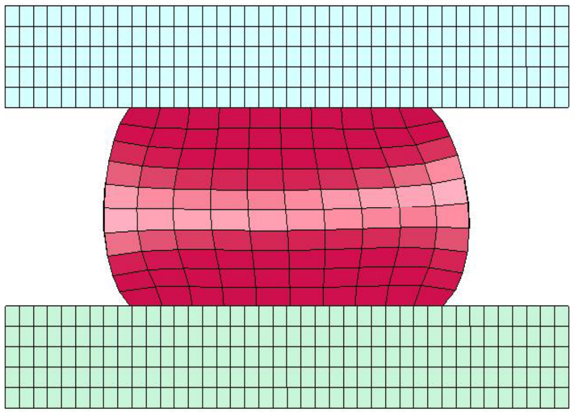
Validation: MAT181 vs. MAT183

- Hill's functional in MAT181 allows for a proper consideration of Poisson's ratio (ν=0.25) and yields to a better agreement to the experiment

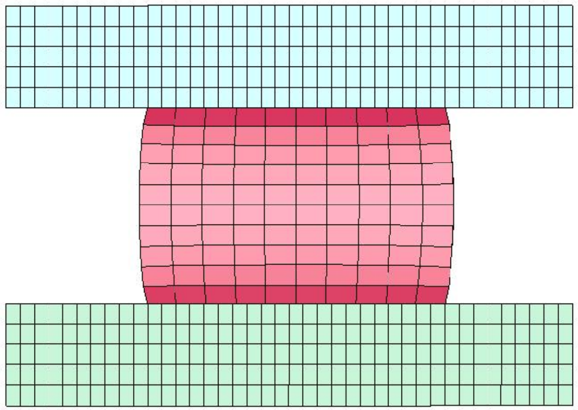




MAT 183, ν = 0.4998



MAT 181, ν = 0.25



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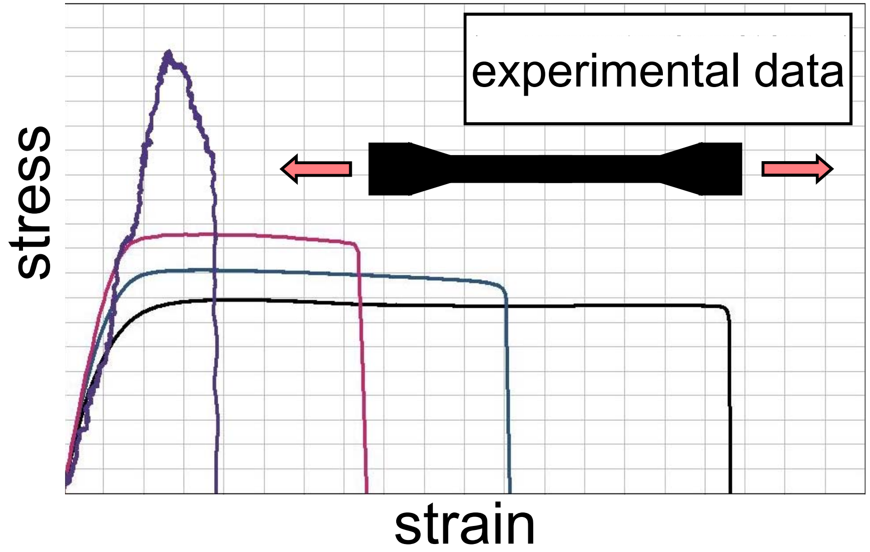
Material Models: Elasto-Plasticity

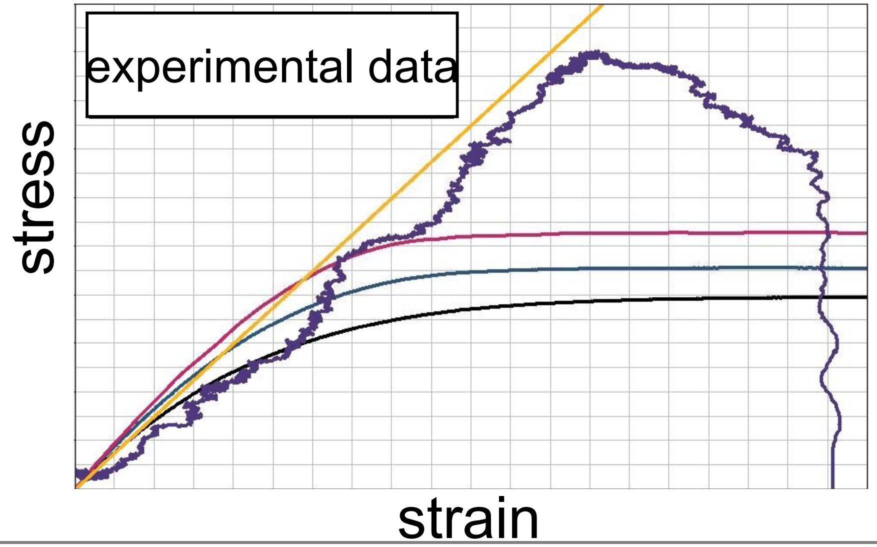
- Although thermoplastics do not show a strict transition from elasticity to plasticity, a elasto-(visco)plastic model is (so far) the best choice:
  - permanent deformation, implemented for shell elements
  - von Mises yield surface still standard for simulation of plastics
  - stable simulation; user-friendly input data (e.g. MAT24 in LS-DYNA)
  - High sophisticated models (SAMP, MF Polymers, …) available now

- In what follows, the validation and verification process (e.g. reverse engineering) is demonstrated for MAT_PIECEWISE_LINEAR_PLASTICITY (MAT_24)

V&V Step 1: Revision of the Test Data; Young's Modulus

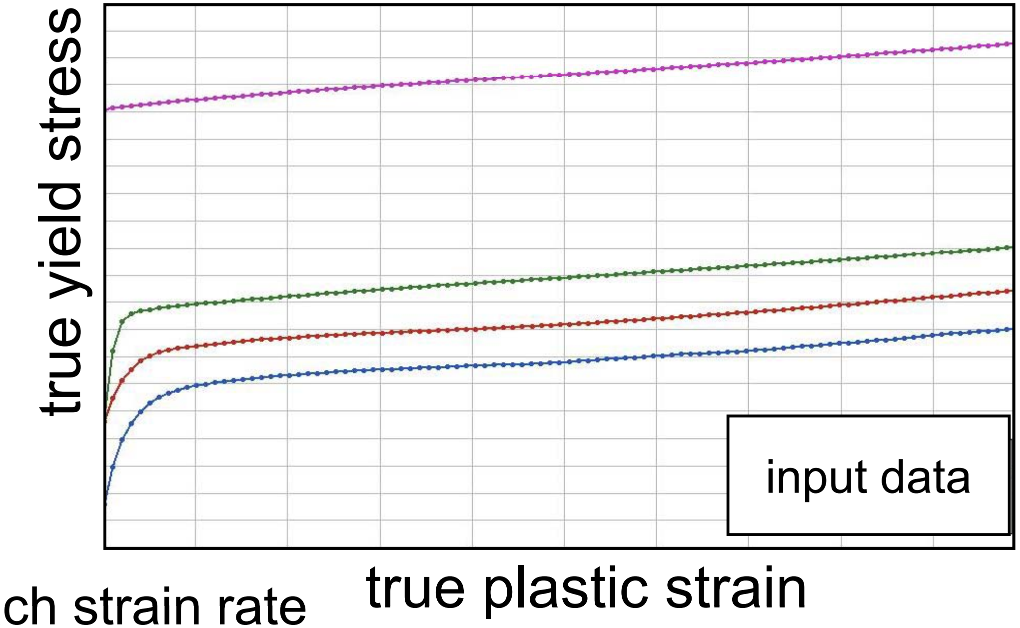
- Test data has to be available as engineering stress vs. engineering strain (Excel / ASCII)
- Visual inspection of the data is necessary first. The goal is to obtain a single sufficiently smooth, i.e. non-oscillatory curve for each strain rate:
  - Eliminate strong oscillating curves
  - Scattering at the same strain rate ?
    - If yes: take the average of selected curves at the same strain rate, i.e. eliminate outlayers
    - If no: take the average of all tests at the same strain rate
- Determine average Young's modulus





V&V Step 2: Conversion, Smoothing and Sampling

- True strain $\varepsilon = \ln(1+\varepsilon_0)$
- true stress $\sigma = \sigma_0(1+\varepsilon_0)$
- This step may be skipped if (local) true stress-strain data is available



- Compute yield curves for each strain rate
- 100 data points are required in the input, thus sampling of the data is necessary:

$$\varepsilon^1 = 0$$
$$\varepsilon^n = \varepsilon^{\frac{nN}{100}}, \quad n = 2,3,\ldots,100$$

$$\sigma^1 = 0$$
$$\sigma^n = \frac{1}{k_e - k_b + 1}\sum_{i=k_b}^{k_e}\sigma^i, \quad n = 2,3,\ldots,100$$
$$k_e = \min\left(N, \frac{N}{50}(i+1)\right), \quad k_b = \max\left(1, \frac{N}{50}(i-1)\right)$$

V&V Step 3: Extrapolation after Necking

- Derive the smoothed curve (that is obtained in step 2) numerically by central difference scheme

$$\left.\frac{d\sigma}{d\varepsilon}\right|_n = \frac{\sigma_{n+1}-\sigma_{n-1}}{\varepsilon_{n+1}-\varepsilon_{n-1}}$$

- Identify the onset of the material instability (necking), i.e. find $\sigma - \frac{d\sigma}{d\varepsilon} = 0 \Rightarrow \varepsilon^*$

where e* is the strain where necking occurs.

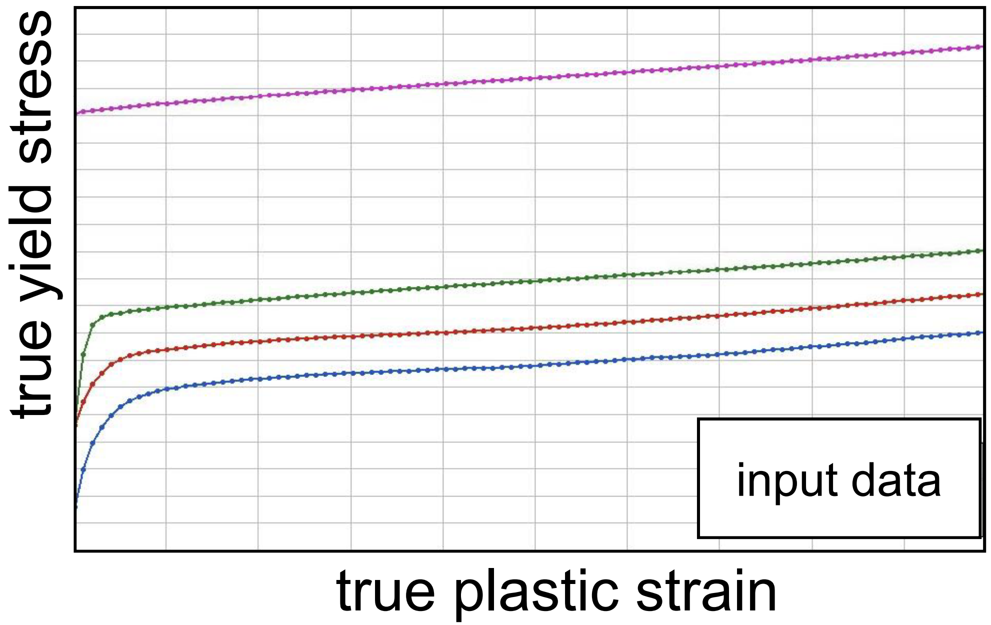
If there is an intersection,
compute for each strain e > e*:

$$\sigma = \sigma^* e^{(\varepsilon-\varepsilon^*)}$$

where s*= s(e*)

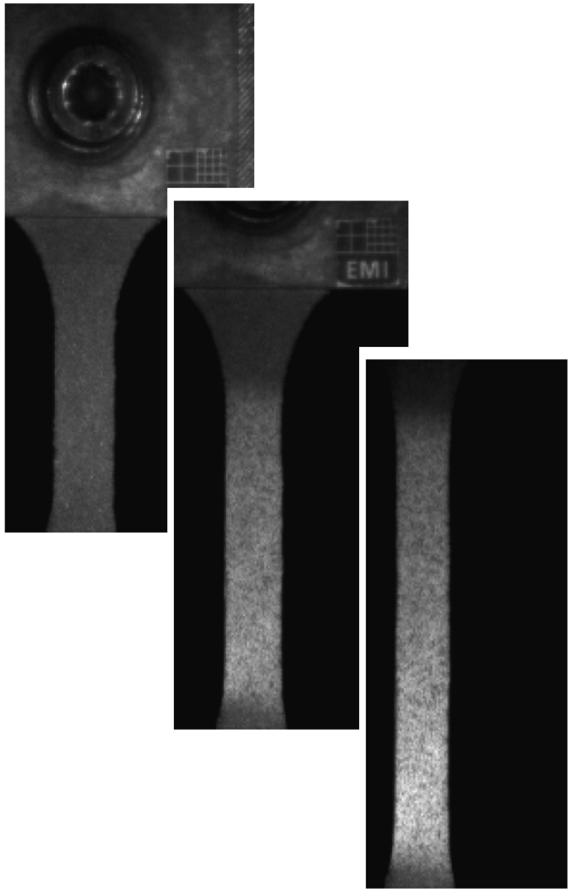
Else Compute the hardening curve:

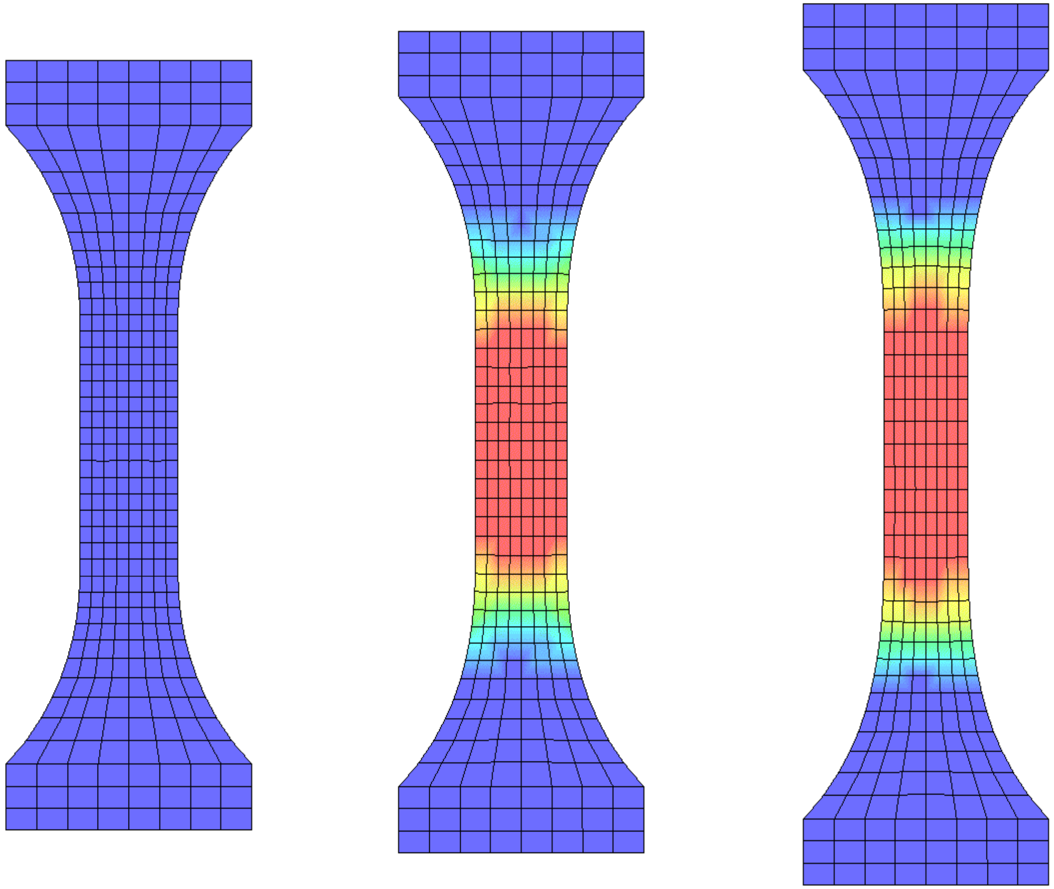
$$\sigma_y = \sigma, \quad \varepsilon^p = \varepsilon - \frac{\sigma}{E}$$



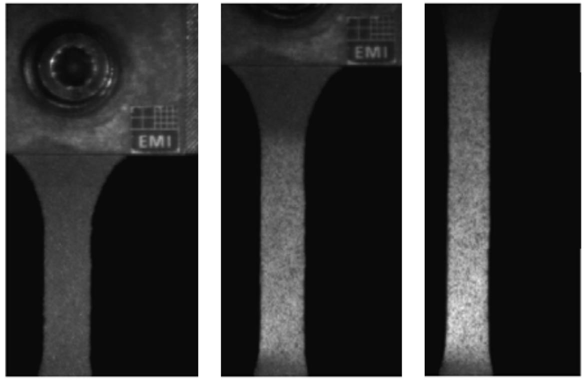
V&V Step 4: Tensile Test Simulation

- Von Mises (piecewise linear) plasticity, linear elastic visco-plastic,
- Generally good representation of tensile responses

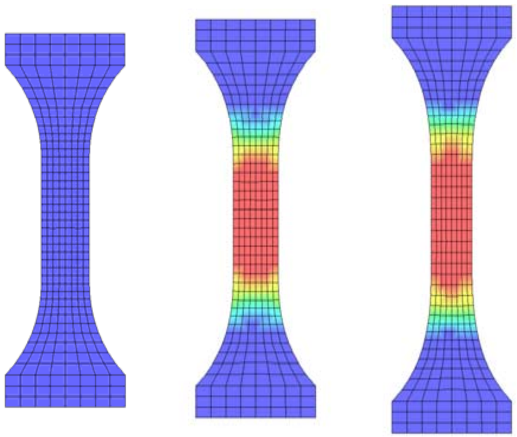


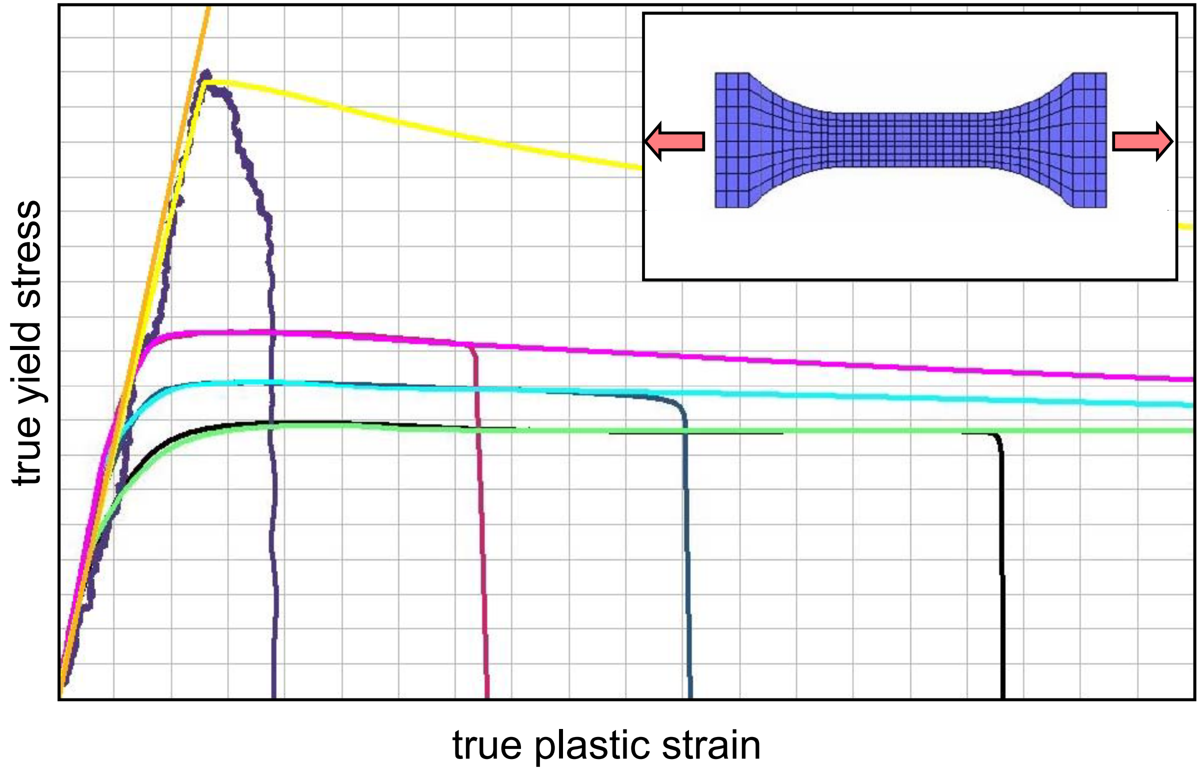


V&V Step 4: Tensile Test Simulation (Loop!)



- Compare force-displacement-curve for each strain rate:
  - Correlation must be exact before necking!
  - If correlation is sufficiently accurate after necking, stop
  - If not, go to step 3 and modify the extrapolation (e.g. automatically by optimization software)



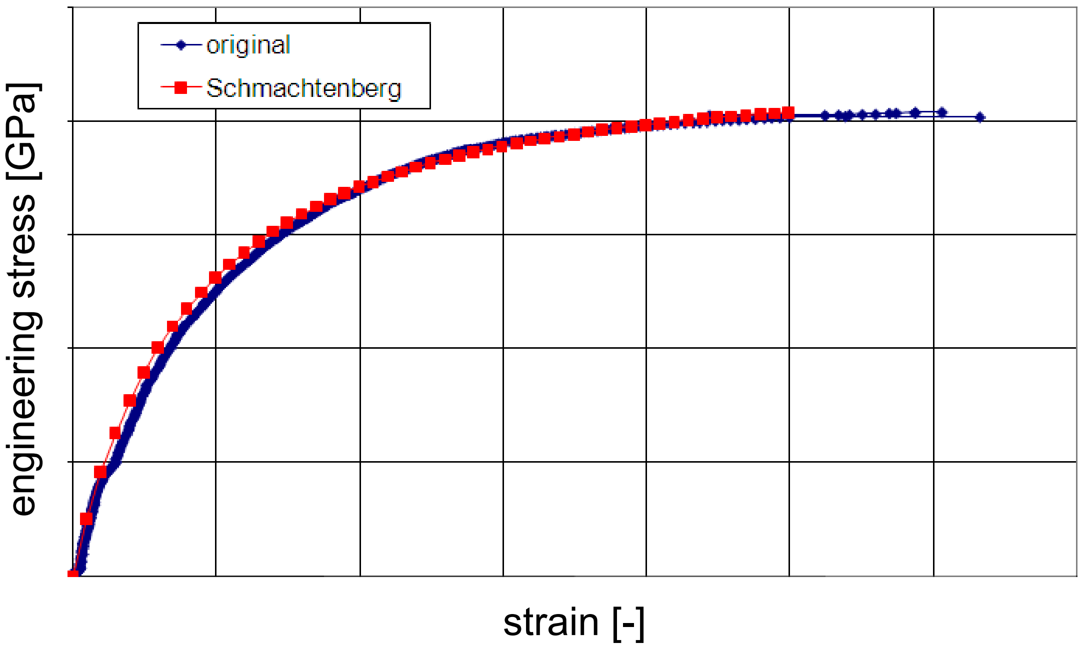


Parameter based Material Laws

- Stress-Strain Relation by Schmachtenberg

$$\sigma = E\varepsilon \frac{1 - D_1\varepsilon}{1 + D_2\varepsilon}$$

- Example:
  Tensile test



Parameter based Material Laws

- Parameter-identification performed by least square fit

$$S(E,D_1,D_2) := \sum_{k=1}^{n}\left[\sigma_k(\varepsilon_k) - E\varepsilon\,\frac{1-D_1\varepsilon}{1+D_2\varepsilon}\right]^2 \rightarrow MIN$$

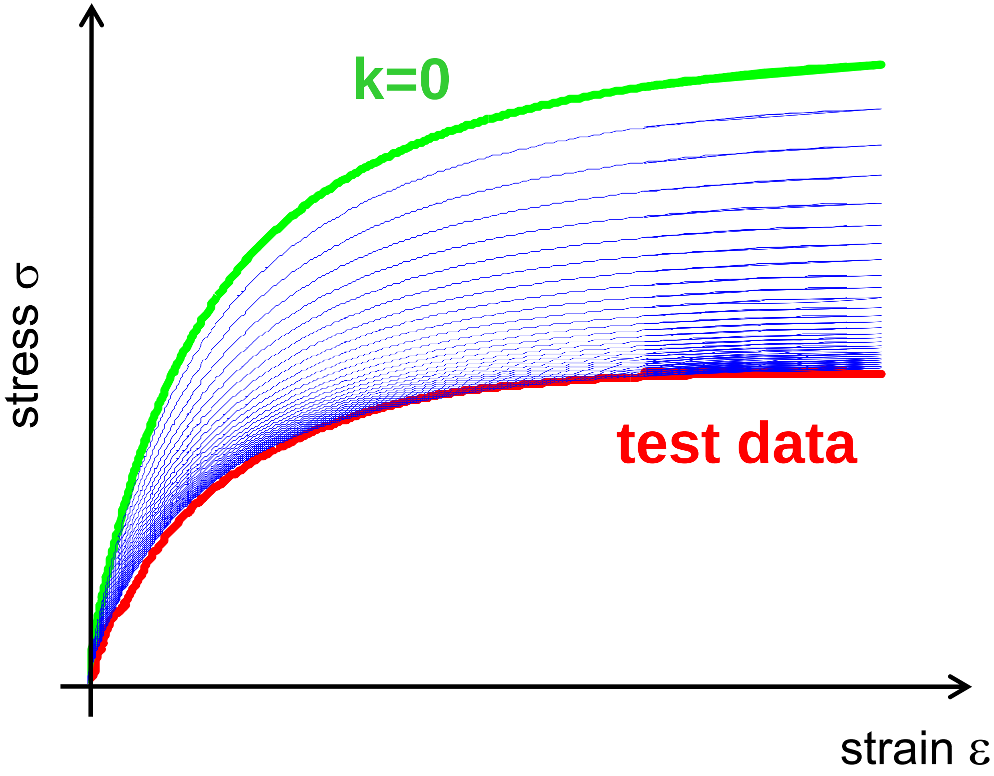
with a gradient method

$$x^{k+1} = x^k - \alpha \nabla S^k$$

$$x^k = \left[E, D_1, D_2\right]^k ,$$

$$\nabla S^k = \left[\frac{\partial S}{\partial E}, \frac{\partial S}{\partial D_1}, \frac{\partial S}{\partial D_2}\right]^k$$

$$\alpha = \text{damping parameter}$$



Parameter based Material Laws

- Strain-Rate Dependency by Johnson Cook

$$\sigma_y\left(\dot{\varepsilon},\varepsilon_p\right)=\sigma_y\left(0,\varepsilon_p\right)\left[\frac{1+\ln\left(\frac{\dot{\varepsilon}}{C}\right)}{p}\right]$$

Compute curves for each strain rate

⇩

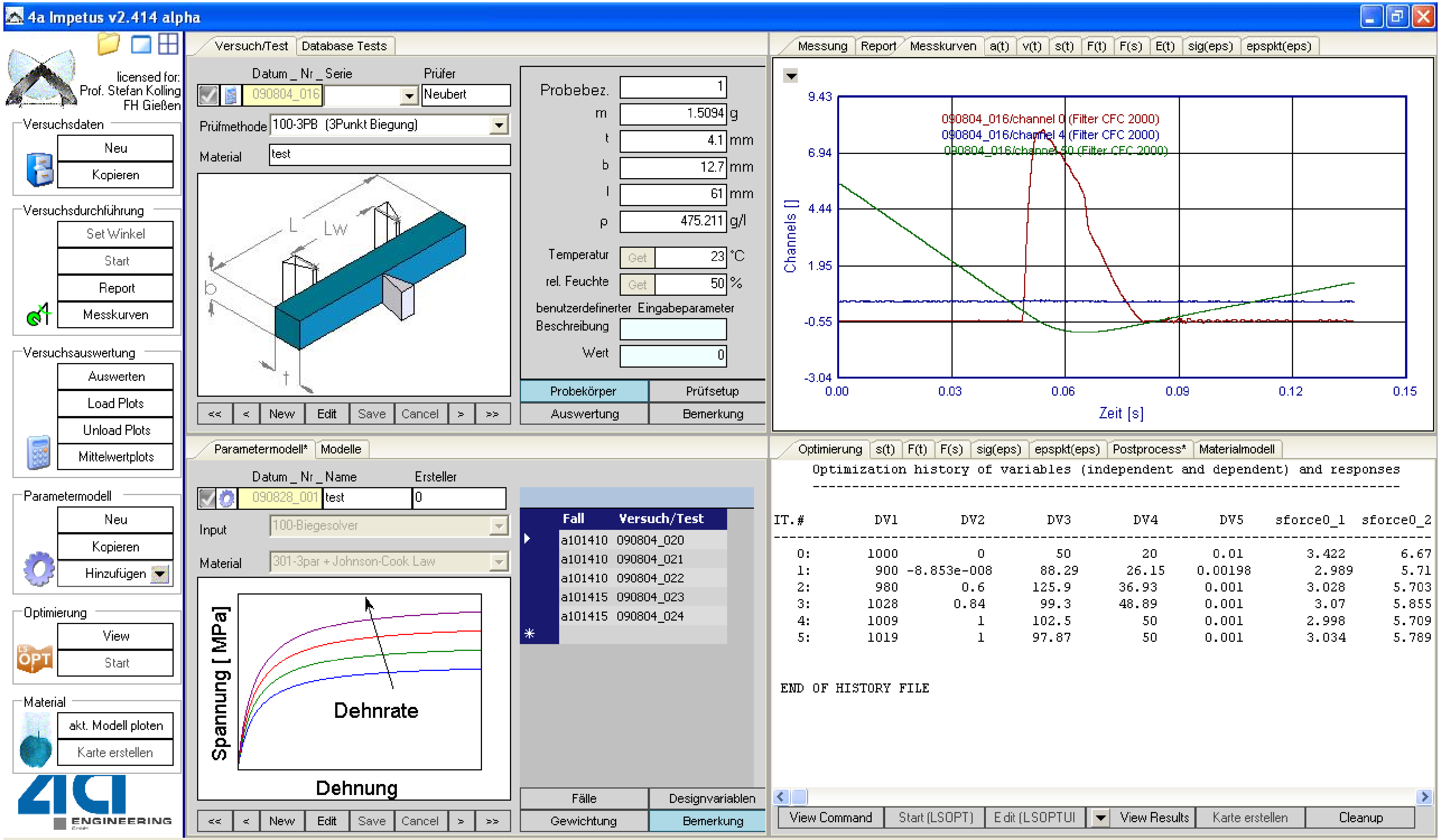
tabulated input in MAT_24

- Cowper Symonds

$$\sigma_y\left(\dot{\varepsilon},\varepsilon_p\right)=\sigma_y\left(0,\varepsilon_p\right)\left[1+\left(\frac{\dot{\varepsilon}}{C}\right)^{\frac{1}{p}}\right]$$

Parameters C, p can be used directly in the MAT_24 card

And now …


4a Impetus v2.414 alpha
licensed for:
Prof. Stefan Kolling
FH Gießen
Versuchsdaten
Neu
Kopieren
Versuchsdurchführung
Set Winkel
Start
Report
Messkurven
Versuchsauswertung
Auswerten
Load Plots
Unload Plots
Mittelwertplots
Parametermodell
Neu
Kopieren
Hinzufügen
Optimierung
View
Start
Material
akt. Modell ploten
Karte erstellen
Versuch/Test
Database Tests
Datum _ Nr _ Serie
Prüfer
090804_016
Neubert
Prüfmethode
100-3PB (3Punkt Biegung)
Material
test
Probebez.
1
m
1.5094 g
t
4.1 mm
b
12.7 mm
l
61 mm
ρ
475.211 g/l
Temperatur
23 °C
rel. Feuchte
50 %
benutzerdefinerter Eingabeparameter
Beschreibung
Wert
0
Probekörper
Prüfsetup
Auswertung
Bemerkung
New
Edit
Save
Cancel
Messung
Report
Messkurven
a(t)
v(t)
s(t)
F(t)
F(s)
E(t)
sig(eps)
epspkt(eps)
090804_016/channel 0 (Filter CFC 2000)
090804_016/channel 4 (Filter CFC 2000)
090804_016/channel 50 (Filter CFC 2000)
Channels []
Zeit [s]
Parametermodell*
Modelle
Datum _ Nr _ Name
Ersteller
090828_001
test
Input
100-Biegesolver
Material
301-3par + Johnson-Cook Law
Spannung [MPa]
Dehnrate
Dehnung
Fall
Versuch/Test
a101410 090804_020
a101410 090804_021
a101410 090804_022
a101415 090804_023
a101415 090804_024
Fälle
Designvariablen
Gewichtung
Bemerkung
Optimierung
Postprocess*
Materialmodell
Optimization history of variables (independent and dependent) and responses
IT.# DV1 DV2 DV3 DV4 DV5 sforce0_1 sforce0_2
0: 1000 0 50 20 0.01 3.422 6.67
1: 900 -8.853e-008 88.29 26.15 0.00198 2.989 5.71
2: 980 0.6 125.9 36.93 0.001 3.028 5.703
3: 1028 0.84 99.3 48.89 0.001 3.07 5.855
4: 1009 1 102.5 50 0.001 2.998 5.709
5: 1019 1 97.87 50 0.001 3.034 5.789
END OF HISTORY FILE
View Command
Start (LSOPT)
Edit (LSOPTUI
View Results
Karte erstellen
Cleanup
4a ENGINEERING