

ROHACELL®

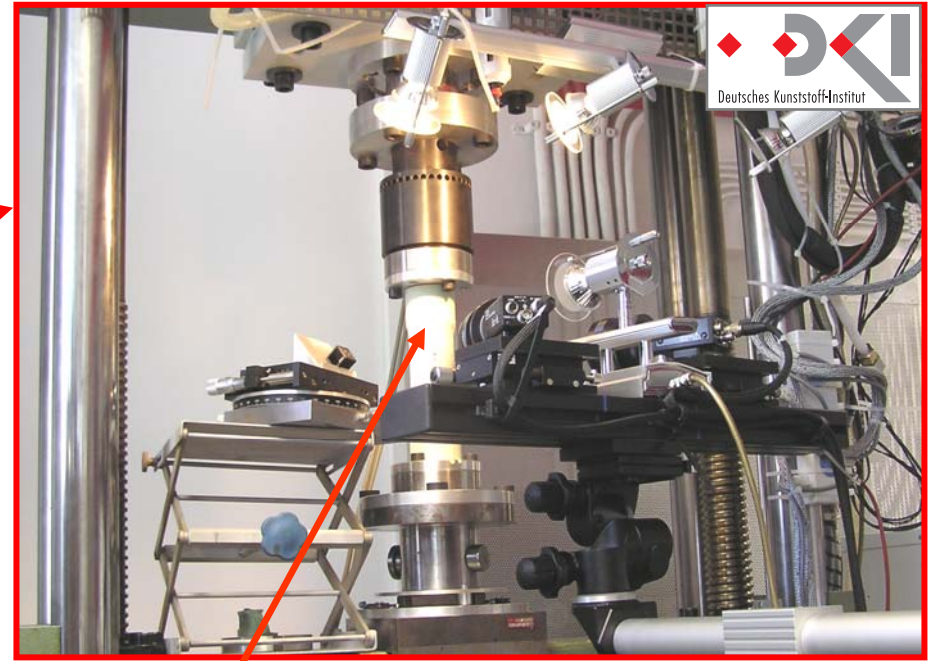
The Core for Sandwich Solutions

**Engineering Services:
3-D Failure Criterion**

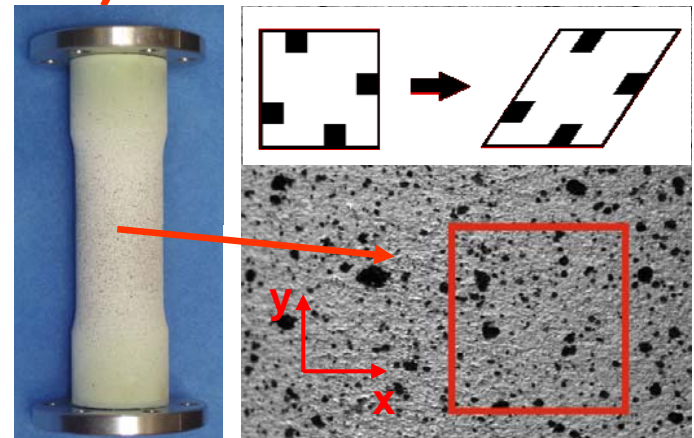


EVONIK
INDUSTRIES

Test Facility: Tension-/Compression-/Torsion-Testmaschine

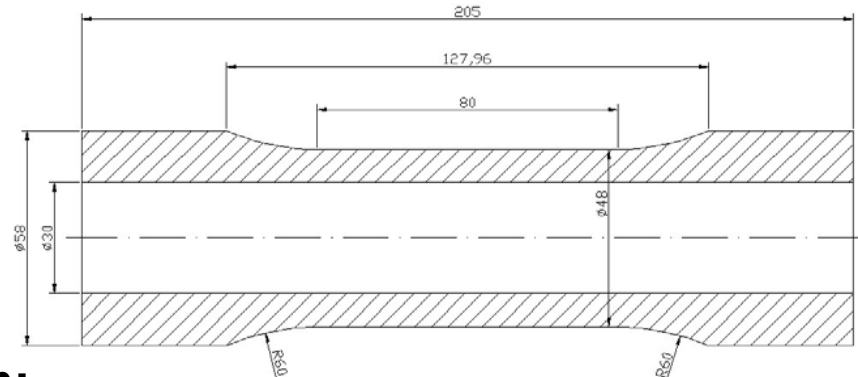


- Using a Tension-/Compression-/Torsion-Test-Machine
- Using an Optical Deformation Measurement System ARAMIS
- Using Tubular Test Specimens made of ROHACELL® 51 WF, 110 WF and 200 WF



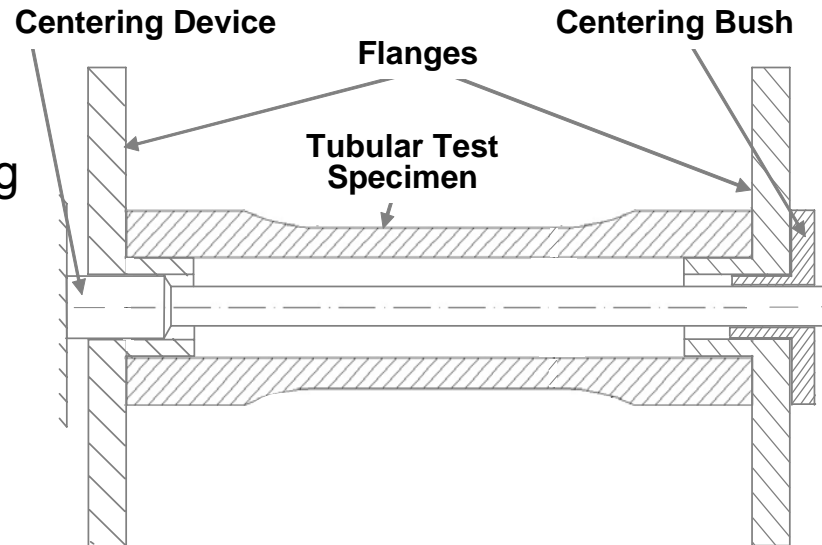
Test Facility: Tension-/Compression-/Torsion-Testmachine

Geometry of the Test Specimen:



Preparation of the Test Specimen:

- Tubular Test Specimens are glued on Flanges
- Test Specimens are assembled using coaxial Centering Device



Tested ROHACELL® Grades und Types:

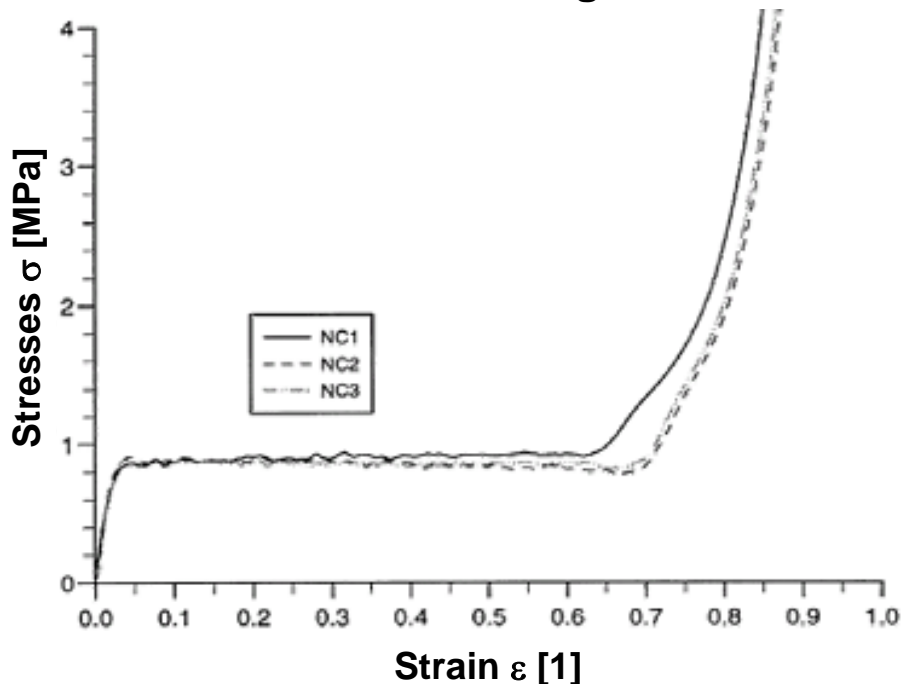
- 51, 110, 200 WF
- 71 RIST
- 21 HP

Analysis of Test Results

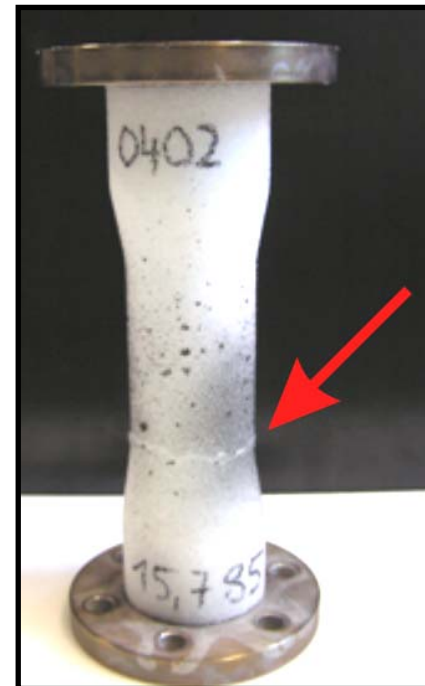
- Compression Test:

Stress at the first Collapse of the Cells is used for Compression Strength

Stress-Strain-Diagram



Failure Mode



- Tension and Shear Test:

Stresses at Breackage Point is used for Tensile and Shear Strength Properties

3-D Failure Criterion Model for ROHACELL®: General Equations



Stress Matrix:

$$\underline{\sigma} = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{12} & \sigma_{22} & \sigma_{23} \\ \sigma_{13} & \sigma_{23} & \sigma_{33} \end{bmatrix}$$

Equivalent Stress σ_v of the 3D Failure Criterion Model Φ_2 :

$$\sigma_v = \frac{\sqrt{(12 a_2 + 12 a_1 + 12) l_2 + (4 a_2^2 + (4 a_1 + 4) a_2 + a_1^2) l_1^2 + a_1 l_1}}{2 a_2 + 2 a_1 + 2}$$

with: 1. Invariant: $l_1 = \sigma_{11} + \sigma_{22} + \sigma_{33}$

2. Invariant: $l_2 = \frac{1}{3} [\sigma_{11}^2 + \sigma_{22}^2 + \sigma_{33}^2 - \sigma_{11} \sigma_{22} - \sigma_{11} \sigma_{33} - \sigma_{22} \sigma_{33} + 3(\sigma_{12}^2 + \sigma_{13}^2 + \sigma_{23}^2)]$

$$a_1 = \frac{k^2 (d - 1)}{d}$$

$$a_2 = \frac{k^2}{d} - 1$$

$$d = \frac{R_{11}^-}{R_{11}^+}$$

$$k = \sqrt{3} \frac{R_{12}}{R_{11}^+}$$

Remarks:

R_{11}^- = Compressive Strength of ROHACELL® Grade and Type

R_{11}^+ = Tensile Strength of ROHACELL® Grade and Type

R_{12} = Shear Strength of ROHACELL® Grade and Type

Effort:

$$A = \frac{\sigma_v}{R_{11}^+}$$

Factor of Safety:

$$RF = \frac{1}{A}$$

Margin of Safety:

$$MS = RF - 1$$

3-D Failure Criterion Model: ROHACELL® WF



| ROHACELL® Type/ Grade | 51 WF | 110 WF | 200 WF |
|---|------------------|------------------|------------------|
| Density [kg/m ³] | 50,4 | 102,8 | 194,8 |
| Parameter a ₁ [1] | -0,31 | 0,07 | 0,45 |
| Parameter a ₂ [1] | 0,00077 | 0,02 | 0,53 |
| Tensile Strength [MPa] | 1,3 | 3,7 | 5,27 |
| Compressive Strength [MPa] | 0,9 | 3,9 | 6,8 |
| Shear Strength [MPa] | 0,6 | 2,2 | 4,3 |
| Storage Condition: Temperature [°C] rel. Humidity [%] | 23 50 | 23 50 | 23 50 |
| Test Condition: Temperature [°C] rel. Humidity [%] | 23 50 | 23 50 | 23 50 |

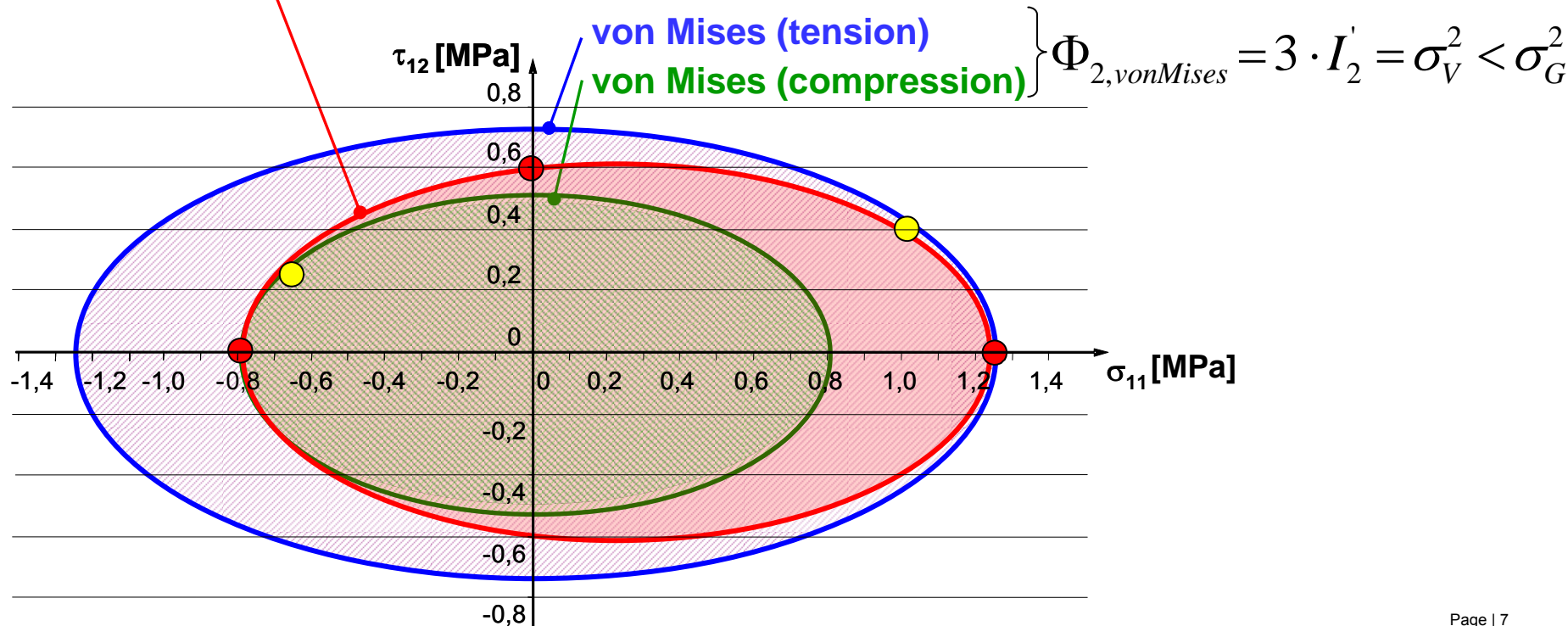
3-D Failure Criterion for ROHACELL[®] 51 WF in σ_{11}/τ_{12} -Plane

3-D Failure Criterion Model:

$$\Phi_2 = \frac{3 \cdot I_2' + a_1 \cdot \sigma_V \cdot I_1 + a_2 \cdot I_1^2}{1 + a_1 + a_2} = \sigma_V^2 < \sigma_G^2$$

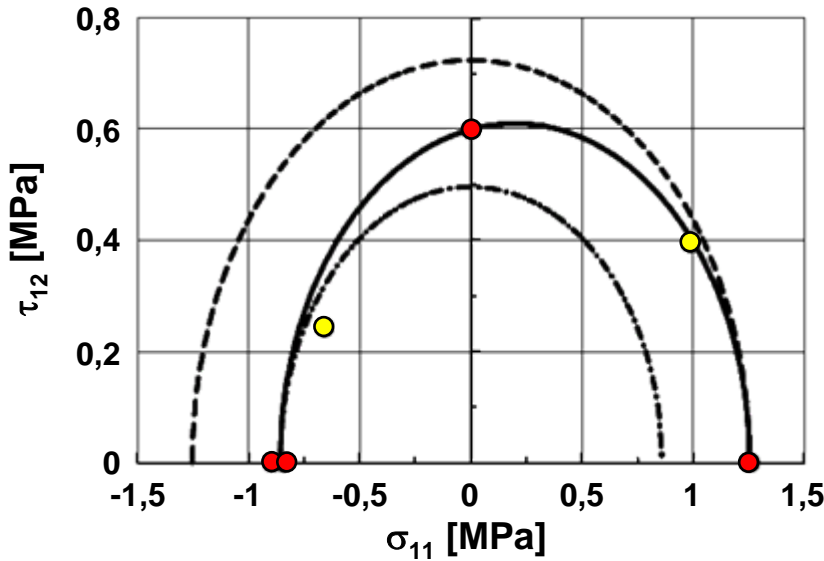
ϕ_2 Model consider:

- Compressible Material Behaviour of ROHACELL[®]
- Strength Differential Effect of ROHACELL[®],
i. e. tension strength \neq compressive strength \neq shear strength

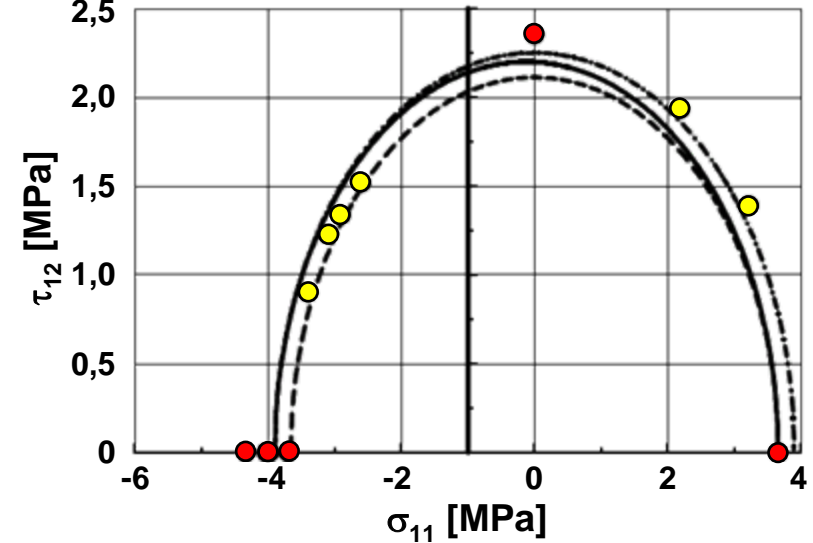


3-D Failure Criterion for ROHACELL[®] 51, 110 and 200 WF in σ_{11}/τ_{12} -Plane

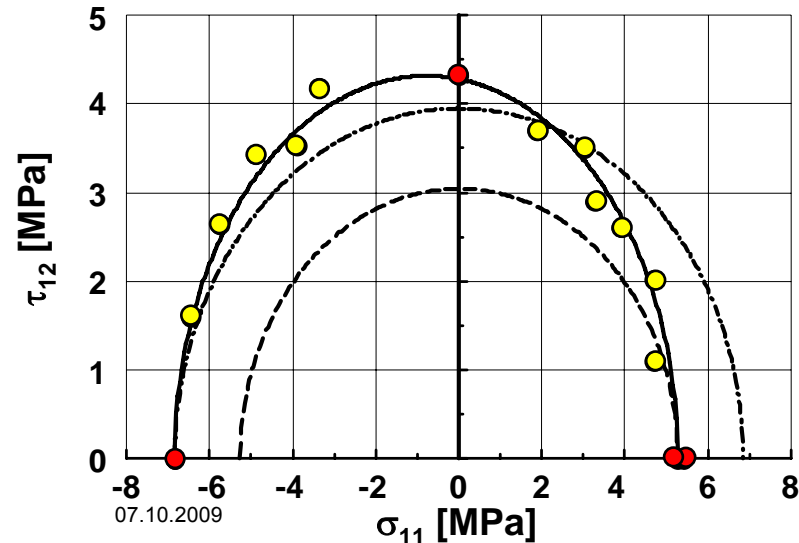
ROHACELL[®] 51 WF



ROHACELL[®] 110 WF



ROHACELL[®] 200 WF



Legend:

— 3-D Failure Criterion Φ_2

$$\Phi_2 = \frac{3 \cdot I_2 + a_1 \cdot \sigma_V \cdot I_1 + a_2 \cdot I_1^2}{1 + a_1 + a_2} = \sigma_V^2 < \sigma_G^2$$

- - Potential Body according to von Mises (Tension)

- · - Potential Body according to von Mises (Compression)

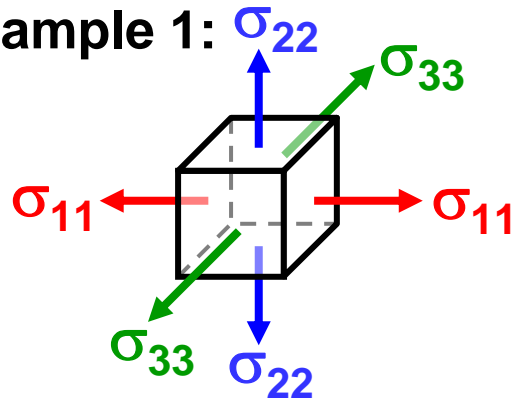
$$3 \cdot I_2 = \sigma_V^2 < \sigma_G^2$$

● Experimental Data for Determination of Φ_2

● Experimental Data for Validation of Φ_2

Example 1: 3-D Failure Criterion Φ_2 in comparison to other Failure Criteria

Example 1:



$\sigma_{11}, \sigma_{22}, \sigma_{33} = 1,25 \text{ MPa} = R_{+11}^+$ (uniaxial Tensile Strength)

und

$\sigma_{12}, \sigma_{13}, \sigma_{23} = 0$

Strength Hypothesis:

Normal Stress Hypothesis (NSH):

$$A_{\text{NSH}} = 1,00$$

Shear Stress Hypothesis according to Tresca:

$$A_{\text{Tresca}} = 0$$

Hypothesis of strain energy of distortion according to von Mises:

$$A_{\text{von Mises}} = 0$$

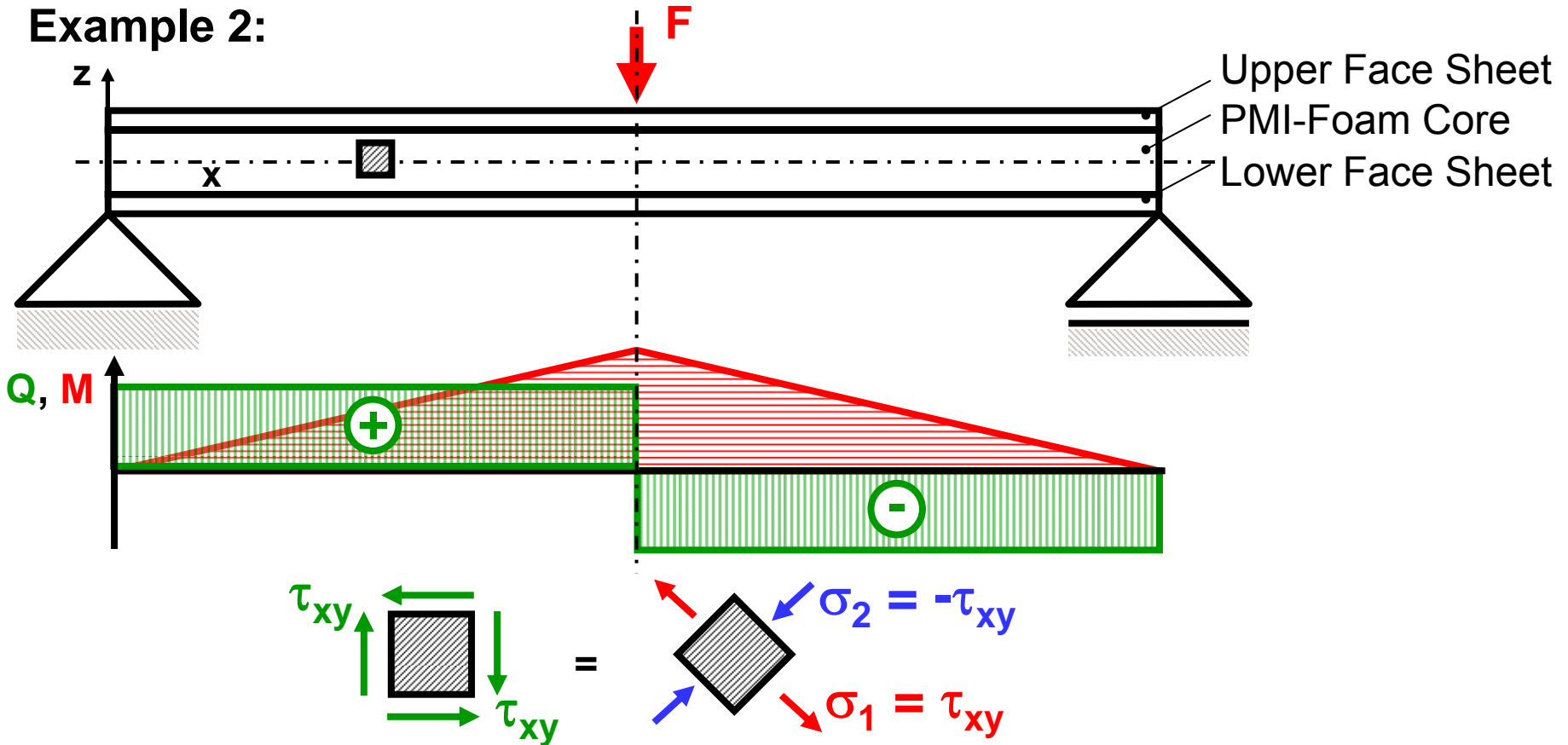
3D-Failure Model according to Φ_2 -Potential:

$$A_{\Phi_2} = 1,43 \quad (A_{\Phi_2} = 1 \text{ bei } \sigma_{11}, \sigma_{22}, \sigma_{33} = 1,13 \text{ MPa})$$

e. g. *ROHACELL*[®] 51 WF

Example 2: 3-D Failure Criterion Φ_2 in comparison to other Failure Criteria

Example 2:

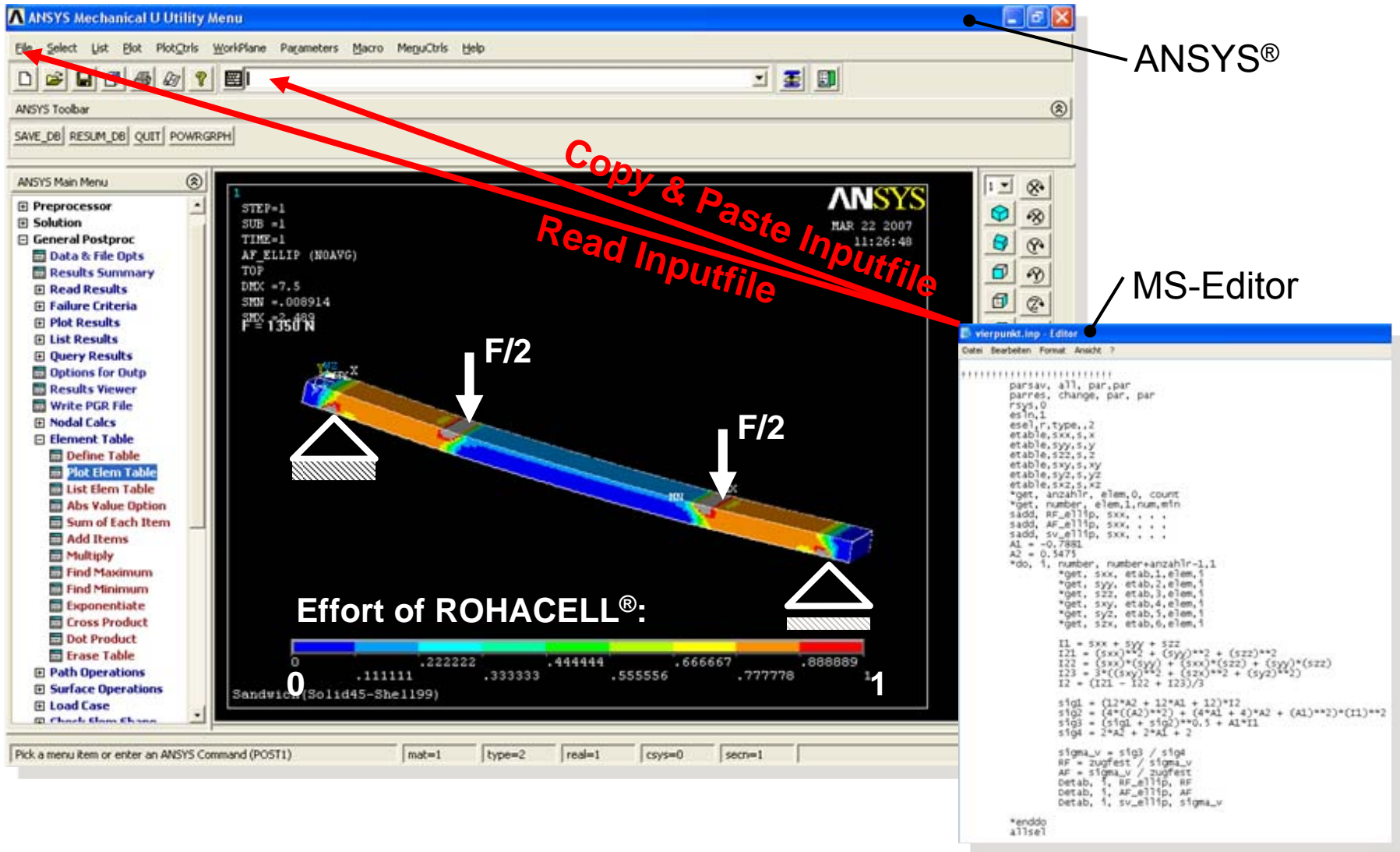


$$\sigma_{11}, \sigma_{22}, \sigma_{33}, \sigma_{13}, \sigma_{23} = 0 \text{ und } \sigma_{12} = \tau_{xy} = R_{12} = 0,6 \text{ MPa}$$

$$A_{\Phi_2} = 1 \quad (\text{vgl. } A_{\text{von Mises}} = 0,83, A_{\text{NSH}} = 0,48, A_{\text{Tresca}} = 0,96)$$

e. g. ROHACELL[®] 51 WF

Implementation of 3-D Failure Criterion Φ_2 in FE-Programs (e. g. ANSYS®)



The image displays the ANSYS Mechanical U Utility Menu interface. The main window shows a 3D stress analysis of a beam, with a color scale ranging from 0 to 1. The beam is supported at both ends by triangular supports. Two downward arrows labeled 'F/2' indicate the applied forces. The text 'Effort of ROHACELL®:' is overlaid on the beam. The ANSYS Main Menu is visible on the left, and the MS-Editor window on the right shows the input file 'vierpunkt.inp'. The MS-Editor window contains the following code:

```

parsav, all, par, par
parres, change, par, par
rsys, 0
esln, 1
esel, r, type, , 2
etable, sxx, s, x
etable, syy, s, y
etable, szz, s, z
etable, sxy, s, xy
etable, syz, s, yz
etable, sxz, s, xz
*get, anzahlr, elem, 0, count
*get, number, elem, 1, num, min
sadd, rf_ellip, sxx, . . .
sadd, af_ellip, sxx, . . .
sadd, sv_ellip, sxx, . . .
A1 = -0.7881
A2 = -0.5475
*do, 1, number, number-anzahlr-1, 1
*get, sxx, etab, 1, elem, 1
*get, syy, etab, 2, elem, 1
*get, szz, etab, 3, elem, 1
*get, sxy, etab, 4, elem, 1
*get, syz, etab, 5, elem, 1
*get, sxz, etab, 6, elem, 1

I1 = sxx + syy + szz
I21 = (sxx)**2 + (syy)**2 + (szz)**2
I22 = (sxx)*(syy) + (sxx)*(szz) + (syy)*(szz)
I23 = 3*((sxy)**2 + (syz)**2 + (sxz)**2)
I2 = (I21 - I22 + I23)/3

sig1 = (I2*A2 + I2*A1 + I2)*I2
sig2 = (4*((A2)**2) + (4*A1 + 4)*A2 + (A1)**2)*(I1)**2
sig3 = (sig1 + sig2)**0.5 + A1*I1
sig4 = 2*A2 + 2*A1 + 2

sigma_v = sig3 / sig4
RF = zugfest / sigma_v
AF = sigma_v / zugfest
detab, 1, rf_ellip, RF
detab, 1, af_ellip, AF
detab, 1, sv_ellip, sigma_v

*enddo
allsel
    
```

Red arrows point from the MS-Editor window to the ANSYS main menu, labeled 'Copy & Paste Inputfile' and 'Read Inputfile'. The ANSYS window title is 'ANSYS Mechanical U Utility Menu'. The MS-Editor window title is 'vierpunkt.inp - Editor'. The ANSYS window shows the following text:

```

STEP=1
SUB =1
TIME=1
AF_ELLIP (NOAVG)
TOP
DMX =7.5
SMN =.008914
SMX =2.488
F =1350 N
    
```

The ANSYS Main Menu is visible on the left, and the MS-Editor window on the right shows the input file 'vierpunkt.inp'. The ANSYS window shows the following text:

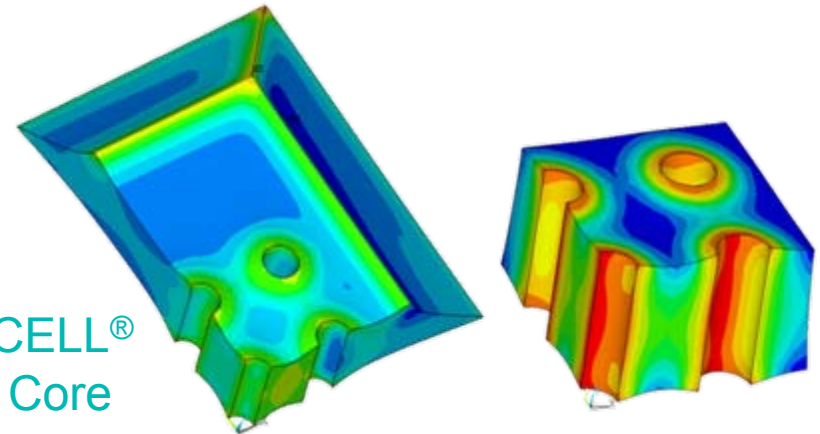
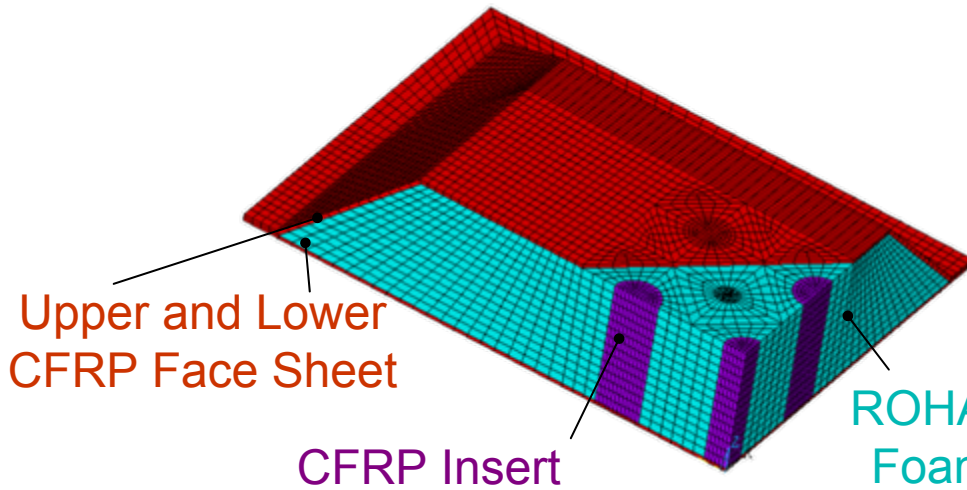
```

STEP=1
SUB =1
TIME=1
AF_ELLIP (NOAVG)
TOP
DMX =7.5
SMN =.008914
SMX =2.488
F =1350 N
    
```

Implementation of 3-D Failure Criterion Φ_2 in Microsoft EXCEL

FE Model

Stress Distribution in the Core Material



$$\sigma_v = \frac{\sqrt{(12 a_2 + 12 a_1 + 12) I_2 + (4 a_2^2 + (4 a_1 + 4) a_2 + a_1^2) I_1^2 + a_1 I_1}}{2 a_2 + 2 a_1 + 2} \quad A = \frac{\sigma_v}{R_{11}^+}$$

| | | | | | | | | | | | | |
|--|---------|------------------|--------------------------------|---------------|---------------|------------------|-------------|--------------------------------|---------------------|--------|------------|-------|
| ROHACELL® Grade | RIST | | | | | | | | | | | |
| ROHACELL® Type | 71 | | | | | | | | | | | |
| Tensile Strength R_{11}^+ [MPa]: | 2,135 | (positive value) | | | | | | | | | | |
| Compressive Strength R_{11}^- [MPa]: | -1,345 | (negative value) | | | | | | | | | | |
| Shear Strength R_{12} [MPa]: | 1,100 | (positive value) | | | | | | | | | | |
| Parameter d: | 0,62998 | | | | | | | | | | | |
| Parameter k: | 0,89239 | | | | | | | | | | | |
| Parameter a_1 : | -0,468 | | | | | | | | | | | |
| Parameter a_2 : | 0,264 | | | | | | | | | | | |
| | | | Stress Components [MPa] | | | Invariant | | Equivalent Stress [MPa] | Effort A [1] | | | |
| | | | σ_{11} | σ_{22} | σ_{33} | τ_{12} | τ_{13} | τ_{23} | I_1 | I_2 | σ_v | A |
| | | | 1,200 | 1,200 | 1,900 | 0,400 | 0,200 | 0,200 | 4,300 | 0,4033 | 1,778 | 0,833 |

Material Effort: A = 0,833 Factor of Safety: RF = 1,2 Margin of Safety: MS = 0,2

- **Development of a new 3-D Failure Criterion Φ_2 to determine the Effort (A), Safety Factor (RF) or Safety of Margin (MS) for PMI-Foams ROHACELL[®]**
3-D Failure Criteria Φ_2 consider:
 - Compressible Material Behaviour
 - Strength Differential Effect
- **3 Parameters are needed to describe the surface of the Breackage in the 3-D Stress Space. These 3 Parameters can be determined by using the Test Results of pure Tension, Compression and Shear Loadings.**
- **Combined Tension/Shear and Compression/Shear Loadings were carried out to validate the 3-D Failure Criteria**
- **3-D Failure Criteria Φ_2 is already implemented in ANSYS[®] (Röhm), ABAQUS[®] (DKI) and Patran/Nastran[®] (Airbus)**
- **The new 3-D Failure Criteria is more suitable for describing the Material Behaviour of ROHACELL[®] than the Potential Body according to von Mises and other Failure Criteria.**
- **Due to the current Results, use of the 3-D Failure Criterion to determine the Material Effort of ROHACELL[®] is advisable.**