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A WORLD OF ENGINEERING SIMULATION

Fracture Failure Bodies of Porous Concrete (foam = similar behavior), Normal Concrete, Ultra-High-Performance-Concrete and of the Lamella Sheet

- *generated on basis of Cuntze's Failure-Mode-Concept (FMC)*

Ralf Cuntze
retired from MAN Technologie AG, Augsburg, Germany,
now linked to Carbon Composites e.V. (CCeV, mechanical engineering),
Augsburg and CC-TUDALIT (civil engineering), Dresden

Presentation captures all models of the fracture bodies 'concrete' engineering' needs

1. **Motivation for a novel Concept to generate Strength Criteria**
2. **Basic Ideas of Cuntze's Failure-Mode-Concept (FMC)**
3. **Application to porous Concrete Stones (Ytong, Hebel)** (*similar to foam material*) — *2D test data available, just of a similar behaving material*
4. **Application to Normal Concrete** — *3D test data available*
5. **Application to UHPC (Ultra High Performance Concrete)** — *3D test data available*
6. **Application to transversaly-isotropic CFRP-Sheets (Polymer-Matrix Lamina)** — *own 2D test data and further 3D were available*

- ***A similar behaving material gives the possibility to set up the Shape of a model***
- ***Measured strength data of the novel material fix the Size of the obtained model***

for armouring in construction rehabilitation ≡ CFRP in concrete

Results of a time-consuming, never funded "hobby" of a retired engineer

CONSTRAINTS in Design Development Process : *Cost and Time Reduction*

Industry looks for robust & reliable analysis procedures
in order to replace the expensive 'Make and Test Method'
as far as reasonable.

Some *testing* remains mandatory in order to figure out *together with* the *modeling*
sufficient knowledge about the behavior of materials and structural parts.
Dependent on the gained knowledge
Virtual Tests will *reduce the amount of* Physical Tests.

Thereby an *improved modeling*
will support

Therein one instrument is the application of Validated Strength Failure Conditions SFCs (strength criteria)

These analysis tools involve SFCs for the failure types:

Yielding (ductile inelastic behaving materials),

Fracture (brittle behaving materials) **which means**

fracture strength failure conditions $F\ (\sigma, R) = 1$ for **obtaining Design Verification.**

in civil engineering: strength R = f

F = failure function, σ = stress, $R = f$ *(in civil engineering)* = strength

The Strength Fracture Body

The surface of the so-called fracture body *is*

- mathematically described by *F*

- built up by the tips of

all multi-axial stress vectors which ‘almost‘ lead to fracture.

For all these fracture stress states is valid:

the reserve factor *RF* = 1, or its inverse

the so-called material stressing effort *Eff* = 1 = 100% (Werkstoffanstrengung)

= 1 / *RF*

F = failure function, *σ* = stress, *R* = *f* *(in civil engineering)* = strength

What was the driving idea behind when generating the FMC ?

To search a possibility

for brittle behaving materials

to *more generally* formulate - for fracture failure -

appropriate strength failure conditions (SFCs) :

analogously to **:**

- failure mode-wise *(shear yielding failure, etc.)* — **Mises, Hashin, Puck etc.**

- stress invariant-based *(J_2 etc.)* — **Mises, Tsai, Hashin, Christensen, etc.**

- obtaining equivalent stresses . — **Mises for shear yielding, Rankine for fracture**

$$e.g.\ \text{'Mises'}: 6 \cdot J_2 = (\sigma_I - \sigma_{II})^2 + (\sigma_{II} - \sigma_{III})^2 + (\sigma_{III} - \sigma_I)^2 = \quad f(\tau)$$

So-called Global and Modal Strength Failure Conditions (SFCs): Description

- **Global SFC** (lumped)**:** *Prager, Ottosen, Willam-Warnke, Tsai*

  describes the full failure surface by one single equation capturing all existing failure modes such as Normal fracture NF or Shear Fracture SF

- **Modal SFC :** *Cuntze , Mises for the mode yielding,*

  describes each failure mode-associated part of the full failure surface by a single equation.

more detailed →

Global versus Modal Strength Failure Conditions (criteria)

1 Global ***strength*** **failure condition** : F ({σ}, {R}) = 1 (usual formulation)

Set of Modal strength failure conditions: F ({σ}, R^{mode}) = 1 (addressed in FMC)

Example: UD

vector of 6 stresses (general)

$$\{\sigma\} = (\sigma_1, \sigma_2, \sigma_3, \tau_{23}, \tau_{31}, \tau_{21})^T$$

vector of 5 strengths

$$\{R\} = (R_{||}^t, R_{||}^c, R_{\perp}^t, R_{\perp}^c, R_{\perp||})^T$$

needs an Interaction of Failure Modes: performed here by a

probabilistic-based 'rounding-off' approach (series failure system model)

directly delivering the (material) reserve factor in linear analysis

in civil engineering: strength R = f

A modal concept – *as found with Cuntze (general) and Puck (for UD material) , Mises (isotropic)* –

builds up the Fracture Failure Surface mode-wise !

Helpful for the designing engineer is the delivery of **equivalent stresses** and of the **material stressing effort** ***Eff.***

mode **material stressing effort *** **(in German "Werkstoffanstrengung")**

The relationship is

$$Eff^{\text{mode}} = \sigma_{eq}^{\text{mode}} \,/\, R^{\text{mode}}$$

mode equivalent stress

mode associated average strength ***(bar over)***

anology to 'Mises'

$$Eff^{\text{fracture mode}} = \sigma_{eq}^{\text{fracture mode}} / R_m$$

$$Eff^{\text{Mises}} = \sigma_{eq}^{\text{Mises}} / R_{po.2}$$

* material stressing effort *Eff = artificial technical term , created together with QinetiQ, UK, during the Wotrld-Wide-Failure-Exercises*

Interaction of adjacent Failure Modes by a '*series failure system'* model in the mode transition zones

= 'Accumulation' of interacting *failure danger portions* Eff^{mode}

$$Eff = \sqrt[m]{(Eff^{\text{mode 1}})^m + (Eff^{\text{mode 2}})^m + \ldots}$$ ***= 1 = 100% , if failure***

with mode-interaction exponent *m* , *from mapping experience*

It is assumed engineering-like : m takes the same value for all

mode transition zones captured by the interaction formula above

Basic Ideas of Cuntze's FMC

- Use of invariants (see Mises), which are linked to a physical mechanism of the deforming solid:
  Following Beltrami, Mises and Mohr-Coulomb: *for isotropic materials*
  - volume change : $\mathbf{I_1}^2$ … ***(dilatational energy)***
  - shape change : $\mathbf{J_2}$ (v. **Mises**) . ***(distortional energy)***
  - friction : $\mathbf{I_1}$ … ***(friction energy)***
- A closed Ansatz-function F = 1 for the fracture body (or a part of it), despite of a possible non-circularity of the meridians
- All parameters are measurable: strengths R and material friction *μ*

isotropic invariants : concrete

$$I_1 = (\sigma_I + \sigma_{II} + \sigma_{III})^T = f(\sigma) \;, \quad 6J_2 = (\sigma_I - \sigma_{II})^2 + (\sigma_{II} - \sigma_{III})^2 + (\sigma_{III} - \sigma_I)^2 = f(\tau)$$

$$27J_3 = (2\sigma_I - \sigma_{II} - \sigma_{III}) \cdot (2\sigma_{II} - \sigma_I - \sigma_{III}) \cdot (2\sigma_{III} - \sigma_I - \sigma_{II})$$

anisotropic invariants : transversely-isotropic UD-sheet

$$I_1 = \sigma_1, \quad I_2 = \sigma_2 + \sigma_3, \quad I_3 = \tau_{31}^2 + \tau_{21}^2, \quad I_4 = (\sigma_2 - \sigma_3)^2 + 4\tau_{23}^2, \quad I_5 = (\sigma_2 - \sigma_3)(\tau_{31}^2 - \tau_{21}^2) - 4\tau_{23}\tau_{31}\tau_{21}$$

Impacts from Material Symmetry, Mohr-Coulomb and Observations (*helpful, when generating SFCs*)

1 If a material element can be homogenized to an ideal (= frictionless) crystal,

then, material symmetry demands for the transversely-isotropic UD-material

- 5 *elastic 'constants' E, ν; 5 strengths R; 5 fracture toughnesses K_c* and
- *2 physical parameters (such as CTE, CME, material friction value μ etc.)*

(for isotropic materials the respective numbers are 2 and 1)

2 Mohr-Coulomb requires for the real crystal another inherent parameter,

- the *physical parameter 'material friction' : UD $\mu_{\perp\|}, \mu_{\perp\perp}$; isotropic μ*

3 Fracture morphology Observations witness:

- Each strength corresponds to a distinct *failure mode*

and to a *fracture type* as Normal Fracture (NF) or Shear Fracture (SF).

above Facts and Knowledge gave the reason why the FMC strictly employs single *independent* failure modes in its failure mode–wise concept.

Detailed Fracture Morphology Impacts on the Failure-Mode-Concept (FMC)

- **Each failure mode represents 1 independent failure mechanism and thereby 1 piece of the complete *failure surface***
- **Each failure mechanism is governed by 1 basic strength** (is observed !)
- **Each failure *mode* can be represented by 1 failure *condition.***

Therefore, equivalent stresses can be computed for each mode !

Cuntze's 3D-Strength Failure Conditions (criteria) for Isotropic Foams, concrete stone

1. SFCs:

$$F^{NF} = \frac{\sqrt{4J_2 - I_1^{\,2}/3} + I_1}{2 \cdot \overline{R}_t} = 1$$

Normal Fracture NF, tension

$$F^{CrF} = \frac{\sqrt{4J_2 - I_1^{\,2}/3} - I_1}{2 \cdot \overline{R}_c} = 1$$

Crushing Fracture CrF, compressive meridian

Ductile behaviour: one failure mechanism or mode, Mises Yielding. **Brittle behaving foam: 2 failure modes NF and CrF.**

2. Considering tensile meridian (bi-axial strength points, failure mode occurs twofold, causing dents on meridians):

Two-fold failure danger can be excellently modelled by employing the often used invariant J_3

$$\Theta_{NF} = \sqrt[3]{1 + D_{NF} \cdot \sin(3\theta)} = \sqrt[3]{1 + D_{NF} \cdot 1.5 \cdot \sqrt{3} \cdot J_3 \cdot J_2^{-1.5}}$$

$$\Theta_{CrF} = \sqrt[3]{1 + D_{CrF} \cdot \sin(3\theta)} = \sqrt[3]{1 + D_{CrF} \cdot 1.5 \cdot \sqrt{3} \cdot J_3 \cdot J_2^{-1.5}}$$

$$Eff^{NF} = c_{NF} \cdot \frac{\sqrt{4J_2 \cdot (\Theta_{NF}) - I_1^{\,2}/3} + I_1}{2 \cdot \overline{R}_t} = \frac{\sigma_{eq}^{NF}}{\overline{R}_t}$$

in Effs now

$$Eff^{CrF} = c_{CrF} \cdot \frac{\sqrt{4J_2 \cdot (\Theta_{CrF}) - I_1^{\,2}/3} - I_1}{2 \cdot \overline{R}_c}$$

3. Mode interaction:

$$Eff^{\,m} = (Eff^{\,NF})^m + (Eff^{\,CrF})^m = 1$$

= surface description of fracture body

4. Closures at both the ends: A paraboloid serves as closing cap and bottom

$$\frac{I_1}{\sqrt{3} \cdot R_t} = s_{cap} \cdot \left(\frac{\sqrt{2J_2 \cdot \Theta_{NF}}}{R_t}\right)^2 + \frac{\max I_1}{\sqrt{3} \cdot R_t}$$

auf die R_t-normierten Lodekoordinaten bezogen

$$\frac{I_1}{\sqrt{3} \cdot R_t} = s_{bot} \cdot \left(\frac{\sqrt{2J_2 \cdot \Theta_{CrF}}}{R_t}\right)^2 + \frac{\min I_1}{\sqrt{3} \cdot R_t}$$

The slope parameters ***s*** are determined connecting the respective hydrostatic strength point with the associated point on the tensile and on the compressive meridian, *maxI*$_1$ must be assessed whereas *minI*$_1$ can be measured. *D* = non-circularity parameter

meridian:= axial cut of fracture body

Cuntze's Engineering Experience

Is the multi-axially tested fracture body (model) known

from a similarly behaving material, then

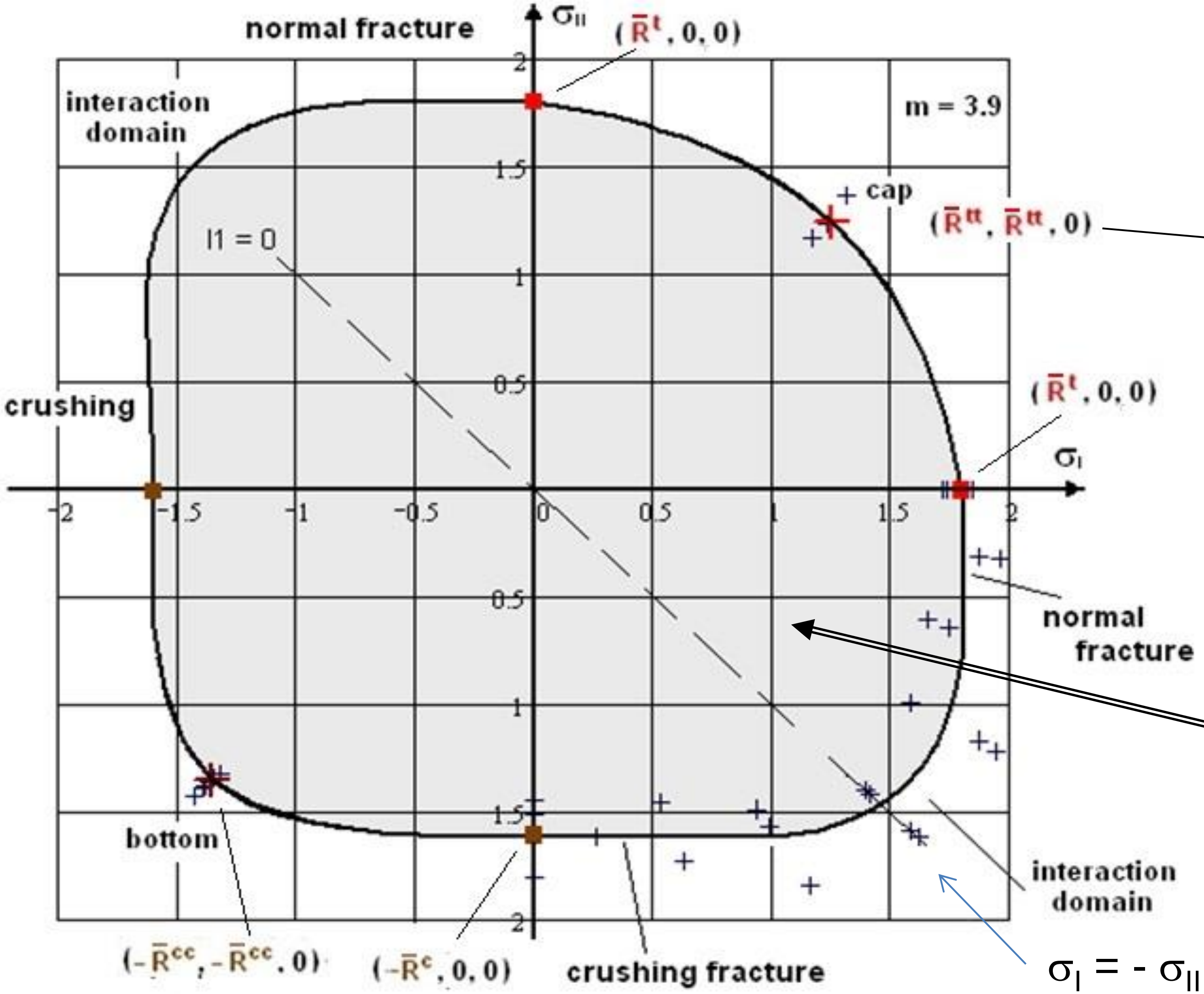
- the Shape of the fracture body of the new material is known and only
- the Size must be fixed by the always to be provided (uni-axial) strengths .

Example fracture body : foam, known > > concrete stone, thereby predictable

2D - Test Data Set and Mapping in the Principal Stress Plane *(brittle, porous)*

Principal Plane Cross-section
(= bias cut of fracture body)

$\sigma_{II}(\sigma_I)$



bi-axial tensile strength

Concrete Stone:
Similar behaviour to
Rohacell 71 IG

No elliptical cross-section as with the Mises-cylinder !

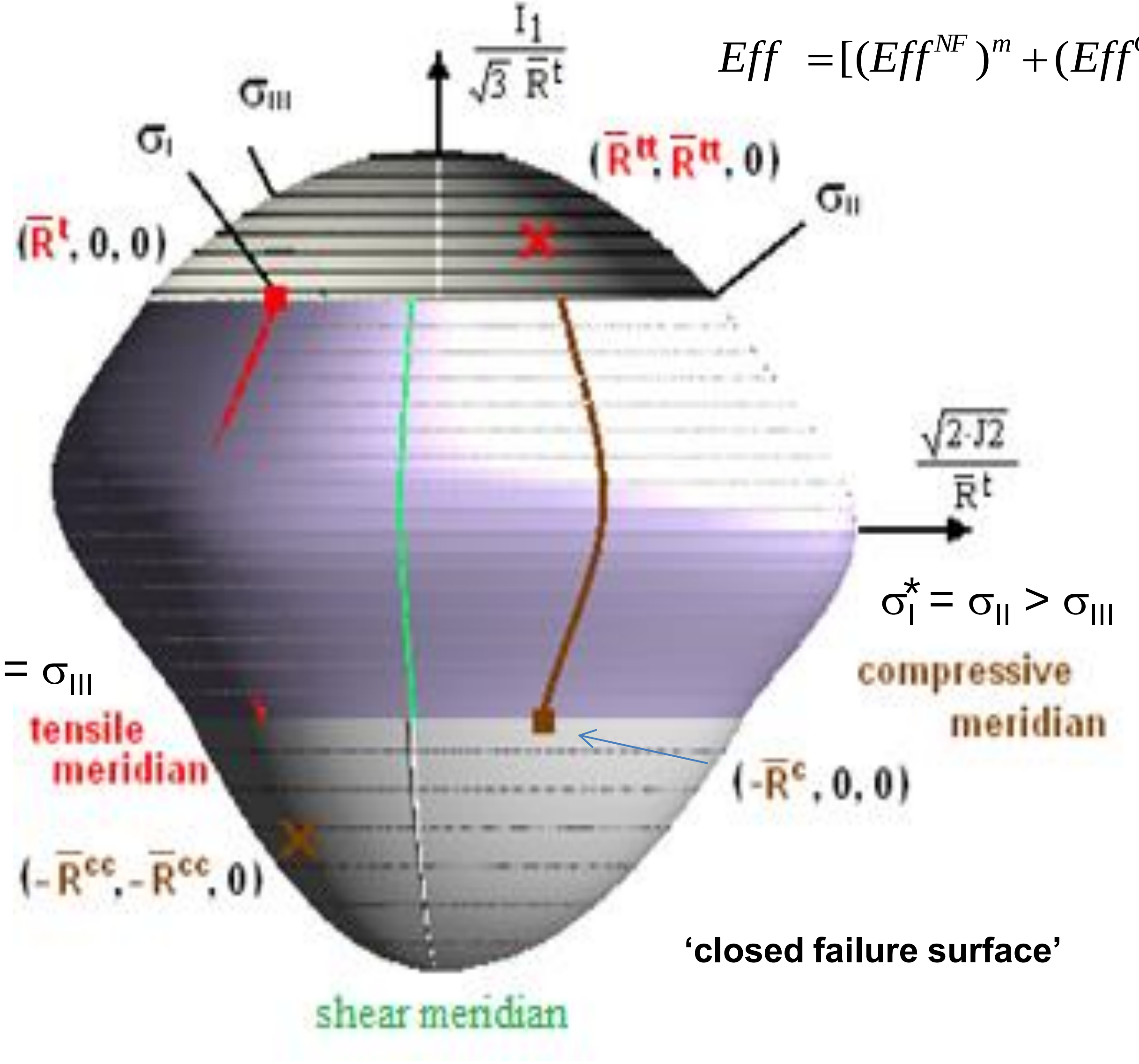
$\sigma_I = - \sigma_{II}$ means shear stress

- **Mapping must be performed in the 2D-plane because fracture data set is given there**
- **The 2D-mapping uses the 2D-subsolution of the 3D-strength failure conditions**
- **The 3D-fracture failure surface (body) is based on the 2D-derived model parameters.**

Courtesy: Dr. Kolupaev
LBF-Darmstadt (DKI),

Fracture Failure Surface (body) and main Meridians of *Rohacell 71 IG foam* (*similar to concrete stone*)

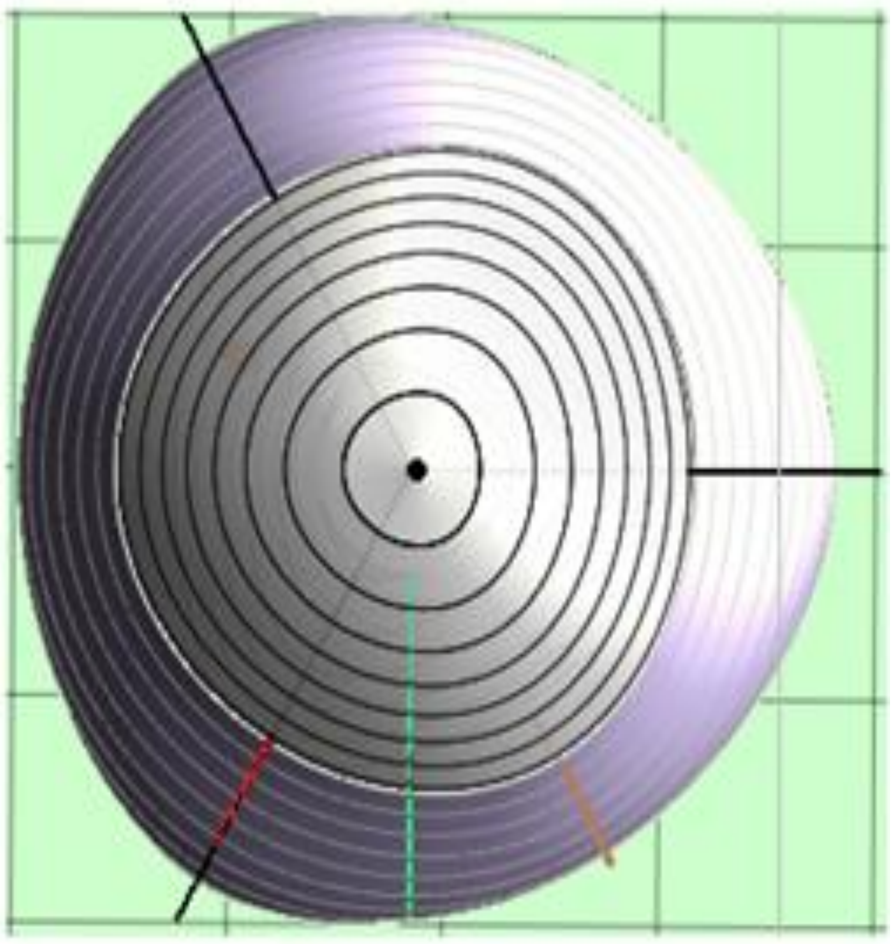
$Eff = [(Eff^{NF})^m + (Eff^{CrF})^m]^{m^{-1}}$ = equation of surface of fracture body



$\sigma_I^* = \sigma_{II} > \sigma_{III}$

$\sigma_I > \sigma_{II} = \sigma_{III}$

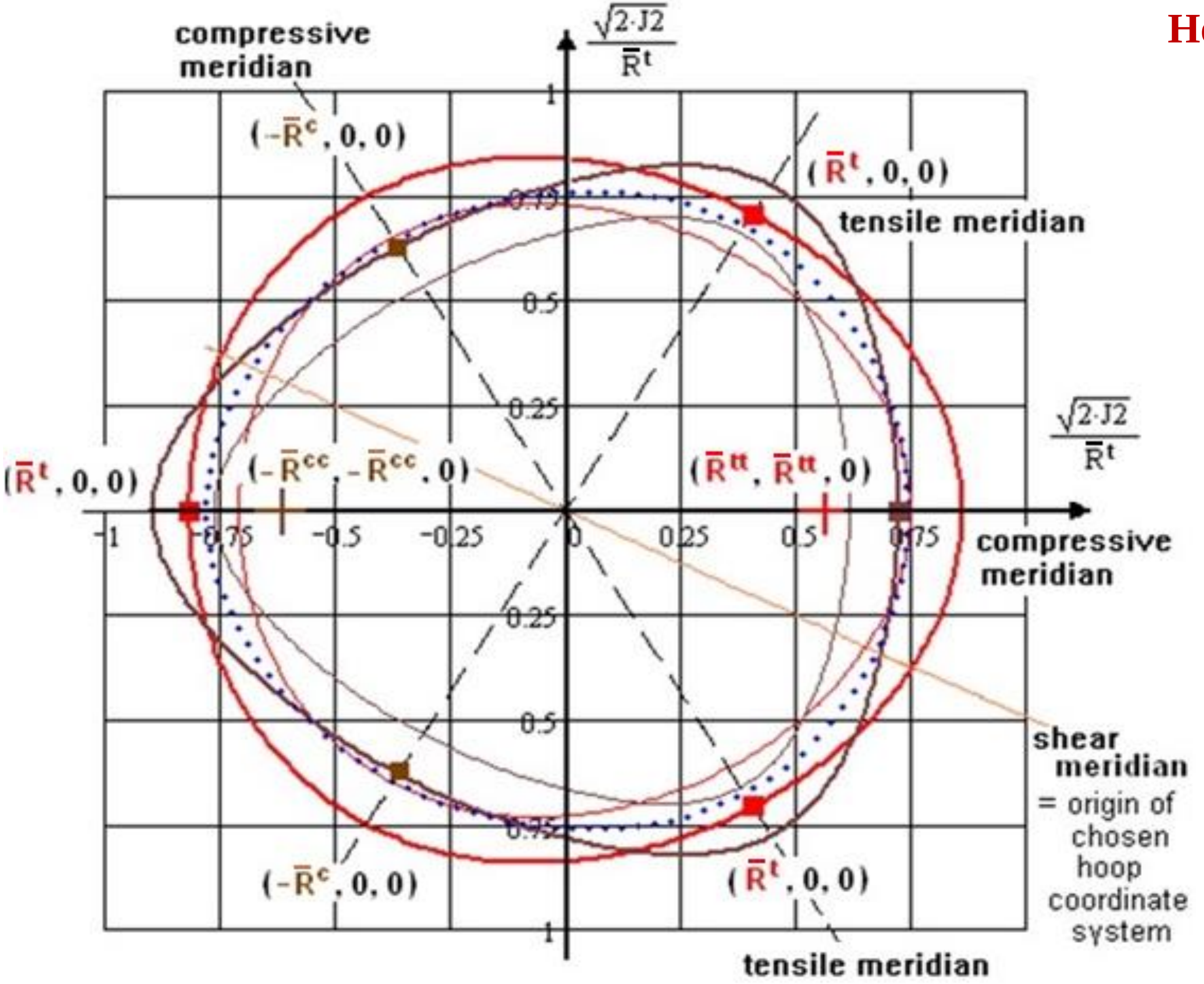
'closed failure surface'



Fracture body of a porous concrete stone with its different meridians (left) and view from top (right). R:= strength ≡ f, t:= tensile, c:= compressive. bar over means mean value, J_2 :='Mises'- invariant, I_1:= sum of principal stresses.(Mathcad plot. Test data, courtesy V. Kolupaev, LBF). s_{cap}= -0.56, s_{bot}=1.09, d_{NF}, d_{CrF} = 0.17,- 0.55, $c_{NF\Theta}$, $c_{CrF\Theta}$ = 0.98, 0.95

* here: σ_I is the mathematically largest stress (most positive one) or Mohr stress

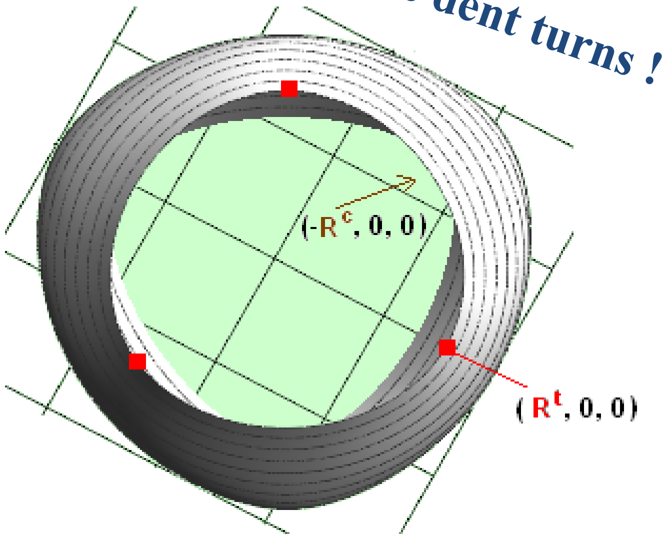
2D-Test Data and Mapping in the Orthogonal Stress Plane (brittle, porous concrete stone)



with characteristic uni-axial and bi-axial strength points X

Hoop Cross-sections of the Fracture Body at various I_1 - levels

The dent turns !



Caps: No test data, cone chosen

at $I_1 = 0$ a circle.

Cuntze's 3D- SFCs for Concrete

Concrete:

$$F^{NF} = c_{NF} \frac{\sqrt{4J_2 \cdot \Theta_{NF} - I_1^{\,2}/3} + I_1}{2 \cdot \overline{R}^{t}} = 1$$

$$F^{SF} = c_{1SF} \cdot \frac{3J_2 \cdot \Theta_{\tau}}{\overline{R}^{c\,2}} + c_{2SF} \cdot \frac{I_1}{\overline{R}^{c}} = 1$$

or in *Effs* after insertation σ = Eff·R into the invariants within *F* = 1

$$Eff^{NF} = c_{NF} \cdot \frac{\sqrt{4J_2 \cdot \Theta_{NF} - I_1^{\,2}/3} + I_1}{2 \cdot \overline{R}^{t}} = \sigma_{eq}^{NF} / \overline{R}^{t} \;, \quad Eff^{SF} = \frac{c_{2SF} \cdot I_1 + \sqrt{(c_{2SF\Theta} \cdot I_1)^2 + 12 \cdot c_{1SF} \cdot 3J_2 \cdot \Theta_{SF}}}{2 \cdot \overline{R}^{c}} = \sigma_{eq}^{SF} / \overline{R}^{c} \;,$$

D = non-circularity parameter. I_1 considers friction

$$\Theta = \sqrt[3]{1 + D \cdot \sin(3\theta)} = \sqrt[3]{1 + D \cdot 1.5 \cdot \sqrt{3} \cdot J_3 \cdot J_2^{\,-1.5}}$$

consideration of volume change (*vc*) under high hydrostatic pressure (if required)

considering Volume change:

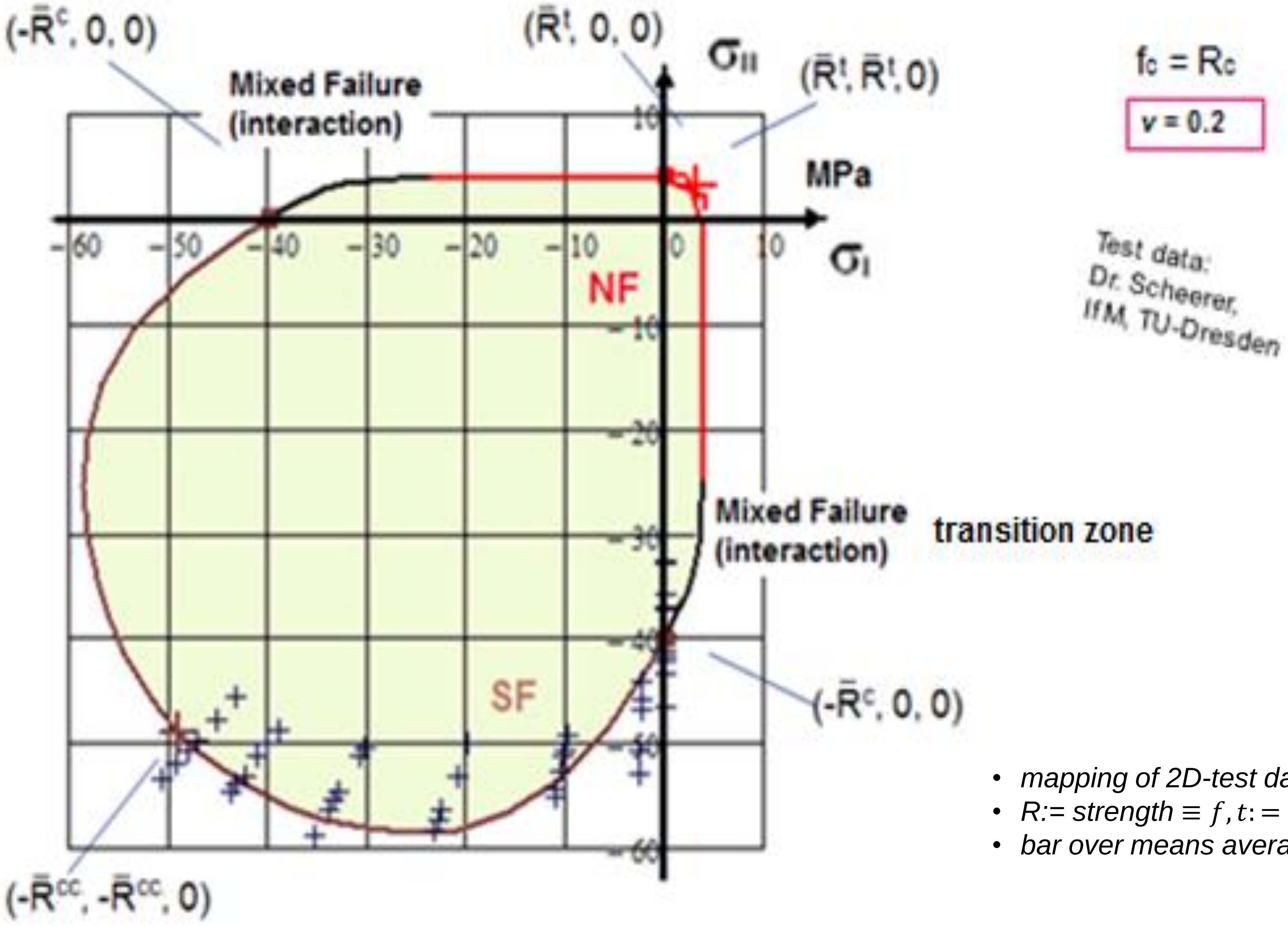
$$F^{NF} = c_{NF} \frac{\sqrt{4J_2 \cdot \Theta_{NF} - I_1^{\,2}/3} + I_1}{2 \cdot \overline{R}^{t}} = 1$$

$$F^{SFvc} = c_{1vc} \cdot \frac{3J_2 \cdot \Theta_{\tau}}{\overline{R}^{c\,2}} + c_{2vc} \cdot \frac{I_1}{\overline{R}^{c}} + c_{3vc} \cdot \frac{I_1^{\,2}}{\overline{R}^{c\,2}} = 1$$

For higher Poisson ratios it must be checked for higher Poisson ratios μ, whether under high bi-axial compression (σ_x, σ_y, σ_{ax} =0) the axial strain approaches the tensile fracture strain !.

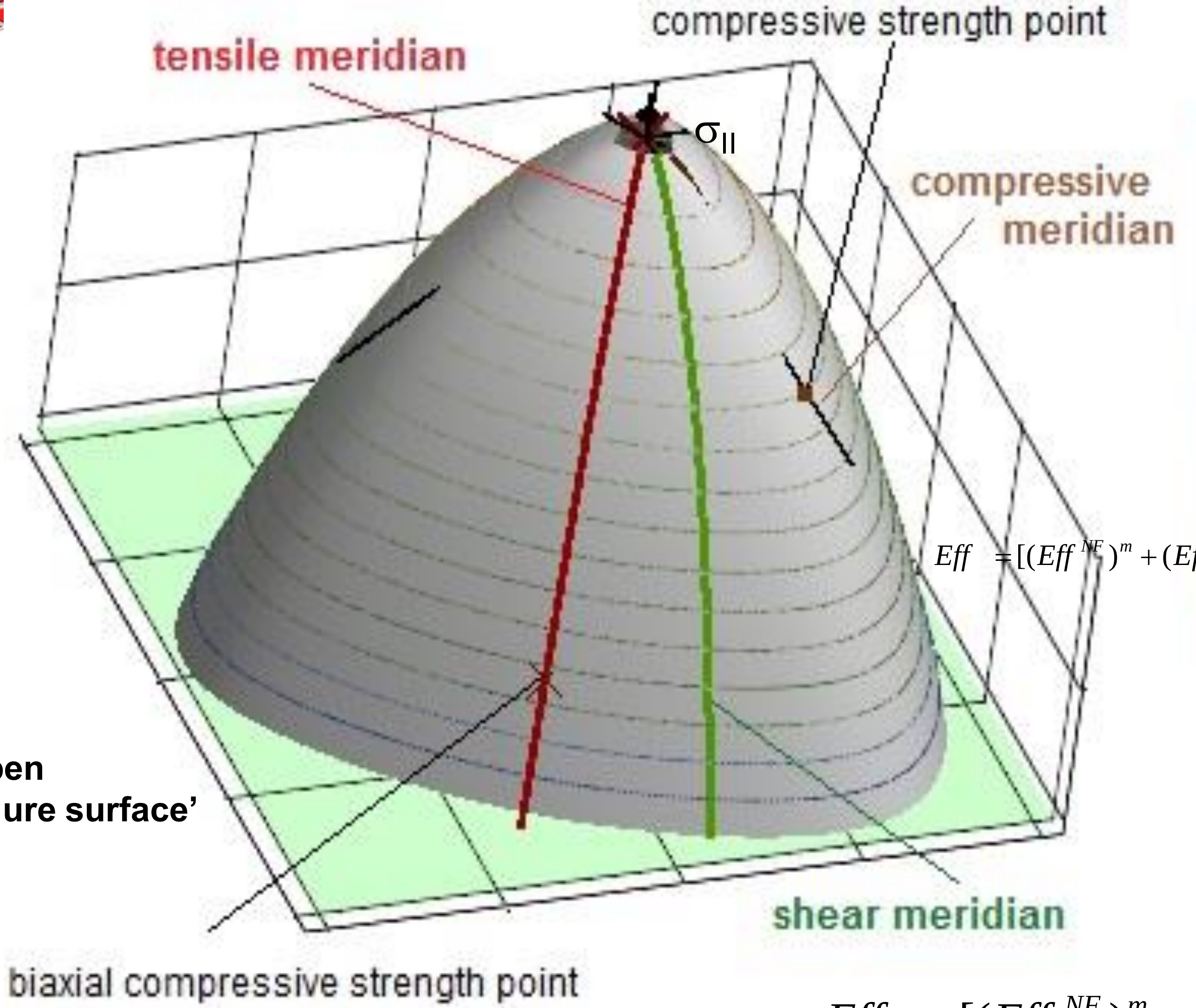
Lesson Learned: A physics-based SFC – usually – describes just one single failure mechnism or mode and does not capture the bi-axial effect of $\sigma_I = \sigma_{II}$, which means capturing a two.fold acting mode

Normal Concrete: Principal Stress Plane = bias cut of fracture body $\sigma_{II}(\sigma_I)$

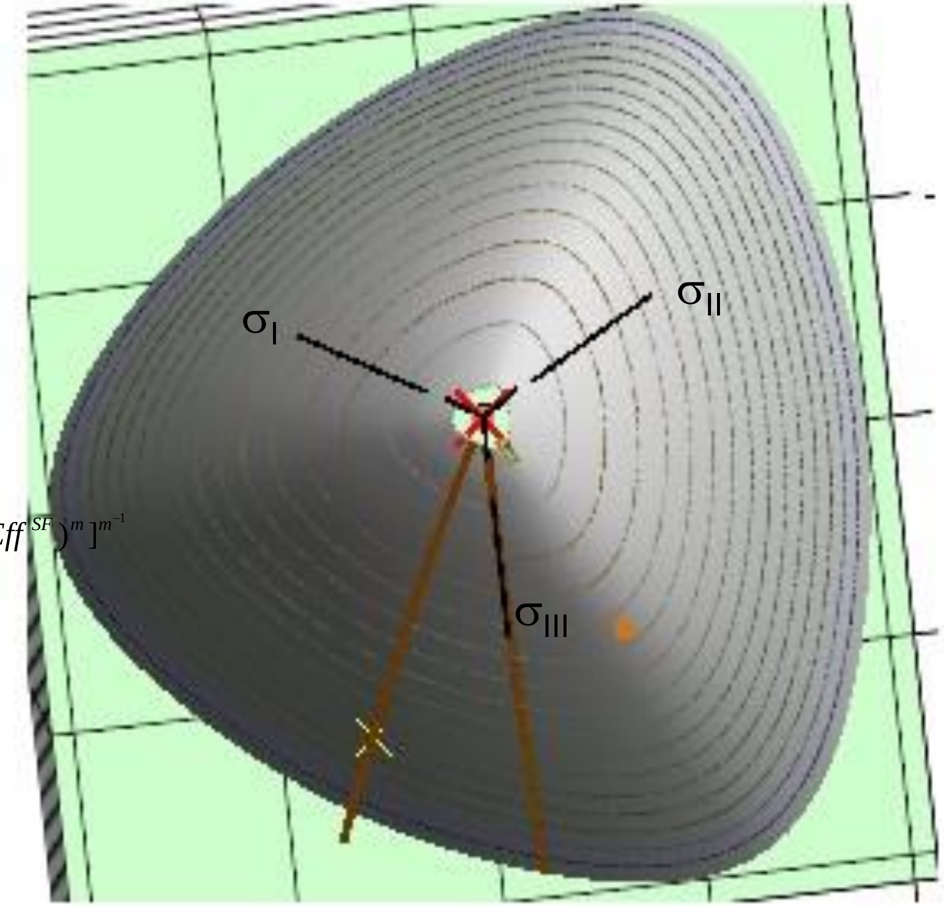


- *mapping of 2D-test data in the principal stress plane.*
- *R:= strength* $\equiv f, t := tensile, c := compressive;$
- *bar over means average value*

Normal Concrete: Fracture Body with its differently deformed meridians



‘open failure surface’

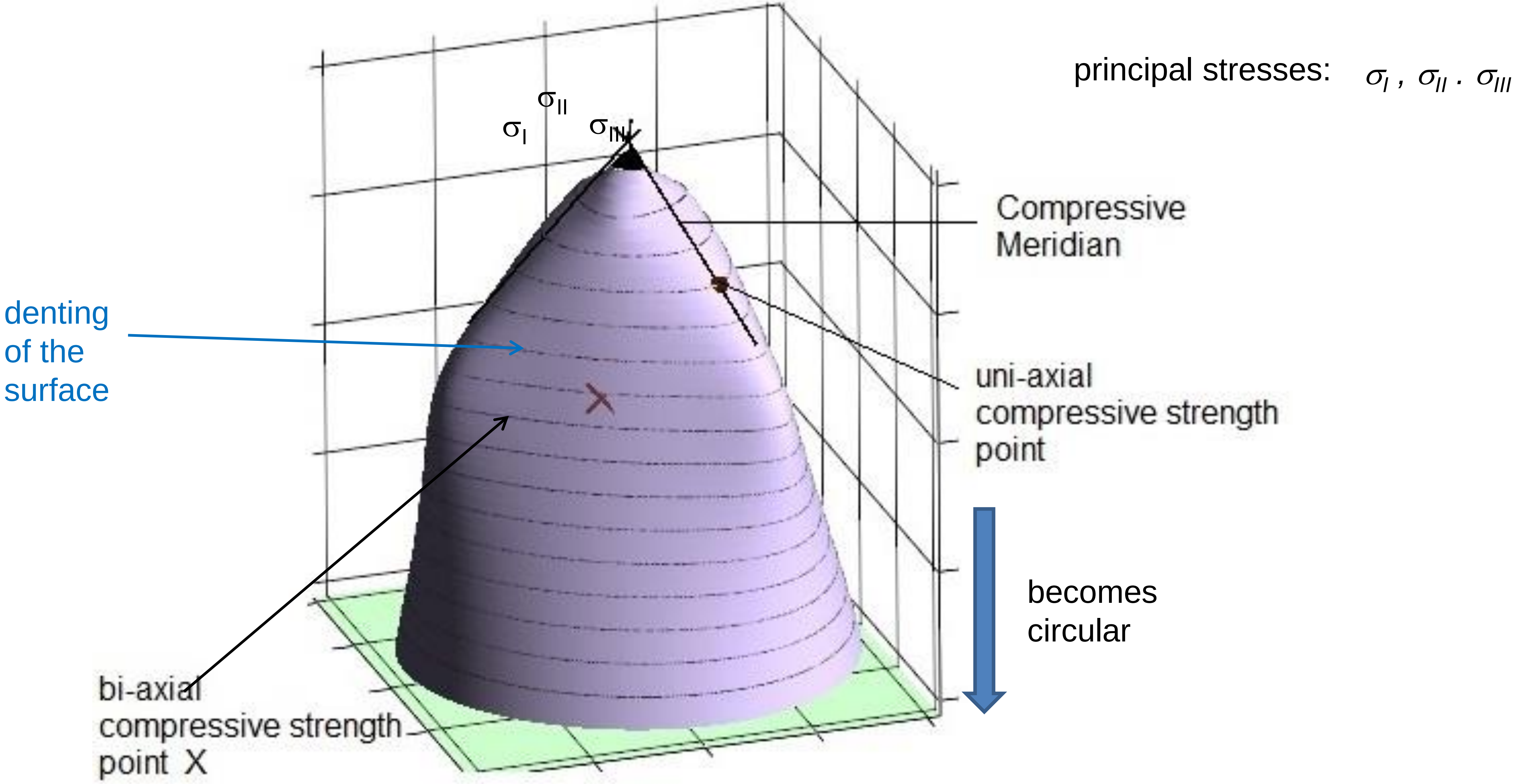


$$Eff \;= [(Eff^{NF})^m + (Eff^{SF})^m]^{m^{-1}} = 1$$ is equation of surface of fracture body

$maxI_1$ = 8.4 MPa (Mathcad plot)

The non-coaxiality decreases with hydrostatic pressure, cross-section becomes circular!

Ultra-High-Performance-Concrete (UHPC): Fracture Body



Cuntze's 3D-SFCs for UD-materials (sheet, lamella) *several times presented at NAFEMS*

(**top-ranked** in the World-Wide-Failure-Exercises-I and –II, 1991-2013. Cuntze is like a simple 'Mises' amongst the UD-SFCs)

FF1 $$Eff^{||\sigma} = \breve{\sigma}_1 / \overline{R}_{||}^{t} = \sigma_{eq}^{||\sigma} / \overline{R}_{||}^{t} ,$$

$\breve{\sigma}_1^* \cong \varepsilon_1^t \cdot E_{||}$ filament strains from FEA — captures axial tensile straining under bi-axial compression

FF2 $$Eff^{||\tau} = -\breve{\sigma}_1 / \overline{R}_{||}^{c} = +\sigma_{eq}^{||\tau} / \overline{R}_{||}^{c} ,$$

$\breve{\sigma}_1 \cong \varepsilon_1^c \cdot E_{||}$

2 filament modes

IFF1 $$Eff^{\perp\sigma} = [(\sigma_2 + \sigma_3) + \sqrt{(\sigma_2 - \sigma_3)^2 + 4\tau_{23}^{\ 2}}] / 2\overline{R}_{\perp}^{t} = \sigma_{eq}^{\perp\sigma} / \overline{R}_{\perp}^{t}$$

IFF2 $$Eff^{\perp\tau} = [(\frac{\mu_{\perp\perp}}{1-\mu_{\perp\perp}}) \cdot (\sigma_2 + \sigma_3) + \frac{1}{1-\mu_{\perp\perp}} \sqrt{(\sigma_2 - \sigma_3)^2 + 4\tau_{23}^{\ 2}}] / \overline{R}_{\perp}^{c} = +\sigma_{eq}^{\perp\tau} / \overline{R}_{\perp}^{c}$$

3 'matrix' modes

IFF3 $$Eff^{\perp||} = \{[2\mu_{\perp||} \cdot I_{23-5} + (\sqrt{(2\mu_{\perp||})^2 \cdot I_{23-5}^{\ 2} + 4 \cdot \overline{R}_{\perp||}^{\ 2} \cdot (\tau_{31}^2 + \tau_{21}^2)^2}] / (2 \cdot \overline{R}_{\perp||}^{\ 3})\}^{0.5} = \sigma_{eq}^{\perp||} / \overline{R}_{\perp||}$$

with $$I_{23-5} = 2\sigma_2 \cdot \tau_{21}^2 + 2\sigma_3 \cdot \tau_{31}^2 + 4\tau_{23}\tau_{31}\tau_{21}$$

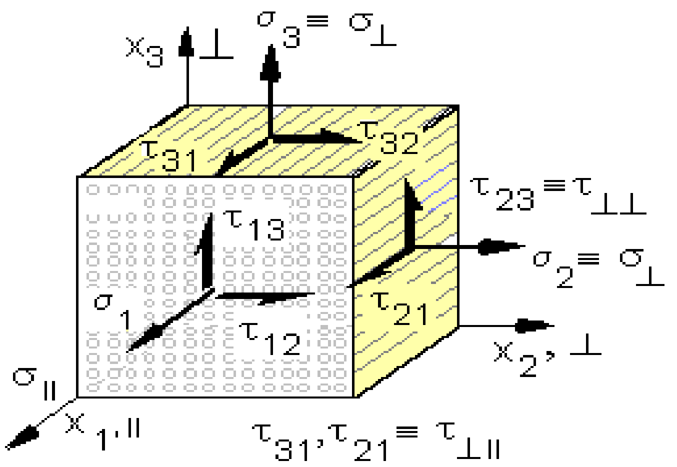
[Cun04, Cun11]

Modes-Interaction $$Eff^m = (Eff^{||\tau})^m + (Eff^{||\sigma})^m + (Eff^{\perp\sigma})^m + (Eff^{\perp\tau})^m + (Eff^{\perp||})^m$$

with influence IFF on FF : $= 1 = 100\%$ is 'onset of failure'

with mode-interaction exponent $2.5 < m < 3$ from mapping test data

Typical friction value data range: $0.05 < \mu_{\perp||} < 0.3, \quad 0.05 < \mu_{\perp\perp} < 0.2$



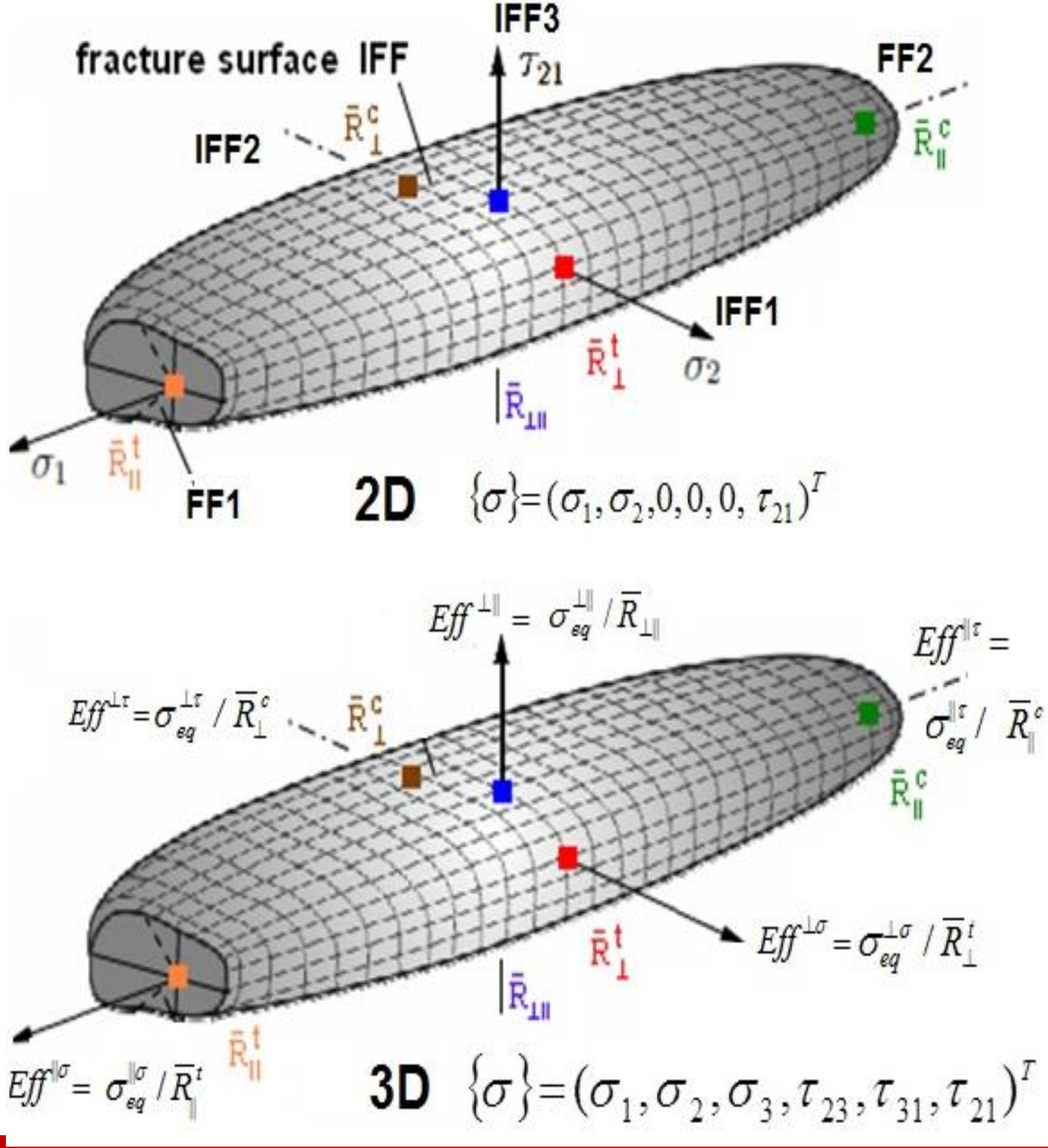
Eff:= material stressing effort (Werkstoffanstrengung), *R*:= UD strength, σ_{eq}:= equivalent stress.
Eff:= artificial word, fixed with QinetiQ in 2011, to have an equivalent English term.
Poisson effect considered*: bi-axial compression strains a filament without any σ_1
t:= tensile, c: = compression, || : = parallel to fibre, ⊥ := transversal to fibre

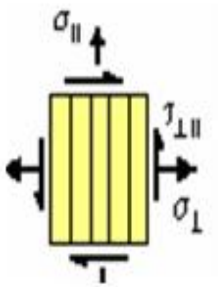
UD Fracture Body for isolated Lamina, Sheet (lamella)

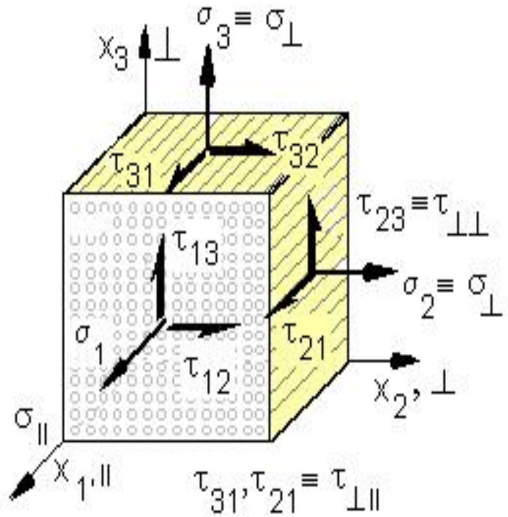
UD = uni-directional

2 D: σ

3 D: σ_{eq}







2D >> 3D

after replacing

σ, τ by σ_{eq}^{mode}

$\nu_{\perp\perp} = 0.4,$

$\nu_{\perp\|} = 0.3$

Conclusions

- **The FMC is a general applicable efficient concept, which**
  is applicable to brittle and ductile, dense and porous, isotropic, transversely-isotropic and orthotropic materials
  improves prediction + simplifies design verification and **delivers equivalent stresses**
- **uses just the <u>measurable model parameters</u> strength *R* and material friction μ**
- **builds** not on the **material type** but on the ***deformation behaviour + texture of the material***
- **delivers a <u>combined formulation</u> of *independent failure modes*,**

  without the well-known drawbacks of a <u>global</u> formulation

  (= '*mathematically forced marriage*' *of in-dependent failure modes)*
- **FMC-based Strength Failure Conditions are relatively simple but describe physics of each single failure mechanism pretty well.**
- **Mapping of above brittle behaving materials was successful; lead to some new findings !**

„The generation of reliable multi-axial fracture test data

with the understanding of the associated fracture mechanisms

is a more effortful work

than the establishment of a theory.

However mind,

a reliable theory, only,

makes the whole practicable.“

Experience from Ralf Cuntze

Some Literature

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[Cun15a] Cuntze, R.: *Static & Fatigue Failure of UD-Ply-laminated Parts – a personal view and more.* ESI-Group, Composites Expert Seminar, Uni-Stuttgart, January 27-28, keynote presentation, see CCeV website)

[Cun15b] Cuntze, R.: *Reliable Strength Design Verification – fundamentals, requirements and some hints.* 3rd. Int. Conf. on Buckling and Postbuckling Behaviour of Composite Laminated Shell Structures, DESICOS 2015, Braunschweig, March 26 -27, extended abstract , conf. handbook, 8 pages (see CCeV website)

[Cun17] Cuntze, R.: Fracture *Failure Bodies of Porous Concrete, Normal Cioncrete, Ultra-High-Performance-Concrete and of the Lamella Sheet-generated on basis of Cuntze's Failure Mode Concept.* Conference handbook NWC2017, NAFEMS Stockholm, June 11-14,

[Kol15] Kolupaev V., Becker W., Massow H. und Kiegelmann E. M.: Mit Schaumstoffen zuverlässig konstruieren, ROHACELL 71 und 110 IG. Carl Hanser, Kunststoffe 2015, Heft 2. (English: see www.kunststoffe-international).

[VDI2014] VDI 2014: German Guideline, Sheet 3 *"Development of Fiber-Reinforced Plastic Components, Analysis".* Beuth Verlag, 2006 (*in German and English, author was convenor).*

For mutual understanding: *What do the following terms mean ??*

Material : homogenized (macro-)model of the envisaged solid

Failure : structural part does not fulfil a distinct functional requirement

such as onset of yielding, onset of brittle fracture, leakage, delamination size limit, frequency bound .

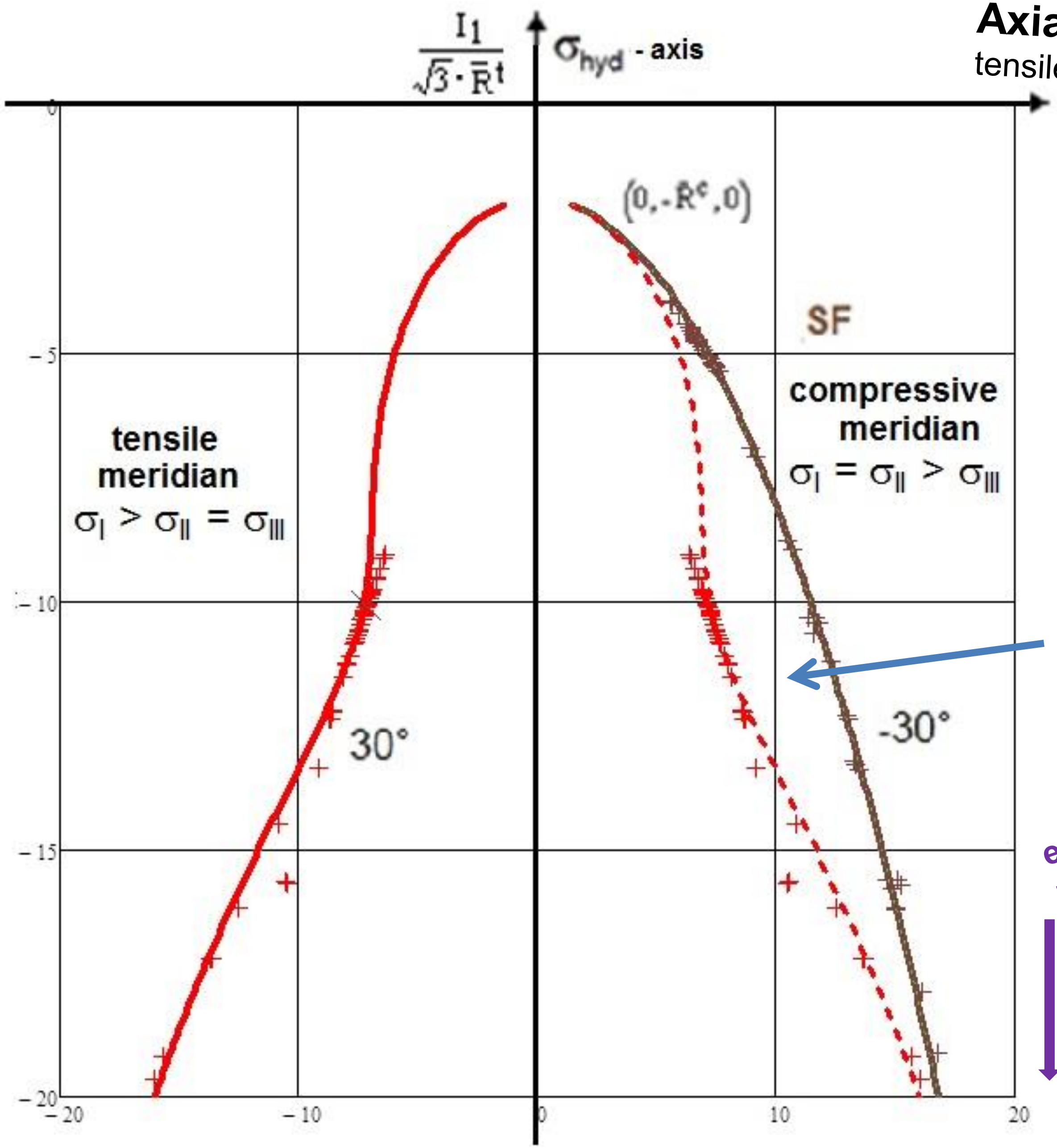
Strength Failure Condition (SFC):

Condition to assess a 'multi-axial failure stress state ' in a critical location of the structural part

= mathematical formulation of the failure surface of the fracture body : $F = 1$

(which is now falsely termed strength criterion , that is defined as $F >=< 1$).

Ultra-High-Performance-Concrete: Tensile and Compressive Meridian



Axial cross-section of the fracture body

tensile meridian and compressive meridian are opposite to another

Procedure with respect to MATHCAD capabilities and with consideration of the confined non-circularity

(both the curves come together) **:**

- Fitting of the course of compressive test data using linear progression in MATHCAD
- Estimation of non-circularity parameter *D*
- Prediction of tensile meridian curve

denting

$\overline{R}^t = 20$ MPa, $\overline{R}^c = 160$ MPa, $\overline{R}^{tt} = 0.89 \cdot \overline{R}^t$ (assumed), $\overline{R}^{cc} = 175$ MPa

Mohr stresses: σ_I , σ_{II} , σ_{III}

end of non-circularity,

MATHCAD : Indirect fitting with Linear Progression tool which allows just a mapping of the compression meridian and a further step to consider the different denting between the compression and the tensile meridian plus to consider the end of the non-coaxiality.
The direct fitting tool MINFEHL did not work, unfortunately in contrast to the prvious experience

(Original test data, courtesy K.Speck, IfM Dresden. Evaluated by the author for the tensile snd compressive meridians)