Die ‚Statische Nachweisführung'
verlangt die Verwendung
validierter Festigkeitsbedingungen sowie
validierter Schadenstoleranzbedingungen.

Während Festigkeitsbedingungen den Versagenseintritt vorhersagen, werden Schadenstoleranzbedingungen zur Überprüfung der Kritikalität eines aufgetretenen technischen Schadens herangezogen.

Bzgl. uni-direktional verstärkter Faser-Kunststoff-Verbunde (FKV) bedeutet dies: Vorhersage

*** von Faserbruch, Zwischenfaserbruch und Delaminationsbeginn des noch nicht schaden-behafteten Bauteils**
sowie
*** der Kritikalität der Delamination (≡ Riss) des schaden-behafteten Bauteils.**

Der Vortrag betrifft lediglich Festigkeitsbedingungen

Die Zunahme des Einsatzes faserverstärkter Kunststoffe (FVK) im Hochleistungsbereich führte dazu, dass seit 1992 - für das Teilgebiet Uni-Direktionaler FKV - in England, durch das Institut QinetiQ, ein weltweiter Wettbewerb "World-Wide-Failure-Exercise (WWFE)" organisiert wurde zur *Überprüfung aktueller Festigkeitsbedingungen*.

Der Autor war Teilnehmer in den beiden ersten Teilen
WWFE-I (gewonnen 2004) und WWFE-II (in 4er-Spitzengruppe 2013).

Wie sich in 2017 herausstellt, sind die gewonnenen WWFE- Erkenntnisse iImmer noch nicht ausreichend in Uni + Industrie + bei FEA-Software-Erzeugern angekommen.

Schade, auch wenn die Nutzung der nur teilweise guten WWFE-Test-Ergebnisse nicht optimal war !!

Daher noch einmal meine aktuelle Sicht und Bewertung des :

World-Wide-Failure-Exercise für UD-Werkstoffe:

– Ergebnisse bereits vergessen oder wirklich noch nicht angekommen?

.

CARBON COMPOSITES

The World-Wide-Failure-Exercises -I and - II for UD-materials

- valuable attempts to validate failure theories
on basis of more or less applicable test data sets **-**

- **Introductory Information**
- **Failure-Mode-Concept-based Strengrth Failure Conditions**
- **Survey on the World-Wide-Failure-Exercises (WWFEs)**
- **Discussion of Quality of provided Test data Sets**
- **Validation Examples WWFE-I (2D) and WWFE-II (3D)**
- **Practical Relevance with 'Lessons Learnt'.**

Ralf Cuntze
Prof. Dr. -Ing. habil. VDI, linked to Carbon Composites e.V. (CCeV), Augsburg.

Results of non-funded personal investigations

Ziele des Ingenieurs

- Validierung der Festigkeitsbedingungen
  durch sog. Abbilden des Verlaufs der Bruch-Testdaten,
  d.h. durch eine mittlere Kurve und mittlere Festigkeitswerte $\overline{R}$

  mit der späteren Abgabe eines zuverlässigen

- Festigkeitsnachweis
  durch Berechnung einer Sicherheitsmarge oder eines
  Last-Reservefaktors)
  $MoS > 0$ oder $RF = MoS + 1 > 1$
  d.h. auf Basis einer statistisch abgeminderten mittleren Kurve und
  Festigkeitswerten R.

What is Failure?

If the structural part does not fulfil its functional requirements (FF, IFF, leakage, deformation limit, delamination size limit, …)

What does Failure Theory in the WWFE definition comprise?

* **UD strength failure conditions (SFCs) to predict interactive FF with IFF**
* **Non-linear modelling of the lamina** (hardening with softening)
* **Implementation of SFCs into a computer code for non-linear analysis**
* **Degradation of matrix material from 2nd-Tg effect, if $p_{hyd} > 200$ MPa**

FF := Fiber Failure, IFF := Inter-Fiber Failure (matrix failure)

Welche Werkstoffkennwerte benötigt man z.B. beim UD-Werkstoff?

Statische Festigkeits-Eigenschaften:

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

+ Reibung

Mohr-Coulomb $\mu_{\perp||}, \mu_{\perp\perp}$

Elastische Eigenschaften:

$$E_{||}, E_{\perp}, G_{||\perp}, \nu_{\perp||}, \;\; (\text{and } \nu_{\perp\perp}, \;\; \text{if } 3D)$$

Physikalische Eigenschaften:

Wärmeausdehnung CTE: $\alpha_{T||}, \alpha_{T\perp}$

Feuchteausdehnung CME: $\alpha_{M||}, \alpha_{M\perp}$

Werkstoffreibung: $\mu_{\perp||}, \mu_{\perp\perp}$

Understanding the terms Material Stressing Effort and Equivalent Stress

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

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

mode equivalentstress

mode associated average strength (bar over)

anology to 'Mises'

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

$$Eff^{\text{Mises}} = \sigma_{eq}^{\text{Mises}} / R_{p0.2}$$

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

$$f_{\text{Res}} = \frac{\text{strength } R}{\text{design stress } \sigma} = \frac{1}{Eff}$$

inverse

in linear case $\text{RF} = f_{\text{Res}}$

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**

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

Reasons for Chosing Invariants when generating Failure Conditions

From Beltrami, Mises (HMH), and Mohr / Coulomb (friction) can be concluded:

Below invariant terms - used in a *failure function* ***F*** - can be dedicated to a physical mechanism in the solid = cubic material element:

- volume change : I_1^2 … ***(dilatational energy)*** | I_1^2 , I_2^2
- shape change : J_2 (Mises) … ***(distortional energy)*** | I_3 , I_4
- and - friction : I_1 … ***(friction energy)*** | I_2

Stress Invariants: ***isotropic materials*** *and* ***: UD materials***

Mohr-Coulomb

These I_1 are different !

Invariant := Combination of stresses, the value of which does not change when altering the coordinate system.

Invariant *I*5 is needed to represent the different behaviour of $\sigma_2(\tau_{21})$ and $\sigma_3(\tau_{21})$

Information available for generating Strength Failure Conditions (SFCs)

1 If a **UD material element can be homogenized to an <u>ideal</u> (= frictionless) crystal,**

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

- 5 *elastic 'constants' , 5 strengths, 5 fracture toughnesses, 5 invariants* and
- *2 physical parameters (such as 2 CTE, 2 CME, etc.)*

(hence, for UD the <u>generic numbers</u> are 5 and 2; for isotropic 2 and 1)

2 Mohr-Coulomb requires for the <u>real UD</u> crystal

2 physical parameters 'material friction' : UD $\mu_{\perp\|}, \ \mu_{\perp\perp}$

In addition:

3 Fracture morphology gives evidence:

Each strength corresponds to a distinct *failure mode*

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

Failure-Mode-Concept: Observed Features

- **Each failure mode represents 1 independent failure mechanism and 1 piece of the complete *failure surface***

- **Each failure mechanism is governed by 1 basic strength**

- **Each failure *mechanism* is represented by 1 failure *condition***

So-called Global and Modal Strength Failure Conditions: *Description*

- **Global SFC :**

  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 :**

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

Two types of Strength Failure Conditions (SFCs) are used

Tsai-Wu

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)

Puck,
Cuntze

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

vector of 6 stresses (general)

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

vector of 5 strengths (UD)

Test data mapping : $R \Rightarrow \bar{R}$ average strength value (here addressed)

Design Verification : R strength design allowable,

- needs an ***Interaction of Failure Modes****:* *performed by a :*

probabilistic-based 'rounding-off' approach (series failure system) in the transition zones between the adjacent mode domains.

Benefits of the <u>modal</u> strength failure conditions (SFCs):

- No more input required than for the usually applied

  <u>global</u> strength failure conditions

- Have not the short-comings of the global conditions that

  - mathematically combine independent failure domains
  - do not directly use the physically necessary friction

    which means a bottle-neck if too few compressive multi-axial failure stress data are available, only, *and*

  if a test point change is required in a distinct mode this will change the shape of the failure surface in independent mode domains which may not be on the safe side !

Each type of a Strength Failure Conditions (SFC) means

Failure Function $F = 1$ or

Material stressing effort $Eff = 100\%$.

$F = 1$ mathematically describes the surface of a failure body.

A simple isotropic example for such a failure body shall be demonstrated

Foam model

State-of- the-Art in *Static Strength Analysis of UD laminas*
best-represented by the results of the *World-Wide-Failure-Exercises*

Organizer : ***QinetiQ , UK*** *(Hinton, Kaddour, Soden, Smith, Shuguang Li)*

Aim: ***'Testing Predictive Failure Theories for***

Fiber–Reinforced Polymer Composites to the full !'

(for UD materials , only)

Procedure of the World-Wide-Failure-Exercises-I, -II (1992-2013)**:**

Part A of a WWFE: ***Blind Predictions on basic strengths, only; no friction-information for treating the compression-related Test Cases was provided !***

Part B of a WWFE: ***Comparison Theory-Test*** *with (reliable)*
Uni-axial 'Failure Stress Test Data' (= basic strength) and
Multi-axial 'Failure Stress Test Data'
(plain test specimens, not notched)

WWFE-I Objective : 2D-Validation with 2D Failure StressTest Data

TC1-TC3 ***UD lamina : for 2D validation of UD models***

TC4-TC14 ***UD lamina-composed Laminates :***

(quasi-isotropic, angle-ply, cross-ply)

for verification of laminate design by multi-axial failure stress envelopes *and* ***stress-strain curves .***

WWFE-II Objective : 3D–Validation with 3D Failure StressTest Data

under hydrostatic pressures up to > 10000 bar = 1000 MPa

TC1 ***Epoxide matrix : for 3D validation isotropic matrix***

TC2-TC7 ***UD lamina : for 3D validation of UD model***

TC8-TC12 ***Laminates*** **:** ***for verification of laminate design.***

WWFE Assumptions for UD Modelling

- **The UD-lamina is macroscopically homogeneous**.

  It can be treated as a homogenized (‘smeared‘) material

- **The UD-lamina is transversely-isotropic:**

  On planes, parallel to the fiber direction it behaves orthotropic and on planes transverse to fiber direction isotropic (quasi-isotropic plane)

- **Uniform stress state about the critical stress ‘point‘ (location). Low stress gradient at the critical stress state location**

Test specimens are *assumed to be : ideal, accurate*

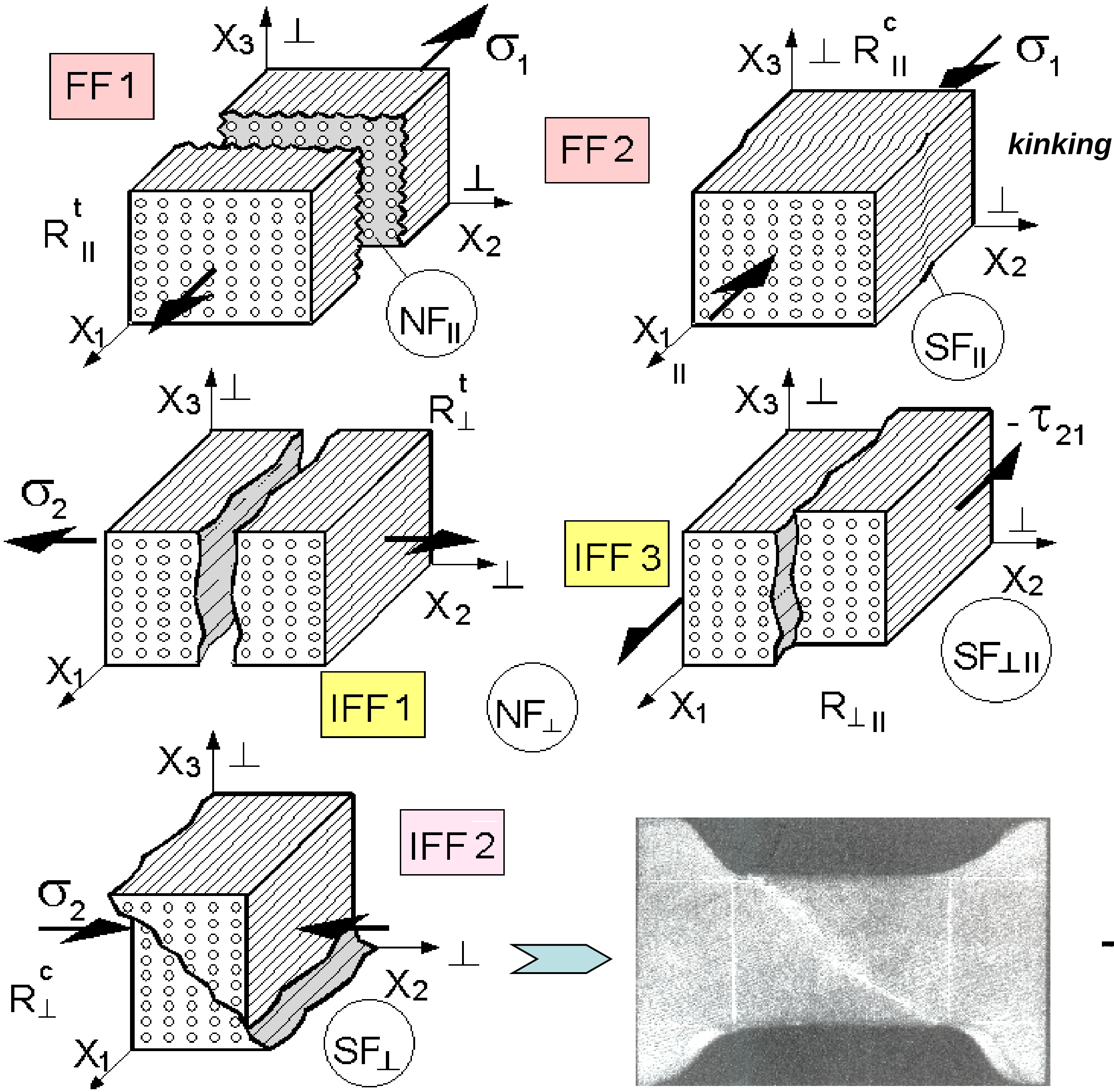
Pore-free material, specimen surfaces polished, well sealed (WWFE-II), fiber volume is constant, tube specimens show no warping and do not bulge, perfect bonding, no layer waviness, no misalignmenrt, **have no edge effects**, …

Observed Strength Failure Modes with Strengths of brittle UD Materials

old picture

t = tension

c = compression

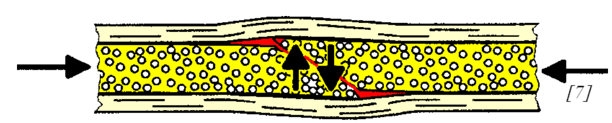


- ▶ 5 Fracture modes exist
  - = 2 FF (Fibre Failure)
  - + 3 IFF (Inter Fibre Failure)

Fracture Types:

NF := Normal Fracture

SF := Shear Fracture



wedge failure type

WWFE-II Set of <u>Modal</u> 3D UD Strength Failure Conditions (criteria)

Invariants replaced by their stress formulations

strains from FEA [Cun04, Cun11]

FF1 $Eff^{||\sigma} = \breve{\sigma}_1 / \overline{R}_{||}^{t} = \sigma_{eq}^{||\sigma} / \overline{R}_{||}^{t}$, $\quad \breve{\sigma}_1 \cong \varepsilon_1^t \cdot E_{||}$ *

FF2 $Eff^{||\tau} = -\breve{\sigma}_1 / \overline{R}_{||}^{c} = +\sigma_{eq}^{||\tau} / \overline{R}_{||}^{c}$, $\quad \breve{\sigma}_1 \cong \varepsilon_1^c \cdot E_{||}$

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

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

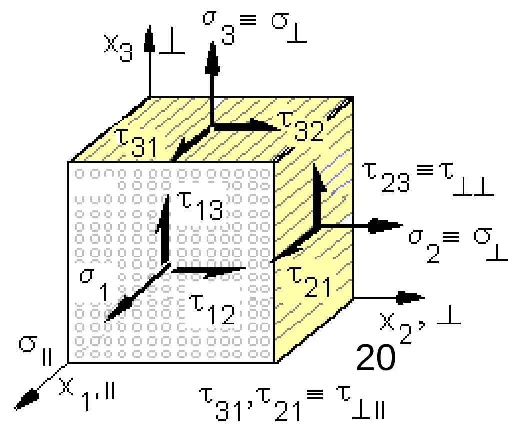
Modes-Interaction :

$$Eff^m = (Eff^{||\tau})^m + (Eff^{||\sigma})^m + (Eff^{\perp\sigma})^m + (Eff^{\perp\tau})^m + (Eff^{\perp||})^m = 1$$

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

(simplified: the same for all transition zones between adjacent mode domains)

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



Poisson effect * : bi-axial compression strains the filament without any σ_1

t:= tensile, c: = compression, || : = parallel to fibre, ⊥ := transversal to fibre

Cuntze's Pre-design Input for 3D UD SFCs (failure criterion)

Test Data Mapping — Design Verification

- **5 strengths :** $\{\bar{R}\} = (\vec{\bar{R}}_{||}^{t}, \bar{R}_{||}^{c}, \bar{R}_{\perp}^{t}, \bar{R}_{\perp}^{c}, \bar{R}_{\perp||})^{T}$ $\{R\} = (R_{||}^{t}, R_{||}^{c}, R_{\perp}^{t}, R_{\perp}^{c}, R_{\perp||})^{T}$

  average (typical) values — **strength design allowables**

- **2 friction values : for 2D** $\mu_{\perp||}$ **, for 3D** $\mu_{\perp||}, \ \mu_{\perp\perp}$

  $\mu_{\perp||} = 0.1$ $\mu_{\perp\perp} = 0.1$

- **1 mode-interaction exponent :** *m = 2.6 .*

values, recommended for pre-design

5 +2 +1 = **8** parameters are only necessary for a 3D use of Cuntze's modal set of equivalent stress-based SFCs !

Laut Veranstalter benötige ich **70** Parameter zur Anwendung meiner Theorie (SFC + nicht-lineare Analyse).

Wer nur linear gerechnet hat, war automatisch besser bewertet ! Die Ingenieure interessiert - im WWFE-Kontext - aber lediglich die Versagensbedingung .

Interaction of Single Strength Failure Modes in the modal FMC

Interaction of adjacent Failure Modes by a *series failure system* model

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

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

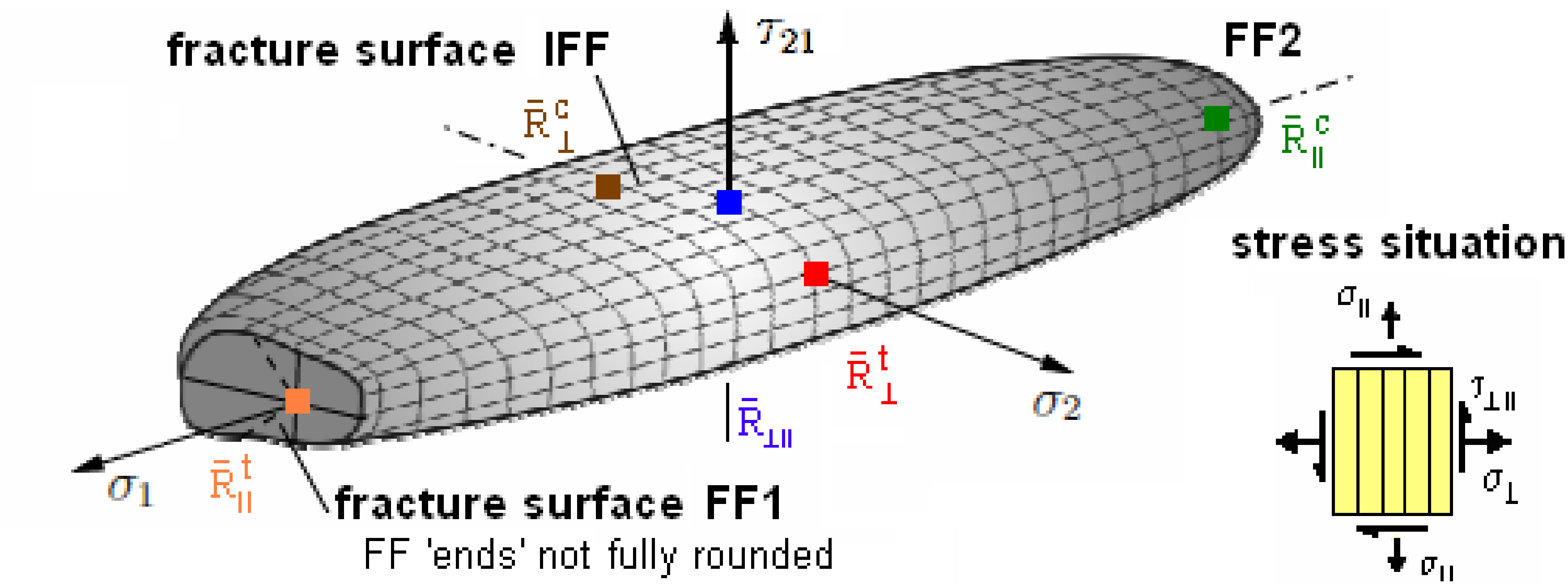
with **mode-interaction exponent** *2.5 < m < 3 from mapping experience*
(simplification: m is taken the same for all interaction-determined transition zones)

as ***modal*** **material stressing effort *** (Werkstoffanstrengung)

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

**** artificial technical term created together with QinetiQ during the WWFE***

Visualization of 2D UD SFCs as Fracture Failure Surface (Body)



$$\{\sigma\} = (\sigma_1, \sigma_2, 0, 0, 0, \ \tau_{21})^T$$

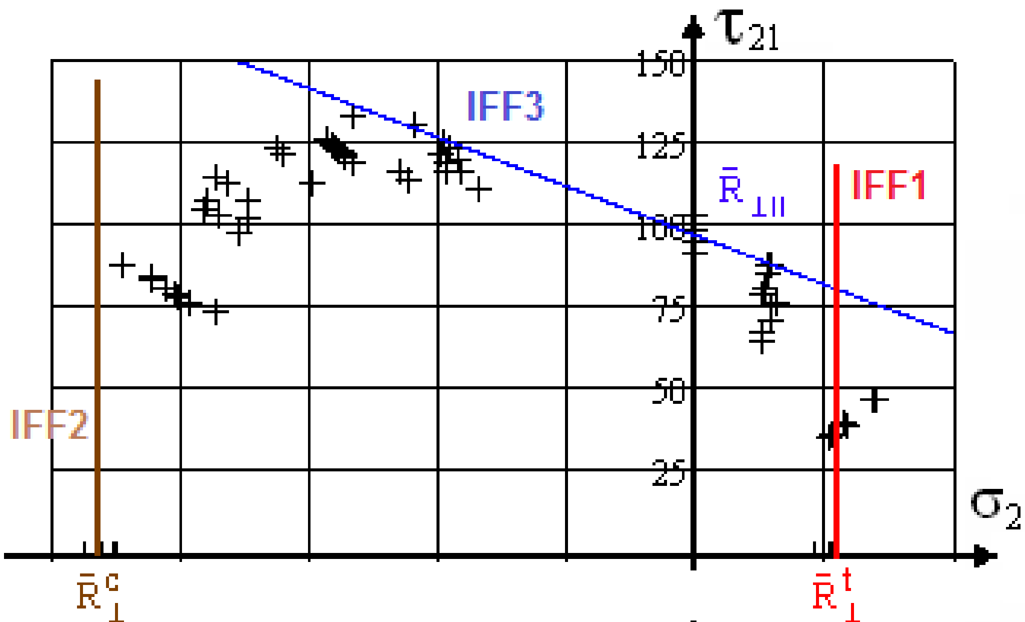
Mode interaction fracture failure surface *of FRP UD lamina*

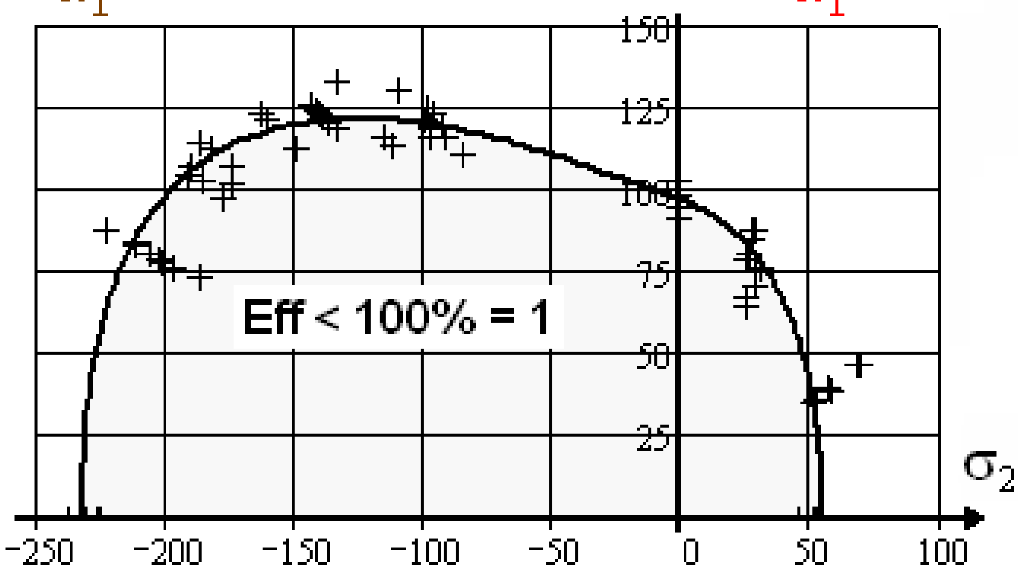
$$Eff^m = \ (Eff^{\parallel\tau})^m + \ (Eff^{\parallel\sigma})^m + \ (Eff^{\perp\sigma})^m + \ (Eff^{\perp\tau})^m + \ (Eff^{\perp\parallel})^m = \ 1$$

(courtesy W. Becker) .

Mapping: Average strengths indicated

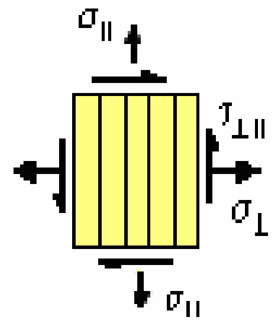
Interaction Visualization of UD Failure Modes $\tau_{21}(\sigma_2)$ $\breve{\sigma}_1 = 0$





Mapping of course of IFF test data in a pure mode domain by the *single Mode Failure Condition.*

3 IFF pure modes = straight lines !.



IFF 1 : $\dfrac{\sigma_2}{\bar{R}_\perp^t} = 1$

IFF 2 : $\dfrac{-\sigma_2}{\bar{R}_\perp^c} = 1$

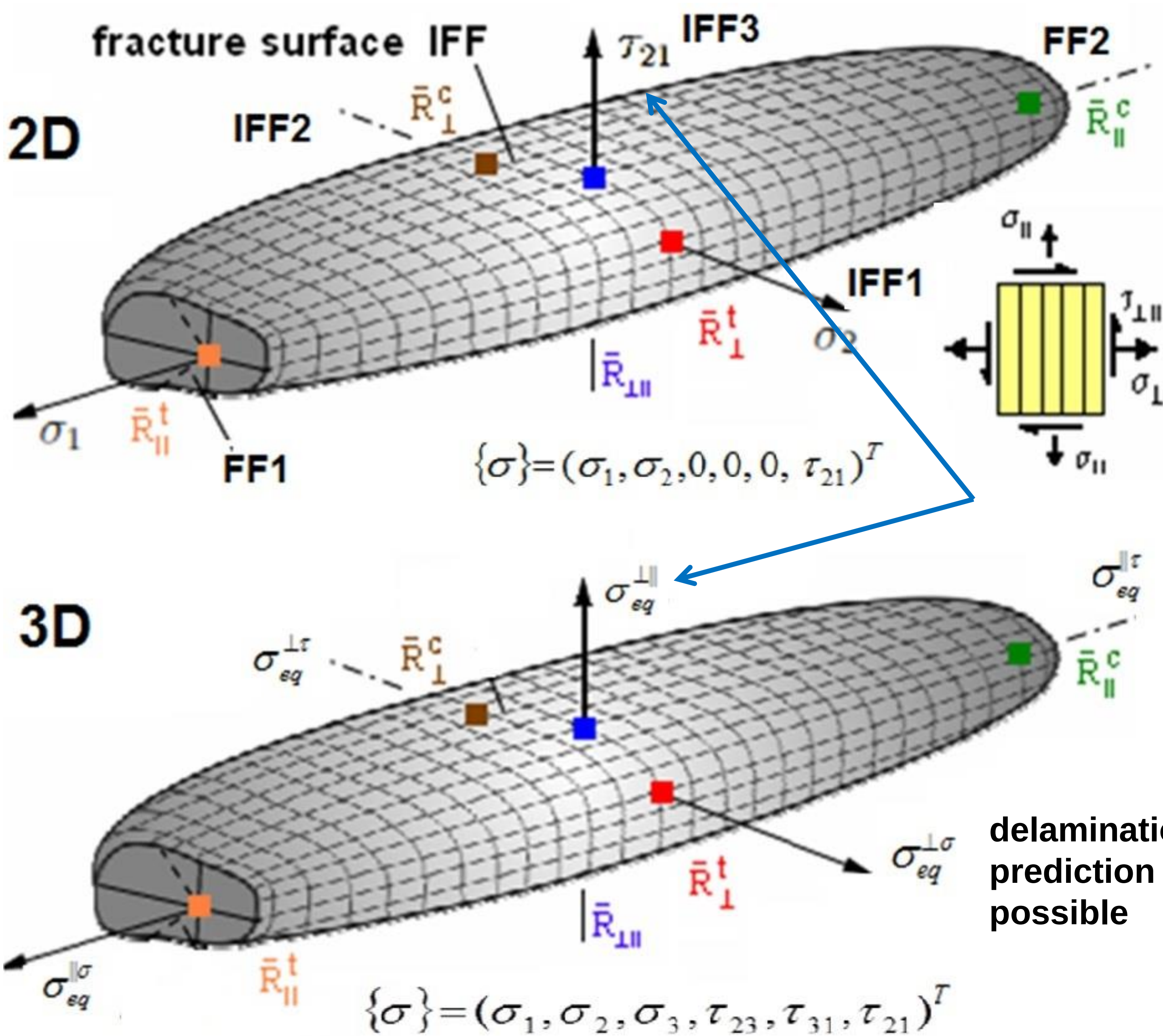
IFF 3* *(2D-simplified) : $\dfrac{|\tau_{21}|}{\bar{R}_{\perp\|} - \mu_{\perp\|} \cdot \sigma_2} = 1$

Mapping of course of test data by *Interaction Model*

$$(Eff^{\perp\sigma})^m + (Eff^{\perp\tau})^m + (Eff^{\perp\|})^m = 1$$

$$m = 2.5, \quad \mu_{\perp\|} = 0.3$$

2D = 3D Fracture surface by replacing the stress by the equiv. stress

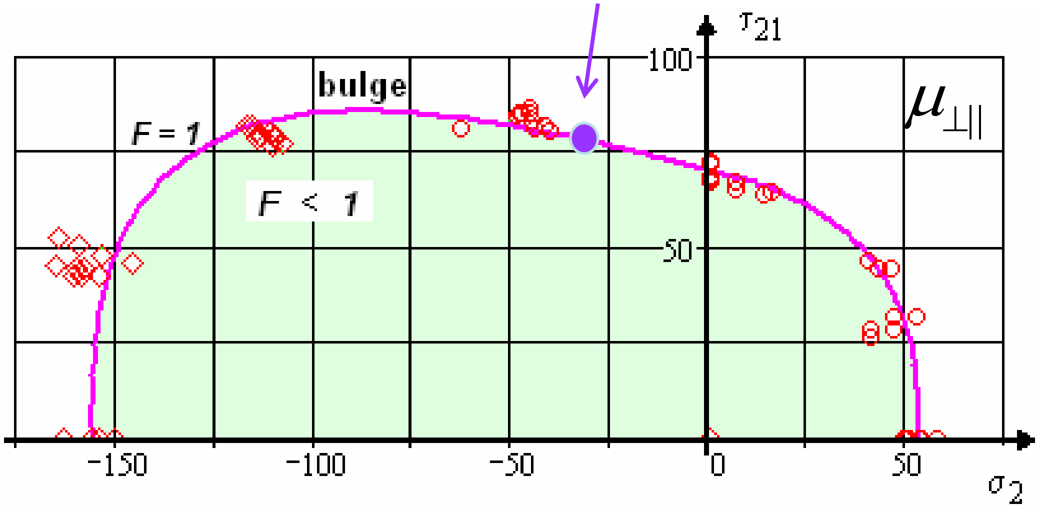


delamination prediction possible

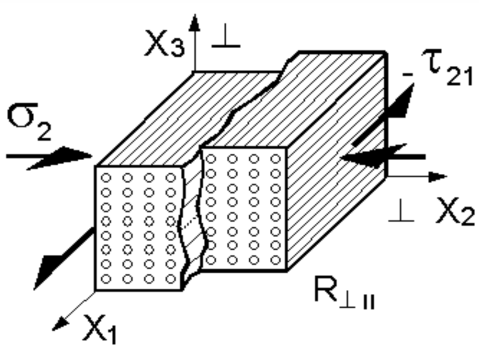
Guess of Friction Values from slopes (bi-axial test points) $\mu_{\perp||}$, $\mu_{\perp\perp}$

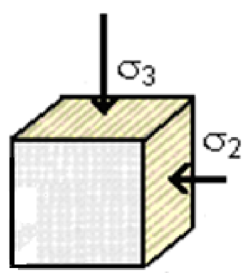
$$|\tau_{21}| = \bar{R}_{\perp||} - \mu_{\perp||} \cdot \sigma_2$$

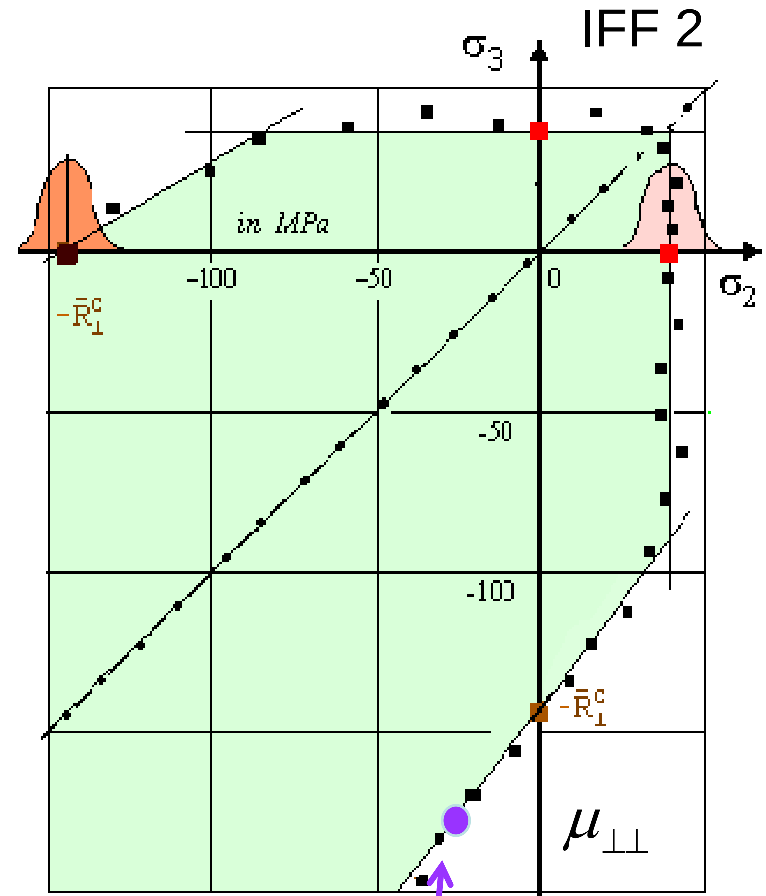
Estimation:
Straight line through magenta point
and associated strength point



IFF 3



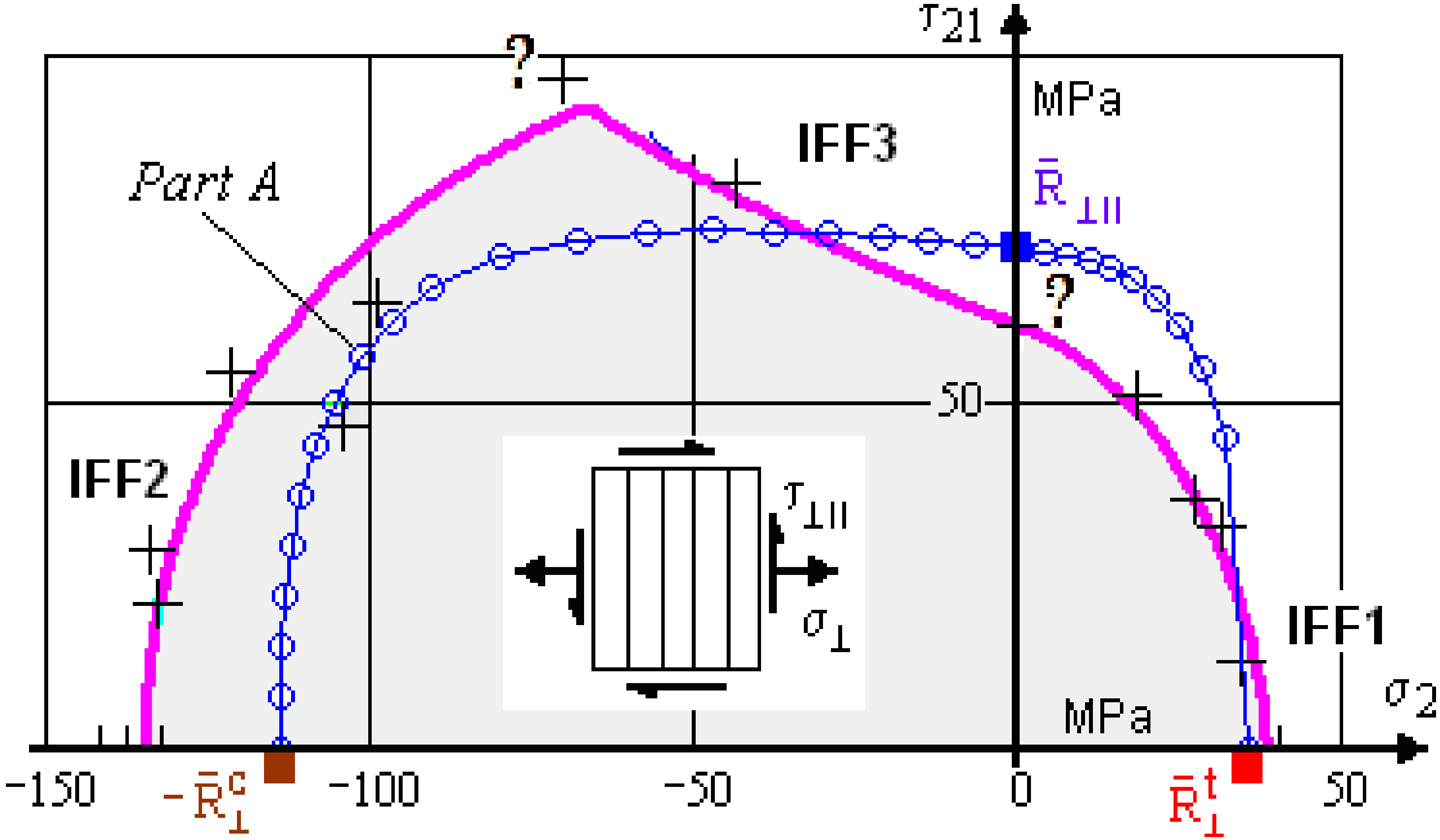




1. Fitting of course of test data (min error square) in 'pure' failure mode domains
2. Estimation with one strength value and one multi-axial failure stress point
3. For $\mu_{\perp\perp}$ in addition : derivation from fracture plane measurements possible.

minimum error square

Test Case 1 (TC 1), WWFE-I, *IFF curve* $\tau_{21}(\sigma_2)$

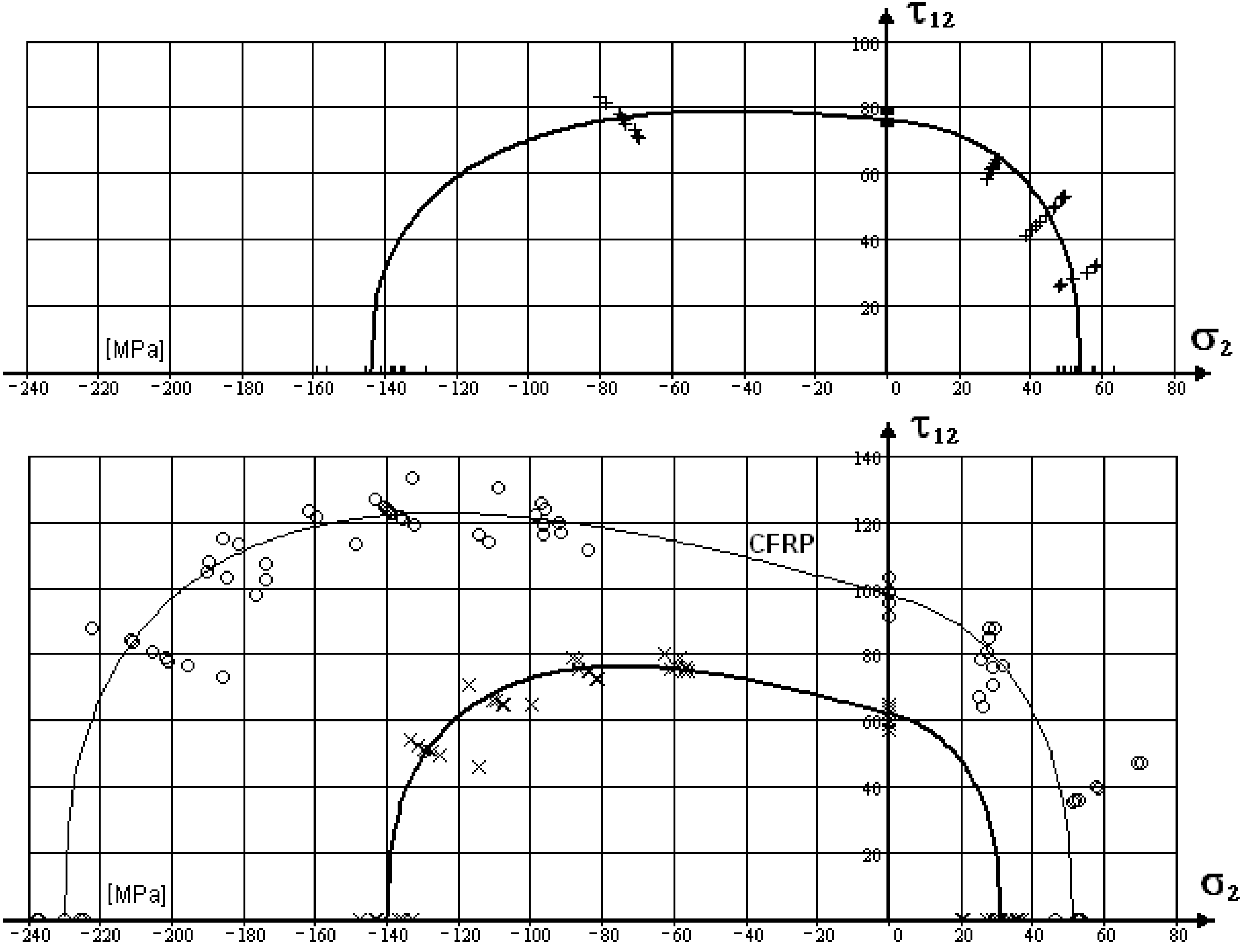


Part A, prediction: 3 Strength data provided, only. No friction value (slope) $\mu_{\perp||}$ given !

Part B, comparison: 3 Strength points altered! 1 doubtful failure stress point left

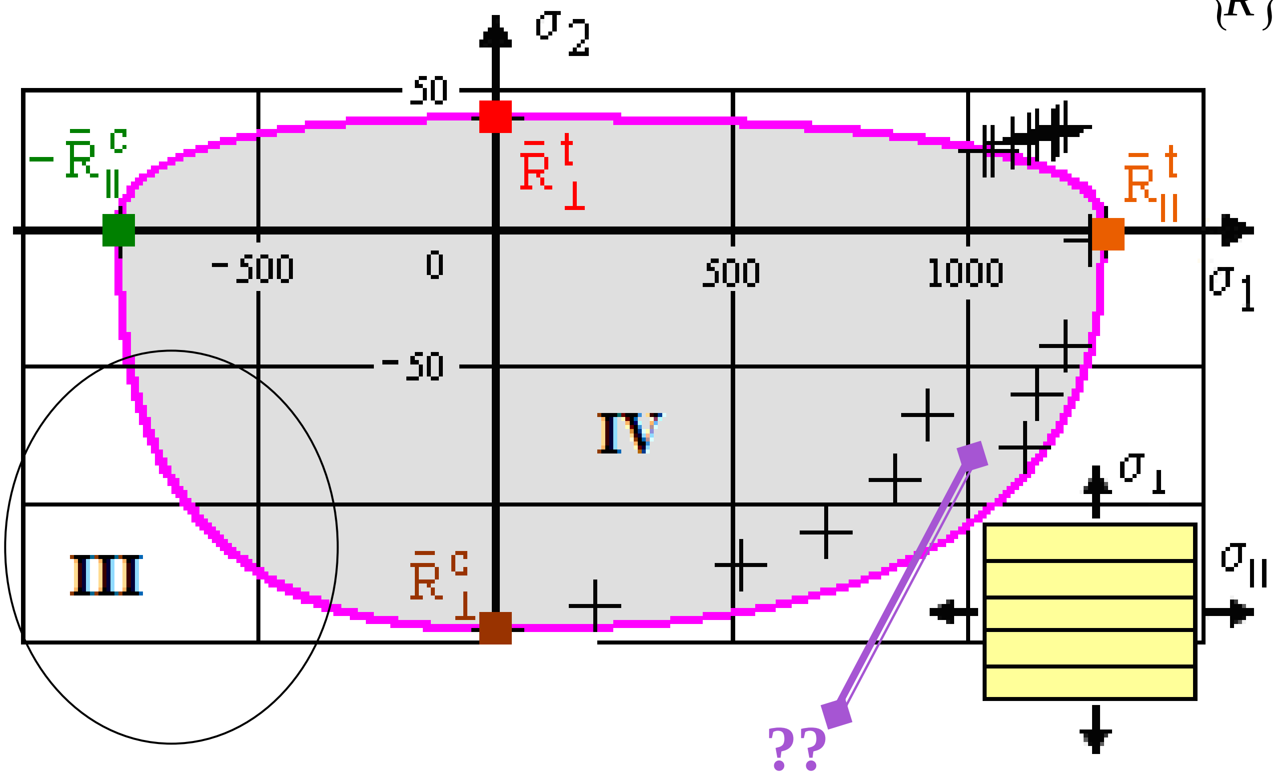
Qinetiq asked us to use unrealistic high friction values to map TC1 ! Not safe side.

Own test results: 2 GFRP, 1 CFRP Test Series



Test Case 3, WWFE-I $\sigma_2(\breve{\sigma}_1 \equiv \sigma_1)$

$\{\bar{R}\} = (1280,\ 800,\ 40,\ 145,\ 73)^T$



Hoop wound tube
UD-lamina.
E-glass/MY750epoxy +

$\sigma_1 = \sigma_{hoop}$

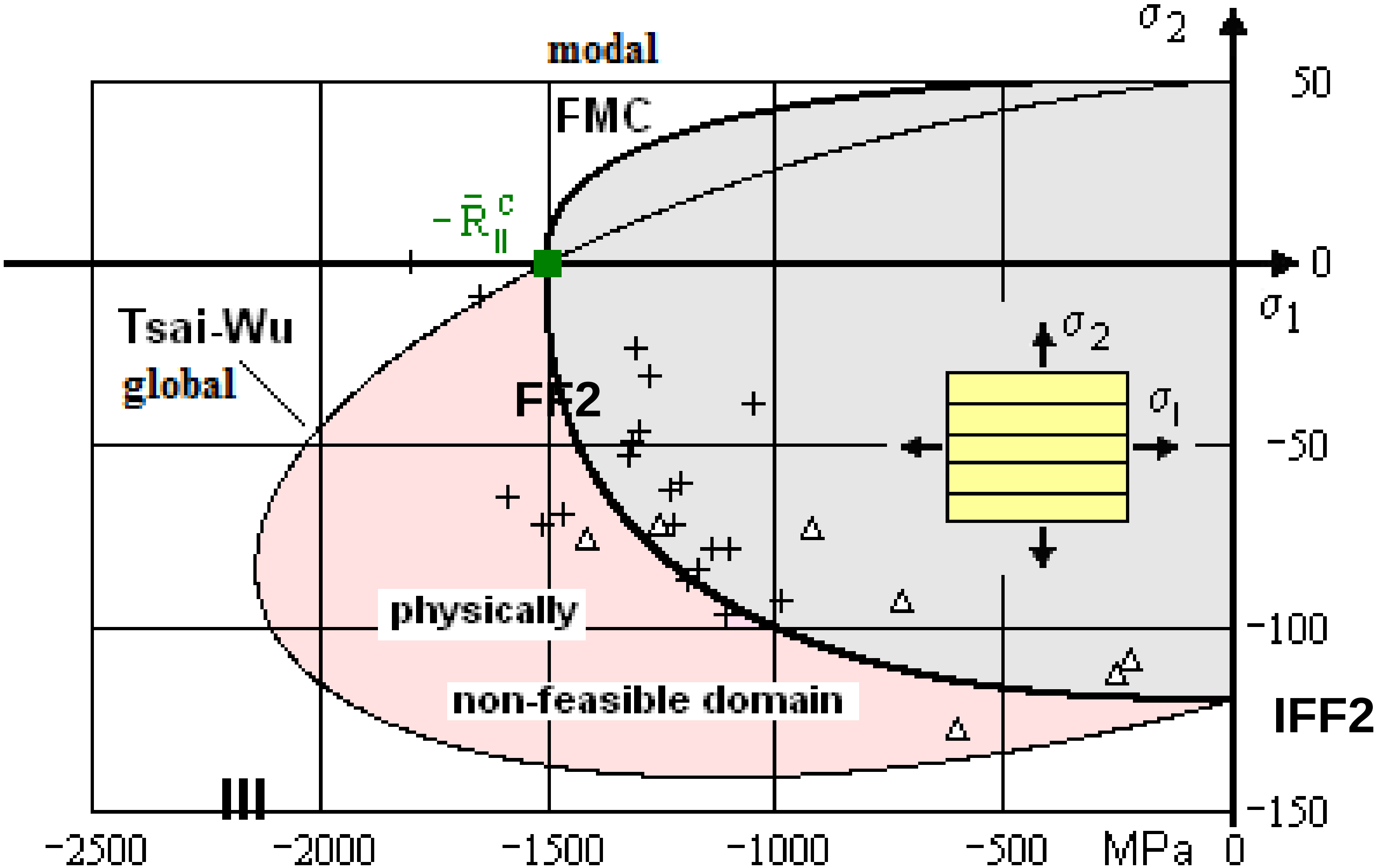
$\sigma_2 = \sigma_{axial}$

Part A: Data of strength points were provided, only

Part B: Test data in quadrant IV show discrepancy , testing?

No data for quadrants II, III was provided ! But, ..

Mapping in the ‘Tsai-Wu non-feasible domain‘ (quadrant III)



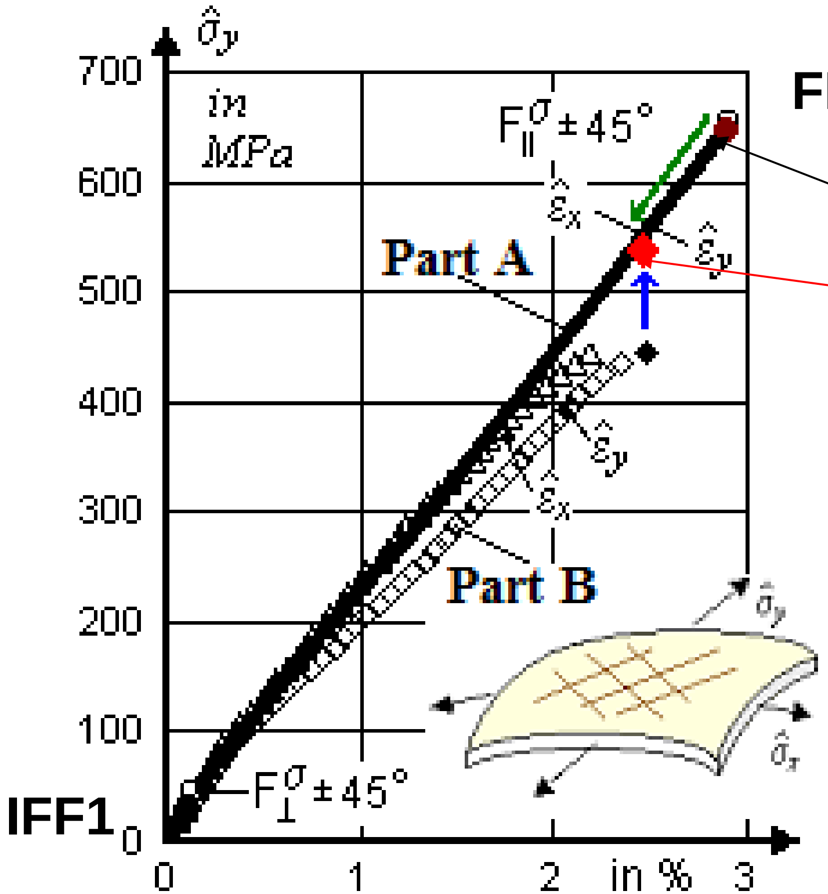
$\sigma_2(\breve{\sigma}_1 \equiv \sigma_1)$

Data: courtesy IKV Aachen, Knops

The modal FMC maps correctly, the *global*
Tsai-Wu formulation predicts a non-feasible domain !

Test Case 13, WWFE-I, Laminate Stress-Strain Curve

$\hat{\sigma}_y : \hat{\sigma}_x = 1 : 1$



$\{\overline{R}\} = (1280,\ 800,\ 40,\ 145,\ 73)^T$

Loading of tube: internal pressure + axial tension.

Laminate: E-glass/MY750. [+45/-45/45/-45]-

Bulging (widening) reported in experiment.

● Final blind prediction point.

◆ Maximum test value *after* correction and shifting.

Mapping quality very good after re-evaluation !

Part A: Data of strength points and the fracture strain were provided

Part B: Increased test data information caused **a reduction of *fracture strain* and to *increase the fracture stress*, as widening of the tube was reported**

Isolated and Embedded Laminas (for WWFE II -TC 3 essential)

Isolated behaviour:

weakest link problem

$$\{R\} = (R^t_{||}, R^c_{||}, R^t_{\perp}, R^c_{\perp}, R_{\perp||})^T$$

Embedded behaviour:

redundancy problem

'healing' versus 'notching'

of neighbour laminas surfaces

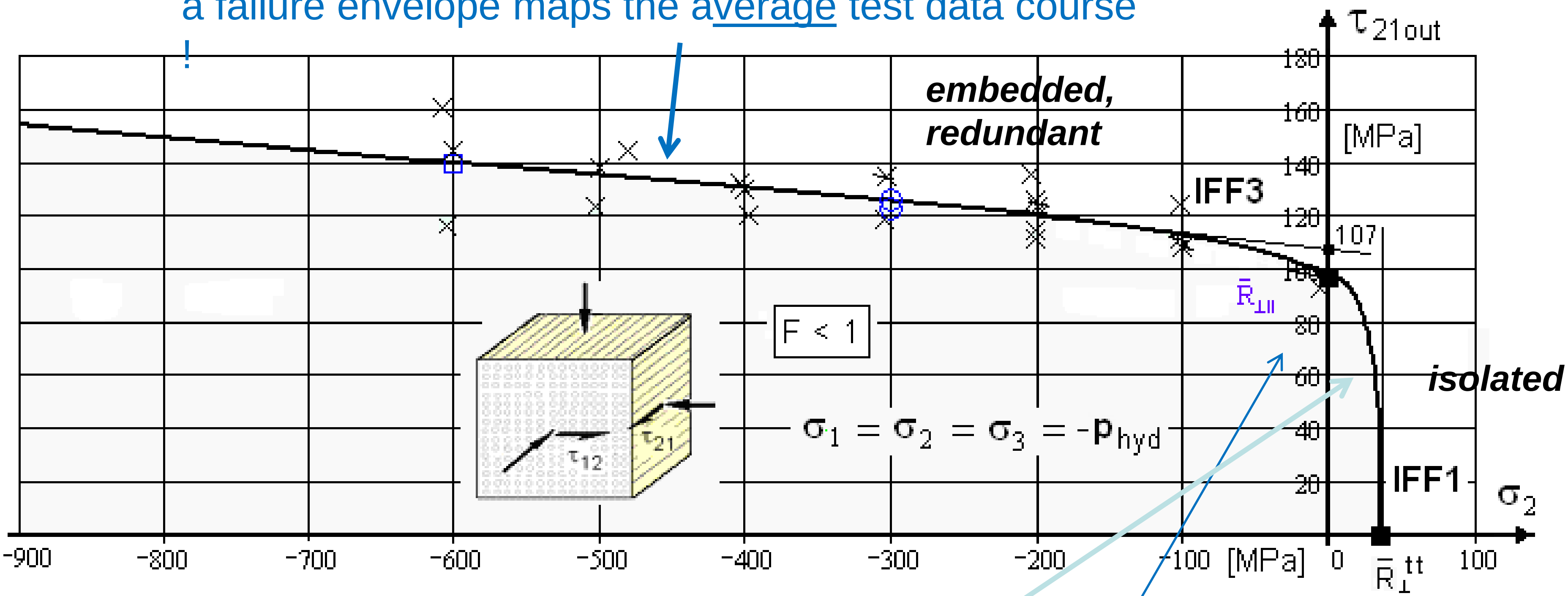
in-situ

Lesson Learnt: Basic strengths are weakest-link data !

Test Case 3, WWFE-II, UD Test Specimen

$\tau_{21}(\sigma_2 = -p_{hyd})$

a failure envelope maps the average test data course !



Good Mapping was obtained in Part B,

after re-evaluation of Part A data and use of the average stress-strain curve instead of the Part A 'upper' stress-strain curve

and a novel physical interpretation of test data, discriminating near $\sigma_2 = 0$, 'isolated' and 'embedded (redundant)' ones !

Test Case 5, WWFE-II, UD test specimen

$\sigma_2(\sigma_1 = \sigma_3)$

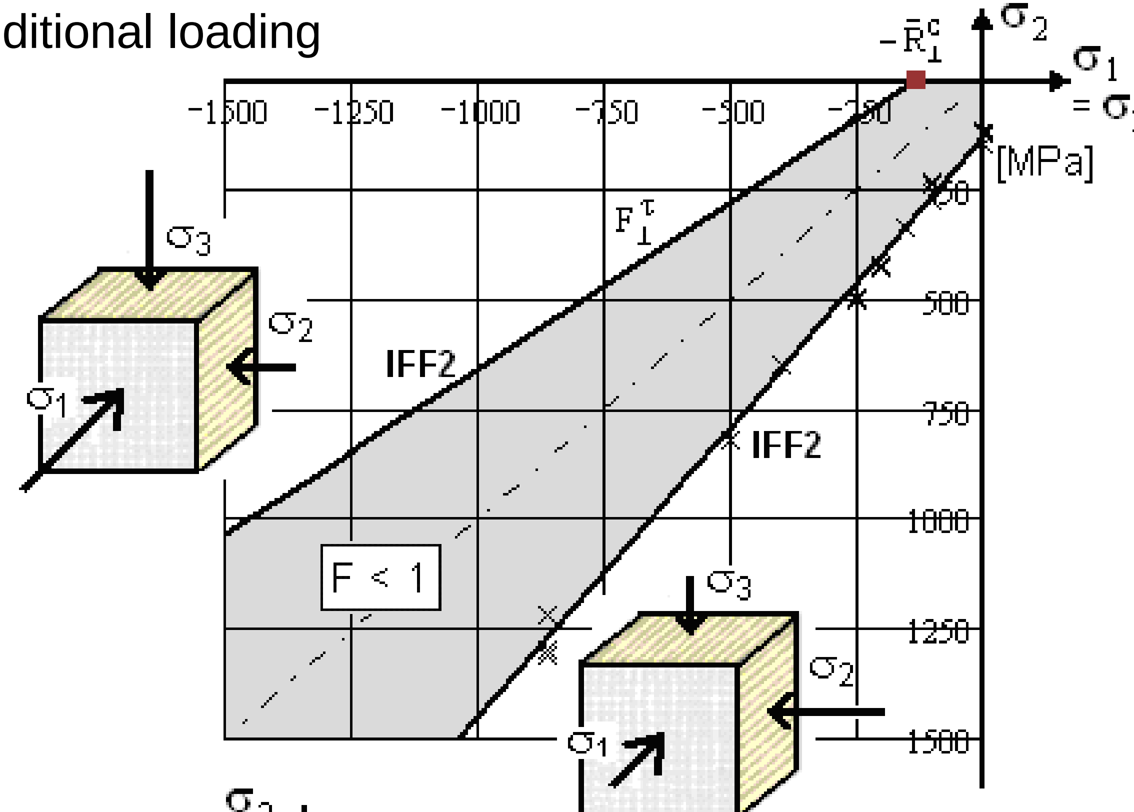
= hydrostatic pressure with additional loading

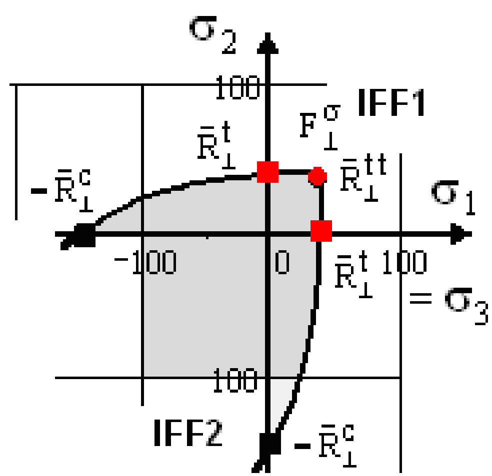
UD E-glass/MY750epoxy.

$\nu_{\perp\|} = 0.28 \quad b_{\perp\perp} = 1.16 \qquad m = 2.8$

$\{\bar{R}\} = (1280,\ 800,\ 40,\ 132,\ 73)^T\ MPa$

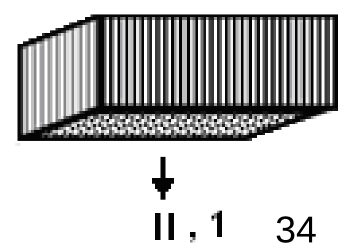
max pressure:
12000 bar = 1200 MPa





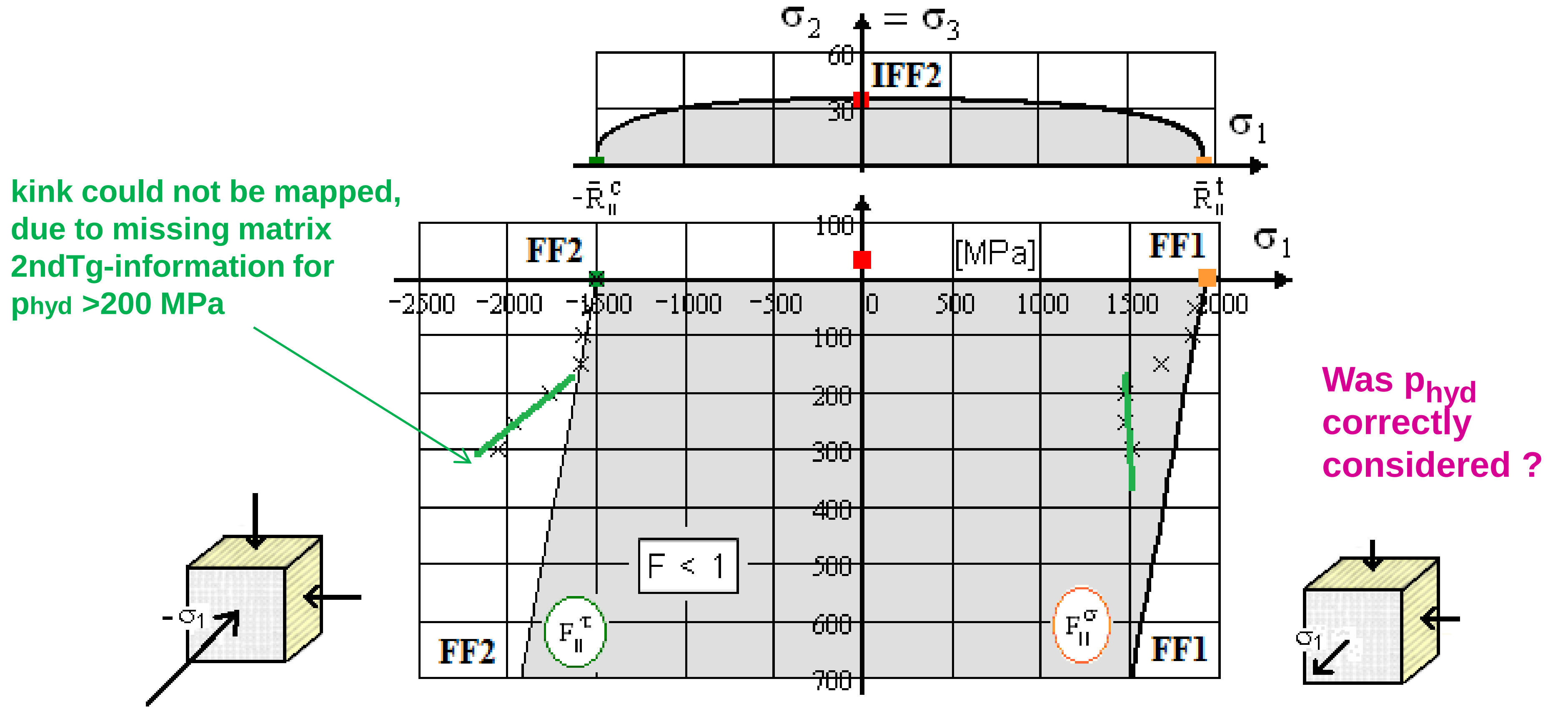
Good Mapping, after QinetiQ was asked to re-evaluate the lower branch test data ! Then, the upper branch was fitting other test data, too.

Both branches are reliable and can be used for validation of the model



Test Case 6, WWFE-II, UD test specimen

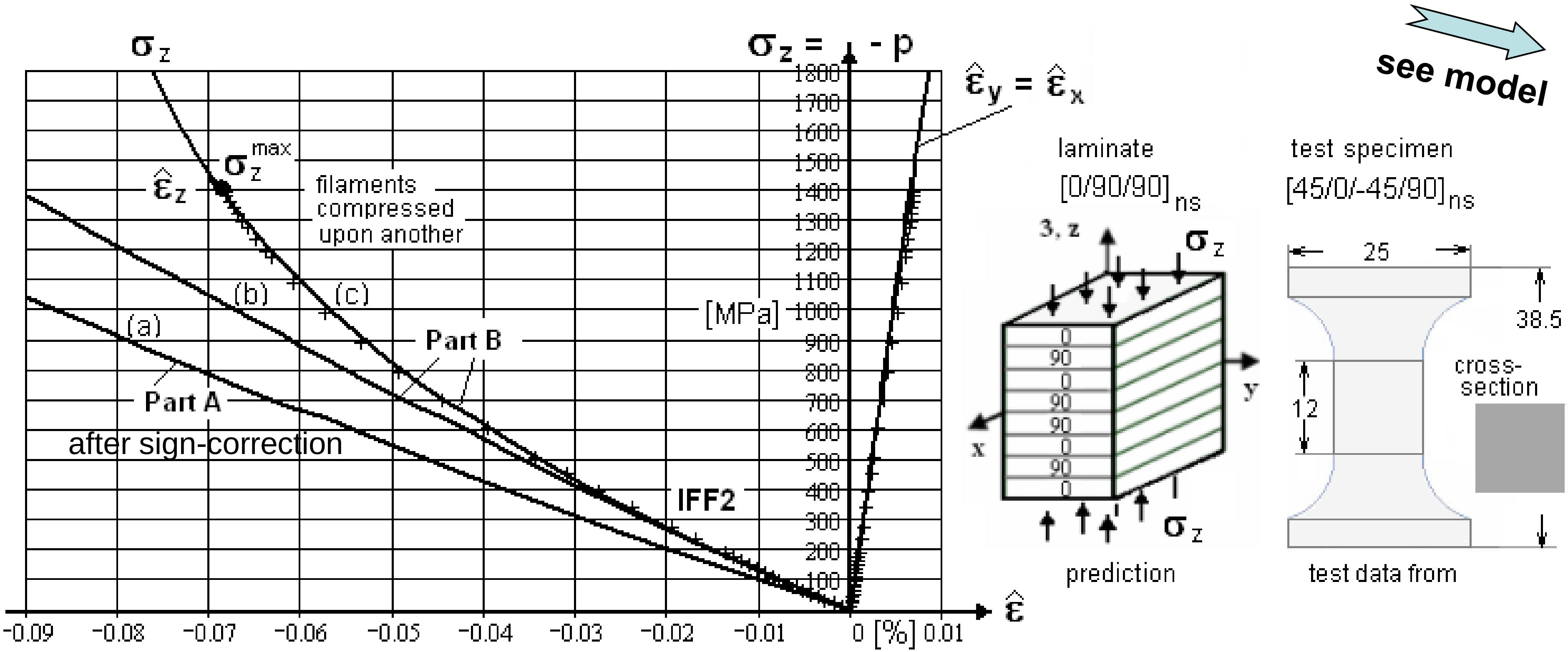
$\sigma_1(\sigma_2 = \sigma_3)$



(1) No mapping possible, due to even Part B-missing 2ndTg information!
TC1-II data – as basic data for prediction – were not accurate
(2) No explanation for oppositely directed slopes given!

⇨ *Result is not acceptable for model validation and design verification!*

Test Case 12, WWFE-II, Laminate Test Specimen (milled from stack)



Good Mapping <u>**after**</u> **novel physical interpretation of test data**

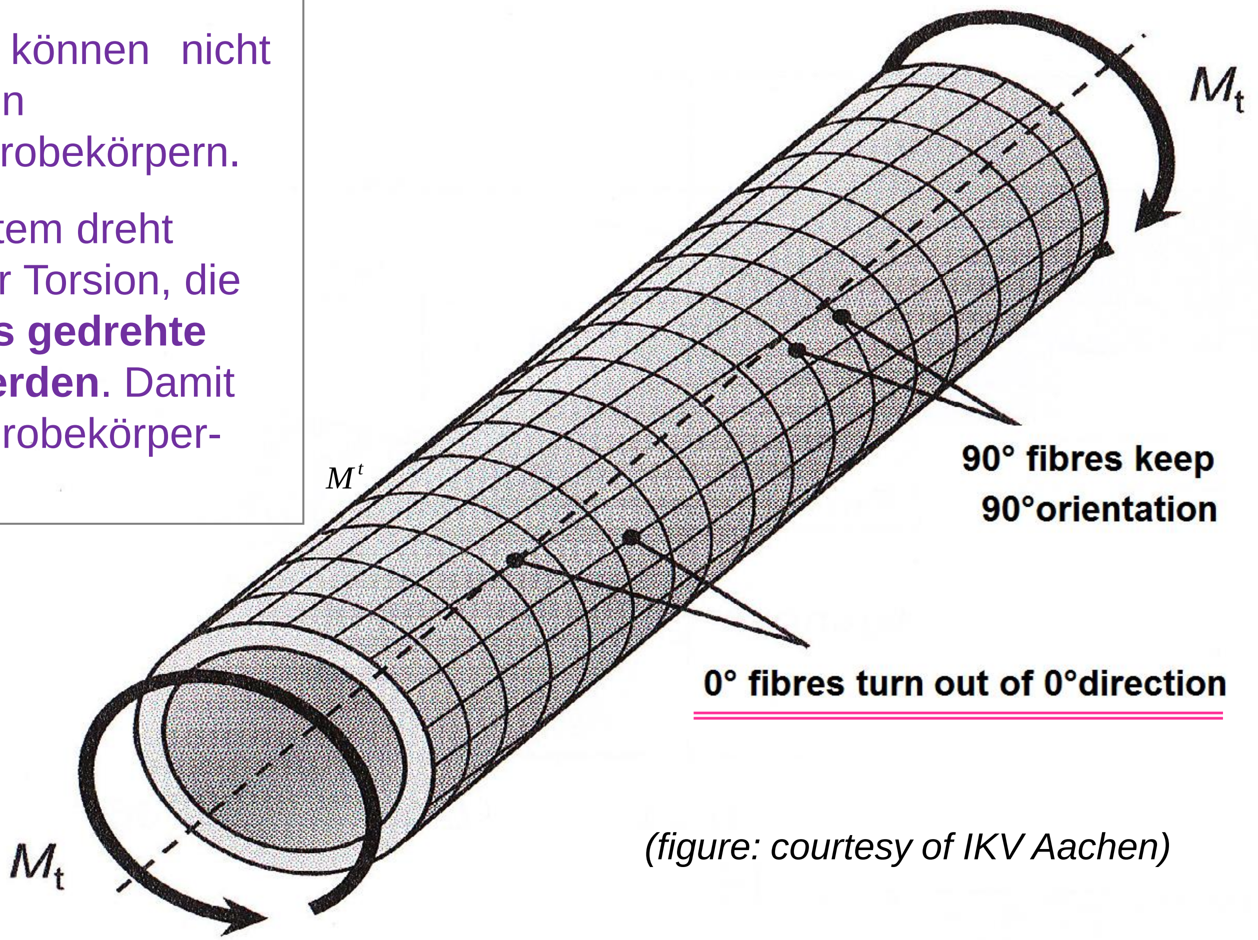
„Filaments are finally compressed to another which stiffens!“ by fitting the Part B data-improved **curve (b) to (c) as pressure-dependent increase of the lateral stiffness** → filament perpendicular E

Lesson Learnt: A <u>***structural***</u> ***failure cannot be described by a (material) SFC !***

WWFE-I und WWFE-II: Zwischenfaserbruchkurve

Part A und B :

- Daten von 0°-Probekörpern können nicht benutzt werden wie die von umfangsgewickelten 90°Probekörpern.
- Das Schichtkoordinatensystem dreht beim 0°-Probekörper unter Torsion, die **Testdaten müssen in das gedrehte System transformiert werden**. Damit waren die erhaltenen 0°-Probekörper-Daten nicht korrekt



(figure: courtesy of IKV Aachen)

Conclusions w.r.t. the extremely effortful WWFEs

<u>FMC</u>-based UD Static Strength Failure Conditions :

1) 2D stress case: Test data mapping was successful, validation achieved
2) 3D stress case: Was successful, if <u>reliable</u> 3D test data were available. This was just partly the case.

The never funded single author is proud on this success, against institutes in the world!

<u>QINETICS statement:</u> The reader shall form a view of my mapping accuracy in the WWFE-II - TCs 2, 3, 4, 12 (doubting my physically-based interpretations). Please, form a view.

General Lessons Learnt *from the WWFEs:*

- **Prediction is not possible if physically necessary friction values must be considered (for shear fracture prediction).**
  Global SFCs do not consider them, therefore have shortcomings.
- **Validation of failure conditions requires a <u>uniform stress field in the critical domain</u>. This was not always given for the WWFE test cases.**
- QinetiQ's comparison of the comntributors' Part A results had no value !

Das Verstehen der Testdaten
– verlässliche Testprotokolle gab es nur teilweise –
nahm die Hälfte der Arbeitszeit ein.

So ist eine ganz wesentliche Erkenntnis des Verfassers
nach insgesamt 2 Arbeitsjahren als Freizeit-Hobby
im Verlauf des langen Wettbewerbs:

**““Die Erzeugung zuverlässiger 3D-Testdaten ist eine größere Herausforderung
als das Aufstellen einer zuverlässigen 3D-Theorie”.**

**“Die ‘Ausbeute‘ dieses tollen Wettbewerbs wäre erheblich größer gewesen, wenn man die verfügbaren Testdaten gemeinsam diskutiert hätte, Veranstalter mit uns Teilnehmern.
Das ist leider nicht geschehen“.**

DANKE

Conclusions w.r.t. FMC

- **The FMC is an efficient concept, which**

  ***** is applicable to brittle and ductile, dense and porous, isotropic, transversely-isotropic and orthotropic materials

  * improves prediction + **delivers equivalent stresses**

- **uses just measurable model parameters: strength *R* and material friction** μ

- **builds** not on the ***material*** type but on the ***material solid deformation behaviour incl. texture of the homogenized material!***

- **delivers a <u>combined formulation</u> of *independent modal failure modes*,**

  without the well-known drawbacks of <u>globa</u>l SFC formulations

  (which means a *‚mathematically forced marriage‘ of in-dependent failure modes)*

- **FMC-based Failure Conditions are relatively simple but describe physics of each single failure mechanism pretty well.**

Literature, *see Carbon Connected*

[Cun96] Cuntze R.: *Bruchtypbezogene Auswertung mehrachsiger Bruchtestdaten und Anwendung im Festigkeitsnachweis sowie daraus ableitbare Schwingfestigkeits- und Bruchmechanikaspekte*. DGLR-Kongreß 1996, Dresden. Tagungsband 3

[Cun04] Cuntze R.: *The Predictive Capability of Failure Mode Concept-based Strength Criteria for Multidirectional Laminates*. WWFE-I, Part B, Comp. Science and Technology 64 (2004), 487-516

[Cun09] Cuntze R.: *Lifetime Prediction for Structural Components made from Composite Materials – industrial view and one idea*. NAFEMS World Congress 2009, Conference publication

[Cun12] Cuntze R.: *The predictive capability of Failure Mode Concept-based Strength Conditions for Laminates composed of UD Laminas under Static Tri-axial Stress States. - Part A of the WWFE-II*. Journal of Composite Materials 46 (2012), 2563-2594

[Cun13] Cuntze R.: *Comparison between Experimental and Theoretical Results using Cuntze's 'Failure Mode Concept' model for Composites under Triaxial Loadings - Part B of the WWFE-II*. Journal of Composite Materials, Vol.47 (2013), 893-924

[Cun13b] Cuntze R.: Fatigue of endless fiber-reinforced composites. 40. Tagung DVM-Arbeitskreis Betriebsfestigkeit, Herzogenaurach 8. und 9. Oktober 2013, conference book

[Cun14] Cuntze R.: associated paper, see http://www.carbon-composites.eu/leistungsspektrum/fachinformationen/fachinformation-2

[Rac87] Rackwitz R. and Cuntze R.: *System Reliability Aspects in Composite Structures*. Engin. Optim., Vol. 11, 1987, 69-76

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

WWFE-I: ***2D (in-plane) loading ,Test Data Packs for 14 Test Cases***

WWFE-II: ***3D loading, Test Data Packs for 12 Test Cases***

WWFE-III: ***Application of advanced failure models based on Damage and Fracture Mechanics Models***

Deals with validating and benchmarking failure theories that are capable of predicting damage, regarding

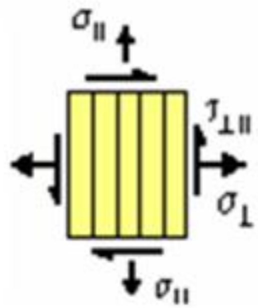
- matrix crack initiation and development,
- delamination initiation triggered by transverse cracks, and
- deformation up to final fracture.

Task: For endless fiber-reinforced polymers
Mapping of courses of test data
by the contributors with
their strength failure conditions (criteria).

Voll-modaler Ansatz von Cuntze

erlaubt Übergang $\sigma \Longrightarrow \sigma_{eq}$

2D, eben



bekanntes Beispiel **Fliessen (Mises)**

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

Übertragung **UD-Bruch (Cuntze)**

$\sigma_{eq}^{Bruchmodus}$ oder $Eff^{Bruchmodus} = \sigma_{eq}^{Bruchmodus} / R_m$

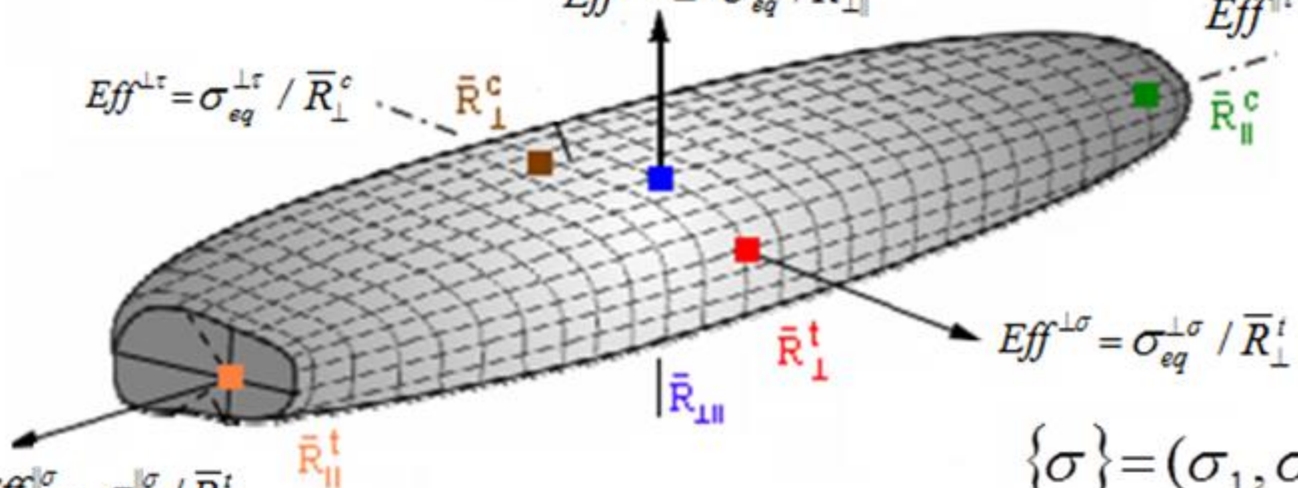
$\{\sigma\} = (\sigma_1, \sigma_2, 0, 0, 0, \tau_{21})^T$

Gewinn: 2D-Bruchkörper = 3D-Bruchkörper

$Eff^{\perp\parallel} = \sigma_{eq}^{\perp\parallel} / \bar{R}_{\perp\parallel}$

$Eff^{\parallel\tau} = \sigma_{eq}^{\parallel\tau} / \bar{R}_{\parallel}^{c}$

$Eff^{\perp\tau} = \sigma_{eq}^{\perp\tau} / \bar{R}_{\perp}^{c}$



3D, räumlich

$Eff^{\perp\sigma} = \sigma_{eq}^{\perp\sigma} / \bar{R}_{\perp}^{t}$

$Eff^{\parallel\sigma} = \sigma_{eq}^{\parallel\sigma} / \bar{R}_{\parallel}^{t}$

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

View the materal‘s behaviour and not its type *such as steel, composite, ceramics, concrete*

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

from a similarly behaving material, then

- the shape of the body of the new material is known and only
- the size must be fixed by its always to be provided (uni-axial) strengths .

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