Formulations of Failure Conditions

- Isn’t it basically just *Beltrami* and *Mohr-Coulomb* ? -

Hencky-
Mises-
Huber

Richard von Mises
1883-1953
Mathematician

Eugenio Beltrami
1835-1900
Mathematician

Otto Mohr
1835-1918
Civil Engineer

Charles de Coulomb
1736-1806
Physician

‘Onset of Yielding‘

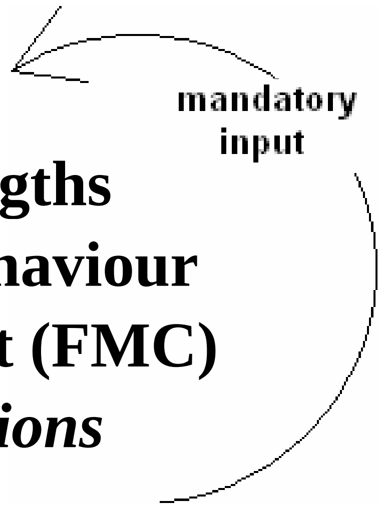
‘Onset of Cracking‘

Prof. Dr.-Ing. habil. **Ralf** Georg **Cuntze** VDI

<u>Strength</u> Failure Conditions of Structural Materials

- Is there Some Common Basis existing ? -

Contents of Presentation: 90 min



1 Introduction to *Design Verification*

2 Stress States & Invariants

3 Observed Strength Failure Modes and Strengths

4 Attempt for a Systematization of Material Behaviour

5 Short Derivation of the Failure Mode Concept (FMC)

6 Visualizations of some Derived *Failure Conditions*

7 Application to 2D UD Test Data (WWFE-I)

8 Application to 3D UD Test Data (WWFE-II)

9 Outlook at Material Modelling of Textiles

Conclusions

Motivation for the Work

Existing Links in the Mechanical Behaviour show up: ***Different structural materials***

- ***can possess similar material behaviour or***
- ***can belong to the same class of material symmetry***

> **similarity aspect**

Welcomed Consequence:

- **The same strength failure function F can be used for different materials**
- **More information is available for pre-dimensioning + modelling**

in case of a newly applied material

from experimental results of a similarly behaving material.

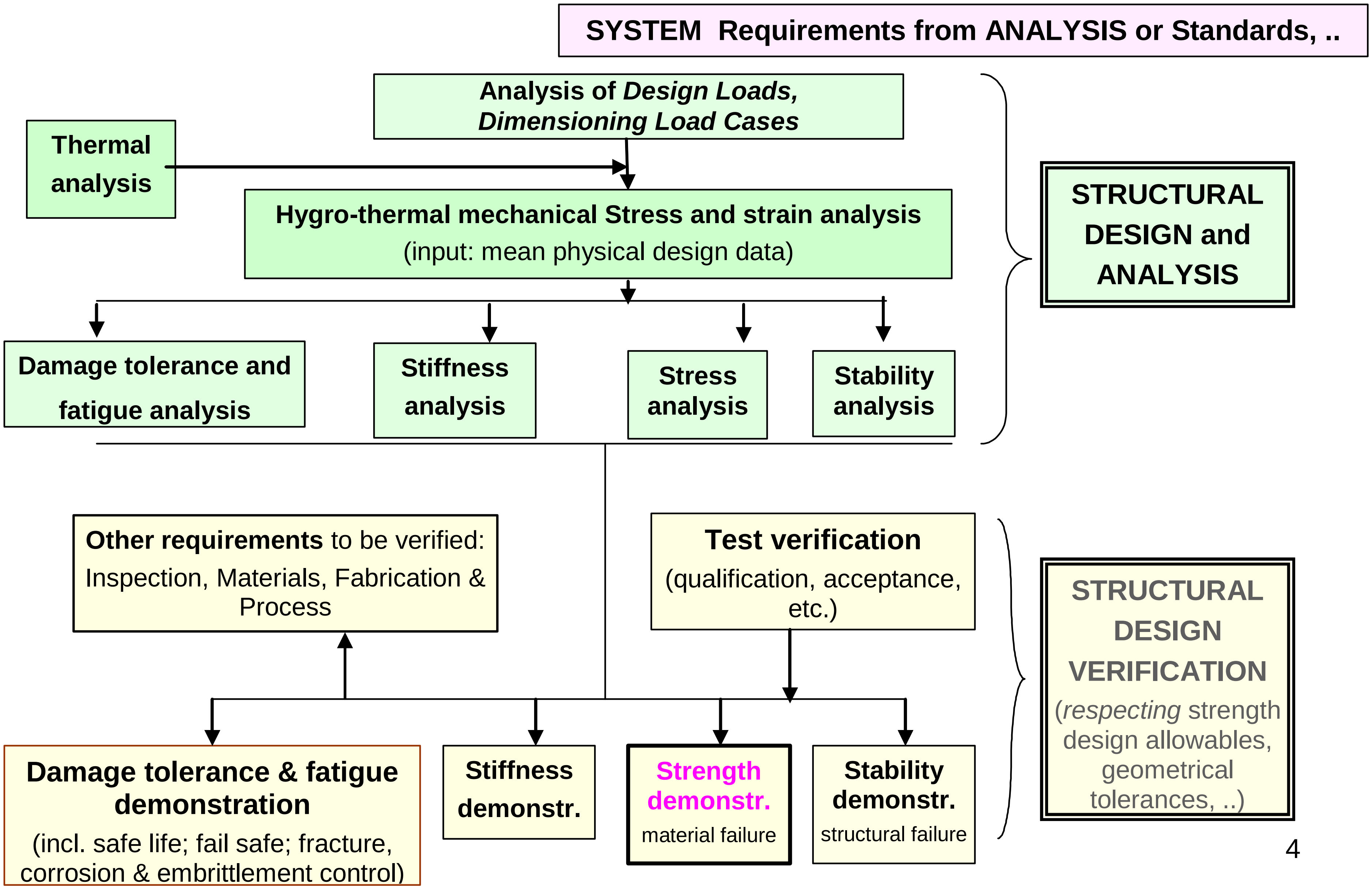
DRIVER:

Author's experience with structural material applications, range 4 K - 2000 K .

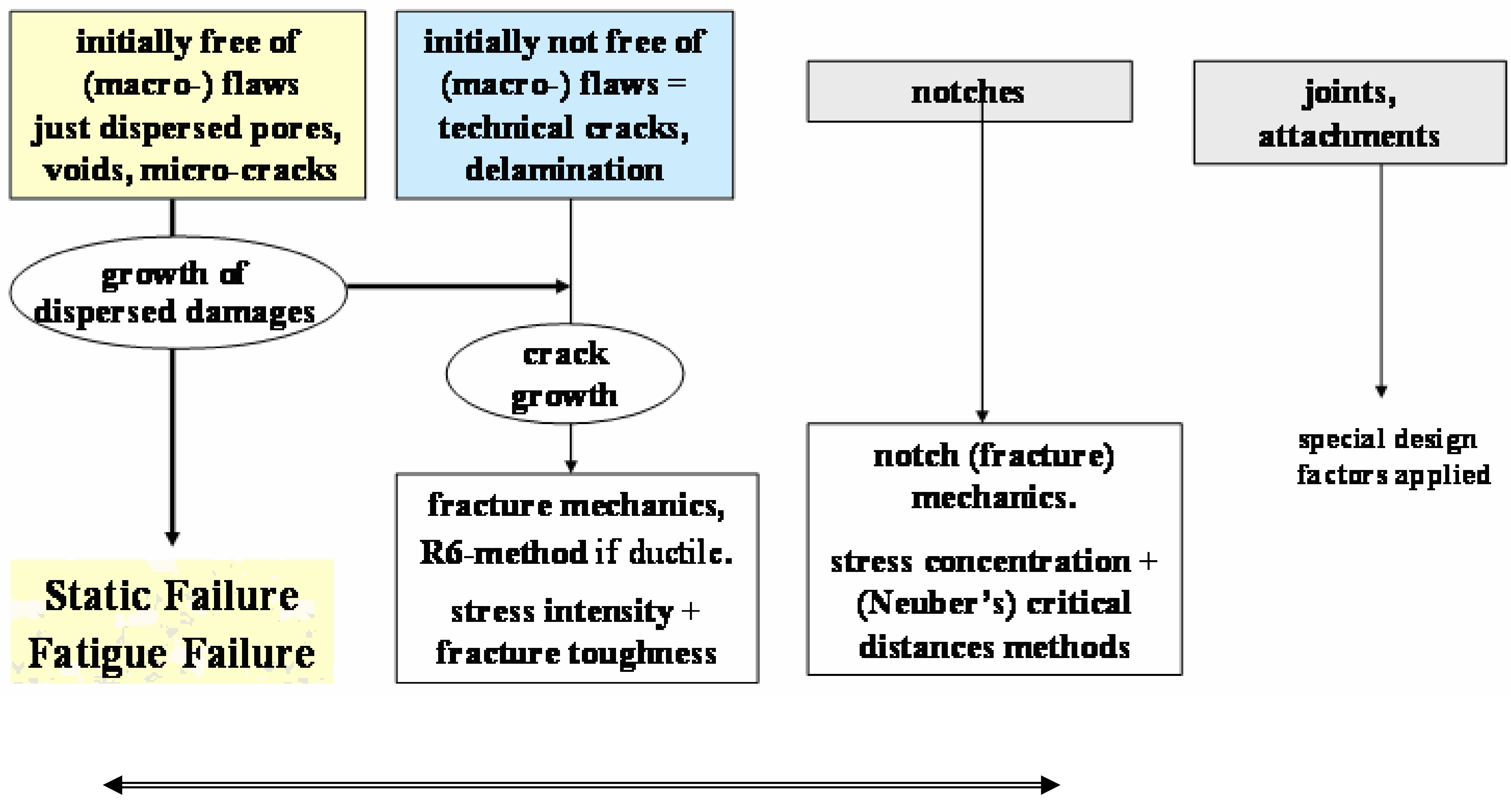
MESSAGE: **Let's use these benefits!**

1 Introduction to Design Verifications

1.1 Structural Analysis Flow Chart [ESA]



1.2 Tools for Demonstration of Structural Integrity



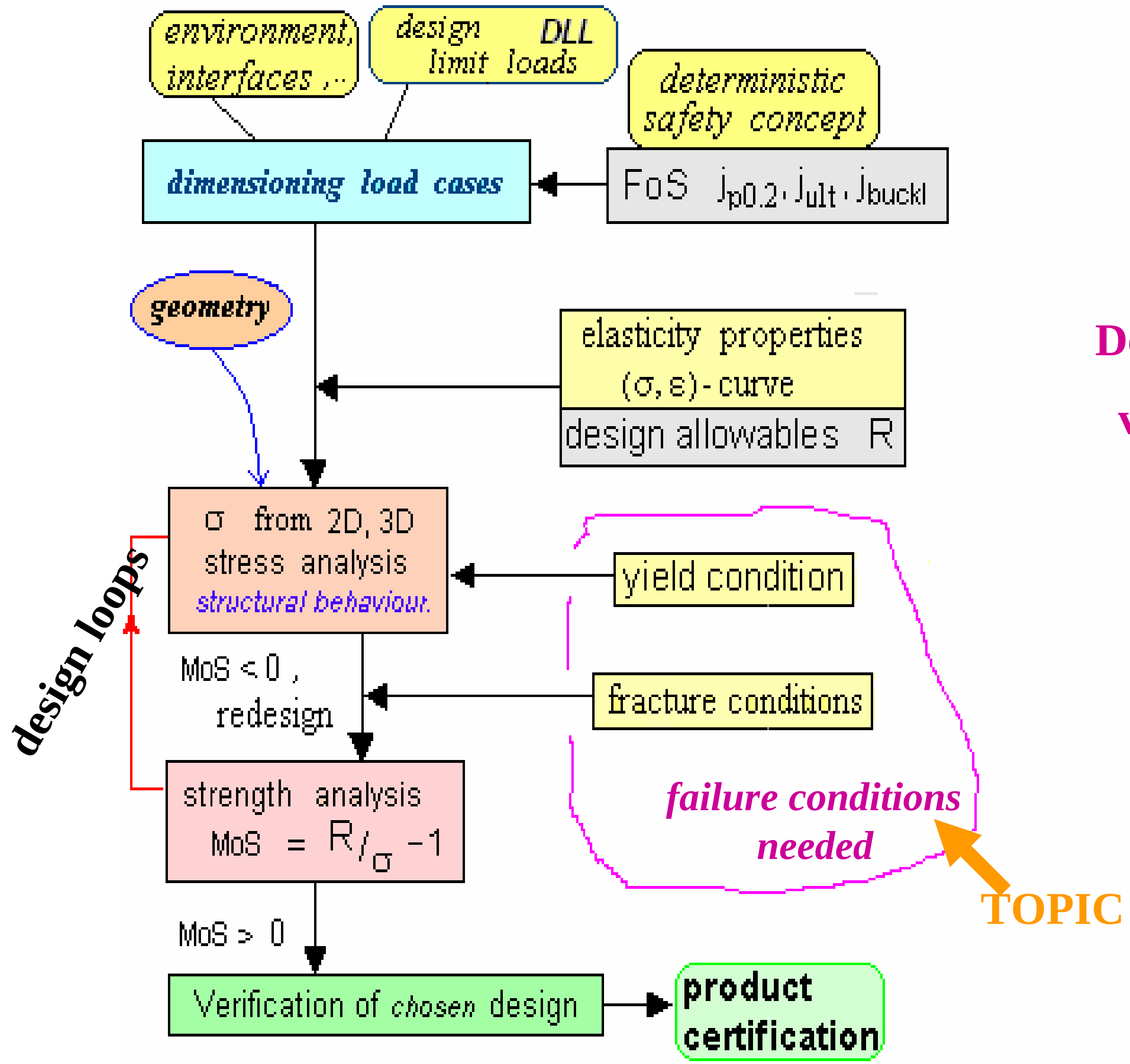
1.3 Structural Mechanics Field

Initial Situation	flaw-free	flaw-free	notched	cracked, delaminated
Theory	Classical Continuum Mechanics	Continuum Damage Mechanics	Notch Fracture Mechanics	Fracture Mechanics
static	strength failure conditions	damage mechanics failure conditions	'Neuber-like' failure conditions	fracture mechanics failure condit.
	stresses	effective stresses	stress concentrations	stress intensities

Effects: cyclic, creeping, impact, strain rate

1 Introduction to Design Verification

1.4 Static Structural Analysis Procedure *(isotropic case for simplification)*



FoS := (design) Factor of Safety

MoS := Margin of Safety

R := strength (resistance).

Design Verification for:

various Design loads:

Design Yield Load (DYL)
$= DLL \cdot j_{p0.2}$ ….. *flight load level*

Design Ultimate Load (DUL)
$= DLL \cdot j_{ult}$ …... *fracture load level*

Design Buckling Load (DBL)
$= DLL \cdot j_{buckl}$ … *fracture load level*

How can we demonstrate strength of design ?

1.5 Strength Failure Conditions: Description

Strength failure conditions are mandatory for the prediction of ***Onset of Yielding*** + ***Onset of Fracture*** for non-cracked materials.

What are Strength Failure Conditions for? *They shall*

- ***assess multi-axial stress states in the critical material point,***

  by **utilizing the uniaxial strength values R** and an **equivalent stress σ_{eq}, representing a distinct actual multi-axial stress state.**

  for *** dense & porous,**
  *** ductile & brittle behaving materials,**
  ductile : $R_{p0.2} \cong R_{c0.2}$ brittle : $R_m^c \geq 3 R_m^t$

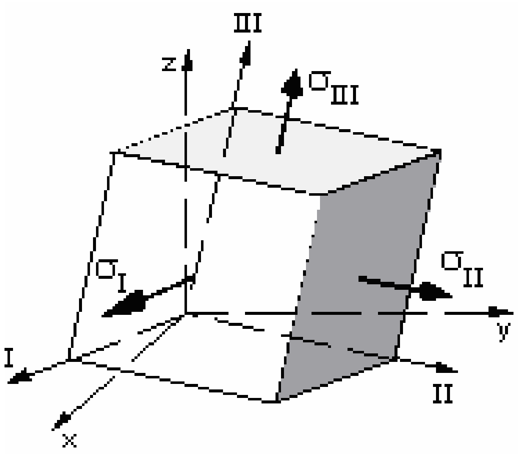
  for *** isotropic material**
  *** transversally-isotropic material (UD := uni-directional material)**
  *** rhombically-anisotropic material (fabrics) + 'higher' textiles etc.**

- ***allow for inserting stresses from the utilized various coordinate systems into stress-formulated failure conditions, -and if possible- invariant-based.***

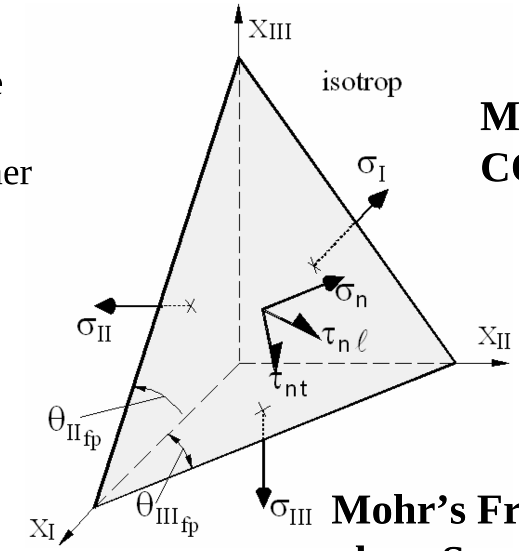
Which kinds of stresses may have to be inserted?

2 Stress States and Invariants

2.1 Isotropic Material (3D stress state), viewing Stress Vectors & Invariants



The stress states in the various COS can be transferred into each other



Mohr's COS

Principal Stresses	**Structural Component Stresses**	**Mohr's Fracture plane Stresses**
$\{\sigma\}_{principal} = (\sigma_I\,,\ \sigma_{II}\,,\ \sigma_{III}\,)^T$	$\{\sigma\}_{comp} = (\sigma_x\,,\ \sigma_y\,,\ \sigma_z\,,\ \tau_{yz}\,,\ \tau_{xz}\,,\ \tau_{xy}\,)^T$	$\{\sigma\}_{Mohr} = (\sigma_\ell\,,\ \sigma_n\,,\ \sigma_t\,,\ \tau_{nt}\,,\ \tau_{t\ell}\,,\ \tau_{\ell n}\,)^T$
$I_1 = (\sigma_I + \sigma_{II} + \sigma_{III})^T = 3\sigma_{oct} \equiv f(\sigma),$	**'isotropic' invariants !** $I_1 = (\sigma_x + \sigma_x + \sigma_z)^T$	$I_1 = (\sigma_\ell + \sigma_n + \sigma_t)^T$
$6J_2 = (\sigma_I - \sigma_{II})^2 + (\sigma_{II} - \sigma_{III})^2 + (\sigma_{III} - \sigma_I)^2$ $= 4(\tau_{III}{}^2 + \tau_{II}{}^2 + \tau_I{}^2) = 9\tau_{oct}{}^2 \equiv f(\tau)$	$6J_2 = (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + (\sigma_x - \sigma_y)^2$ $+6(\tau_{yz}{}^2 + \tau_{zx}{}^2 + \tau_{xy}{}^2)$ (*Mises, HMH*)	$6J_2 = (\sigma_n - \sigma_t)^2 + (\sigma_t - \sigma_\ell)^2 + (\sigma_\ell - \sigma_n)^2$ $+6(\tau_{nt}{}^2 + \tau_{t\ell}{}^2 + \tau_{n\ell}{}^2)$

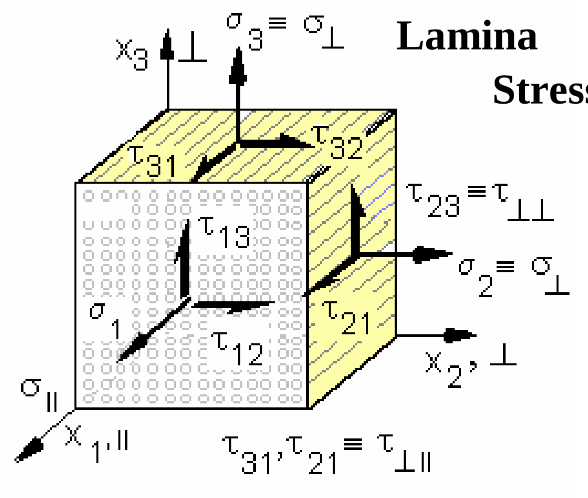
$$27J_3 = (2\sigma_I - \sigma_{II} - \sigma_{III})(2\sigma_{II} - \sigma_I - \sigma_{III})(2\sigma_{III} - \sigma_I - \sigma_{II}), \quad I_\sigma = 4J_2 - I_1{}^2/3, \quad \sigma_{mean} = I_1/3$$

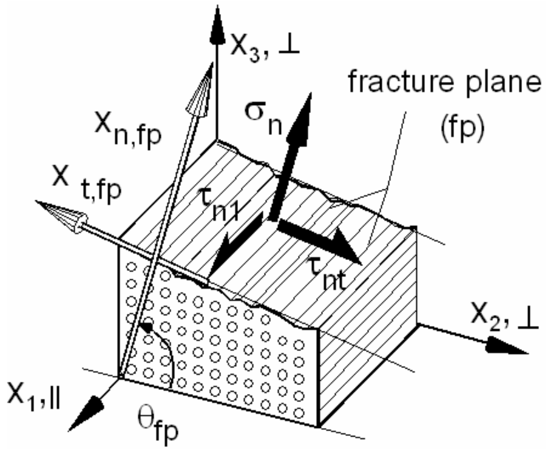
Invariant := Combination of stresses –powered or not powered- the value of which does not change when altering the coordinate system.

2 Stress States and Invariants

2.2 Transversely-Isotropic Material (◄ Uni-Direct. Fibre-Reinforced Plastics)

Transformation of lamina stresses into the quasi-isotropic plane stresses





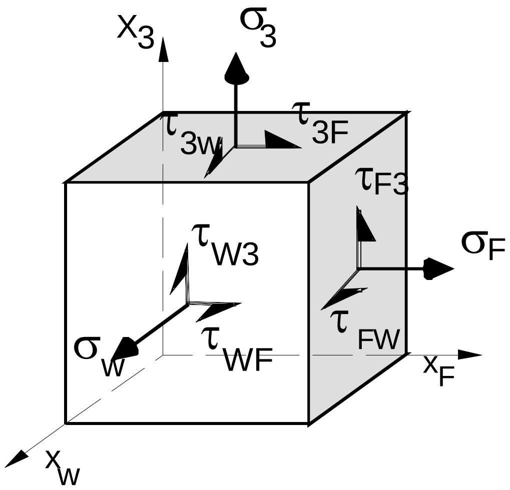
Mohr, Puck, Hashin: Fracture is determined by the (Mohr) stresses in the fracture plane !

$\{\sigma\}^{quasi-isotropic\ plane}_{principal} = (\sigma_1, \sigma_2^p, \sigma_3^p, 0, \tau_{31}^p, \tau_{21}^p)^T$	$\{\sigma\}_{lamina} = (\sigma_1, \sigma_2, \sigma_3, \tau_{23}, \tau_{31}, \tau_{21})^T$	$\{\sigma\}_{Mohr} = (\sigma_\ell, \sigma_n, \sigma_t, \tau_{nt}, \tau_{t\ell}, \tau_{\ell n})^T$
$I_1 = \sigma_1, \quad I_2 = \sigma_2^p + \sigma_3^p$ $I_3 = \tau_{31}^{p\,2} + \tau_{21}^{p\,2}$	$I_1 = \sigma_1, \quad I_2 = \sigma_2 + \sigma_3$ $I_3 = \tau_{31}^2 + \tau_{21}^2$ **'UD invariants'!** *[Boehler]*	$I_1 = \sigma_1, \quad I_2 = \sigma_n + \sigma_t$ $I_3 = \tau_{t\ell}^2 + \tau_{n\ell}^2$
$I_4 = (\sigma_2^p - \sigma_3^p)^2 + 0$ $I_5 = (\sigma_2^p - \sigma_3^p)(\tau_{31}^{p\,2} - \tau_{21}^{p\,2}) + 0$	$I_4 = (\sigma_2 - \sigma_3)^2 + 4\tau_{23}^2$ $I_5 = (\sigma_2 - \sigma_3)(\tau_{31}^2 - \tau_{21}^2) - 4\tau_{23}\tau_{31}\tau_{21}$	$I_4 = (\sigma_n - \sigma_t)^2 + 4\tau_{nt}^2$ $I_5 = (\sigma_n - \sigma_t)(\tau_{t\ell}^2 - \tau_{n\ell}^2) - 4\tau_{nt}\tau_{t\ell}\tau_{n\ell}$

2 Stress States and Invariants

2.3 Orthotropic Material (rhombically-anisotropic ◄ woven fabric)

Homogenized = smeared
***woven fabrics* material element**



Warp (W), Fill(F).

3D stress state:
Here, just a formulation in fabrics lamina stresses makes sense!

$$\{\sigma\}_{lamina} = (\sigma_W, \sigma_F, \sigma_3, \tau_{3F}, \tau_{3W}, \tau_{FW})^T$$

Fabrics invariants ! *[Boehler]*:

$$I_1 = \sigma_W,\ I_2 = \sigma_F,\ I_3 = \sigma_3,$$
$$I_4 = \tau_{3F},\ I_5 = \tau_{3W},\ I_6 = \tau_{FW}$$

more, -however simple- invariants necessary

(homogenized) Orthotropic Material is the material of the highest structural rank

quasi-laminar composite

3 Observed Strength Failure Modes and Strengths

3.1a Isotropic Material *brittle , dense*

if brittle: failure = fracture

Which failure types (brittle or ductile) are observed ?

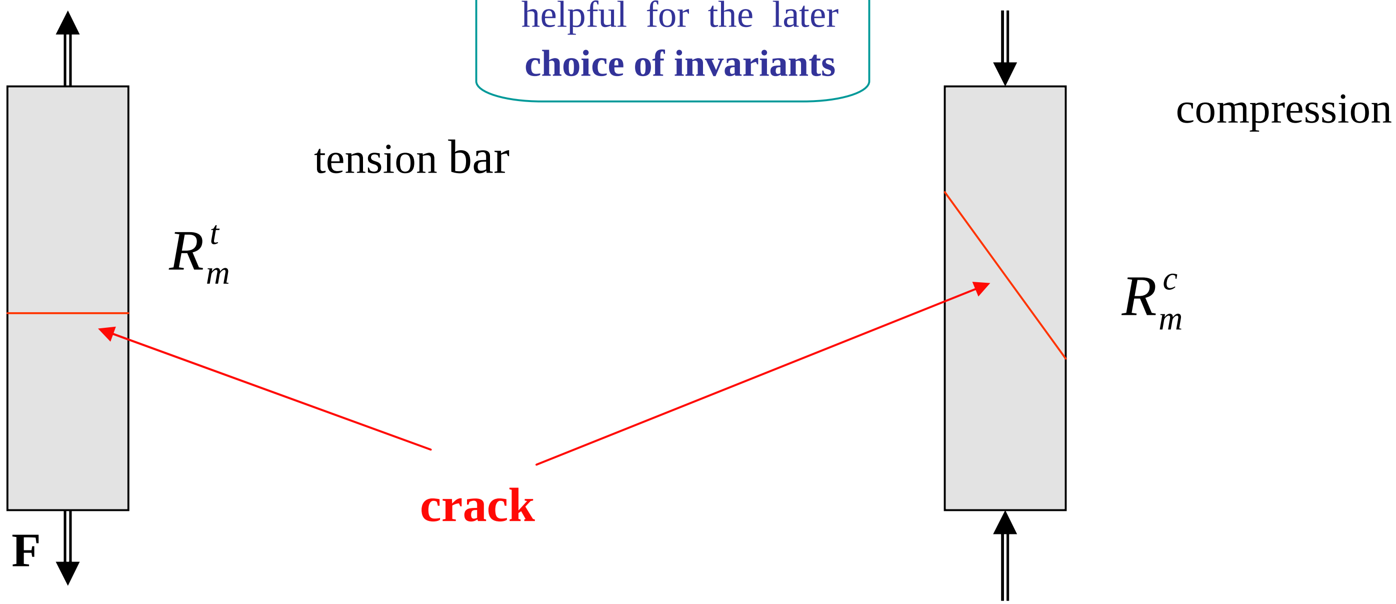
Cleavage fracture (NF) (Spaltbruch, Trennbruch) :

- poor deformation before fracture
- 'smooth' fracture surface

Shear fracture (SF) :

- shear deformation before fracture

knowledge is helpful for the later **choice of invariants**



conclusion: ▶ **2 strengths** to be measured

3 Observed Strength Failure Modes and Strengths

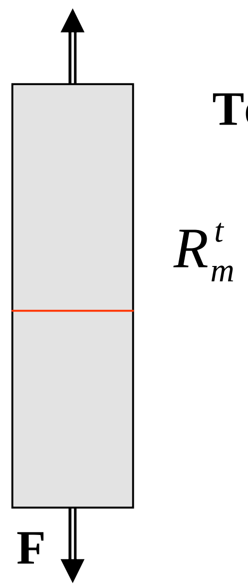
3.1b Isotropic Material *brittle*, *porous*

if brittle: failure = fracture failure

Normal Fracture (NF) (Spaltbruch, Trennbruch) :

- poor deformation before fracture
- rough fracture surface

Tension

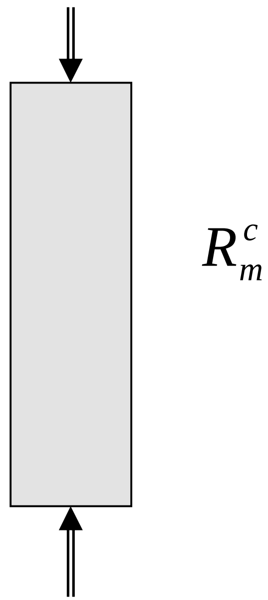


Crushing Fracture (CrF): ⇐ **SF**

- volumetric deformation before fracture

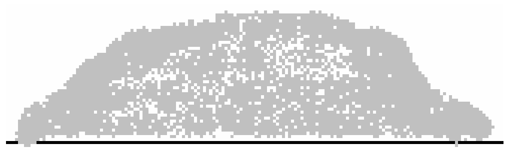
helpful for the later **choice of invariants**

Compression



result of the compression test

= ***hill of fragments*** ***(crumbs)***



= decomposition of texture

▶ **2 strengths** to be measured

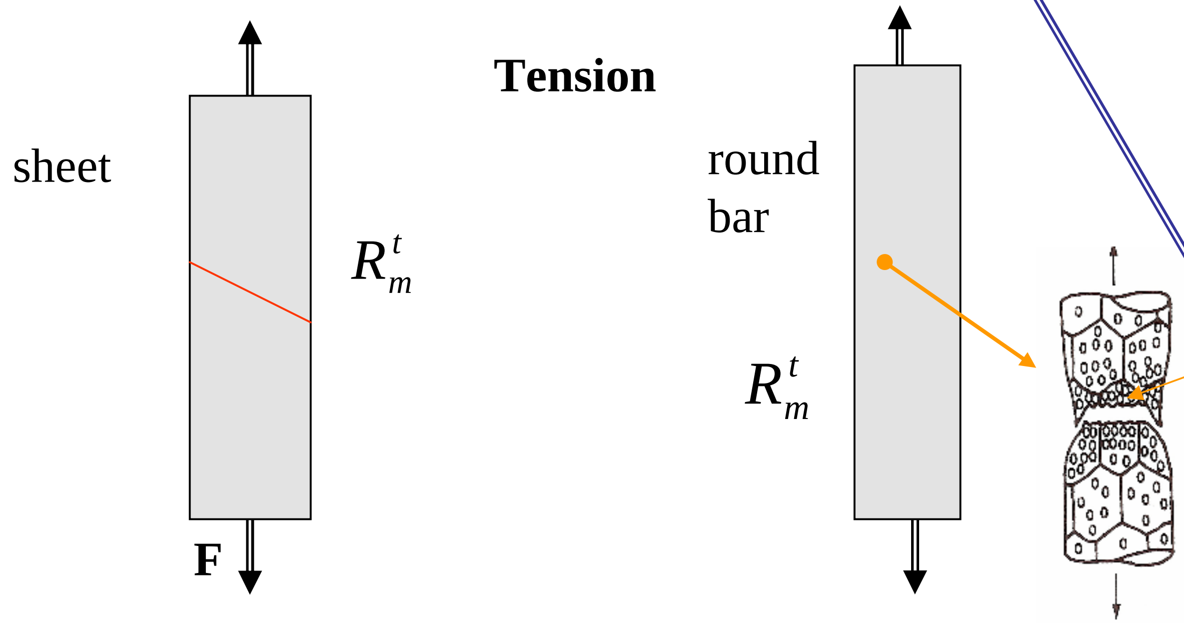
3 Observed Strength Failure Modes and Strengths

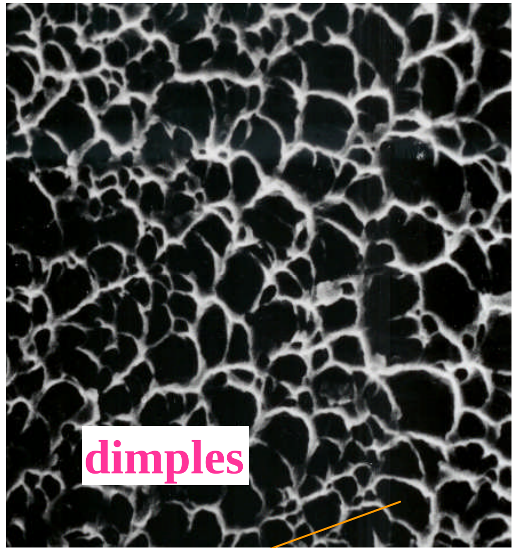
audience familiar ??

3.1c Isotropic Material *dense, ductile (most of the aerospace nmaterials)*

Shear fracture (SF) :

- *shear deformation* observed before fracture (maximum load)
- later in addition, *volume change* before rupture ('Gurson domain')
- dimples under tension.



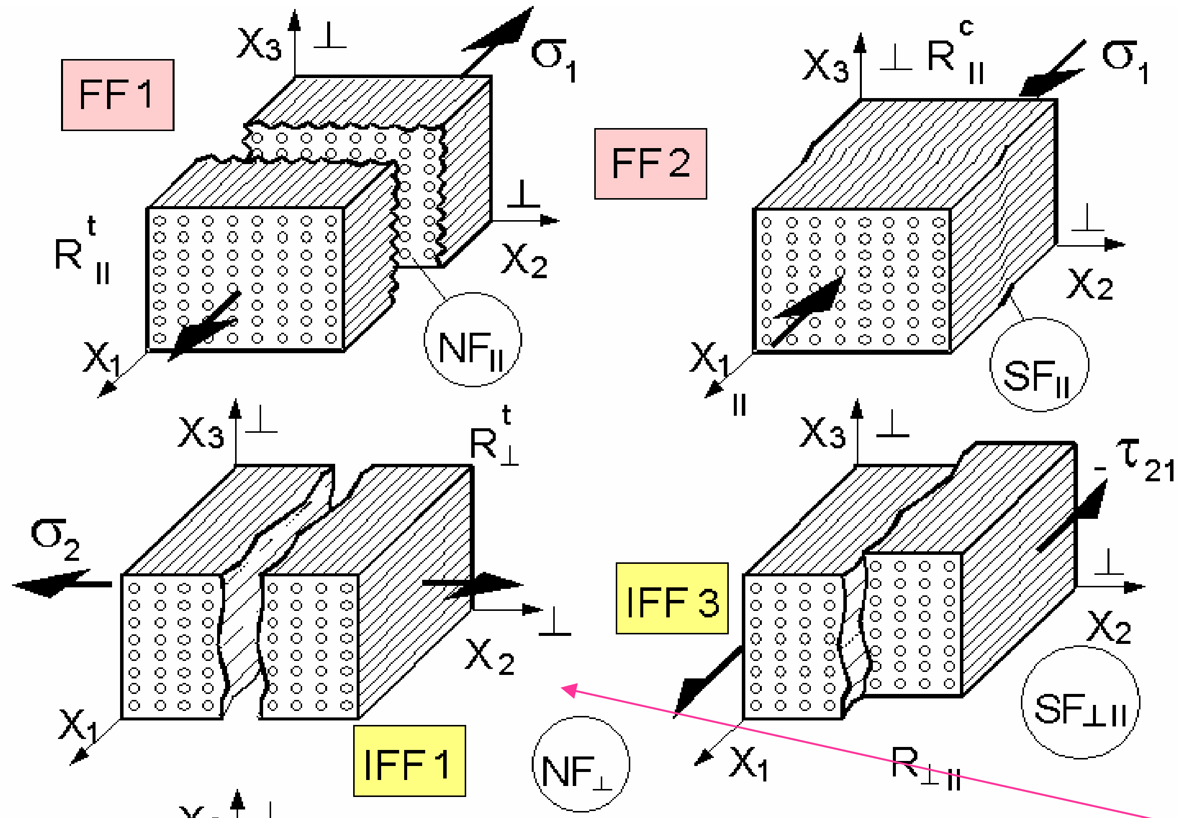


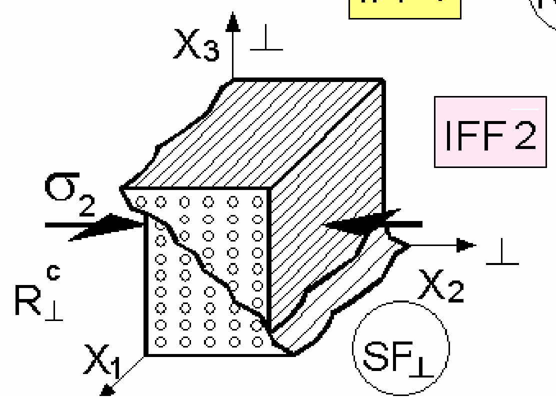
first a **diffuse** and later **local** ***necking*** + **void growth**

►	**1 strength, R_m^t** to be measured **(= *load-controlled* value),**
•	**R_m^c is neither existing nor necessary for design ,** **$R_{c0.2}$ is the design driving strength.**

3 Observed Strength Failure Modes and Strengths

3.2a Schematical UD Failure Modes *(known from fractography of UD specimens)*





wedge type

t = tension

c = compression

▶ 5 Fracture modes exist

= 2 FF (Fibre Failure)

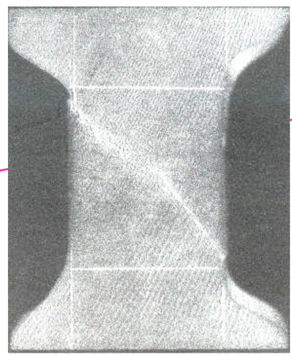
\+ 3 IFF (Inter Fibre Failure)

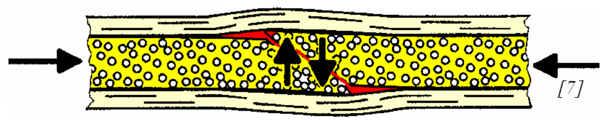
Critical in a loaded laminate are: FF1, FF2 + possibly IFF2 !

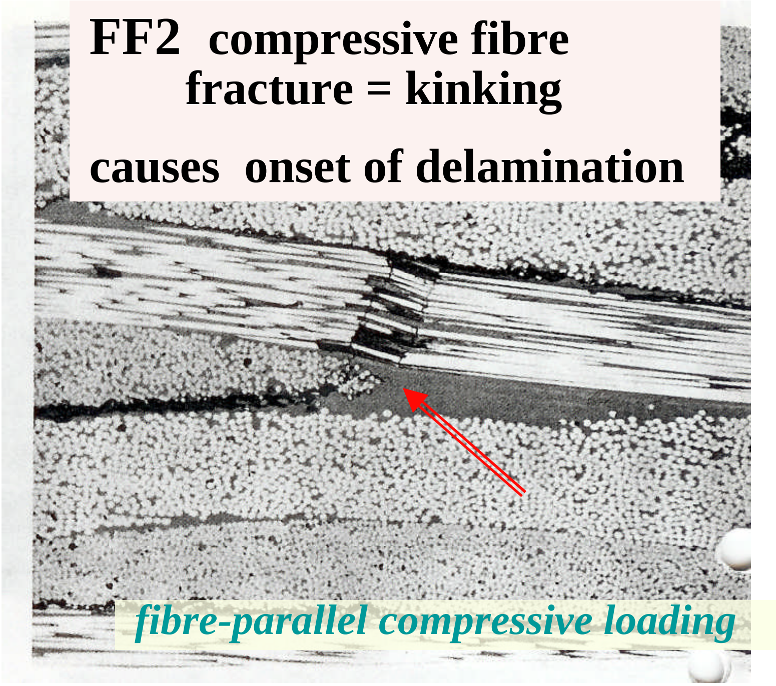
macroscopically:

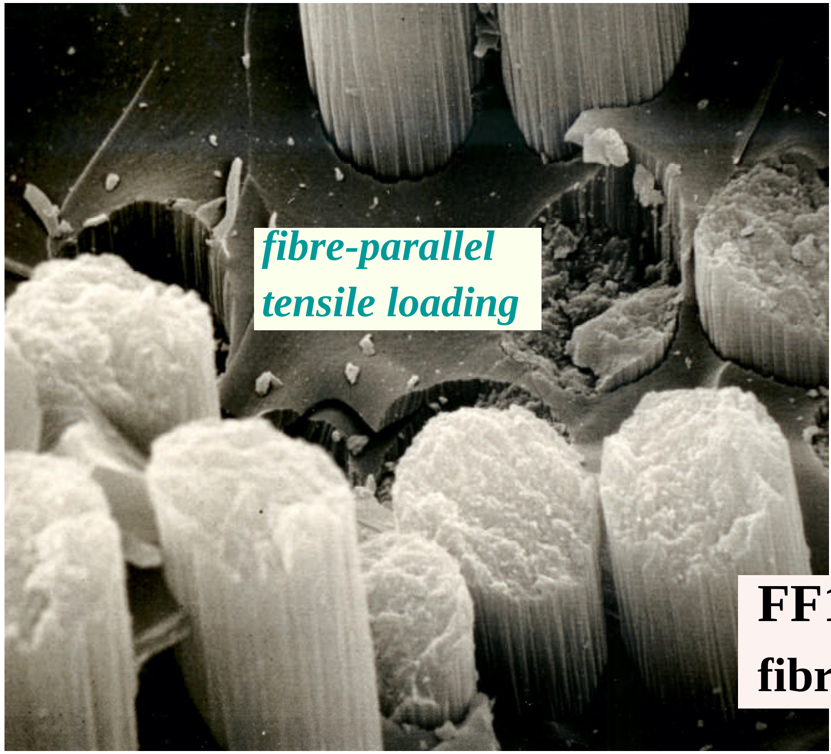
NF := Normal Fracture

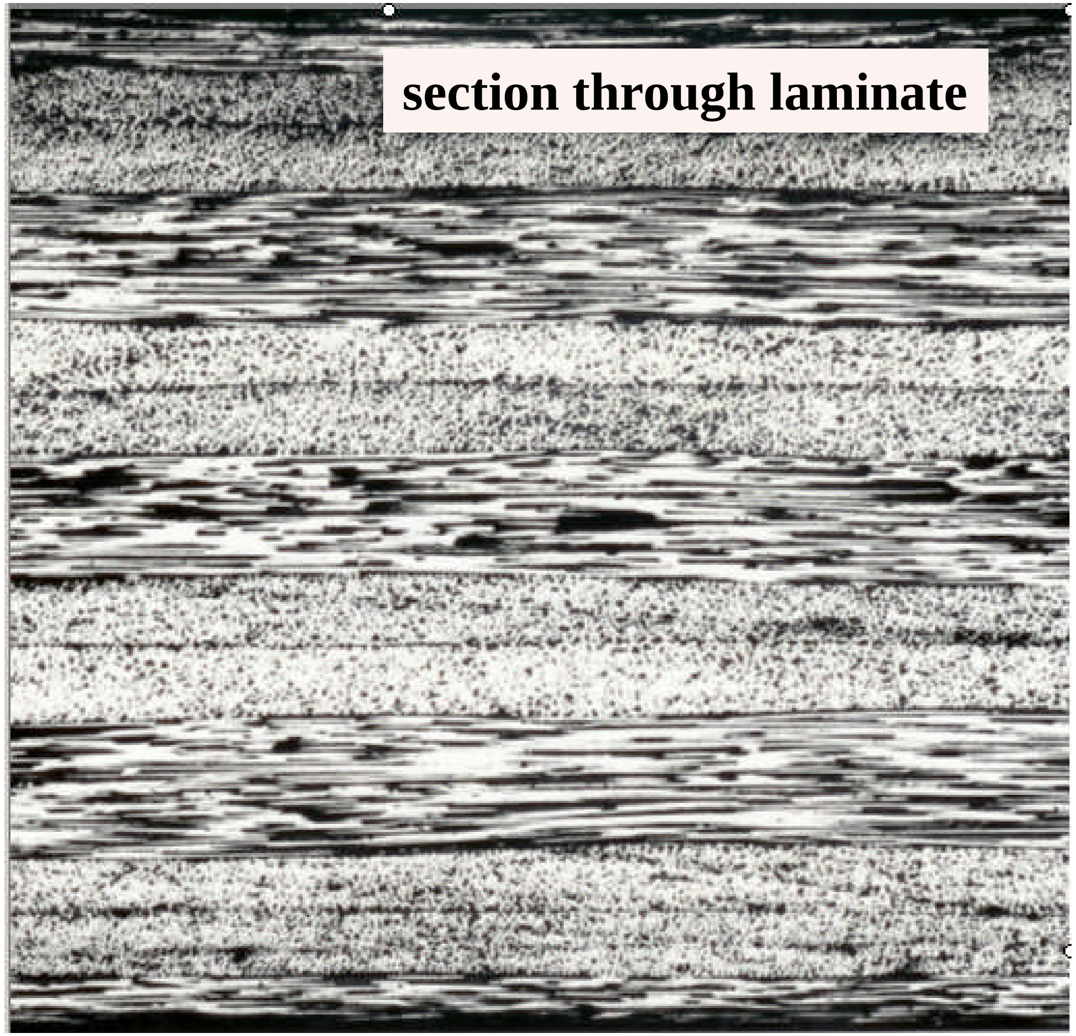
SF := Shear Fracture









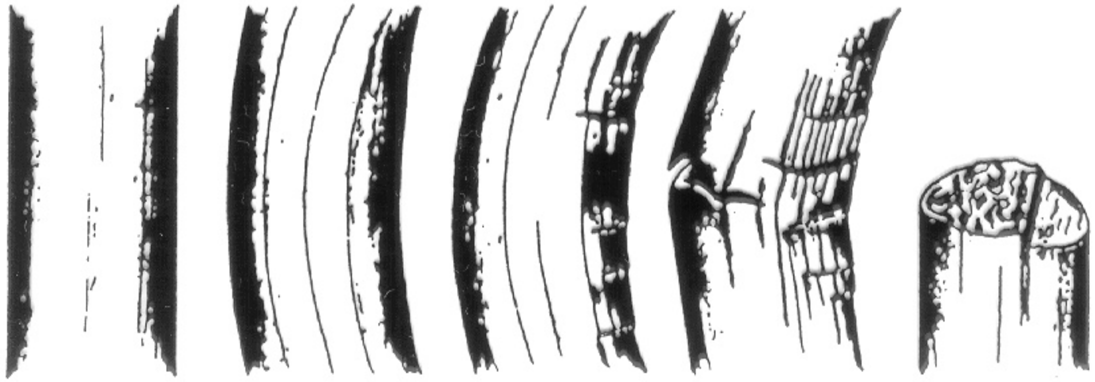


3.3a Fractography pictures as proofs

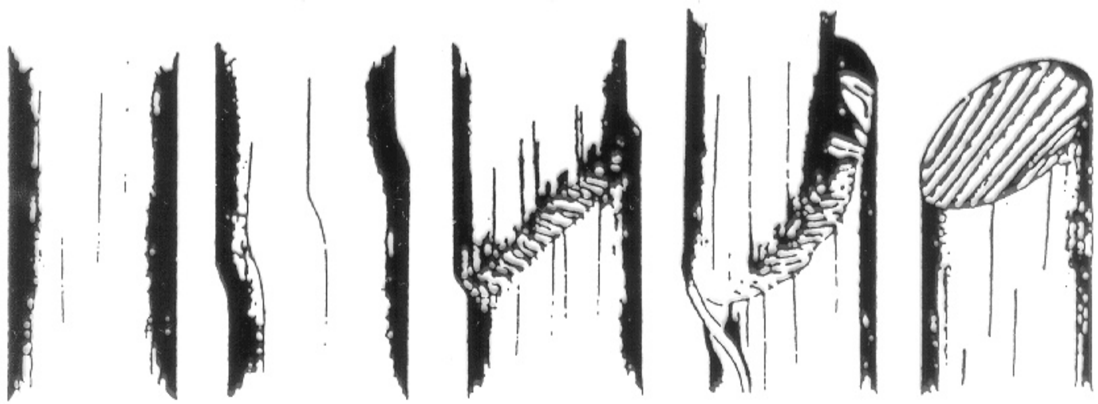
3 Observed Strength Failure Modes and Strengths

3.3b Failure mechanisms of compressed carbon filaments

PAN



Mesophase pitch



Courtesy: K. Schulte, TUHH

3 Observed Strength Failure Modes and Strengths

3.4 Orthotropic Material (woven fabrics)

Fractography exhibits no clear failure modes.

In this material case always multiple cracking is caused under tension, compression, bending, shear !

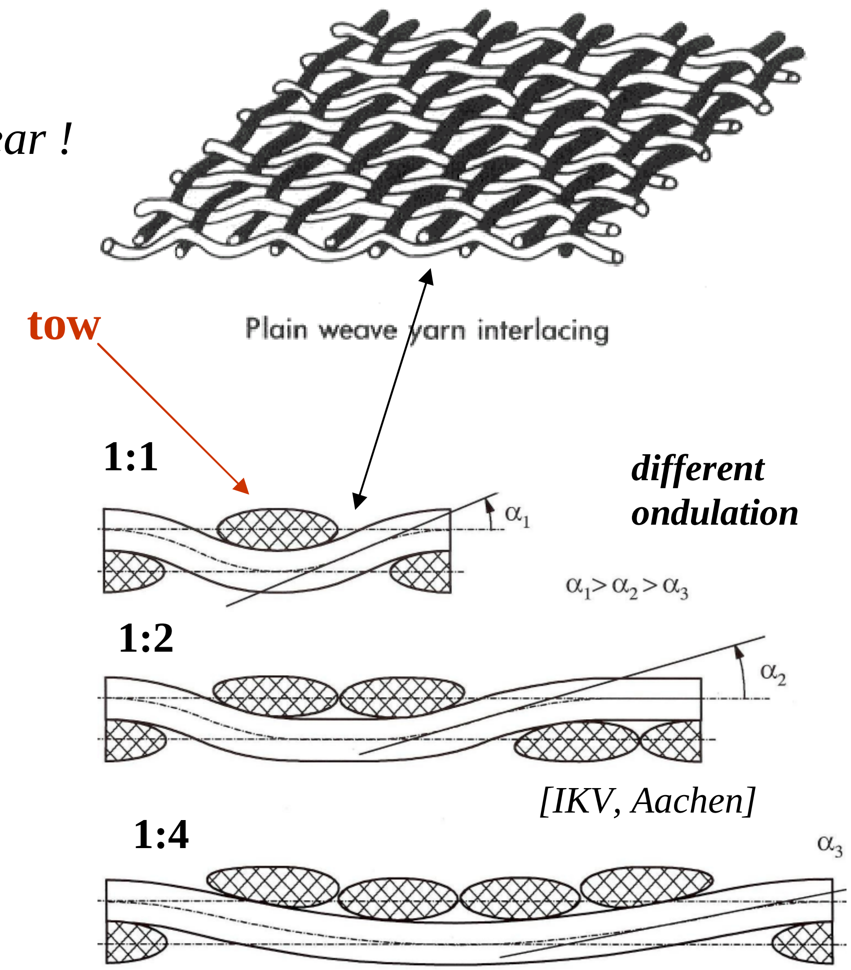
= diffuse micro-cracking

► **9 (6** *if F=W* **) strengths** to be measured

Lessons learned:

- Strengths have to be <u>defined</u> according to material symmetry
- Modelling depends on fabrics type !

next level above UD

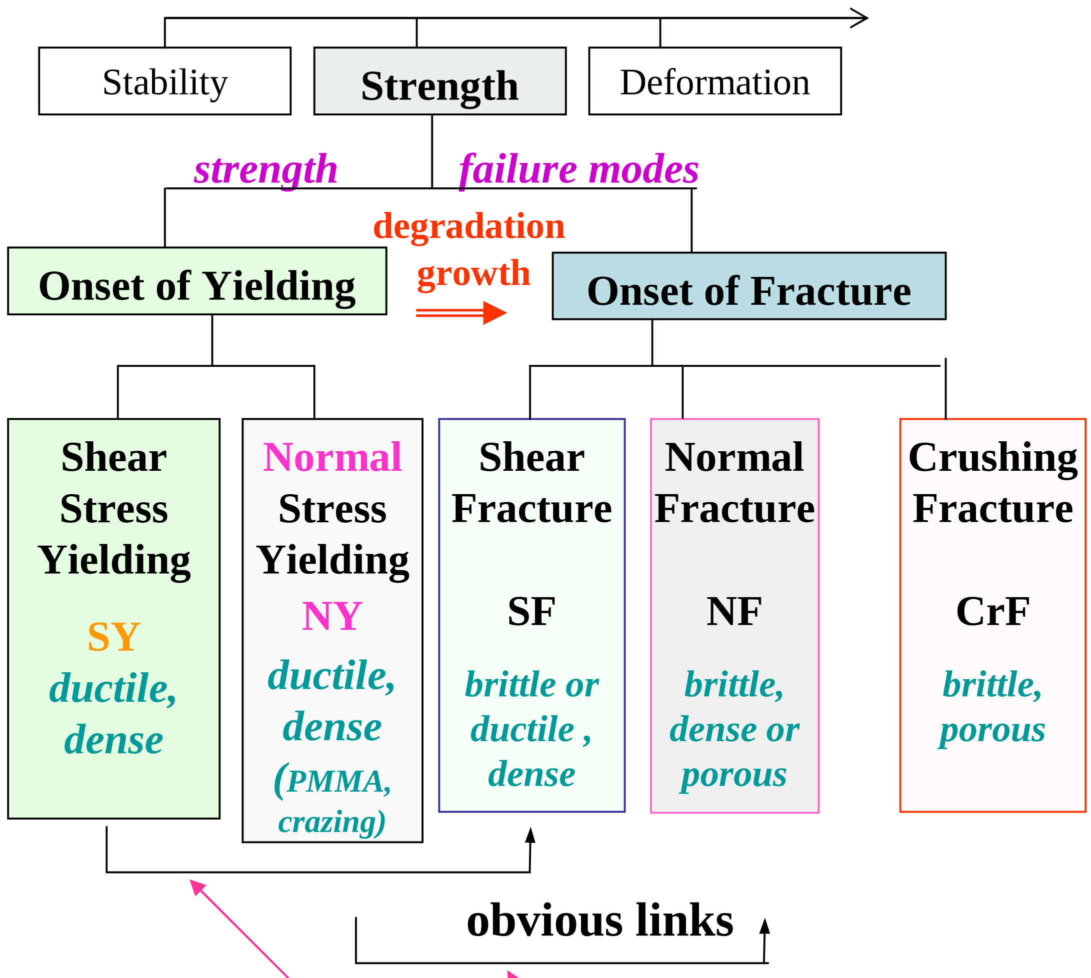


approximately UD-describable

about quasi-laminar

4 Attempt for a Systematization of Material Behaviour

4.1a Scheme of Strength Failures for *isotropic materials*



The growing yield body (SY or NY)

is confined by the fracture surface (SF or NF)**!**

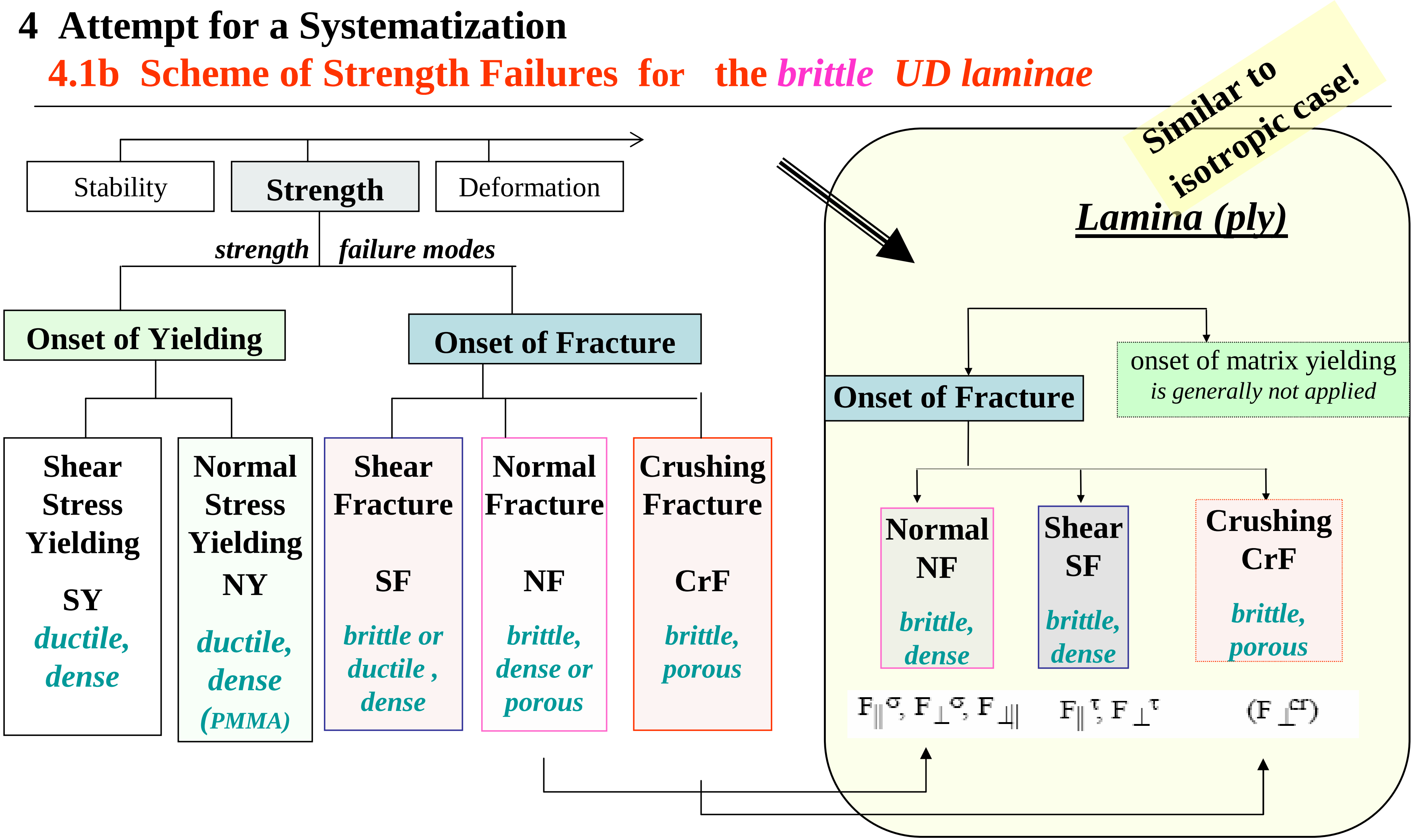
◄ = ***kinds of fracture***

Lesson learned from Mapping Test Data:

The same mathematical form of a failure condition holds - from ‘onset of yielding‘ to ‘onset of fracture‘ - if the physical mechanism remains !

4 Attempt for a Systematization

4.1b Scheme of Strength Failures for the *brittle* *UD laminae*



+ **delamination failure of *laminate***

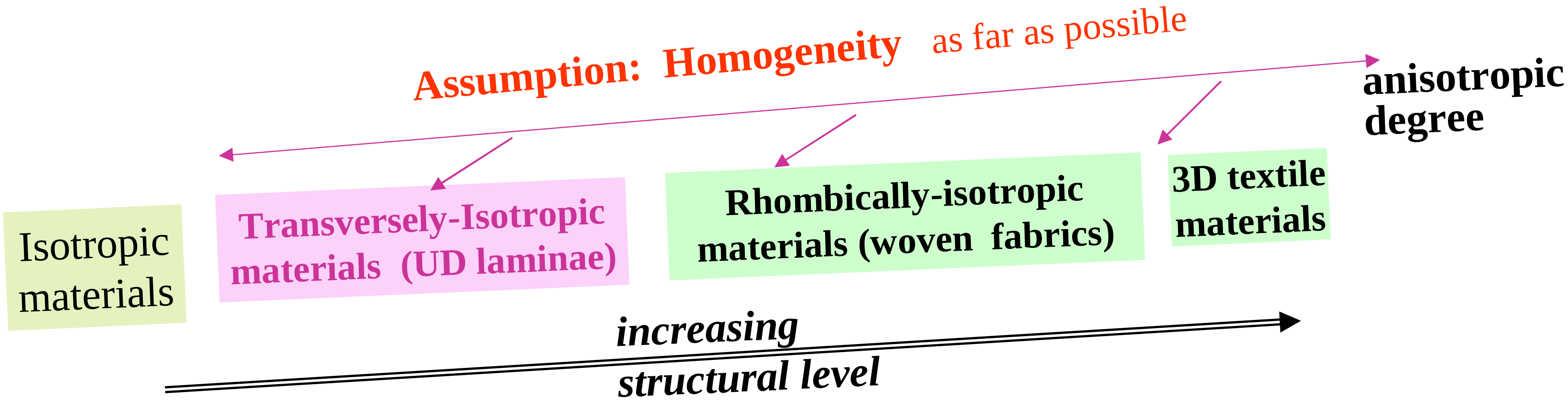
Lessons learned:

** There are coincidences between brittle UD laminae and brittle isotropic materials*

** Increased degradation occurs in the* laminate *beyond onset of the first IFF*

4 Attempt for a Systematization

4.2 Material Homogenizing (smearing) + Modelling, Material Symmetry



Material symmetry shows:

Number of strengths ≡ number of elasticity properties !

Application of material symmetry knowledge:

- *Requires that homogeneity is a valid assessment for the <u>task-determined</u> model ,*

but, if applicable

- A *minimum number of properties has to be measured, only* (cost + time benefits) !

It's worthwhile to structure the establishment of strength failure conditions

4.3 Proposed Classification of Homogenized (assumption) Materials

A Classification helps to structure the Modelling Procedure:

Failure Type / *Consistency*	**brittle, semi-brittle** Design Ultimate Load	**(quasi-) ductile** Design Yield Load
dense	fibre re-inforced plastics , mat, woven fabrics, grey cast iron, matrix material, amorphous glass C90-1,.	Glare, ARALL, metal alloys braided textiles
porous	foam, fibre re-inforced ceramics	sponge

design Driving Load (→ Design Yield Load)

failure: fracture (brittle, semi-brittle); functional or usability limit (ductile)

e.g. limiting strain

Lession Learnt:

Modelling, Structural Analysis + Design Verification strongly depend on material behaviour + consistency

4 Attempt for a Systematization

4.4 Resistance (strength) Quantities according to Material Symmetry

allocation to crystals	Isotropic	Transversely-isotropic	Rhombically-anisotropic
Symmetries	2	5	[6 if W ≡ F] (9)
material	***matrix, ceramics, isotropic foam***	***UD-lamina, mat, NCF, sandwich foam***	***fabrics***
elasticity quantities	*E , nue* (2)	$E_{\|\|}$, *E⊥, G||⊥, nue⊥||, nue⊥⊥* (5)	*Ew, EF, GWF, vFW, E3,* (9) *v3W, v3F, GF3, GW3*
strengths failure modes	*Rt, Rc* (2)	*R||t, R||c, R⊥t, R⊥c, R⊥||* (5) → *5 modes (2 FF, 3 IFF)*	*Rwt, Rwc, RFt, RFc, R3t,* (9) *R3W, RFW, R3F, R3c* → 9 modes [6 if W ≡ F]
fracture toughnesses	(2) K^{t}_{Ic}, K^{c}_{IIc}	(5) $K^{t}_{\|\|c}, K^{c}_{\|\|c}, K^{t}_{\perp c}, K^{c}_{\perp c}, K_{\perp\|\|c}$	K^{t}_{3c} , ... (9)

4 Attempt for a Systematization

4.5 Self-explaining Notations for Strength Properties (homogenised material)

		Fracture Strength Properties									
	loading	**tension**			**compression**			**shear**			
	direction or **plane**	1	2	3	1	2	3	12	23	13	*fmulae to be checked*
9	**general orthotropic**	R_1^t	R_2^t	R_3^t	R_1^c	R_2^c	R_3^c	R_{12}	R_{23}	R_{13}	**comments**
5	**UD, ≅ non-crimp fabrics**	$R_{\parallel}^t$ NF	$R_{\perp}^t$ NF	$R_{\perp}^t$ NF	$R_{\parallel}^c$ SF	$R_{\perp}^c$ SF	$R_{\perp}^c$ SF	$R_{\parallel\perp}$ SF	$R_{\perp\perp}$ NF	$R_{\parallel\perp}$ SF	$R_{\perp\perp} = R_{\perp}^t / \sqrt{2}$ (compare Puck's modelling)
6	**fabrics**	R_W^t	R_F^t	R_3^t	R_W^c	R_F^c	R_3^c	R_{WF}	R_{F3}	R_{W3}	*Warp = Fill*
9	**fabrics general**	R_W^t	R_F^t	R_3^t	R_W^c	R_F^c	R_3^c	R_{WF}	R_{F3}	R_{W3}	*Warp ≠ Fill*
5	**mat**	R_{1M}^t	R_{1M}^t	R_{3M}^t	R_M^c	R_{1M}^c	R_{3M}^c	R_M^τ	R_M^τ	R_M^τ	$R_M^\tau\,(R_M^t)$
2	**isotropic**	R_m SF	R_m SF	R_m SF	*deformation-limited*			R_M^τ	R_M^τ	R_M^τ	*ductile, dense* $R_M^\tau = R_m / \sqrt{2}$
		R_m NF	R_m NF	R_m NF	R_m^c SF	R_m^c SF	R_m^c SF	R_m^σ NF	R_m^σ NF	R_m^σ NF	*brittle, dense* $R_M^\sigma = R_m^t / \sqrt{2}$

NOTE: *As a consequence to isotropic materials (European standardisation) the letter R has to be used for strength. US notations for UD material with letters X (direction 1) and Y (direction 2) confuse with the structure axes' descriptions X and Y . *Effect of curing-based residual stresses and environment dependent on hygro-thermal stresses. *Effect of the difference of stress-strain curves of e.g. the usually isolated UD test specimen and the embedded (redundancy) UD laminae. R_m := 'resistance maximale' (French) = tensile fracture strength (superscript t here usually skipped), R:= basic strength. Composites are most often brittle and dense, not porous! SF = shear fracture

5 Short Derivation of the Failure Mode Concept (FMC)

5.1 Failure Theory and Failure Conditions

A **3D Failure Theory** has to include*: Example UD lamina*

1. Failure Conditions to ***assess multi-axial states of stress***
2. Non-linear Stress-strain Curves of UD lamina material as input
3. Non-linear Coding for structural analysis of Laminate

A Failure Condition is the mathematical formulation of the failure surface

Pre-requisites for failure conditions are, to be

- simply formulated , numerically robust,

- physically-based, and therefore, need only few information during pre-dimensioning

- shall allow for a simple determination of the design driving reserve factor.

F := Failure function. Failure envelope := curve that envelopes several failure curves. t,c :=tension, compression.
A stress-based (safe side, however) reserve factor is applicable, if linear analysis is sufficient as engineering approach.

5 Short Derivation of the Failure Mode Concept (FMC)

5.2 Fundamentals of the FMC (*example*: UD material)

Remember:

- **Each of the observed fracture failure modes was linked to one strength**
- **Symmetry of a material showed :** ***Number of strengths =*** $R_{\parallel}^{t}, R_{\parallel}^{c}, R_{\perp\parallel}, R_{\perp}^{t}, R_{\perp}^{c}$

  number of elasticity properties ! $E_{\parallel}, E_{\perp}, G_{\parallel\perp}, \nu_{\perp\parallel}, \nu_{\perp\perp}$

Due to the facts above the

FMC postulates in its '*<u>Phenomenological Engineering Approach</u>*' :

► Number of failure modes = number of strengths, too !

e.g.: isotropic = 2 or above transversely-isotropic (UD) = 5

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

5. Short Derivation of the *Failure Mode Concept (FMC)*

5.3 Driving idea behind the FMC

A possibility exists to *more generally* formulate failure conditions

- **failure mode-wise** *(shear yielding etc.)* — **Mises, Hashin, Puck etc.**
- **stress invariant-based** *(J_2 etc.)* — **Mises, Tsai, Hashin, Christensen, etc.**

5 Short Derivation of the Failure Mode Concept (FMC)

5.4 General on Global Formulation & Mode-wise Formulation

F >=< 1 is failure criterion

• **A failure condition is the mathematical formulation, F = 1, of the failure surface:**.

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

= 'fully interactive conditions' which include several modes

$$\{R\} = (R_1, R_2, \ldots R_i)^T$$

Several mode **failure conditions :** ***F ({σ},*** R^{mode}***) = 1*** **(used in Cuntze's FMC).**

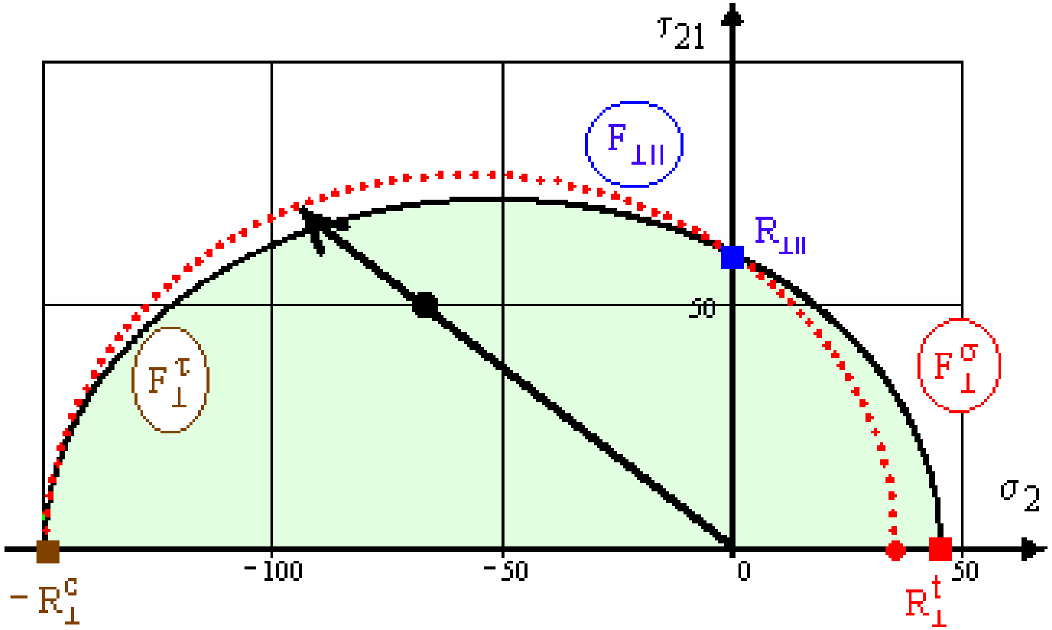
mode-associated strength

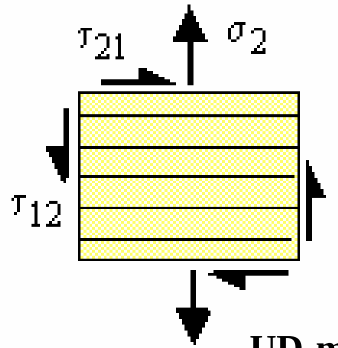
Lesson learned from application of global failure conditions:

A change, necessary in one failure mode domain, has an impact on other physically not related failure mode domains , however, in general not on the safe side .

► Decision: Chose a Mode-wise Formulation !

5.5 Possible Drawback of a Global Failure Condition





UD-material or

transversally- isotropic material

The numerically practical, so-called 'Global Failure Surface'–Fit covers more than one single failure mechanism (e.g.: ZTL condition in HSB):

$$\frac{\sigma_2^{\;2}}{\overline{R}_\perp^t \cdot \overline{R}_\perp^c} + \sigma_2 \cdot \left(\frac{1}{\overline{R}_\perp^t} - \frac{1}{\overline{R}_\perp^c}\right) + \frac{\tau_{21}^{\;2}}{\overline{R}_{\perp\parallel}} = 1$$

⇒ ***Draw back*** ***:*** ⇒ ***A change , necessary in one failure mode domain, has an effect on a physically not related other failure mode domain***

$$\left(\frac{\sigma_2}{\overline{R}_\perp^t}\right)^m + \left(\frac{-\sigma_2}{\overline{R}_\perp^c}\right)^m + \left(\frac{|\tau_{21}|}{\overline{R}_{\perp\parallel} - b_{\perp\parallel} \cdot \sigma_2)}\right)^m = 1$$

5 Short Derivation of the Failure Mode Concept (FMC)

5.6 Basic Features of the FMC

- **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*** (interaction of acting stresses).

- **Interaction of Failure Modes:**
  Probabilistic-based 'rounding-off' approach (series model)
  directly delivering the reserve factor in linear analysis.

5. Short Derivation of the *Failure Mode Concept (FMC)*

5.7 Main Aspects

1) **1 failure *condition* represents 1 Failure *Mode*** *(interaction of acting stresses)*.
2) **Interaction of adjacent Failure Modes by a *series failure system* model**

   to map the full course of all test data

$$(Eff)^m = (Eff^{mode1})^m + (Eff^{mode2})^m + \ldots + \ldots = 1$$

with Stress Effort Eff := portion of load-carrying capacity of the material $\equiv \sigma_{eq}^{mode} / R^{mode}$

and Interaction coefficient m of modes.

NOTE: The presentation shall just provide

with a <u>general view at the material behaviour links</u> and not

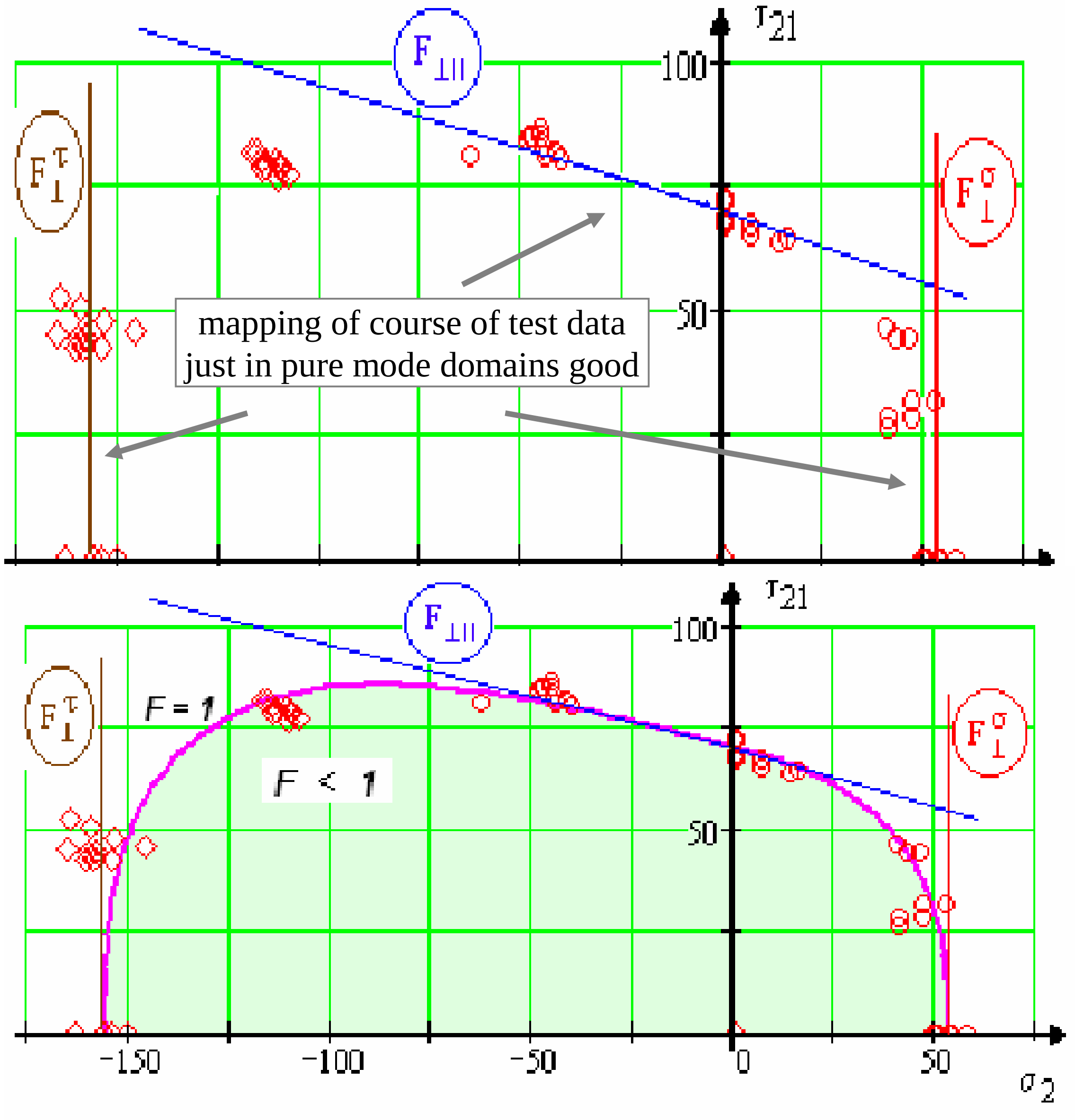
with a detailed information on the derived strength failure conditions !

How is above *interaction of modes* performed?

5. Short Derivation of the *Failure Mode Concept (FMC)*

5.8a Interaction of Strength Failure Modes (example: UD, the 3 IFF)

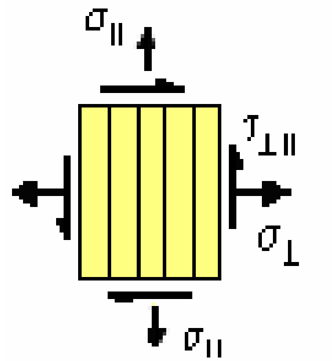
Failure Mode Interaction:



Stress Interaction:

Interaction of all the stresses active in a mode

performed by the
Mode Failure Function



Ppure modes = straight lines !

Mapping of course of test data performed by the introduced FMC Interaction Model

How is this achieved? →

5. Short Derivation of the *Failure Mode Concept (FMC)*

5.8b Interaction of Strength Failure Modes (example: UD, the 3 IFF)

Stress efforts of the 3 pure IFF modes = 3 straight lines :

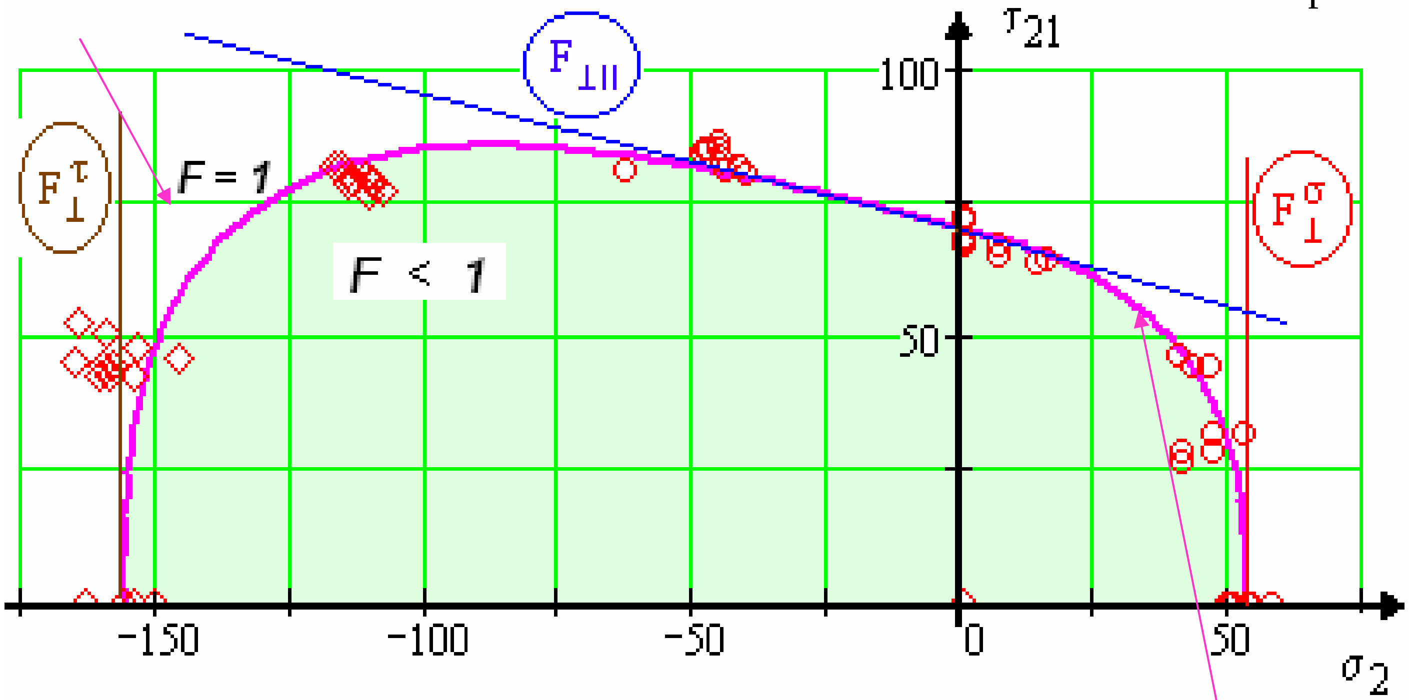
$$Eff_{\perp}^{\sigma} = \frac{\sigma_2}{\overline{R}_{\perp}^{t}}, \quad Eff_{\perp}^{\tau} = \frac{-\sigma_2}{\overline{R}_{\perp}^{c}}. \quad Eff_{\perp\|} = \frac{|\tau_{21}|}{\overline{R}_{\perp\|} - \mu_{\perp\|} \cdot \sigma_2},$$

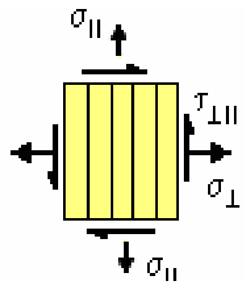
All failure modes, 3 IFF + 2 FF, are interacted in one single (*global*) failure condition

magenta curve:

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

corresponds to a *series failure system*





hoop wound GFRP tube:

E-glass/LY556/HT976

* *For UD laminae m =2.5 - 3; a smaller value is more on the safe side*

* *Approximately the same value of m is valid for every interaction zone*

5. Short Derivation of the *Failure Mode Concept (FMC)*

5.9 Physical-based Choice of Invariants when generating Failure Conditions

---

* Beltrami : "At 'Onset of Yielding' the material possesses a distinct ***strain energy*** composed of *dilatational energy* (I_1^2) and *distortional energy* ($J_2 \equiv Mises$) ".

* So, from Beltrami, Mises (HMH), and Mohr / Coulomb (friction) can be concluded:

Each invariant term in the *failure function* ***F*** may be dedicated to one physical mechanism in the solid = cubic material element:

- volume change : I_1^2 … ***(dilatational energy)***
- shape change : J_2 (**Mises**) … ***(distortional energy)***

and - friction : I_1 … ***(friction energy)***

Stress Invariants: ***isotropic materials***

Mohr-Coulomb

5. Short Derivation of the *Failure Mode Concept (FMC)*

5.9 Physical-based Choice of Invariants when generating Failure Conditions

* So, from Beltrami, Mises (HMH), and Mohr / Coulomb (friction) can be concluded:

Each invariant term in the *failure function* ***F*** may be dedicated to one physical mechanism in the solid = cubic material element:

- volume change : I_1^2 … ***(dilatational energy)***
- shape change : J_2 (**Mises**) … ***(distortional energy)***

and - friction : I_1 … ***(friction energy)***

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

I_1^2 , I_2^2
I_3 , I_4
I_2

: UD materials !

Mohr-Coulomb

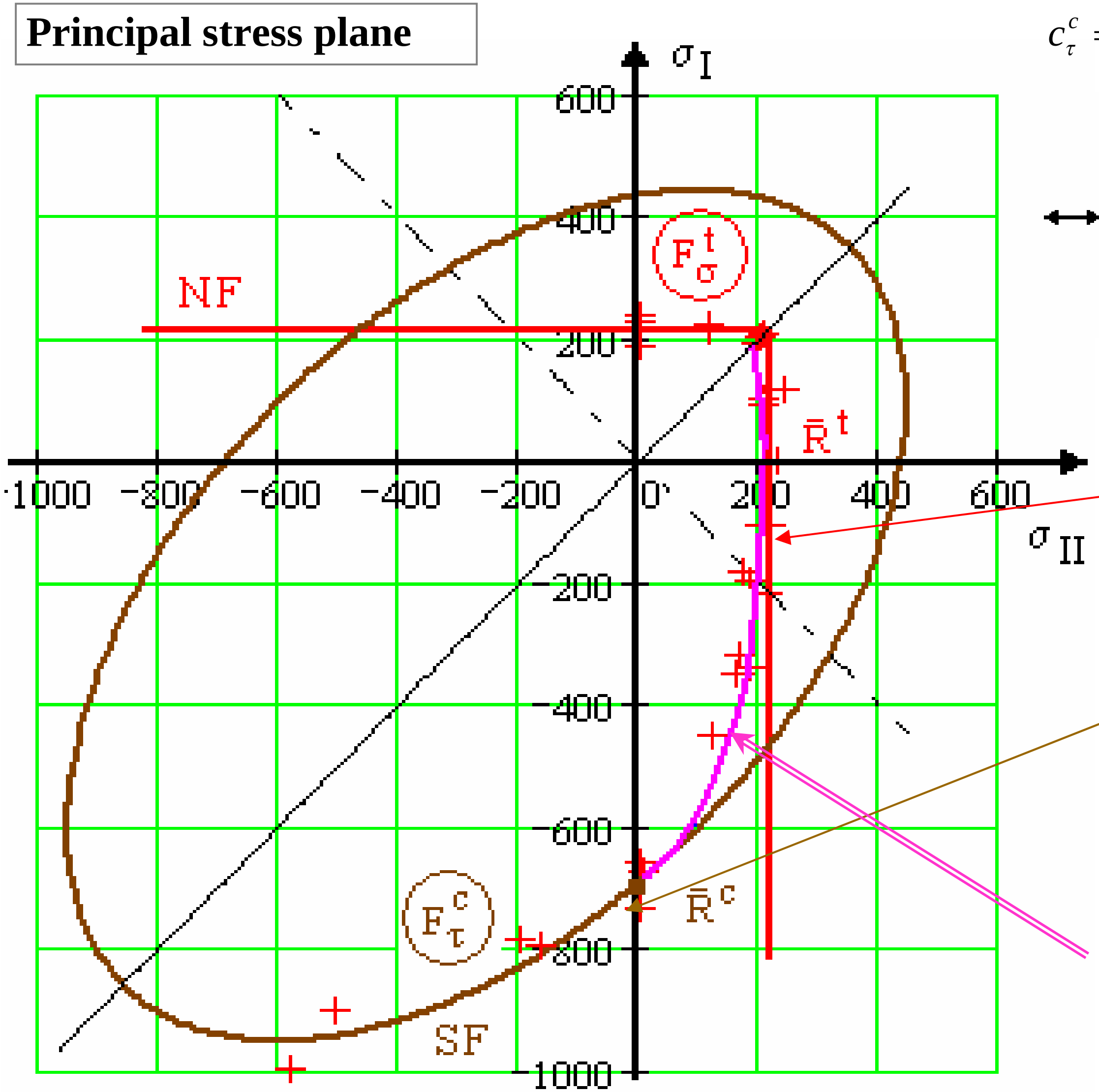
Remember:

These I_1 are different !

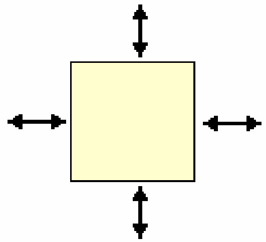
Lesson Learnt: Use the right invariant in the actual case !

6 Visualisation of some Derived Failure Conditions

6.1 Grey Cast Iron (brittle, dense, microflaw-rich), *Principal stress plane*



$c_\tau^c = a_\tau^c - 1, \quad a_\tau^c = 1.58 \qquad m = 3.1 \qquad \bar{R}^t = 215\,MPa; \quad \bar{R}^c = 690\,MPa$



$$\{\sigma\}_{principal} = (\sigma_I, \sigma_{II}, 0)^T$$

$$F_\sigma^t = \frac{\sqrt{I_\sigma} + I_1}{2 \cdot \bar{R}^t} = 1$$

NF deformation poor

$$F_\tau^c = a_\tau^c \frac{3J_2}{\bar{R}^{c2}} + c_\tau^c \frac{I_1}{3\bar{R}^c} = 1$$

shear change — friction — **SF**

= 2 Mode Failure Conditions

Interaction zone

Lessons learned: Basically, *Dense concrete and Glass C 90 will have same failure condition*

6 Visualisation of some Derived Failure Conditions

6.2a Concrete (isotropic, slightly porous) *Kupfer's data*

Octahedral stresses (B-B view)

$$F_\sigma^t = \frac{\sqrt{I_\sigma} + I_1}{2\overline{R}_m^t} = Eff_\sigma^t = 1$$

deformation poor

hyperbola

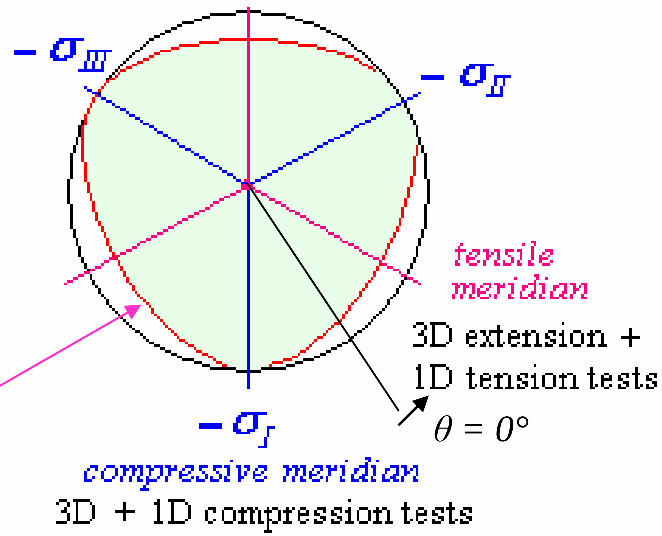
shape + volume change + friction: Mohr-Coulomb :

$$F_\tau^c = a_\tau^c \frac{3J_2 \cdot \Theta}{\overline{R}_m^{c\,2}} + b_\tau^c \frac{I_1^{\,2}}{\overline{R}_m^{c\,2}} + c_\tau^c \frac{I_1}{\overline{R}_m^c} = 1$$

(closed failure surface)

paraboloide

Isotropic materials possess 120° symmetry :



Lessons learned from test data viewing**:**

- *Course of concrete test data shows a big bandwidth*
- *The reason for the bandwidth is not only the test scatter but the stress-state dependent 'double' failure probability causing non-coaxiality in the octahedral plane. The difference between the so-called tensile (extension) meridian and the compression meridian is to be considered.*

Basically, the differences in the octahedral (deviatoric) plane can be described by :

$$\Theta \Rightarrow \sqrt[3]{1 + d \cdot sin(3\theta)}$$

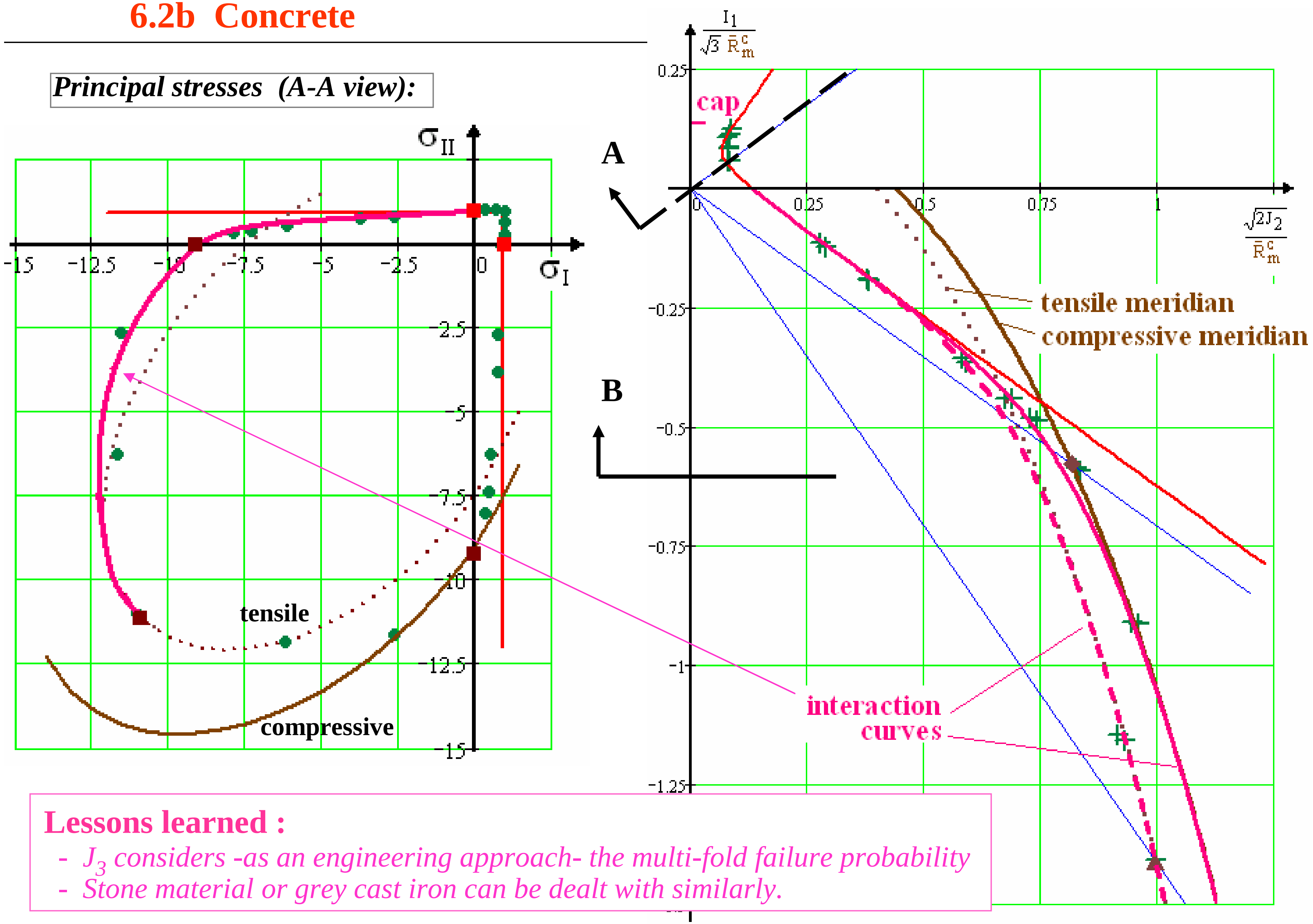
$$sin(3\theta) = 3\sqrt{3}J_3 / (2J_2^{\,3/2}),$$

[de Boer, et al] $d \leq 0.5$, *convex*

Remark Cuntze: J_3 practically describes the effect of the doubly acting failure mode, no relation to a new mechanism.

6 Visualisation of some Derived Failure Conditions

6.2b Concrete



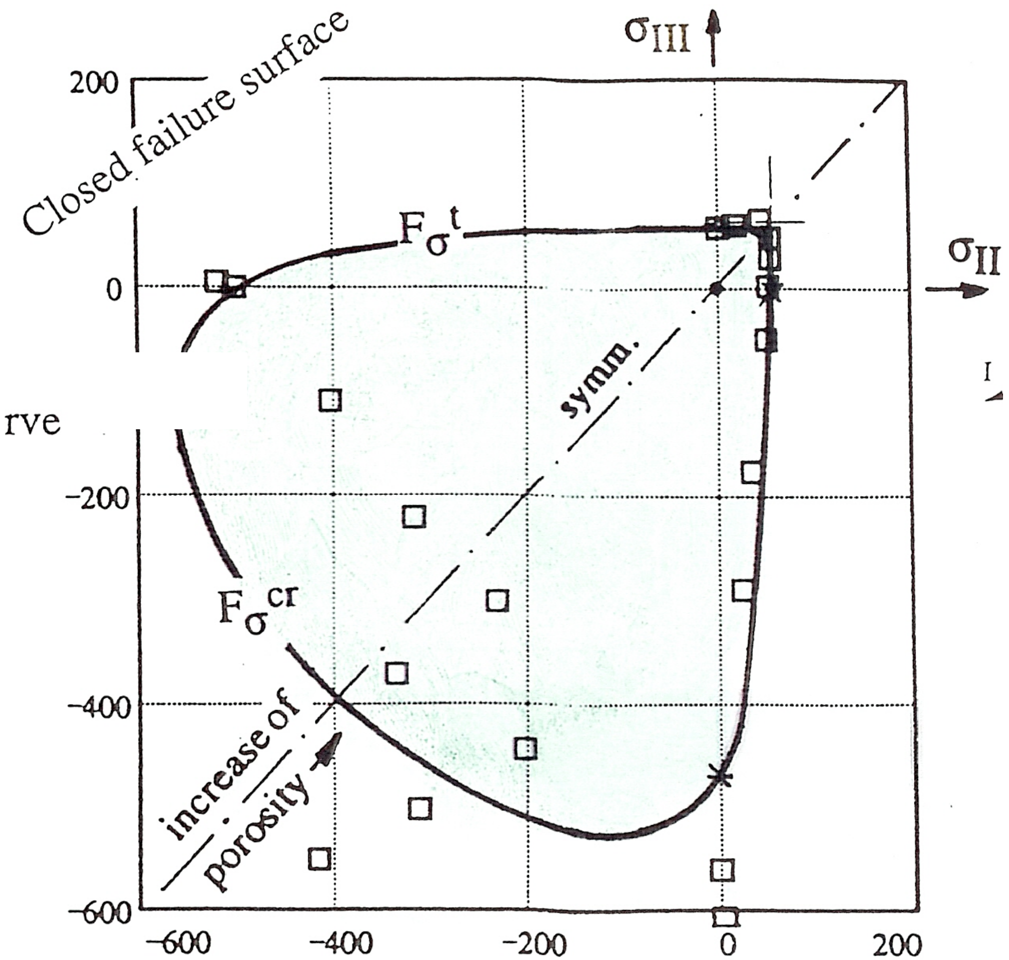
Lessons learned :

- *J_3 considers -as an engineering approach- the multi-fold failure probability*
- *Stone material or grey cast iron can be dealt with similarly.*

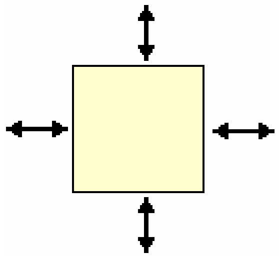
6 Visualisation of some Derived Failure Conditions

6.3 Monolithic Ceramics (brittle, porous isotropic material)

Principal stress plane



$c^{cr} = a^{cr} - 1$ ***[Kowalchuk]***



$$F_\sigma^t = \frac{\sqrt{I_\sigma} + I_1}{2 \cdot \overline{R}^t} = 1$$ deformation poor

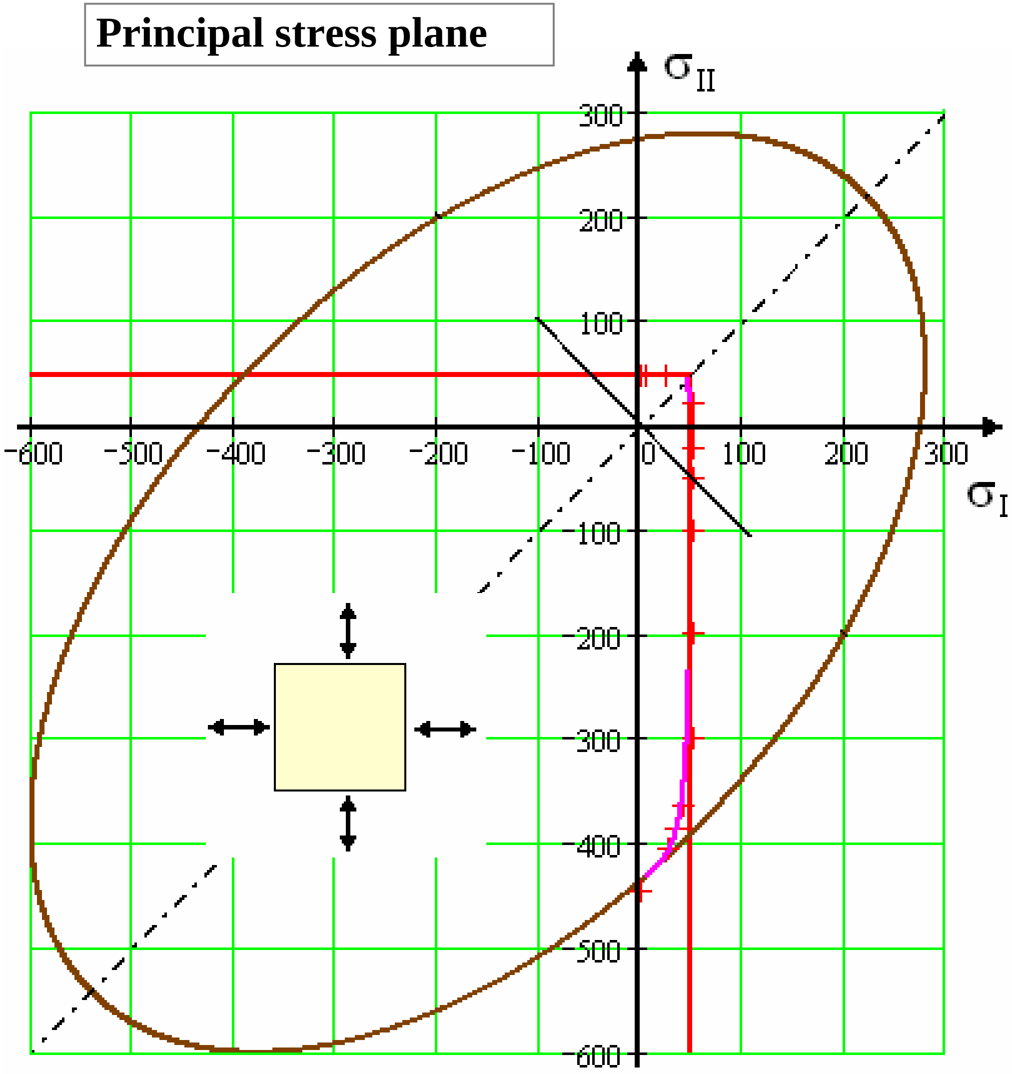
$$F^{cr} = a^{cr} \frac{3J_2}{\overline{R}_m^{c\,2}} + \; + c^{cr} \left(\frac{I_1}{\overline{R}_m^c} \right)^2 = Eff^{cr} = 1$$

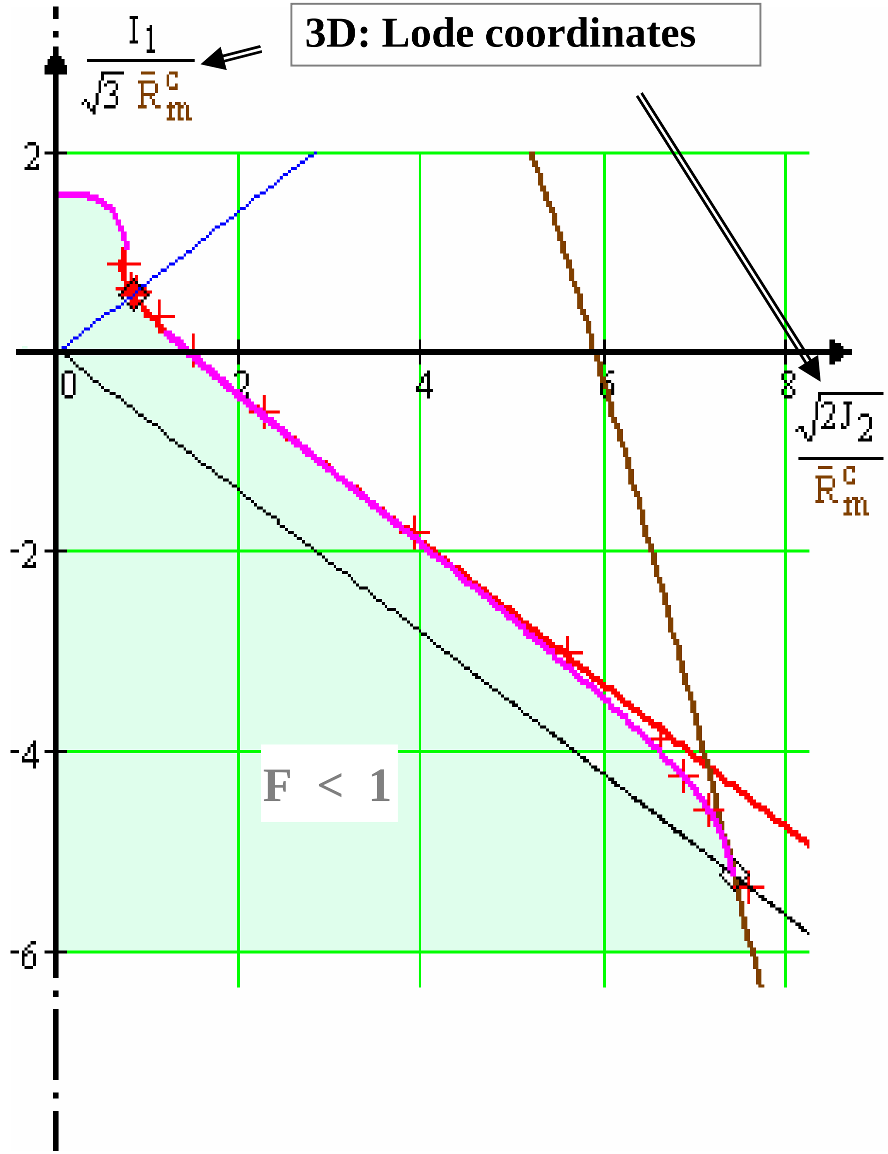
shear change **volume change**

Lessons learned: ***Same failure condition as very porous concrete***

6 Visualisation of some Derived Failure Conditions

6.4 Glass C 90 (brittle, dense isotropic material) *ISS window pane*

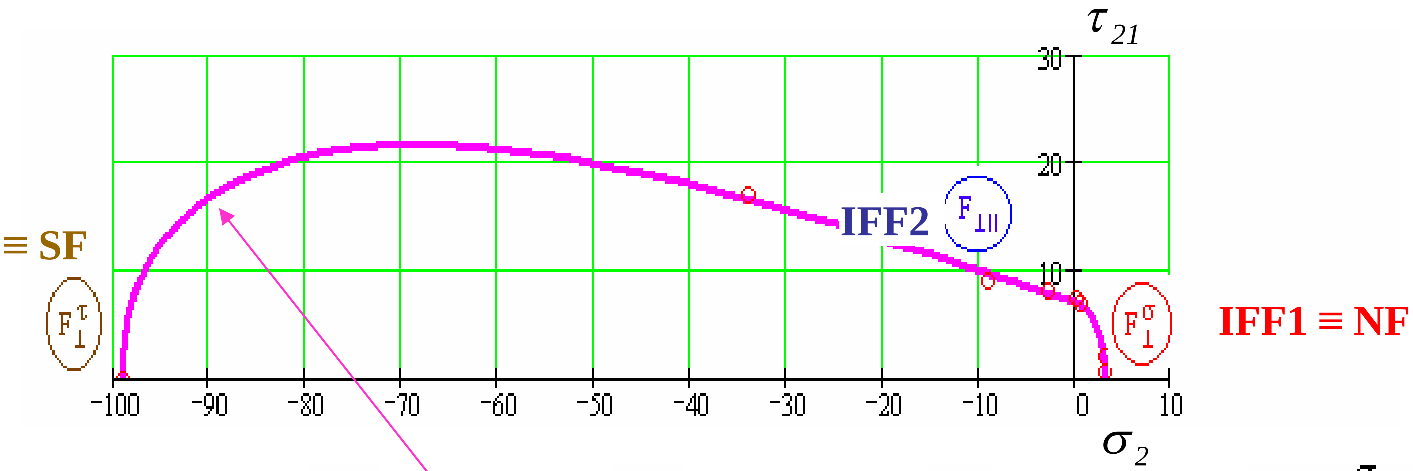




6 Visualisation of some Derived Failure Conditions

6.5 UD Ceramic Fibre-Reinforced Ceramics (C/C) (brittle, porous, tape)

$\{\bar R\} = (\bar R_\parallel^t, \bar R_\parallel^c, \bar R_\perp^t, \bar R_\perp^c, \bar R_{\perp\parallel}) = (-, -, 3, 99, 7)^T, \; m = 2.3, \; b_{\perp\parallel} = 0.3$ *[Diss. B. Thielicke, 1997]*

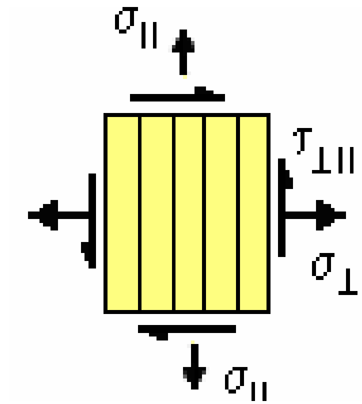


$F_\perp^\sigma$ $F_{\perp\parallel}$ $F_\perp^\tau$

Interaction equation :

$$\left(\frac{\sigma_2}{\bar R_\perp^t}\right)^m + \left(\frac{-\sigma_2}{\bar R_\perp^c}\right)^m + \left(\frac{|\tau_{21}|}{\bar R_{\perp\parallel} - b_{\perp\parallel} \cdot \sigma_2}\right)^m = 1$$

deformationless — shear — friction (Mohr-Coulomb)

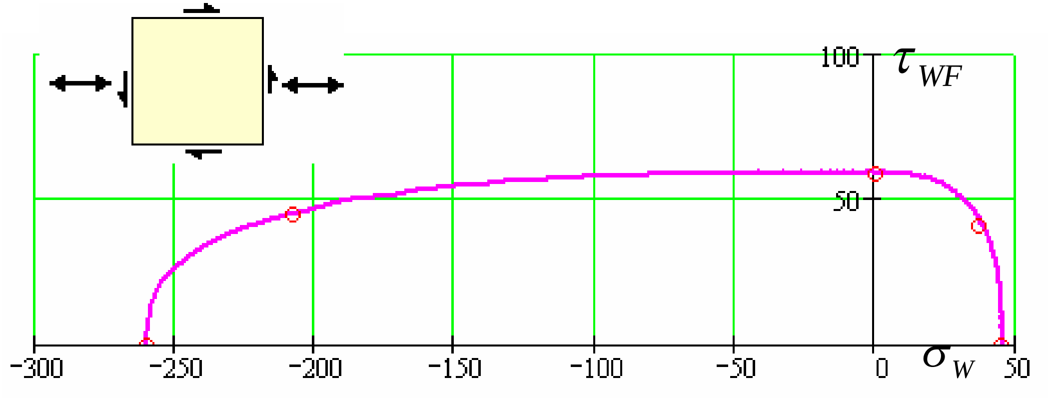


Invariants applied: I4, I2 — I3 , I2

Lesson learned: ***Same failure condition as with UD-FRP***

6 Visualisation of some Derived Failure Conditions

6.6 Fabric Ceramic Fibre-Reinforced Ceramics (CFRC) (brittle, porous)



C/C-SiC, T= 1600°C

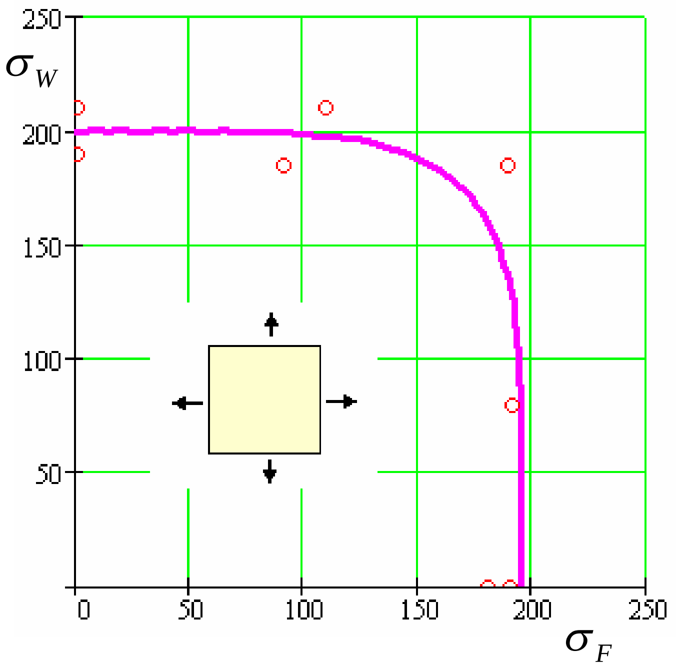
[Geiwitz/Theuer/Ahrendts 1997] ,

*tension/compression-torsion-**tube??***

$$\{\bar{R}\} = (\bar{R}_{\parallel}^{t}, \bar{R}_{\parallel}^{c}, \bar{R}_{\perp}^{t}, \bar{R}_{\perp}^{c}, \bar{R}_{\perp\parallel}) = (-, -, 45, 260, 59)^T$$

$m = 2.8$

$$\left(\frac{\sigma_W}{\bar{R}_W^t}\right)^m + \left(\frac{-\sigma_W}{\bar{R}_W^c}\right)^m + \left(\frac{\tau_{WF}^{\,2}}{\bar{R}_{WF}^{\,2}}\right)^m = 1$$



$$\{\bar{R}\} = (\bar{R}_W^t, \bar{R}_W^c, \bar{R}_F^t, \bar{R}_F^c, \bar{R}_{WF}, \bar{R}_3^t, \bar{R}_3^c, \bar{R}_{3F}, \bar{R}_{3W})^T$$

$\{\bar{R}\}$ = *vector of mean strength values*

C/SiC, ambient temperature *[MAN-Technologie, 1996],*

tension/tension tube

$$\{\bar{R}\} = (200, -, 195, -, -,,,,)^T, \; m = 5$$

$$\left(\frac{\sigma_W}{\bar{R}_W^t}\right)^m + \left(\frac{\sigma_F}{\bar{R}_F^t}\right)^m = 1$$

W = weft, F = Fill (warp)

NOTE: For woven fabrics enough test information for a real validation is not yet available!

6 Visualisation of some Derived Failure Conditions

6.7 Conclusions from the Beltrami-based *Failure Mode Concept* applications

---

- **FMC is an efficient concept, that improves prediction + simplifies design verification**

  is applicable to brittle + ductile, dense + porous, isotropic → orthotropic material

  - if clear failure modes can be identified and
  - if the homogenized material element experiences a *volume* or *shape change* or *friction*

- **Delivers a global formulation of *'individually'* combined independent failure modes, without the well-known drawbacks of global failure conditions**

  which *mathematically combine in-dependent failure modes* .

- **Failure conditions are simple but describe physics of each failure mechanism pretty well**

- **Several Material behaviour Links have been outlined:**

  Paradigm: Basically, a compressed brittle *porous* concrete can be described like a tensioned ductile *porous becoming* metal ('Gurson' domain)

Builds not on the material but ***on material behaviour !***

7 Special Applications to 2D UD Test Data (WWFE-I)

7.1 Recall: History of Hypotheses / Approaches

Mohr's statement : for brittle composites

“The strengths of a material are determined by the stresses on the fracture plane”.
(**t**he fracture plane may be inclined wrt the action plane of the external stresses).

Paul’s modification of the Mohr-Coulomb hypothesis :

"A brittle material will fracture in either that plane where the shear stress τ_{nt} reaches a critical value which is given by the shear resistance of a fibre parallel plane increased by a certain amount of friction caused by the simultaneously acting compressive stress σ_n on that plane.
Or, it will fracture in that plane, where the maximum principal stress (σ_{II} or σ_{III}) reaches the transverse tensile strength ".

Hashin (1980) proposed a modified Mohr-Coulomb IFF approach but did not pursue this idea due to numerical difficulty. Also in this paper, he included an invariant-based global quadratic approach (includes 3 IFF).

Puck bases his IFF conditions on Mohr and Hashin and interacts the stresses σ_n, τ_{nt}, τ_{n1} on the IFF fracture plane. He uses simple polynomials (parabolic or elliptic) to formulate a (master-)fracture body in the (σn, τnt, τn1)-space

Cuntze uses 3 different invariant IFF conditions, based on the idea that for each of these fracture conditions either the $\sigma_\perp$- , or the ‘$\tau_{\perp\perp}$’- or the $\tau_{\perp||}$-stress is dominant.

7 Special Applications to UD Test cases

7.2 Set of 3D (2D) Static Failure Conditions for Plain UD material

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

FF1: $Eff^{\|\sigma} = \sigma_1 / \overline{R}_{\|}^{t} = \sigma_{eq}^{\|\sigma} / R_{\|}^{t}$ with $\sigma_1 \cong \varepsilon_1^t \cdot E_{\|}$,

FF2: $Eff^{\|\tau} = -\sigma_1 / \overline{R}_{\|}^{c} = +\sigma_{eq}^{\|\tau} / \overline{R}_{\|}^{c}$ with $\sigma_1 \cong \varepsilon_1^c \cdot E_{\|}$,

• **filament !** modes. 3D

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

,

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

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

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

$= \sigma_{eq}^{\perp\|} / \overline{R}_{\perp}^{\perp\|}$ with $I_{23-5} = 2\sigma_2 \cdot \tau_{21}^2 + 2\sigma_3 \cdot \tau_{31}^2 + 4\tau_{23}\tau_{31}\tau_{21}$.

matrix modes

The indices σ, τ mark the failure mode driving stress ! * Limit of homogenization (smearing)

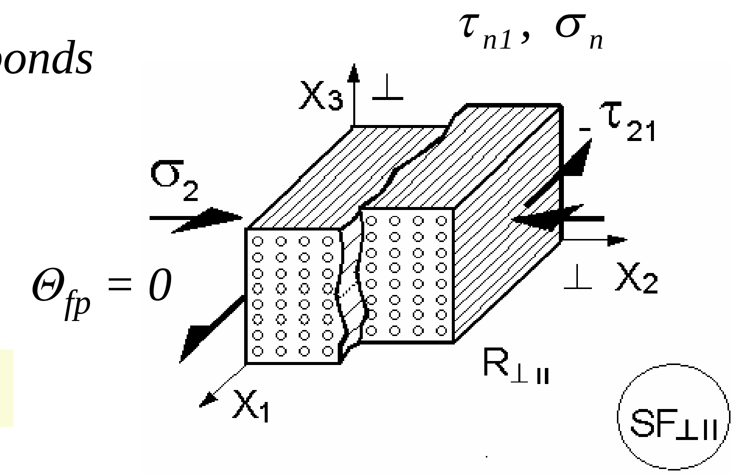
7.3a Determination of the 2 Friction Parameters (Mohr-Coulomb relationship

$$\tau_{21} = R_{\perp\|} - b_{\perp\|} \cdot \sigma_2$$: *FMC corresponds*

IFF 2 :

$$\tau_{n1} = R_{\tau}^{\perp\|} - \mu_{\perp\|} \cdot \sigma_n$$: *Mohr*

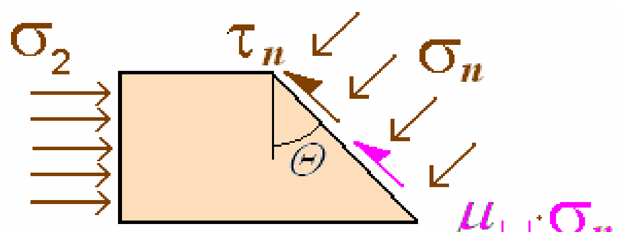
cohesion strength — *material internal friction coefficient*



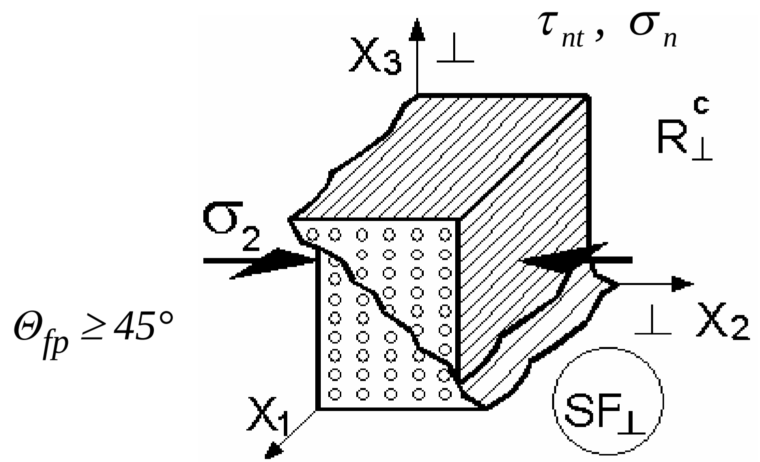
Linear **Mohr-Coulomb approach + denotation**

IFF 3 :

$$\tau_{nt} = R_{\tau}^{\perp\perp} - \mu_{\perp\perp} \cdot \sigma_n$$



$$\sigma_n = \cos^2\Theta \cdot \sigma_2$$
$$\tau_n = -\sin\Theta \cdot \cos\Theta \cdot \sigma_2$$



Parabolic Mohr-Coulomb approach (possible, but not applied here):

$$\tau_{nt}^{\ 2} = R_{\tau}^{\perp\perp} \cdot (R_{\tau}^{\perp\perp} - \mu_{\perp\perp}^{parab} \cdot \sigma_n)$$

7.3b Determination of the 2 Friction Parameters (linear Mohr-Coulomb relationship

From evaluation of the test data

$$\theta^c_{fp} = 55°, \; R^c_\perp = 104 \; MPa$$

FMC:

$$b^\tau_\perp \sqrt{I_4} \; = \bar{R}^c_\perp - (b^\tau_\perp - 1) I_2$$

$$b^\tau_\perp = \frac{1}{1 + (\cos 2\Theta^c_{fp})} = \frac{1}{1 - \mu_{\perp\perp}}$$

$$b^\tau_\perp = \; 1.52$$

Mohr-Coulomb:

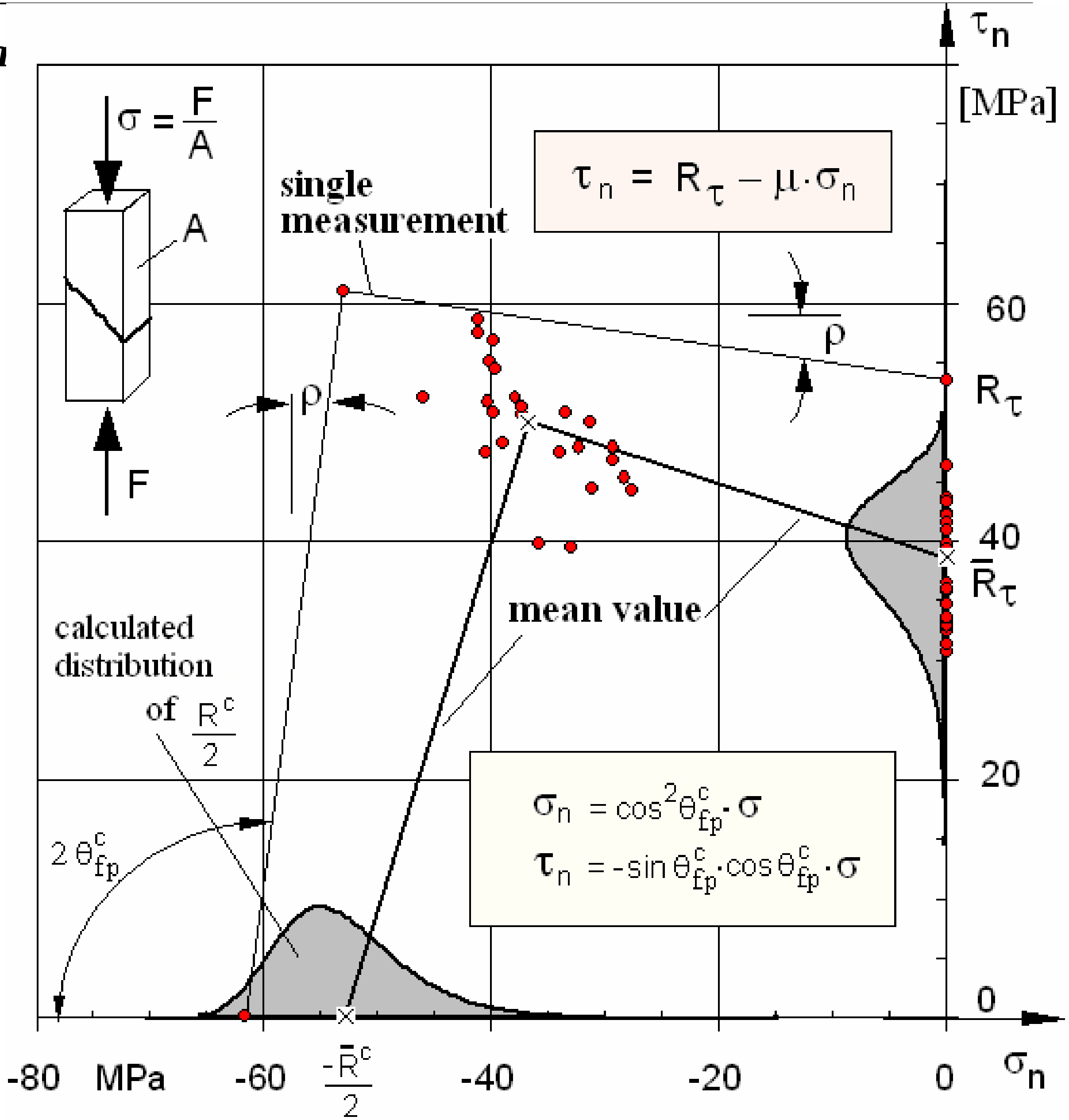
$$\tau_n = \; (R^{\perp\perp}_\tau - \mu_{\perp\perp} \cdot \sigma_n)$$

$$\mu_{\perp\perp} \geq -\cos 2\Theta^c_{fp},$$

$$\mu_{\perp\perp} = 0.34$$

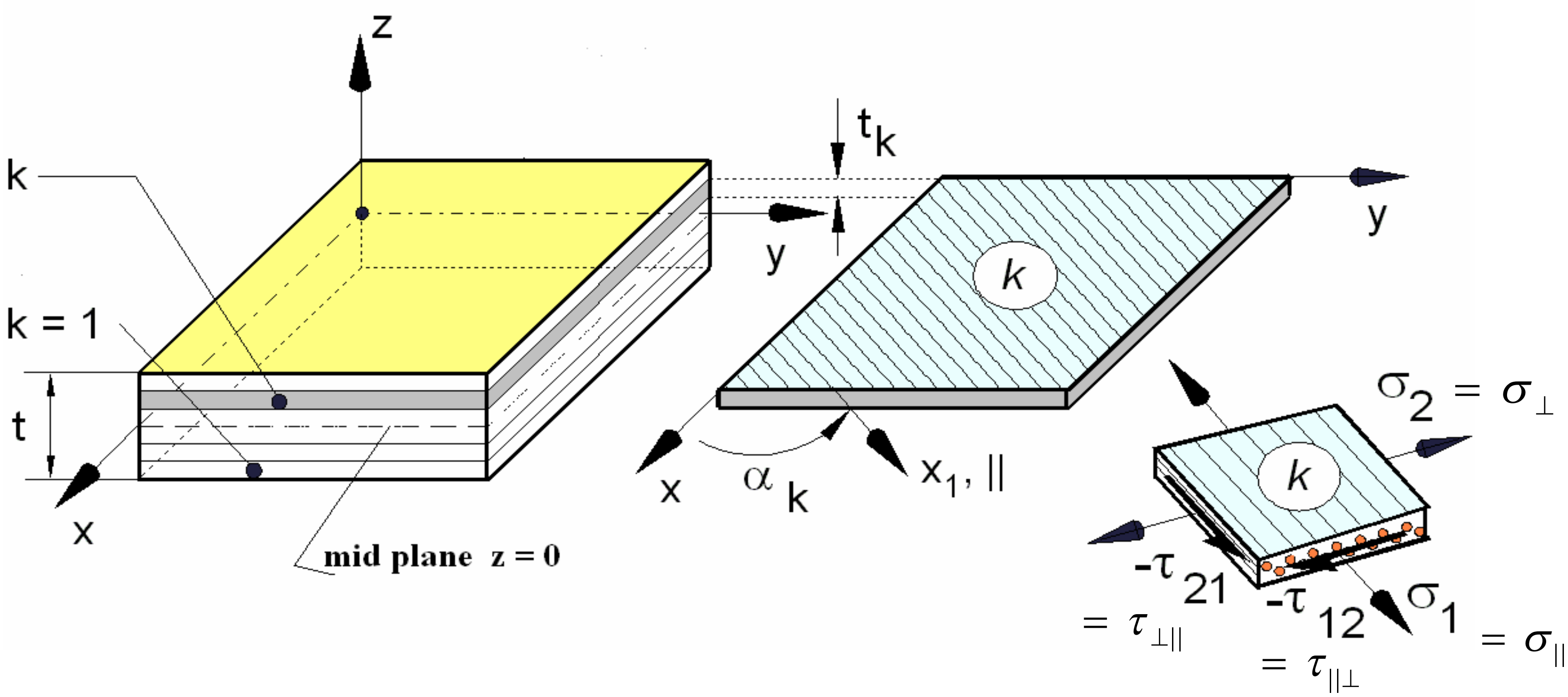
$$R^{\perp\perp}_\tau = R^c_\perp \frac{1 + \cos 2\Theta^c_{fp}}{2}$$

$$R^{\perp\perp}_\tau = 36.4 \; MPa$$



7 Application to 2D UD Test Data (WWFE-I)

7.3 UD lamina: In-plane State of Stresses



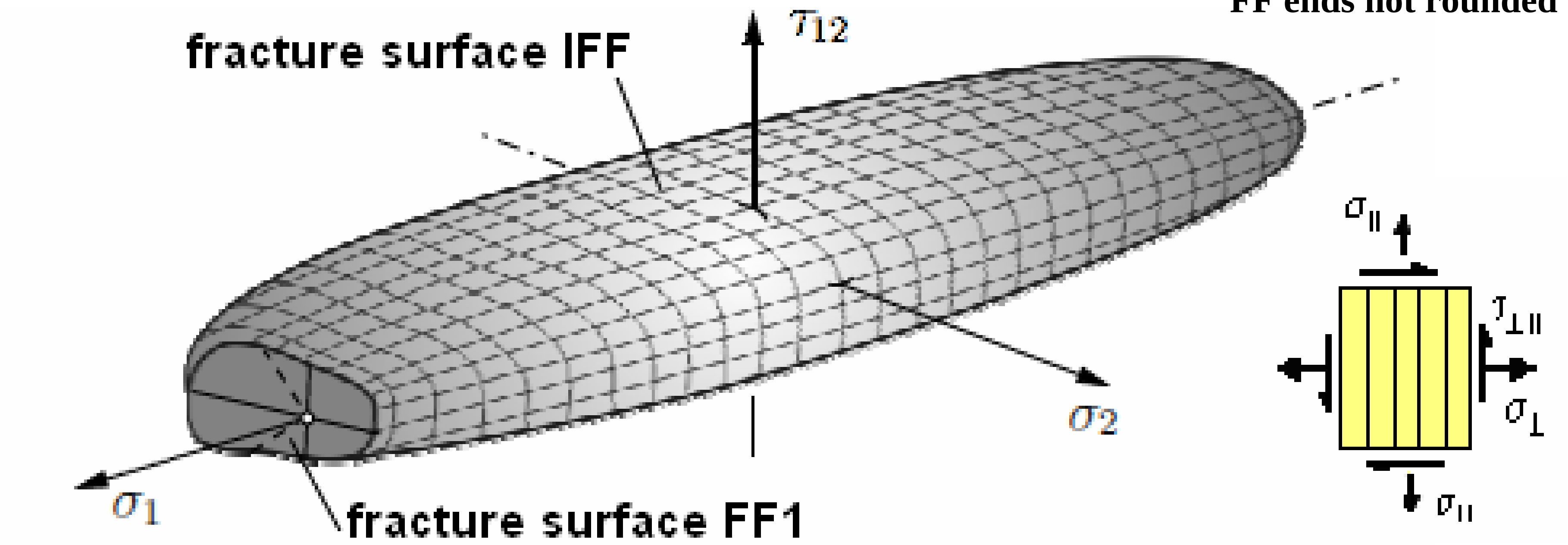
2D Stress state: lamina stresses

$$\{\sigma\} = (\sigma_1,\ \sigma_2,\ \sigma_3 = 0,\ \tau_{23} = 0,\ \tau_{31} = 0,\ \tau_{21})^T$$

7 Specific Applications to 2D UD Test Data (WWFE-I)

7.4 Fracture Surface (2D) of a UD material

FF ends not rounded

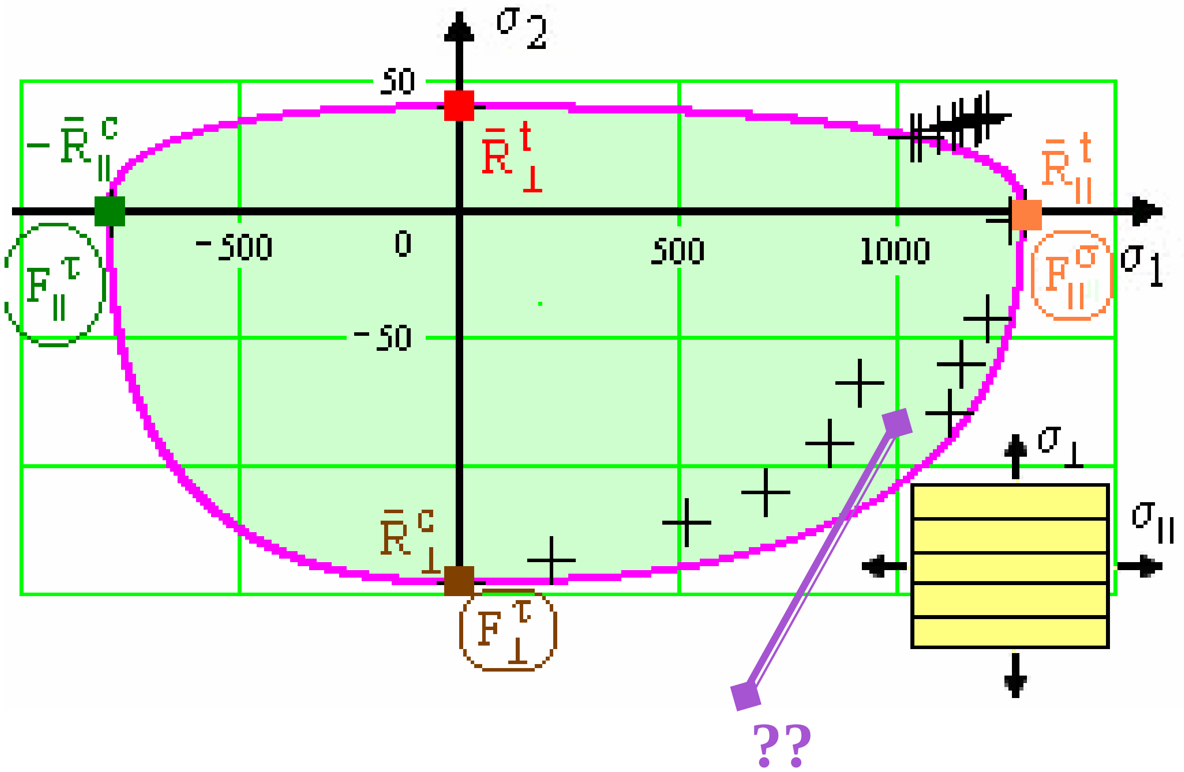


$$\left[\frac{\varepsilon_1^t \cdot E_{\parallel}}{\overline{R}_{\parallel}^t}\right]^m + \left[\frac{-\varepsilon_1^c \cdot E_{\parallel}}{\overline{R}_{\parallel}^c}\right] + \left(\frac{\sigma_2}{\overline{R}_{\perp}^t}\right)^m + \left(\frac{-\sigma_2}{\overline{R}_{\perp}^c}\right)^m + \left(\frac{|\tau_{21}|}{\overline{R}_{\perp\parallel} - b_{\perp\parallel} \cdot \sigma_2)}\right)^m = 1.$$

Figure: courtesy W. Becker

7 Specific Applications to 2D UD Test Data (WWFE-I)

7.5 Fracture Surface (2D) of a UD material $\sigma_2(\sigma_1)$



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

$$\sigma_1 = \sigma_{hoop}$$

$$\sigma_2 = \sigma_{axial}$$

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

- ***strength points were provided***
- ***test data show discrepancies***

7 Application to 2D UD Test Data (WWFE-I)

7.6 Fracture Surface (2D) of a UD material τ_{21}, σ_1

***IFF curve*,**

UD-lamina T300/BSL914C epoxy.

Corrected test data , due to non-linearly computed shear deformation angles γ .

Herewith, transformation of given stresses

$$(\sigma_1, \sigma_2, \tau_{21})$$

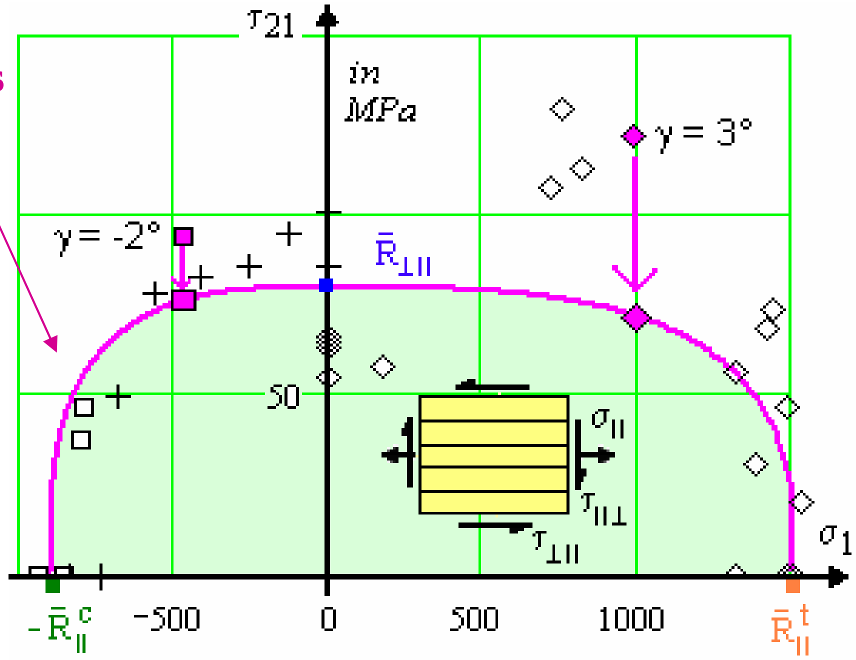
into the real lamina stresses

.

$$(\sigma_{||}, \sigma_{\perp}, \tau_{\perp||})$$

$$\{\bar{R}\} = (1500,\ 900,\ 27,\ 200,\ 80)^T, \quad m = 3.1$$

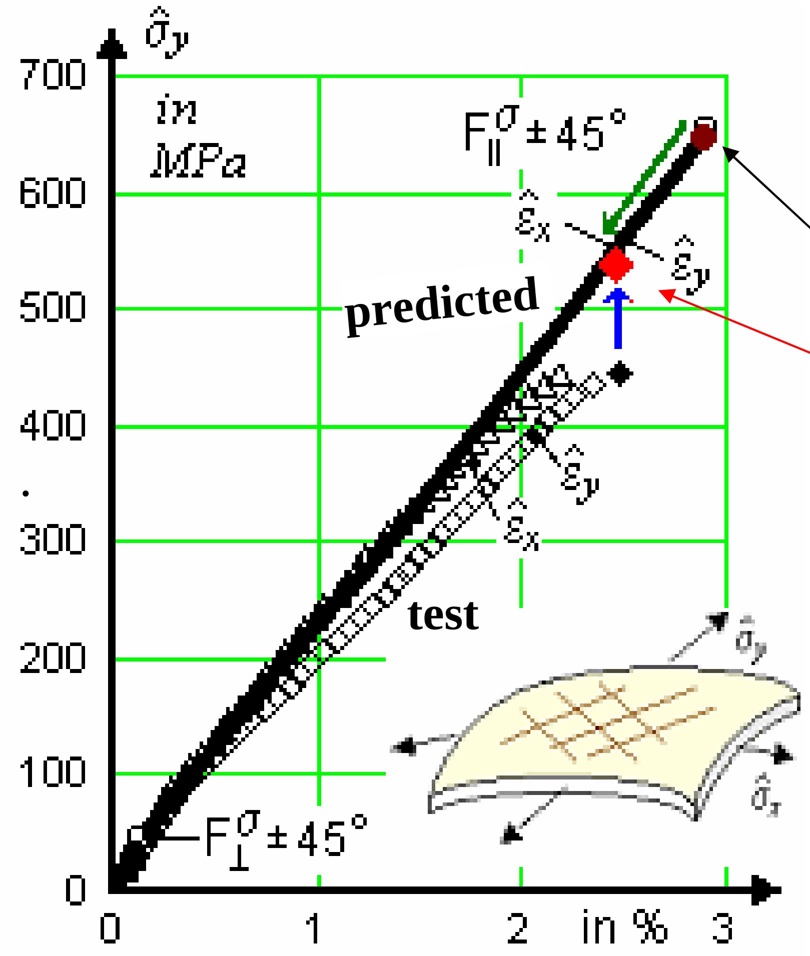
IFF envelopes



Axially ! **wound tube**

7 Application to 2D UD Test Data (WWFE-I)

7.7 Stress-strain Curve of a Laminate (2D) of a UD material



<u>Stress-strain curves</u> for $\hat{\sigma}_y : \hat{\sigma}_x = 1 : 1$

loading: internal pressure + axial tension.

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

Bulging reported in experiment.

- Final blind prediction point.
- Maximum test value *after* correction and shifting.

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

<u>Lessons learned:</u>

* test: final fracture strains and hoop strength < theory values
* test curves should lie on another (mechanics, manufacture)
* mapping quality of full theory is not judged
* checking analysis by netting theory
(applying the measured strains and stiffness) reveals:
- tensile strength value,- provided for analysis, must be lower
- test strains at fracture require a higher hoop stress → shift

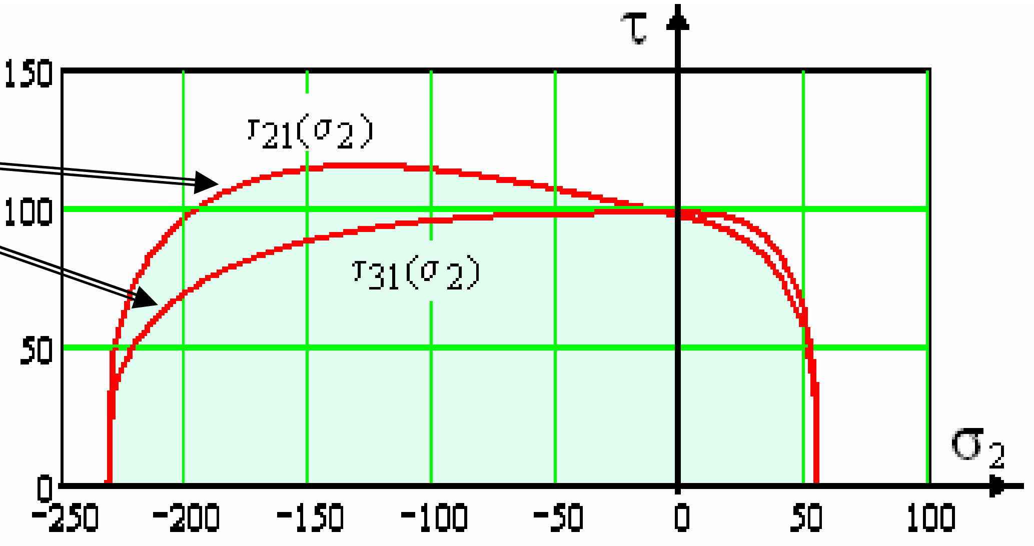
** **mapping quality very good after re-evaluation**.*

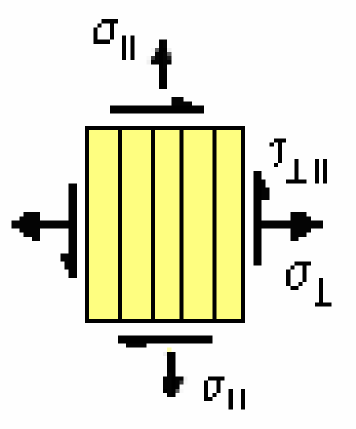
7.8 Failure Curves of a UD material $\tau_{21}(\sigma_2),\ \tau_{31}(\sigma_2),\ \tau_{21}(\sigma_1) \approx \tau_{21}(\varepsilon_1 \cdot E_{||})$

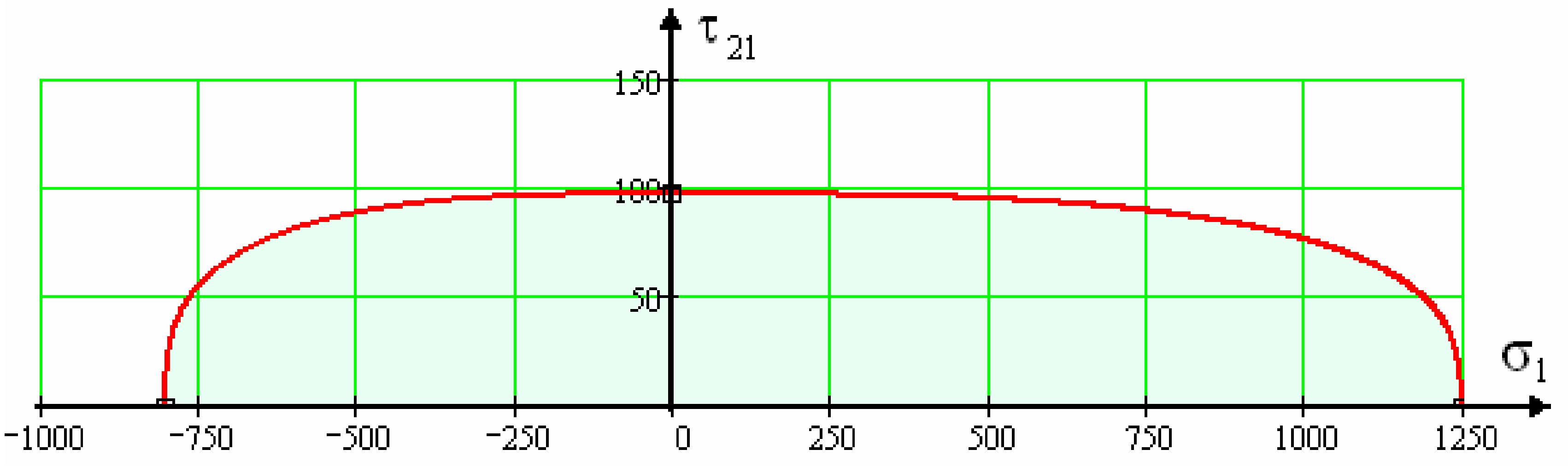
difference

Different due to a different action plane

τ_{31}, σ_2







Hydrostatischer Druck bis 1000 MPa

Wichtig für:

Hochbeanspruchte Lager,

Tragschlaufen von Hubschrauberflügeln,

Verankerung von Brücken-Spannkabeln,

U-Boot etc.

8 Application to 3D UD Test Data (WWFE-II)

8.2 General on WWFE-II

Testdaten für 12 Test Cases geliefert:

- TC1 *epoxidmatrix,*
- TC2-TC7 *UD*
- TC8-TC12 *endlosfaser-verstärkte Laminate.*

Bisherige Ergebnisse des Validierungsprozesses zeigen:

- Die Testdaten sind nicht immer klar dargestellt, zum Teil widersprüchlich bis eventuall ‘falsch‘ (vielleicht nur die Darstellung ?)
- Ihre Interpretation stellt höchste Anforderungen.

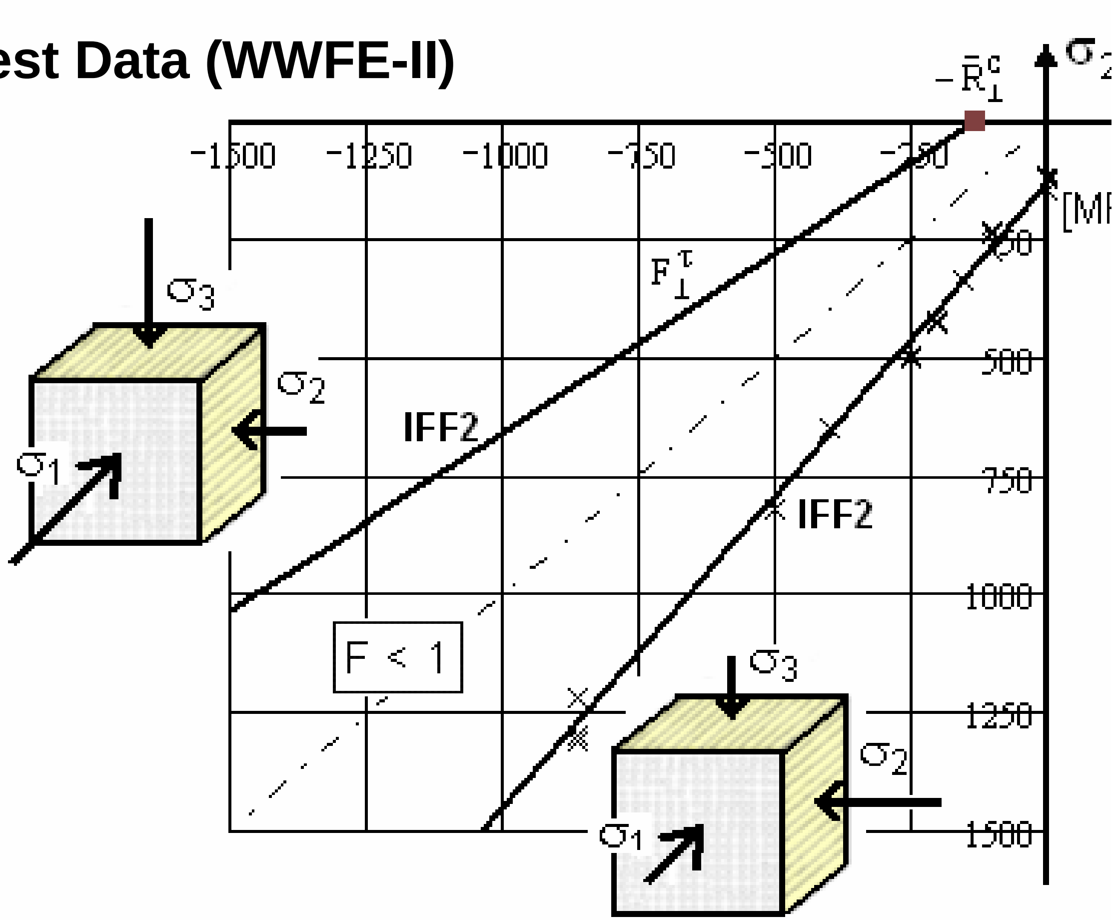
Erstes Fazit :

- Die größere Herausforderung war/ist im WWFE-II die Durchführung geeigneter Tests nebst sorgfältiger Evaluierung der Testergebnisse und nicht die Theorie
- Die Theorie benötigt man natürlich zu einer sinnvollen Evaluierung.
- Der Schwerpunkt liegt mehr in der Werkstoffwissenschaft als in angewandter Strukturmechanik.

8 Application to 3D UD Test Data (WWFE-II)

8.3 Test Case 5

UD E-glass/MY750epoxy.

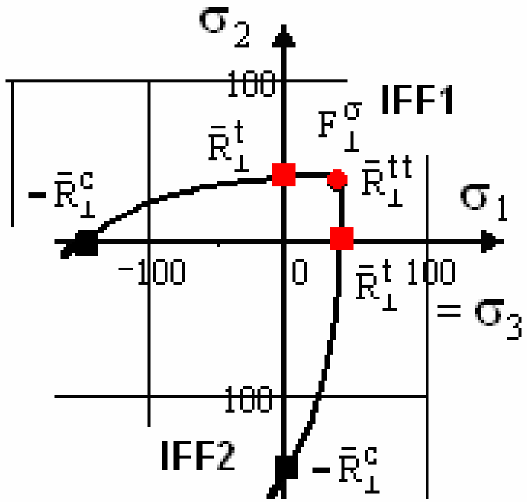


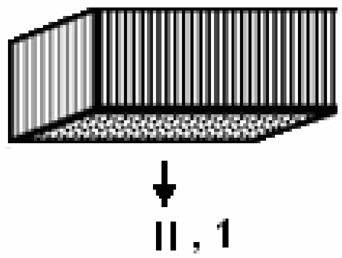
$$\{\bar{R}\} = (1280,\ 800,\ 40,\ 132,\ 73)^T\ MPa$$

$$\nu_{\perp||} = 0.28$$

$$b_{\perp\perp} = 1.16$$

$$m = 2.8,$$



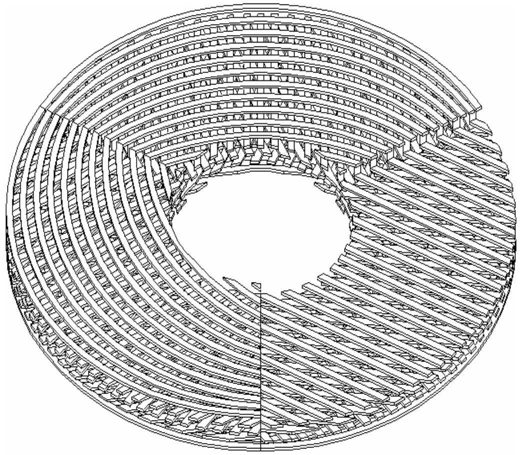


9 Material Modelling of Textiles

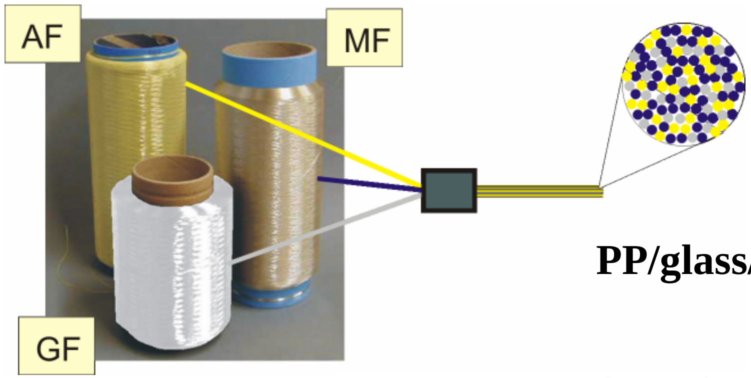
9.1a Overview on the Various Textile Composites Types

Manufacturing: pre-pregging, wet winding, RTM, ..
Filaments: glass, aramide, carbon, ceramics, ..
Matrices : thermosets, thermoplastics, ceramics,

Fibre preforms :
from ***roving, tape, weave, braid (2D, 3D), knit, stitch,*** or mixed as in a ***preform hybrid***

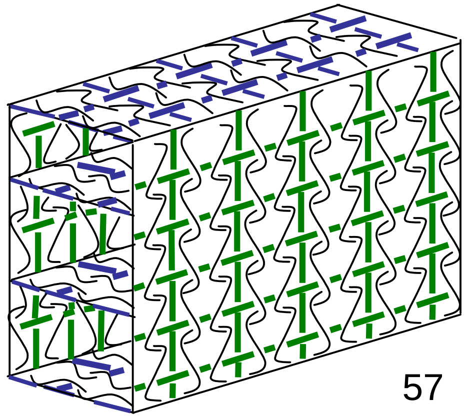


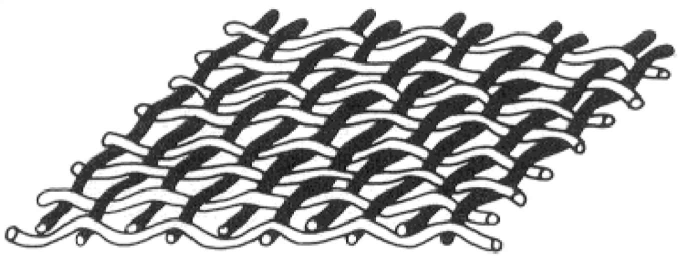
variable-axial
textile reinforcement



PP/glass/aramide

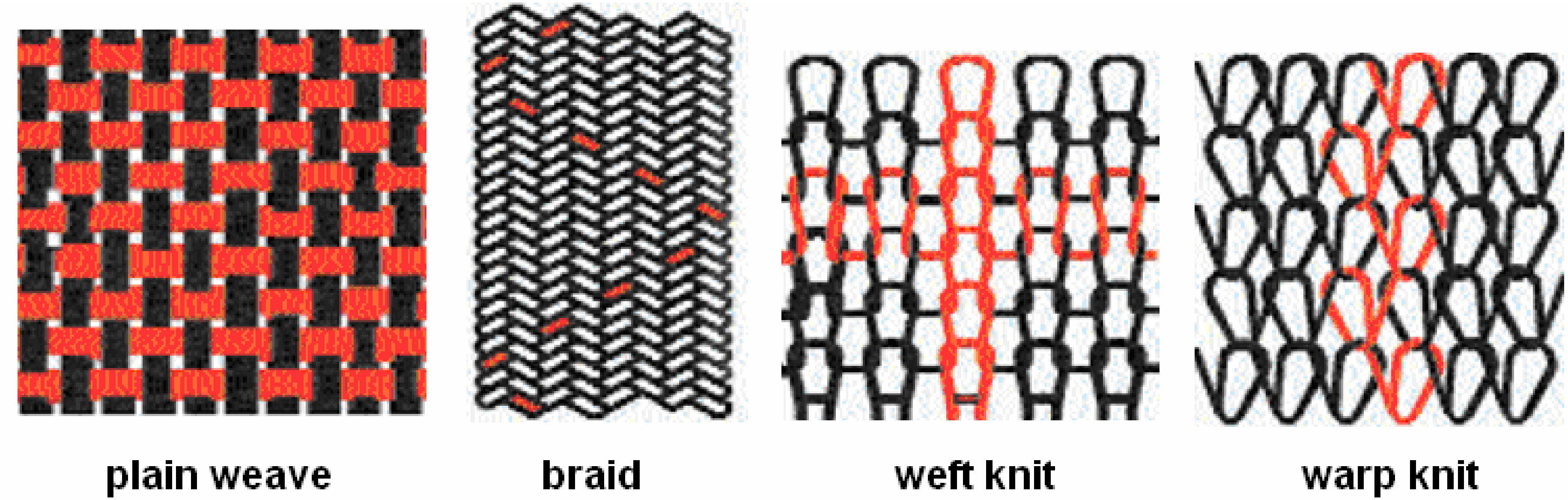
SPACER FABRICS aus textilen Hybridgarnen (GF/PP)



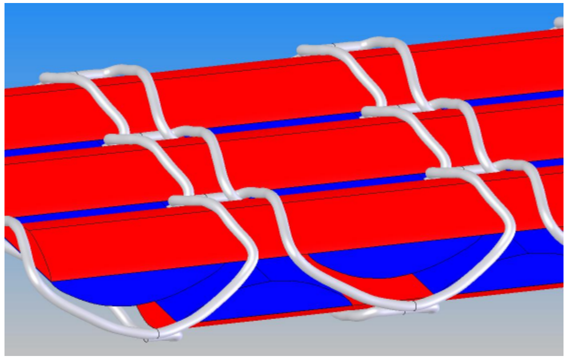


Plain weave yarn interlacing

9.1b Some Types of Fabrics (textiles)



non-crimp fabrics (NCF)



Preforms are harder to impregnate with increasing structural level

Basic layers of a laminate:

UD-layer → Non-crimp fabric layer → Plain weave layer → 3D textiles

Modelling

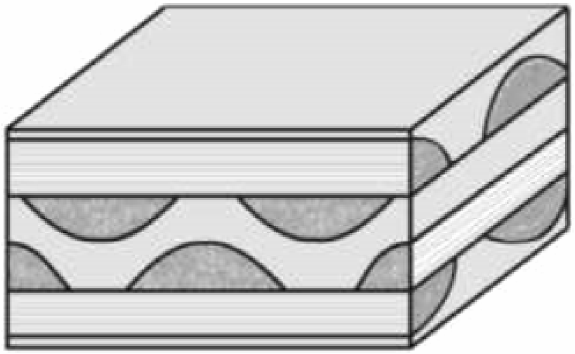
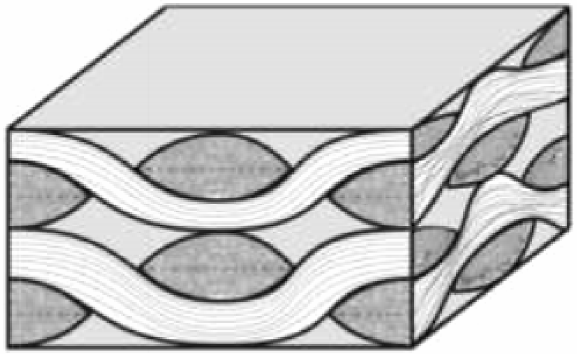
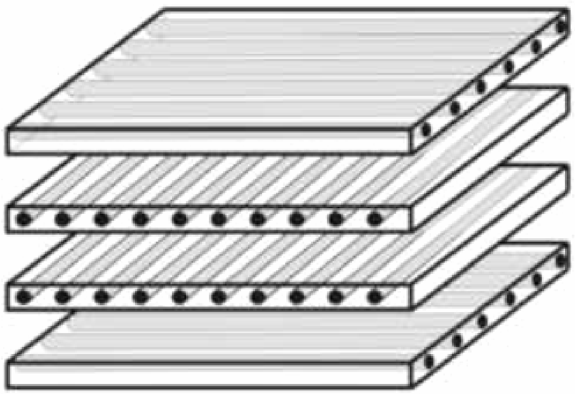
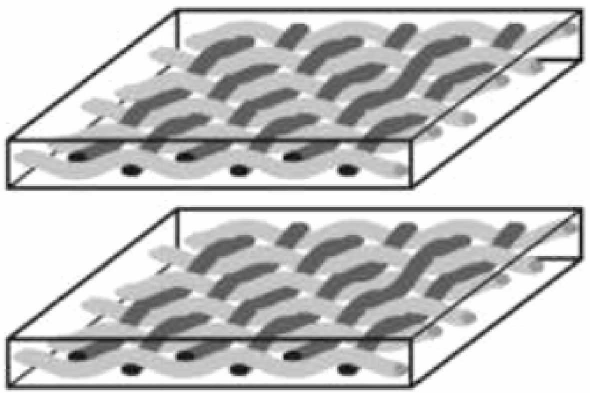
may be lamina-based, sub-laminate-based (e.g. non-crimp fabrics) or laminate-based !

- **Is performed, if applicable, *according to the distinct symmetry of the envisaged material (e.g. UD)***
- **Chosen material model *determines the number of strengths, of elasticity properties to be measured, and type of test specimen !***

textile-specific classification	composite-specific classification	
	quasi-laminar composites	non-laminar composites
2D textiles	woven fabrics braided fabrics	
3D textiles	weft-knitted fabrics non-crimp fabrics TFP structures	3D-woven fabrics 3D-braided fabrics 3D-knitted fabrics

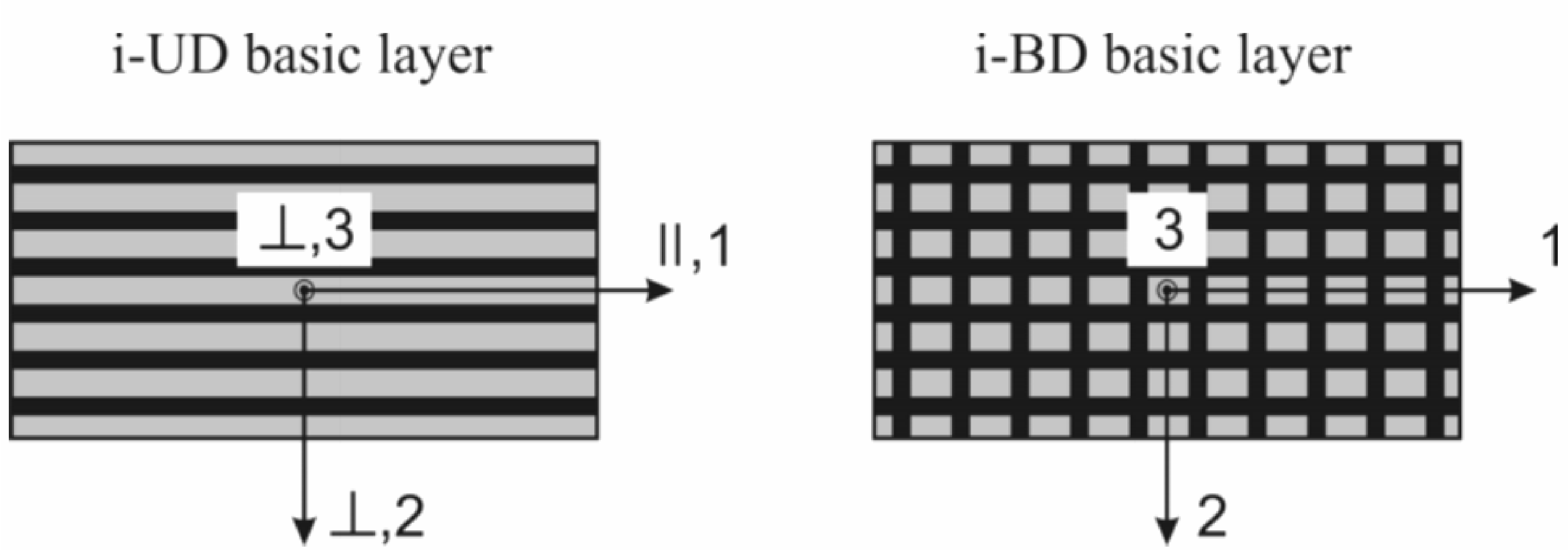
9 Material Modelling of Textiles

9.5a Decomposition of Textiles into Equivalent basic Layers

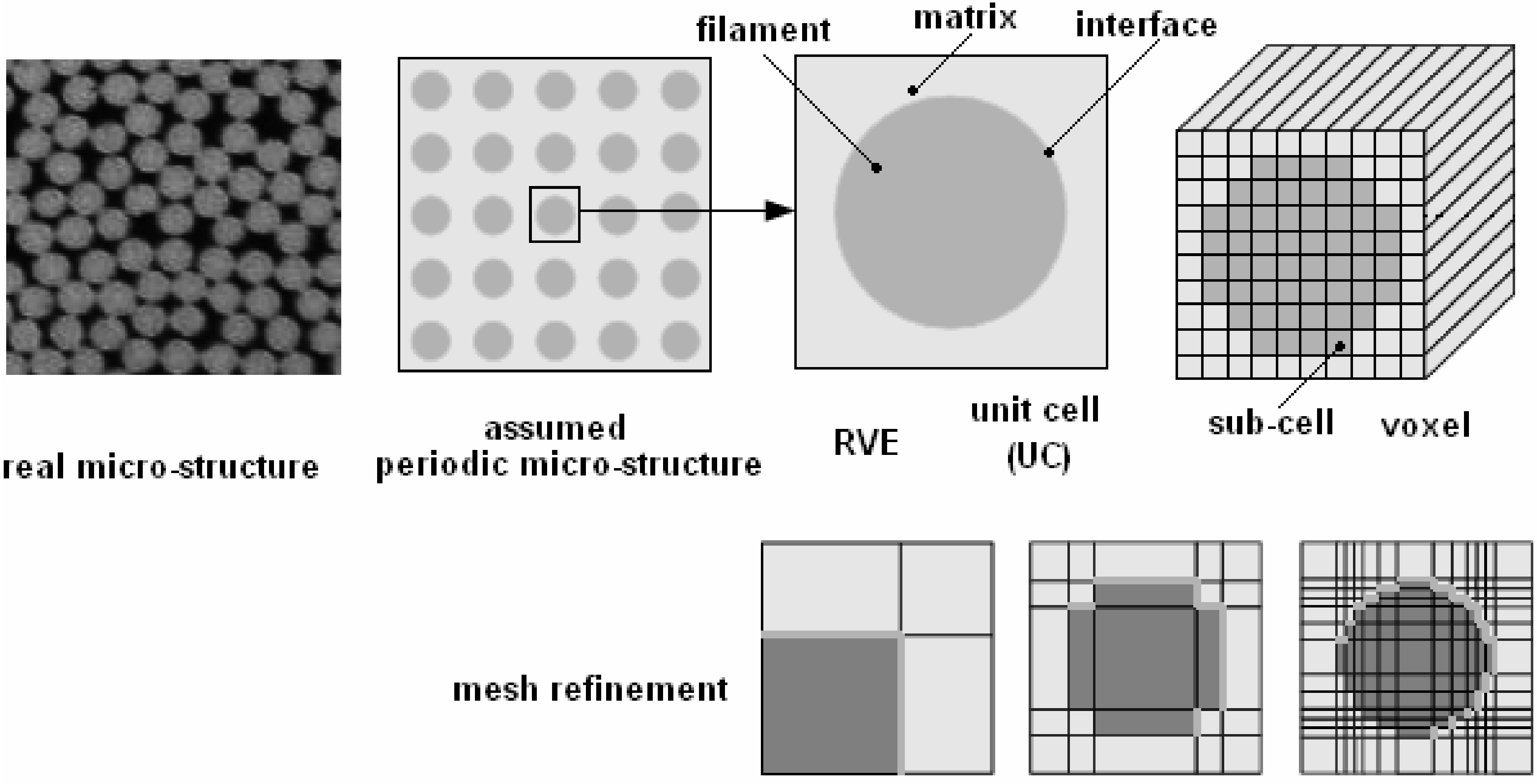
damage phenomenology	dominant discrete damage	dominant diffuse damage
geometry		
modelling as	idealised unidirectional basic layers 	idealised bidirectional basic layers 

Decomposition depends on textile architecture and damage phenomenology

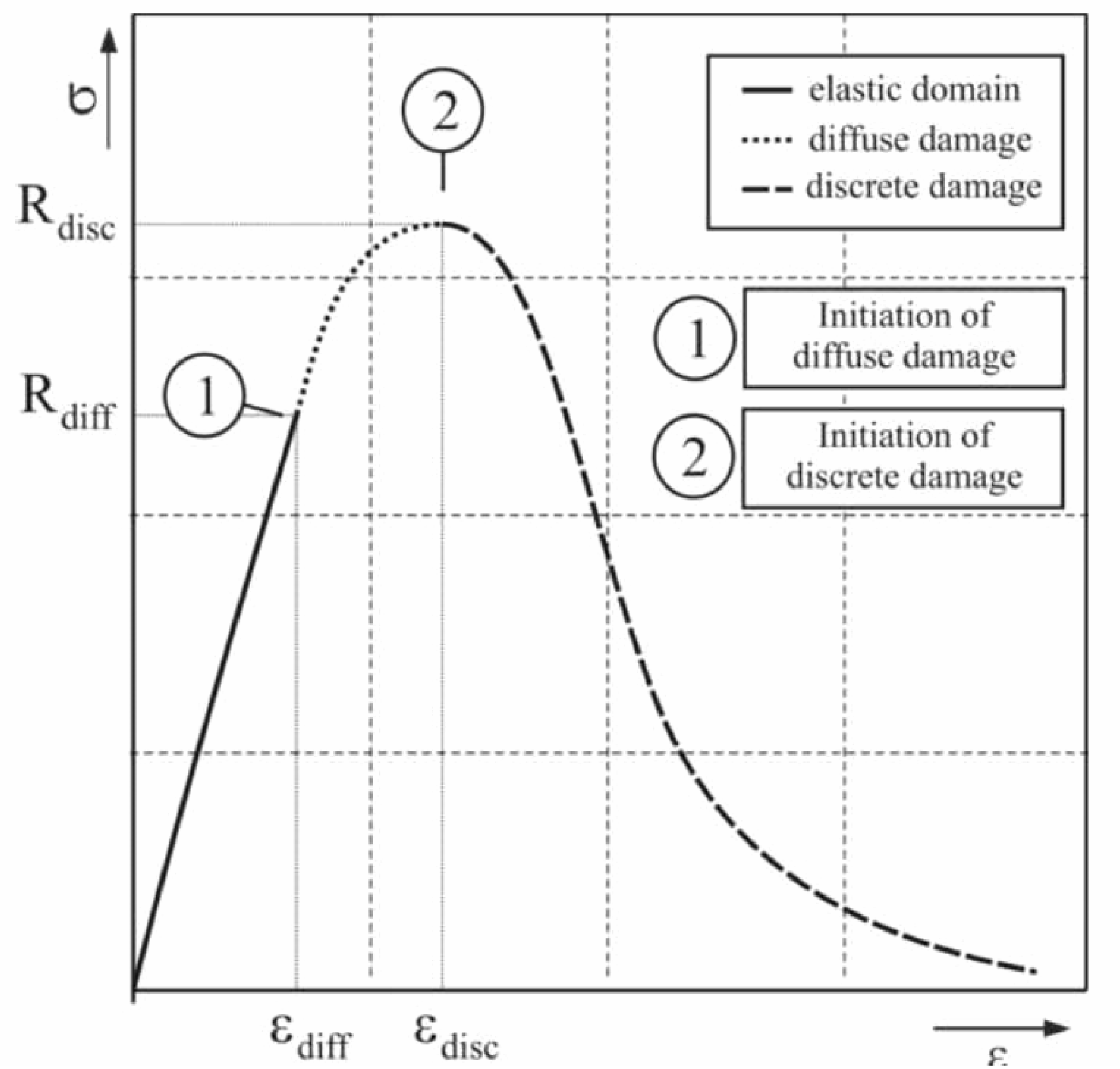
9.5b Basic Layers



9.6 Modelling of Representative Volume Elements by Sub-Cells

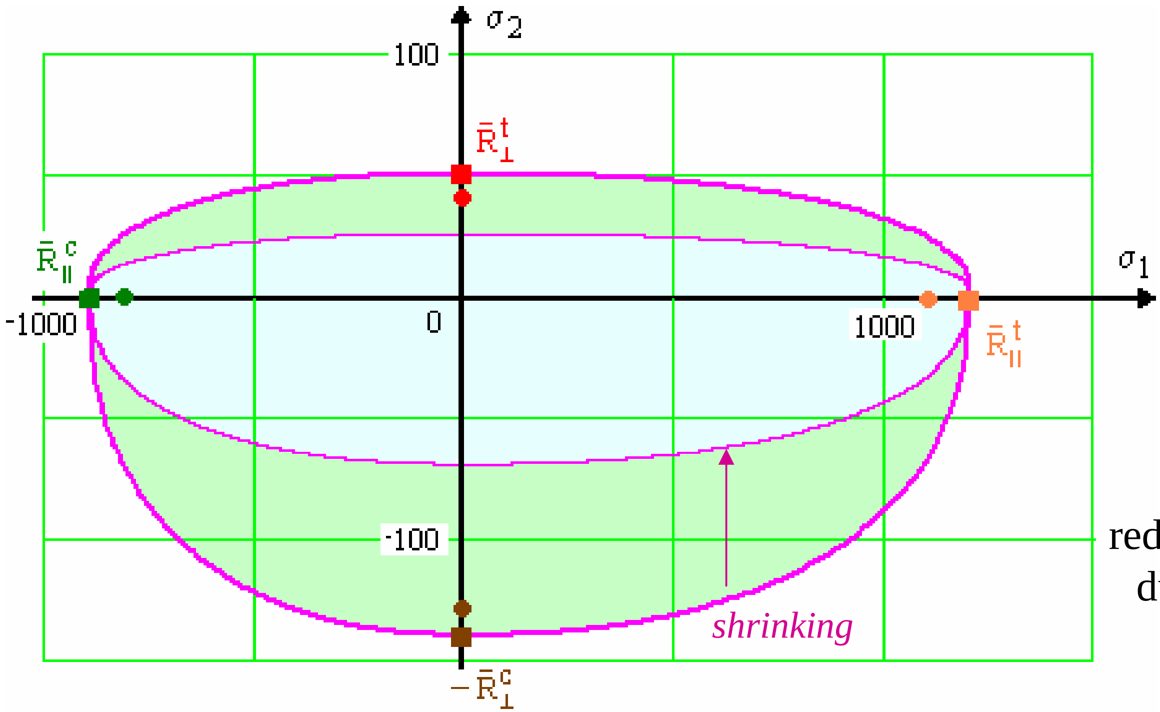


9.7 Stress-strain curve with its diffuse and discrete damage portions (Böhm, 2008)



Laminate

9.8. IFF Degradation of a quasi-laminar Lamina (non-linear structural analysis)



(Cross-Section of the 2D failure body)

originally and after **shrinking** due to a

distinct IFF degradation.

reduction of strengths due to degradation

IFF failure curve

$$\left(\frac{\sigma_2}{\bar{R}_\perp^t}\right)^m + \left(\frac{-\sigma_2}{\bar{R}_\perp^c}\right)^m + \left(\frac{|\tau_{21}|}{\bar{R}_{\perp\parallel} - b_{\perp\parallel}\cdot\sigma_2)}\right)^m = 1$$

Points, marked in the figure, are depicted here to highlight effects that are essential for

the initial failure load (validity of linearity assumption) and

the final failure load (laterally shrinking failure body)

On the Validity of Strength Failure Conditions

Even in plain (smooth) stress regions a strength condition can be only a necessary condition which may be not sufficient for the prediction of 'onset of fracture', i.e. for the *in-situ lateral strength in an embedded lamina*, see e.g. [Flaggs-Kural 1982].

A condition must be necessary + sufficient !

And, when applying test data from (*isolated* lamina) tensile coupons to an *embedded* lamina in a laminate, one has to consider that tensile coupon tests deliver test *results of weakest link type*.
An embedded or even an only one-sided constraint lamina, possesses *(in-situ) redundant behaviour.*

In case of discontinuities such as notches with steep stress decays only a *toughness + characteristic length-based energy balance condition* may form a sufficient fracture condition.

Attempts to *link* 'onset of fracture/cracking' *prediction methods* for structural components are actually undergone, see e.g. [Leguillon 2002].