CCeV-Thementag, St. Martin im Innkreis, CoLT Prüf und Test GmbH
Zuverlässigkeit und Lebensdauer von CFK-Bauteilen
September 8, 2016 ; 20 + 5 min

Static Failure and Fatigue Failure of UD ply-composed Structural Parts *(novel treatment)*

1 Introduction to Static and Fatigue Design
2 Cuntze’s Failure-Mode-Concept-based Strength Criteria
3 Cuntze’s Fatigue Life Estimation Method
4 Generation and Interpretation of UD Haigh Diagrams
5 Steps of the Fatigue Life Prediction Method Proposed
Conclusions

Example: Transversely-isotropic UD-CFRP

Results of a time-consuming, never funded „hobby“

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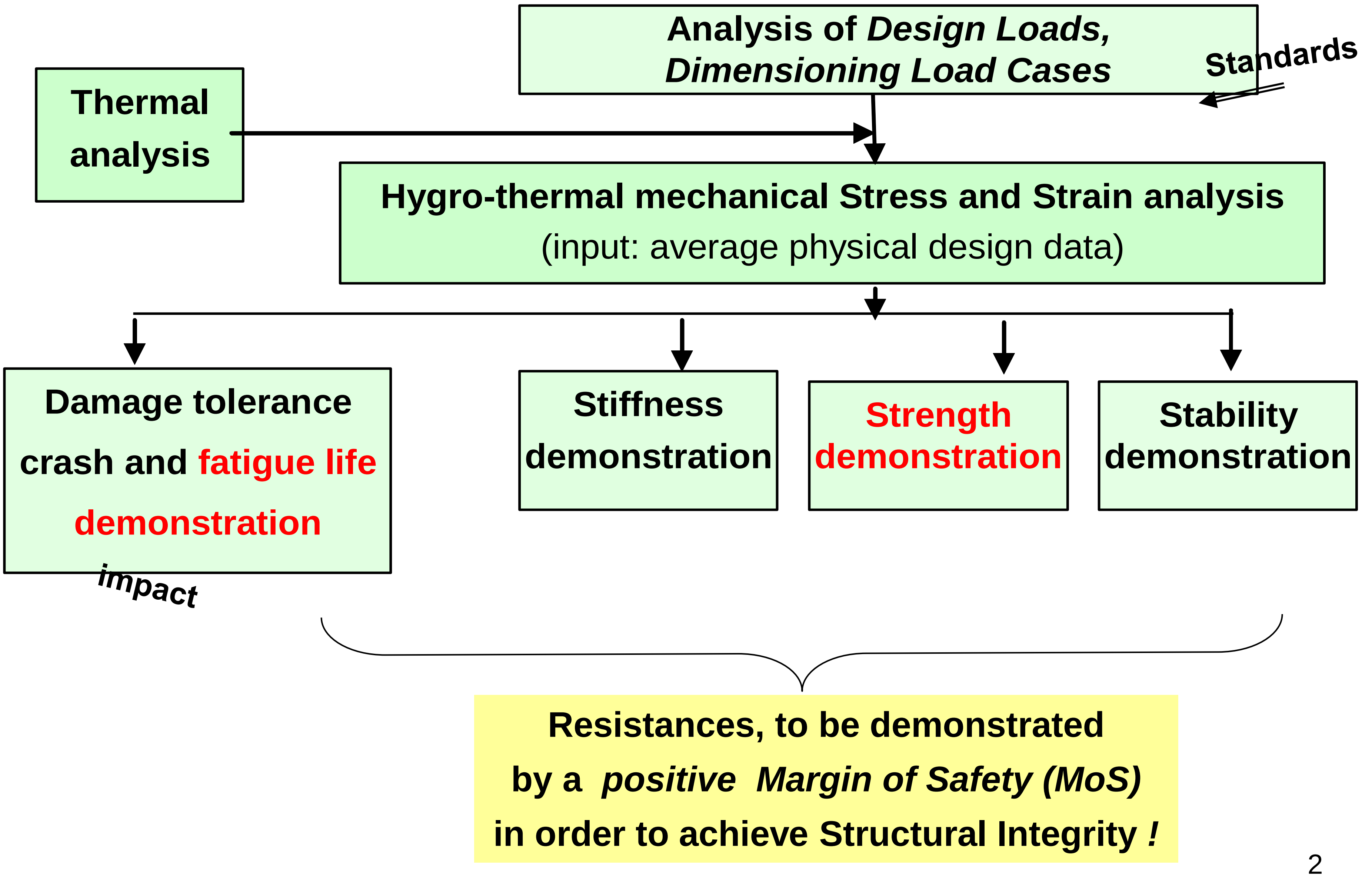
linked to Carbon Composite e.V.(CCeV) Augsburg, heading the Working Groups „Engineering“ + „Modeling Fiber-Reinforced Concrete“

Flow Diagram: Structural Design and Design Verification



Analysis of *Design Loads, Dimensioning Load Cases*

Standards

Thermal analysis

Hygro-thermal mechanical Stress and Strain analysis
(input: average physical design data)

Damage tolerance crash and fatigue life demonstration

impact

Stiffness demonstration

Strength demonstration

Stability demonstration

Resistances, to be demonstrated
by a *positive Margin of Safety (MoS)*
in order to achieve Structural Integrity *!*

Verification Levels of the Structural Part

- **Stress**, locally at a critical material ‘point‘: **continuumsmechanics, strength criteria**
  verification by a *basic strength* or a *multi-axial failure stress state*
  Applied stresses are local stresses

- **Stress concentration** at a notch (stress peak at a joint): **notch mechanics**
  verification by a *notch strength (usually Neuber-like, Nuismer, etc..)*
  ‘Far‘-field stresses are acting and are not directly used in the notch strength analysis

- **Stress intensity** (delamination = crack): **fracture mechanics**
  verification by a *fracture toughness (energy –related)*
  Applied stresses are ‘far‘-field stresses.(far from the crack-tip)

gilt statisch wie zyklisch

Design Verification by theoretical prediction

STATIC :

- Reserve Factor is load-defined :

$$RF = \frac{\text{Predicted Failure Load}}{j \cdot \text{Design Limit Load}} > 1.$$

Material Stressing Effort : *Eff = 100% if RF = 1* (Anstrengung)

Material Reserve Factor :

$$f_{\mathrm{Res}} = \frac{\text{Strength Design Allowable}}{\text{Stress at } j \cdot \text{Design Limit Load}} > 1.$$

if linear situation, then : $f_{\mathbf{Res}} = RF = 1 / Eff$

Demonstration of MoS > 0 or RF = MoS + 1 > 1

CYCLIC :

$$RF_{life} \approx \frac{\text{Predicted Lifetime}}{j_{life} \cdot \text{Design Limit Lifetime}} > 1.$$

- Determination of Inspection time
- Determination of Replacement time

Some Definitions *What is ??*

Material : homogenized (smeared) model of the envisaged complex material which might be a material combination

Failure : structural part does not fulfil its functional requirements such as FF = fiber failure, IFF = inter-fiber-failure (matrix failure), leakage, deformation limit, delamination size limit, …)

Fatigue : process, that degrades material properties

Damaging (not also damage, as used in English literature) : process wherein the results, the damaging portions, finally accumulate to a damage size such as a macro-scopic delamination.

The accumulation tool usually is *Miner‘s Damaging Accumulation Rule* (model)

Damage : sum of the accumulated damaging or an impact failure, that is judged to be critical. Then, *Damage Tolerance Analysis* is used to predict damage growth under further cyclic loading.

State of the Art: **Static** **Strength Analysis** ***of UD laminas*** **represent 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 !'

(was for the transversely-isotropic UD materials , only)

Method of the World-Wide-Failure-Exercises (since 1991**):**

Part A of a WWFE: ***Blind Predictions on basic strength data***

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, no notch)

State of the Art : Cyclic Strength Analysis of UD Laminas (plies)

- **No Lifetime Prediction Method available, applicable to any Laminate**
- **Procedures base – as with metals – on stress amplitudes and mean stress correction**
- **Procedures base on specific laminates and therefore cannot be generally applied**
- **Presently: Engineering Approach:**

  ***Static Design Limit Strain* of $\varepsilon < 0.3\%$,** negligible matrix-microcracking.

  Design experience proved: No fatigue danger given

- **Future : *Design Limit Strain* shall be increased** (EU-project: MAAXIMUS)

  Beyond $\varepsilon \approx 0.5\%$ *first filament breaks , diffuse matrix-microcracking*

  ***changes to a discrete localized* one .**

Usually, *fiber-dominated laminates*
are used in high-stress applications

⇨

Fig. 1: Isolated (generates hardening curve) and embedded (softening curve part) of the UD material

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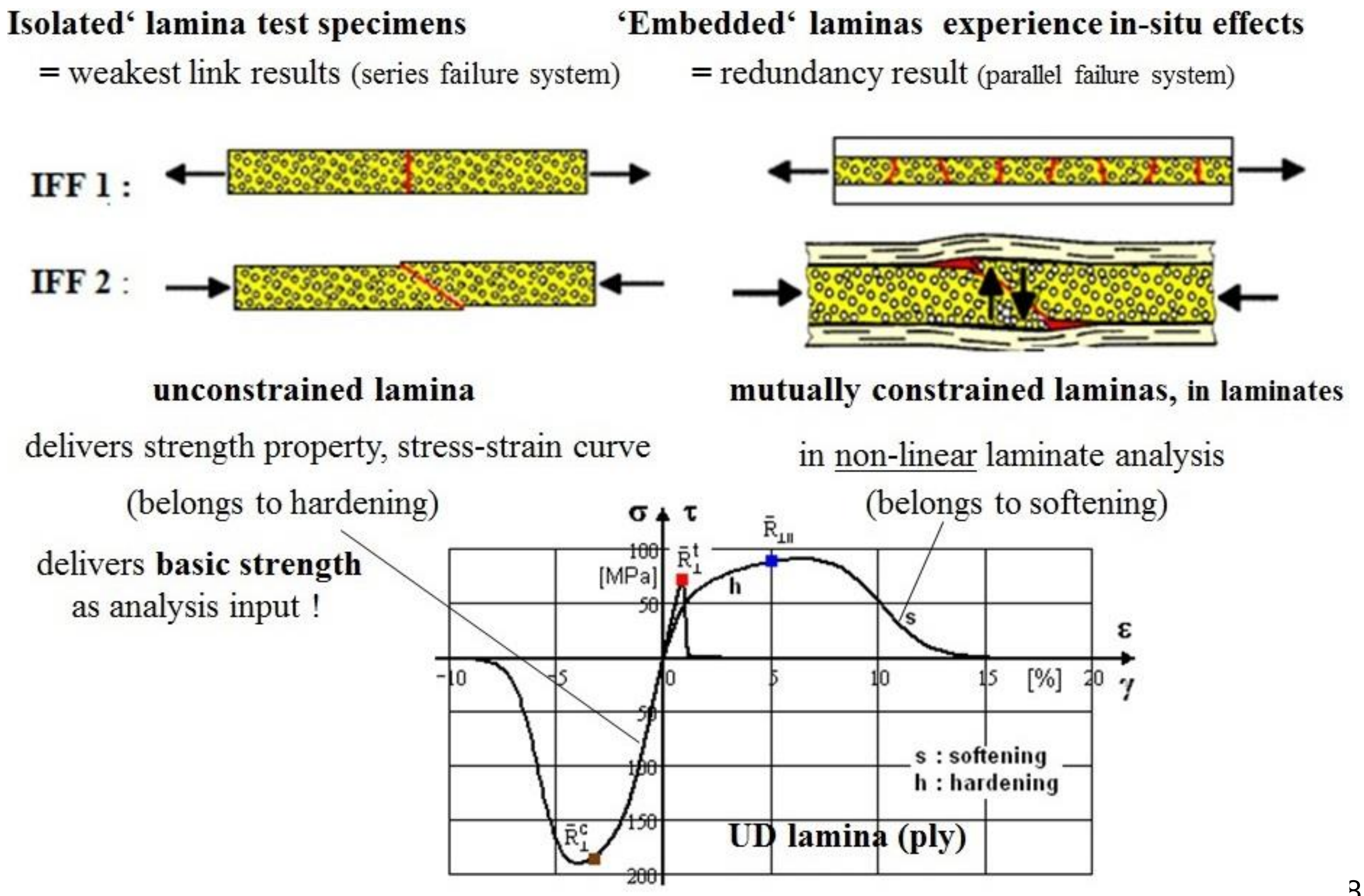

Isolated' lamina test specimens

= weakest link results (series failure system)

'Embedded' laminas experience in-situ effects

= redundancy result (parallel failure system)

unconstrained lamina

delivers strength property, stress-strain curve

(belongs to hardening)

mutually constrained laminas, in laminates

in <u>non-linear</u> laminate analysis

(belongs to softening)

delivers **basic strength**

as analysis input !

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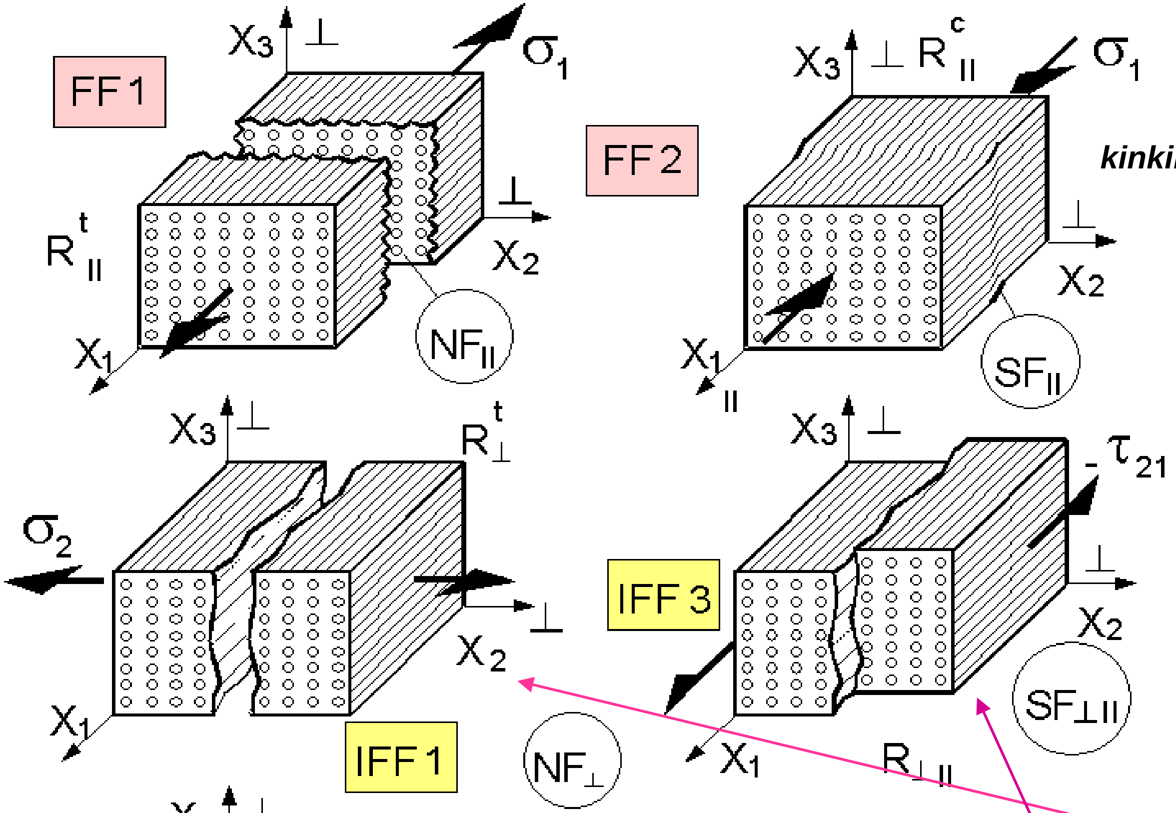
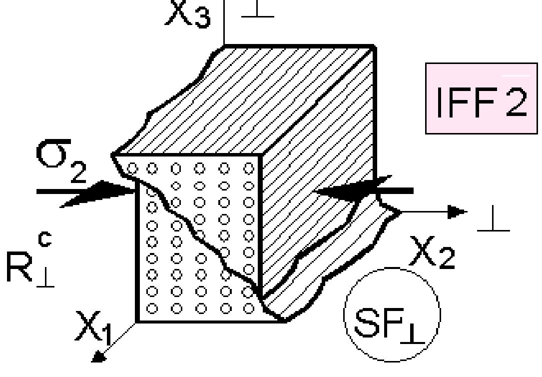
Observed Fracture ‘Planes‘: Transversely-isotropic UD Material

[Cun04]

t = tension

c = compression





wedge type

- ▶ 5 Fracture modes exist

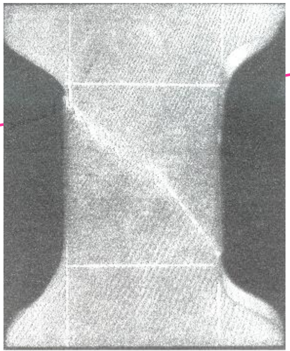
= 2 FF (Fiber Failure)
+ 3 IFF (Inter Fiber Failure)

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

from these observations follow ..

NF := Normal Fracture

SF := Shear Fracture



Basic Features of the author‘s Failure-Mode-Concept (FMC)

and a Confirmation that transversely-isotropic UD Materials exhibit a 5-fold material symmetry characteristic = 5 Strengths, 5 Failure Modes

---

- **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 !!

Consequently, this separation requires :

An interaction of all 5 Modal Failure Modes !

Cuntze‘s Set of Modal 3D UD Strength Failure Conditions (criteria)

Cuntze = Mises under the UD criteria

Invariants replaced by their stress formulations

strains from FEA

[Cun04, Cun11]

FF1 $Eff^{\|\sigma} = \breve{\sigma}_1 / \bar{R}^t_{\|} = \sigma^{\|\sigma}_{eq} / \bar{R}^t_{\|}$, $\breve{\sigma}_1 \cong \varepsilon^t_1 \cdot E_{\|}$ *

FF2 $Eff^{\|\tau} = -\breve{\sigma}_1 / \bar{R}^c_{\|} = +\sigma^{\|\tau}_{eq} / \bar{R}^c_{\|}$, $\breve{\sigma}_1 \cong \varepsilon^c_1 \cdot E_{\|}$

2 filament modes

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

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

3 matrix modes

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

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 :

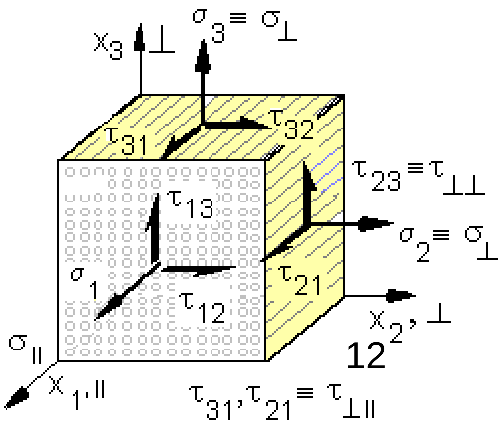
$$Eff^m = (Eff^{\|\tau})^m + (Eff^{\|\sigma})^m + (Eff^{\perp\sigma})^m + (Eff^{\perp\tau})^m + (Eff^{\perp\|})^m = 1$$

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

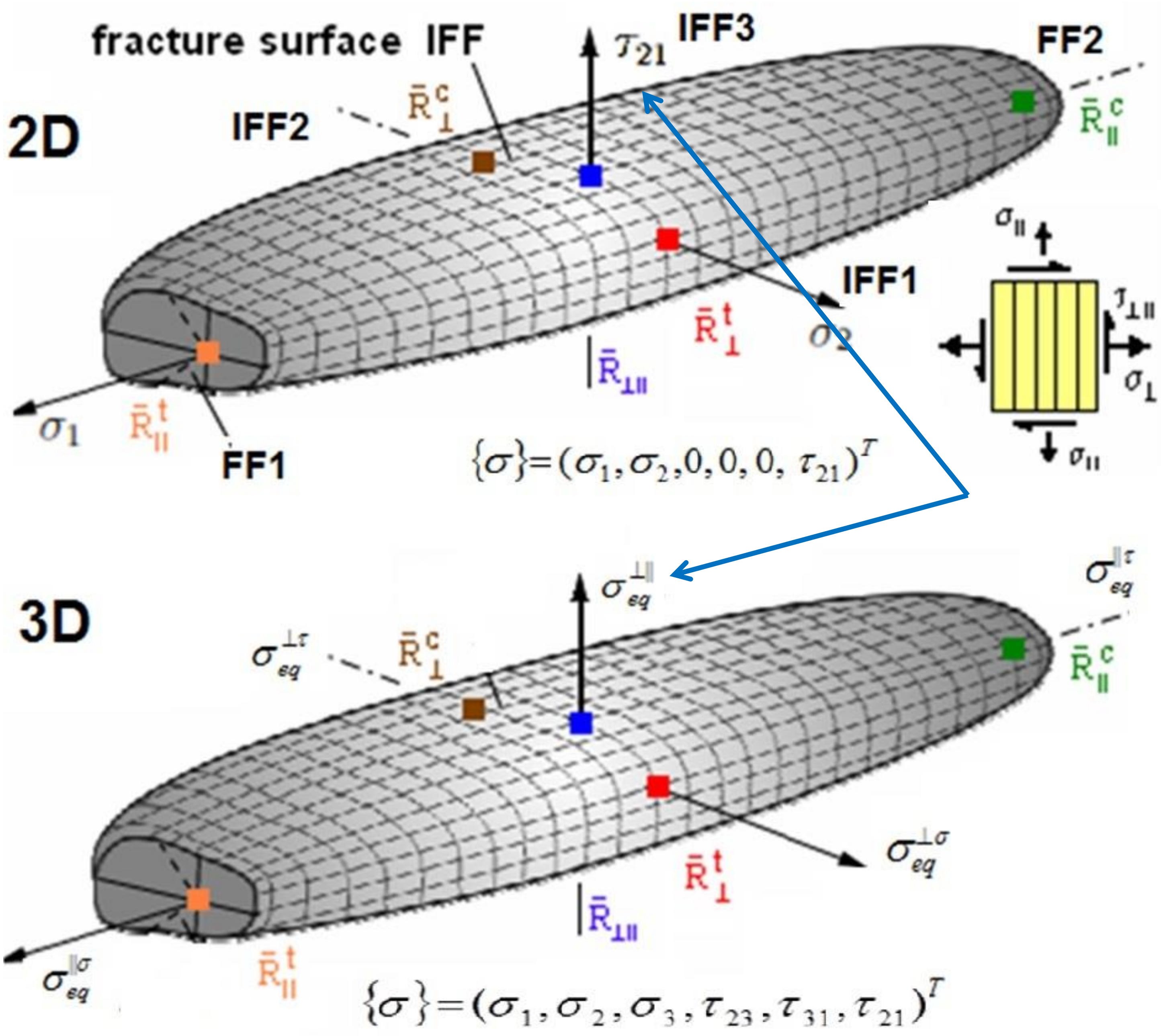
Typical friction value data range: $0.05 < \mu_{\perp\|} < 0.3, \quad 0.05 < \mu_{\perp\perp} < 0.2$

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

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



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



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

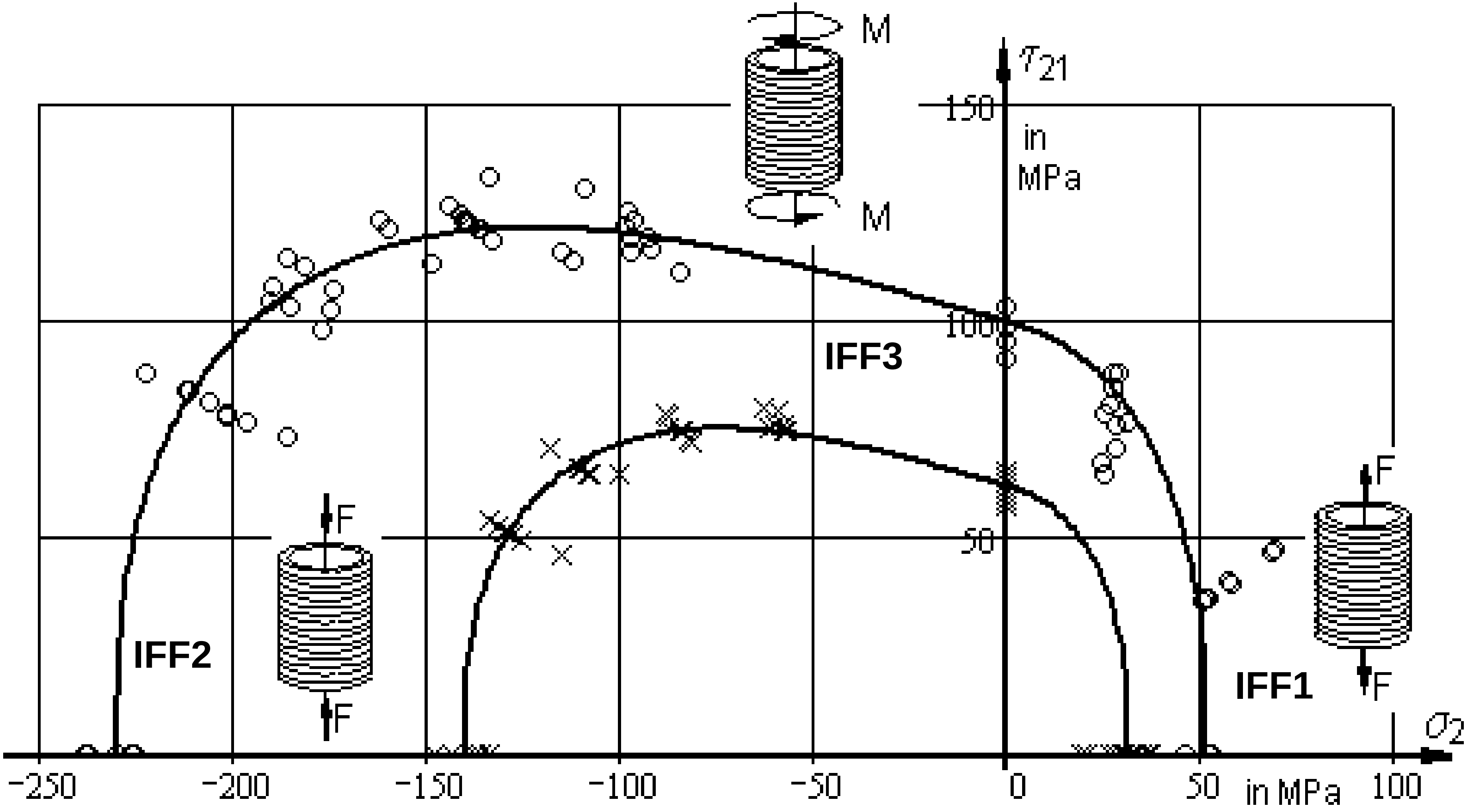
$$\{\sigma\}=(\sigma_1,\sigma_2,\sigma_3,\tau_{23},\tau_{31},\tau_{21})^T$$

Self-explaining, symbolic Notations for Strength Properties

		Fracture Strength Properties									
	loading	**tension**			**compression**			**shear**			
	direction or **plane**	1	2	3	1	2	3	12	23	13	
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}	**friction**
5	**UD**	$R_{\parallel}^{t}$ 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	$\mu_{\perp\perp}, \ \mu_{\perp\parallel},$
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}	$\mu_{W3}, \ \mu_{F3}, \ \mu_{WF}$
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	*(UD, turned direction)*
2	**isotropic matrix**	R_m SF	R_m SF	R_m SF	*deformation-limited*			R_M^τ	R_M^τ	R_M^τ	μ
		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	μ

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

IFF Cross–section of the Fracture Failure Body (surface)



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> ***„Fatigue is the black art,***
>
> ***to produce financial black holes“***
>
> [J. Draper]

Schädigungstreiber bei sich duktil und spröd verhaltenden Werkstoffen

- **Duktiles Werkstoffverhalten** (Beispiel: isotrope Metalle)

  1 Mechanismus = "Schubspannungsgleiten"

  passiert unter allen zyklischen Beanspruchungen:

  Zugspannungen, Druckspannungen, Schub- und Torsionsspannungen !

  Deswegen kann dieser einzige Mechanismus 'Schubspannungsbasiertes Gleiten' mit einer einzigen Fließbedingung beschrieben werden!

- **Sprödes Werkstoffverhalten bei isotropen Werkstoffen**

  ***2** Schädigung erzeugende **Mechanismen** wirken*

  (ingenieurmäßige Berücksichtigung durch sog. Mittelspannungskorrektur)

- **Sprödes Werkstoffverhalten bei UD- Werkstoffen**

  ***5** Schädigung erzeugende **Mechanismen** wirken*

  (Ansätze mit und ohne Mittelspannungskorrektur)

Was sind die benötigten zyklischen Größen?

- Wöhlerkurven $R = const = \sigma_{unter} / \sigma_{ober}$
- Schädigungsakkumulationshypothese
- Quantifizierte Schädigungs‘portionen‘ (-inkremente)

Dazu Anwendbarkeit der statischen Festigkeitshypothesen, wenn die

Statischen Festigkeitswerte **durch**

Restfestigkeitswerte für eine bestimmte Lebensdauer

ersetzt werden.

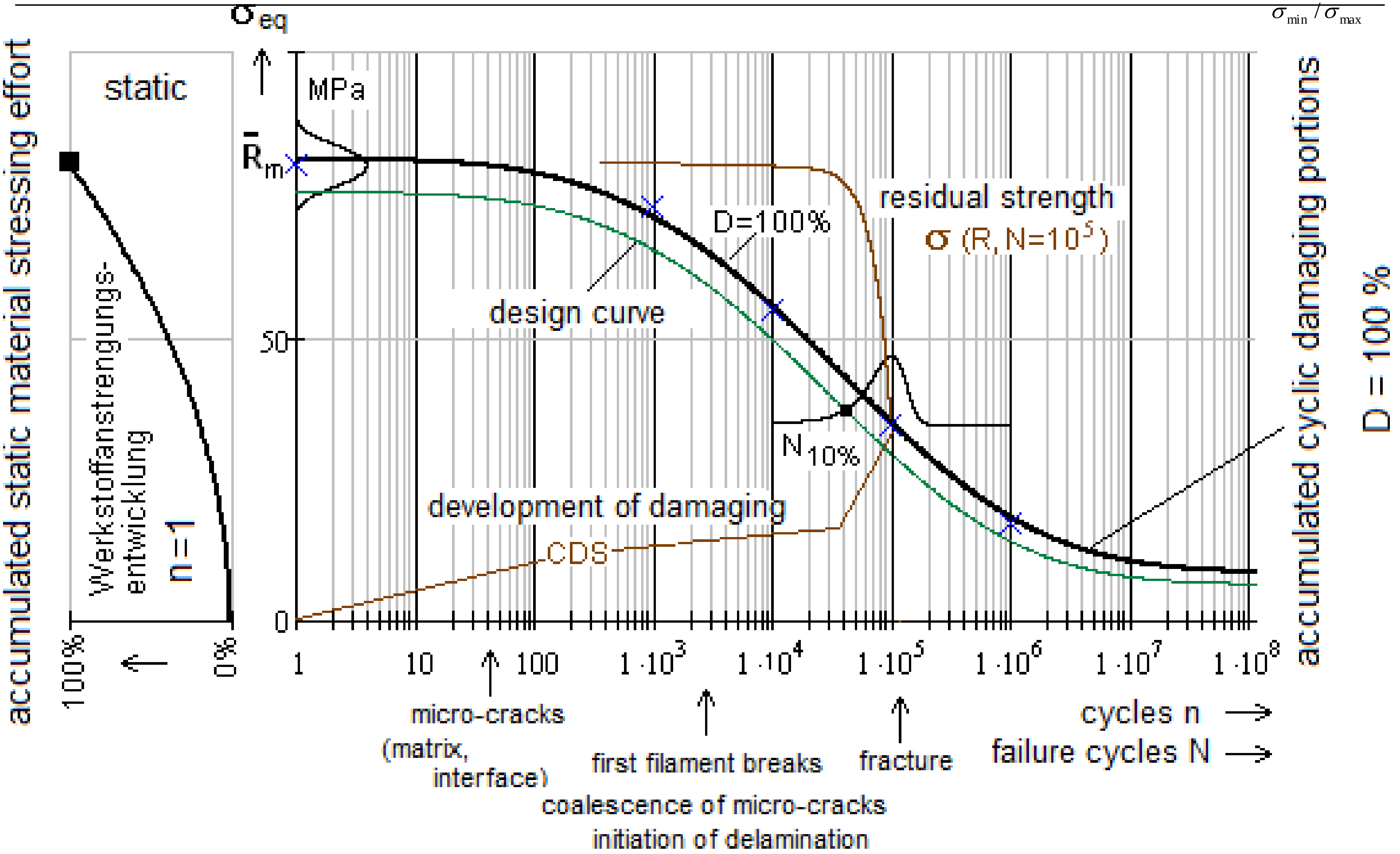
Statische Anstrengungssumme *Eff* (material stressing effort)

wird durch

Zyklische Schädigungssumme *D*

ersetzt !

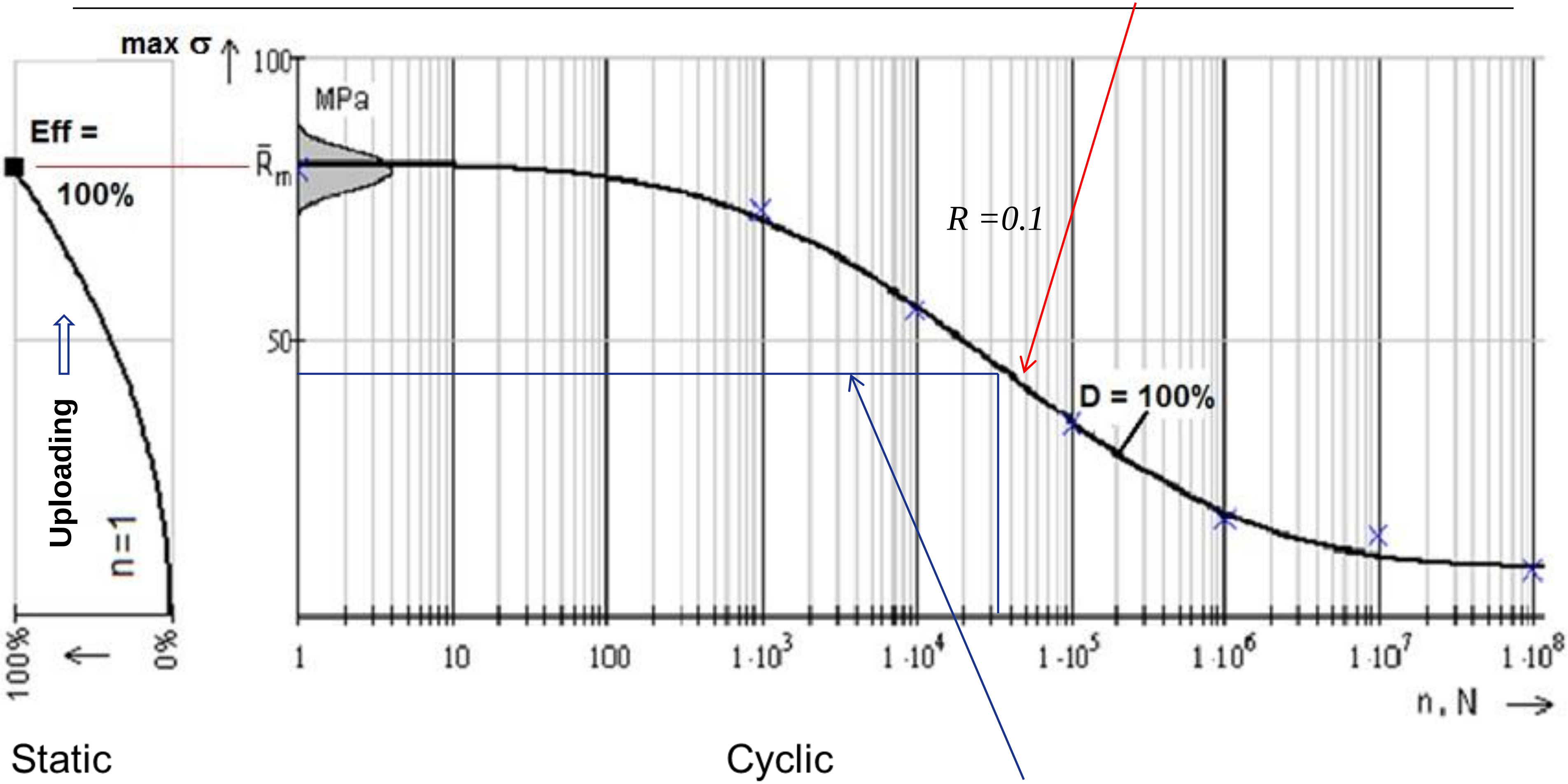
ber failure mode, D = sum of accumulated damaging portions, CDS = characteristic damaging state; Eff = material stressing effort (“Werkstoff-Anstre



FF:= fibre failure. IFF:= Inter Fibre Failure

CDS:= characteristic damage state at the end of diffuse damaging

Static and cyclic development of damaging, S-N-curve



Static

R_m basic strength

Cyclic

residual strength $\sigma(R,N)$

Analogous limits of the material capacities :

- Static : material stressing effort Eff = 100 %
- Cyclic : material damaging sum D = 100 %

For brittle behaving materials it is advantageous to use $max\sigma \equiv R_m$ instead of $\Delta\boldsymbol{\sigma}$

Parameter-Weibull-Ansatz – *allgemeine Form*

$$\sigma_{\max}(n) \quad = c_1 + (c_2 - c_1) / \exp\left(\frac{\log(N)}{c_3}\right)^{C_4}.$$

$$\log(N) = c3 \cdot [\ln(\frac{c_2 - c_1}{\sigma_a - c_1})]^{1/C4}$$

Deutsche akademische Forschergruppe ist seit fast 6 Jahren aktiv auf dem vereinbarten aussichtsreichsten gemeinsamen Nenner *physikalisch-basiert (Versagensmodi), schicht-orientiert.*

Ziel: Versagensmodus-basierte Lebensdauer-Vorhersagemethode

Schritte bei der Lebensdauerabschätzung

1 Input

Betriebsbelastungen: Last-Zeit-Kurven (Modellierung mit rain flow, ..)

Sicherheitskonzept: Design to Life **j_{Life} = 3 – 4**

2 Übertragung der Betriebsbelastungen in Beanspruchungen (Spannungen) mittels Strukturanalyse)

3 Bereiche der Ermüdungsanalyse

LCF: high stressing,

HCF: intermediate stressing

VHCF: low stressing and strains (SPP1466)

4 Erfassung der Betriebsbelastung

Zeitbereich: Zyklus-für-Zyklus oder Kollektiv-für-Kollektiv (weniger Rechenaufwand)

Frequenzbereich: Lastspektren (Verlust der Last-Reihenfolge) oder Blockbelastungen, etc.

Schädigungstreiber bei spröden zyklisch beanspruchten Composites

Annahmen: Falls Versagensmechanismen(-modi) gleich?

- Dann auch die schädigungstreibenden Versagensparameter gleich.
- Übertragbarkeit statisches Versagen auf Ermüdung möglich,

Dabei schädigen ebene (2D) und räumliche (3D) Spannungszustände

Meßbare Schädigungsgrößen:

Mikrorißdichte, Restfestigkeit, Reststeifigkeit

FMC-based UD Strength Failure Conditions, Damaging drivers

- **Ductile material behaviour (e.g. many metals):**

  **** Slip band shear yielding - as damaging driver - occurs under cyclic tensile stress, compressive stress, and under shear stress !***

  **** Therefore, this single mechanism***

  shear stress–caused yielding can be principally described by

  one yield failure condition to determine the needed damaging portions !

  (Formulation is in normal stresses, but the shear stress is the damaging driver).

  **** Increasing with brittleness, lifetime estimation is corrected by accounting for the 'Mean stress effect'*** σ_{mean}

  (considers by Goodman Diagram that more mechanisms really act).

fatigue

topics

Brittle material behaviour :

**** Many mechanisms, causing damaging, must be considered***

Question is whether a correction by the 'Mean stress effect' makes sense.

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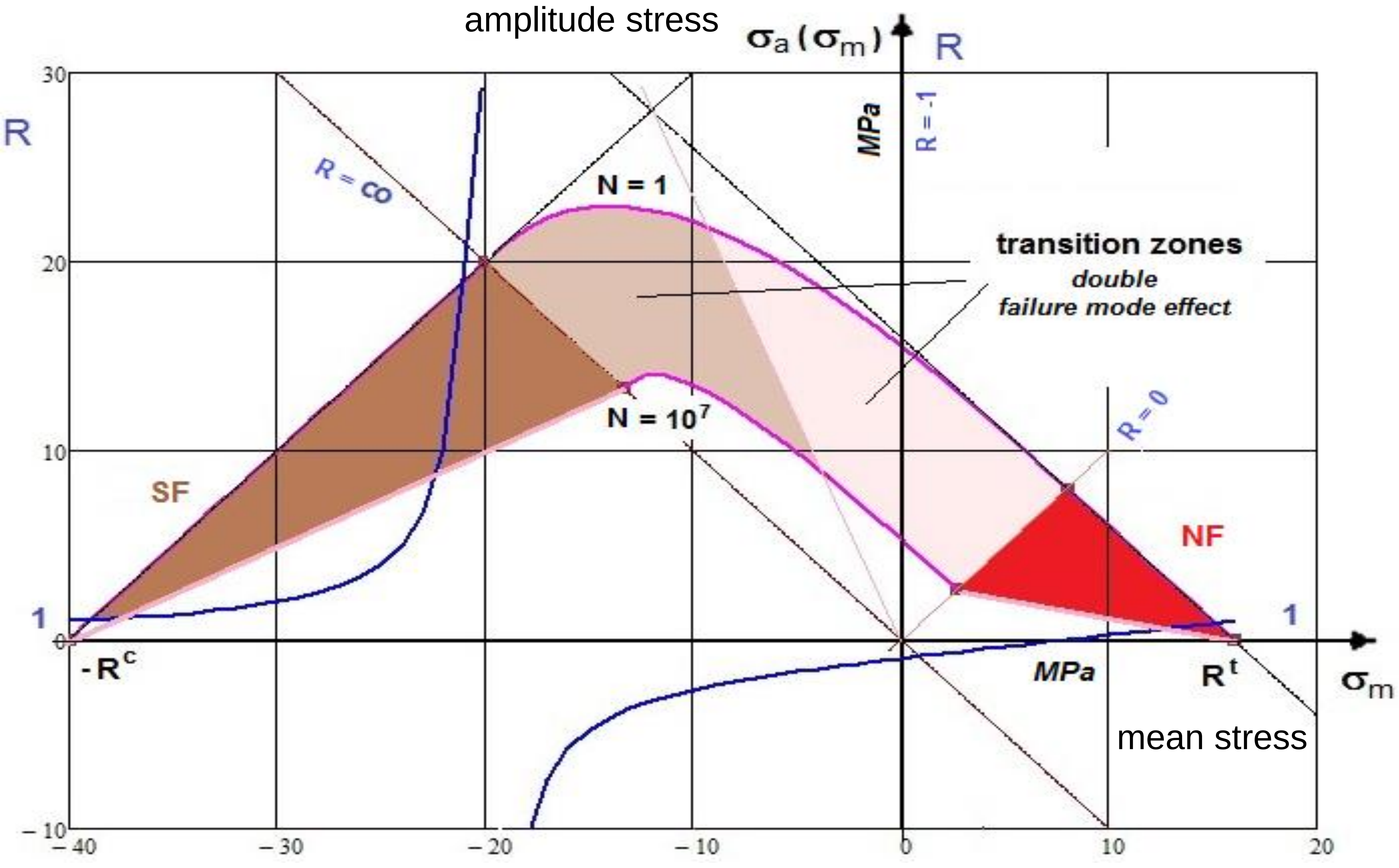
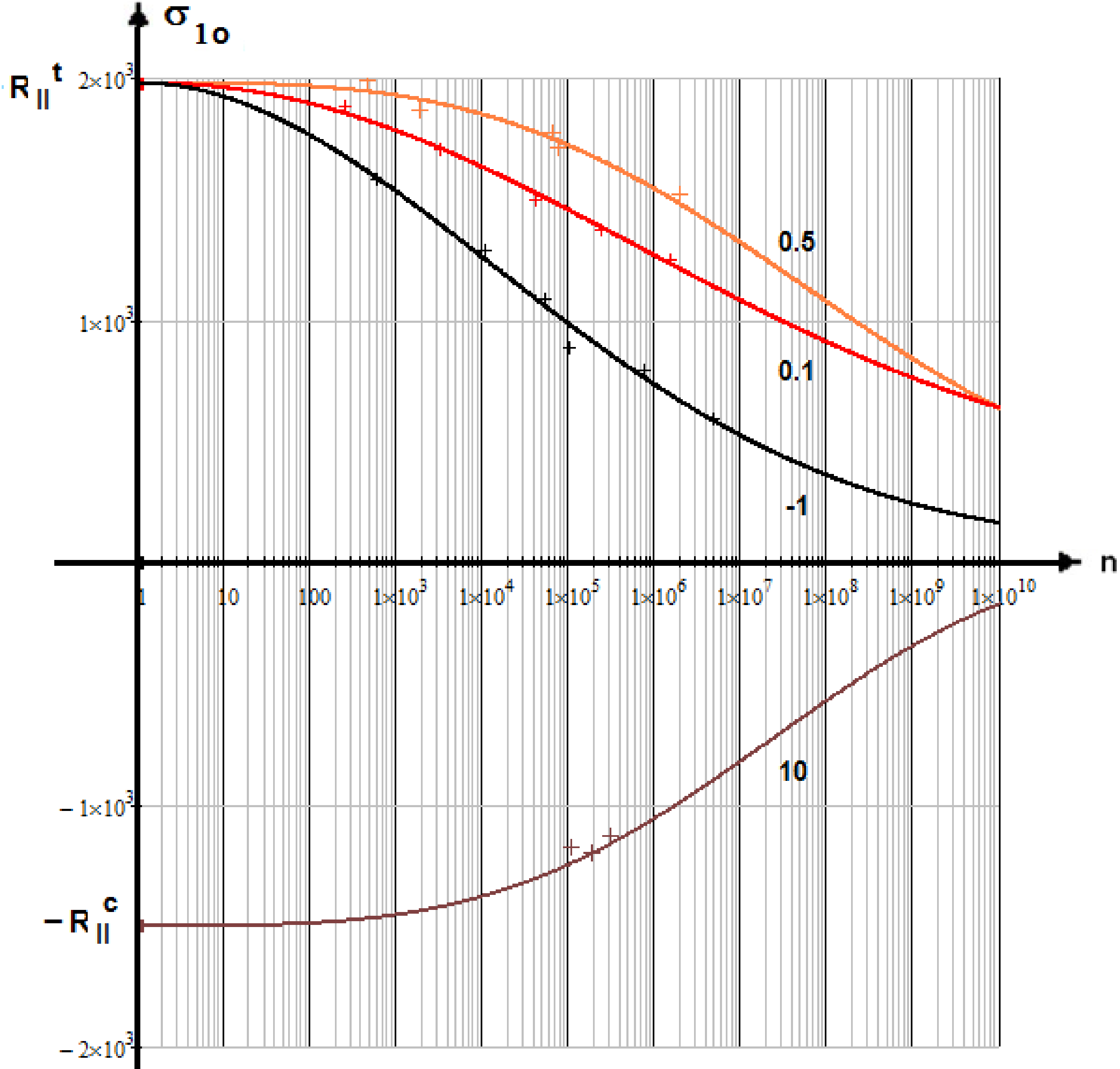
Novel Haigh Diagram of a Brittle behaving Isotropic Material



R **:= stress ratio $\sigma_{min}/\sigma_{max}$**

NF = Normal Fracture, SF = Shear Fracture, *N* = fracture cycle number

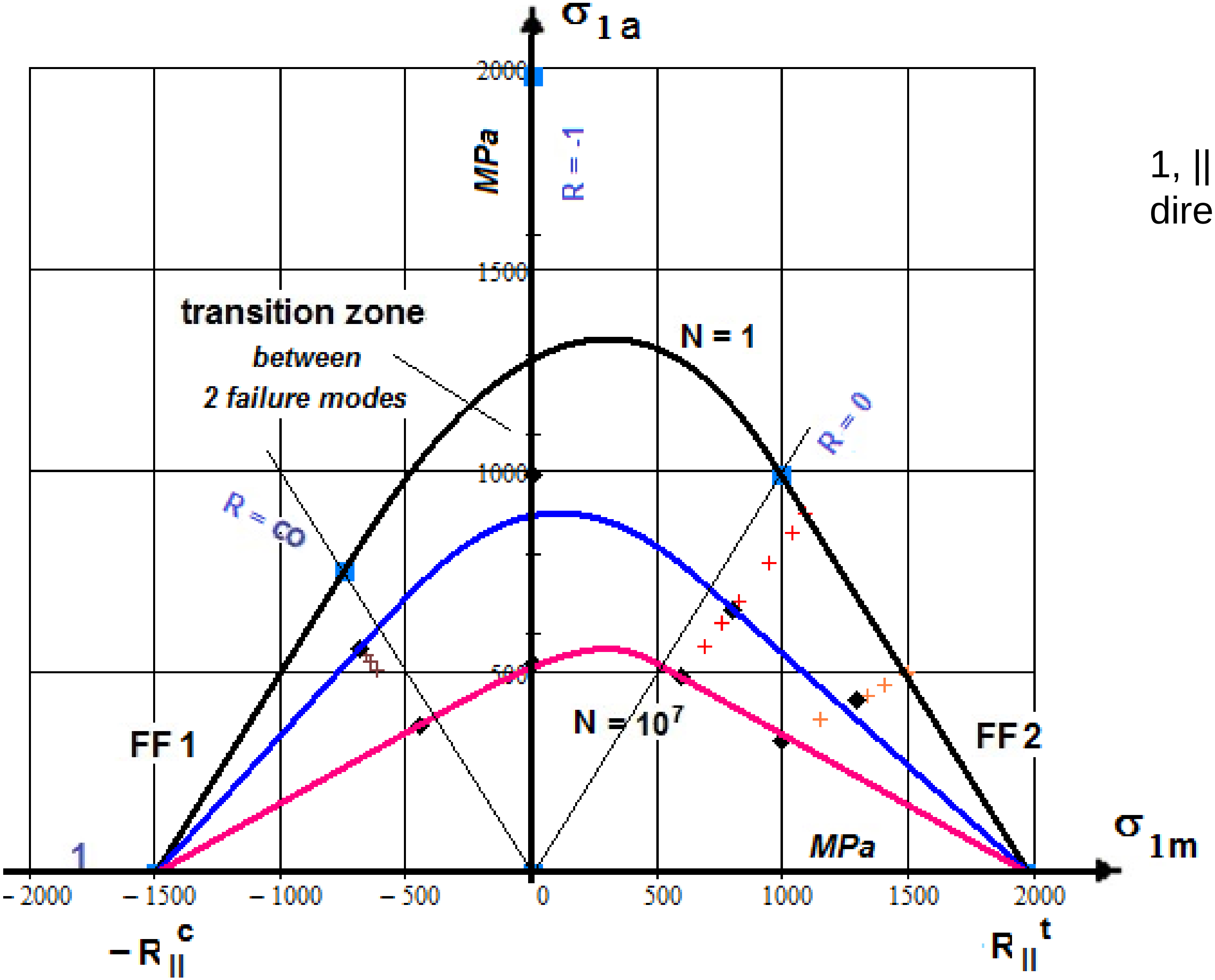
Semi-log FF1-FF2-linked S-N curves [data, courtesy Kawai, Suda]



1, || = fiber direction

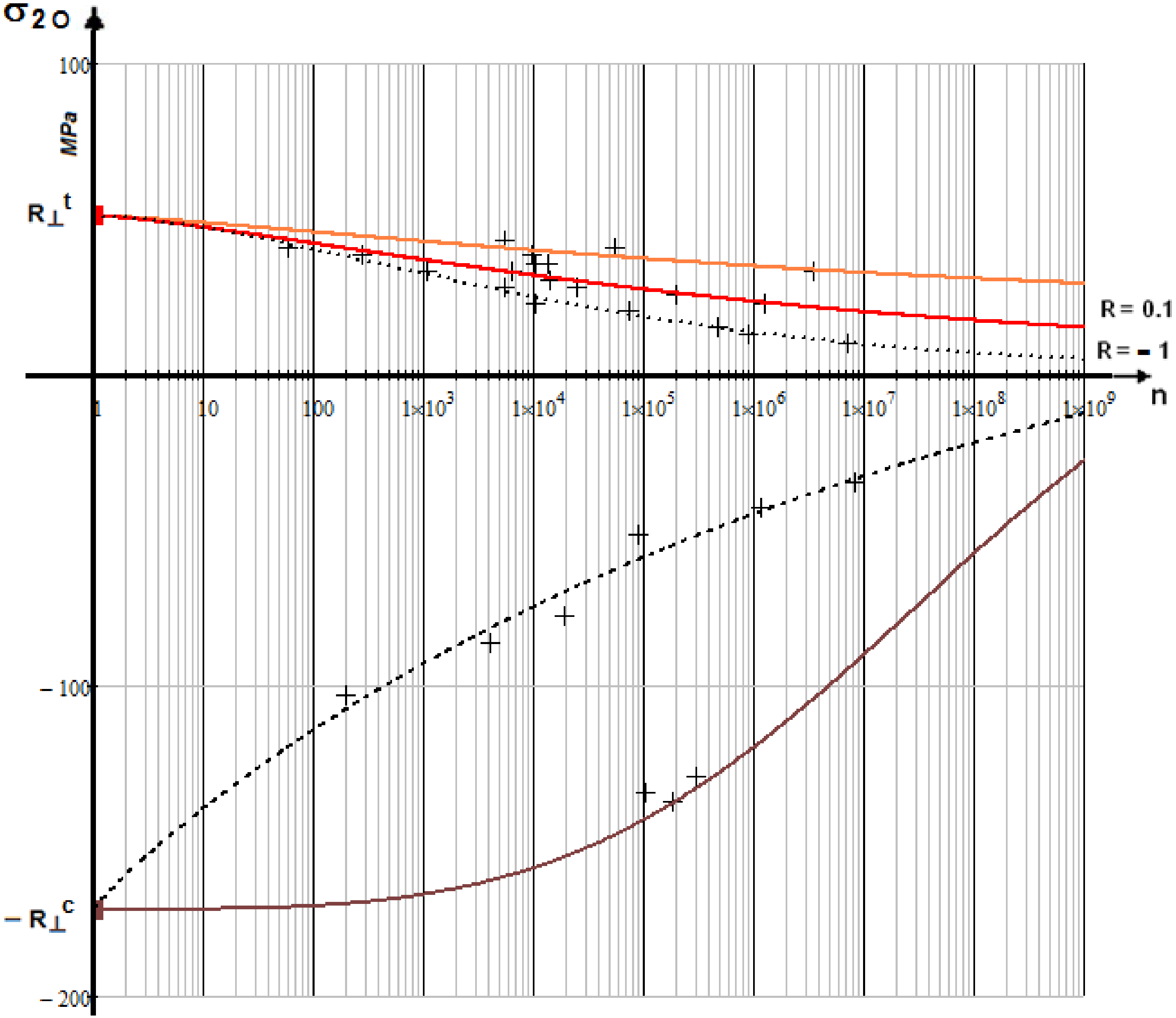
FF1-FF2 Haigh diagram

displaying the failure mode domains, transition zone, test data [Hah14] and the analytically determined fix points for the predicted constant life curves



1, || = fiber direction

: **Semi-log IFF1-IFF3-linked S-N curves** *[data, courtesy C. Hahne]*



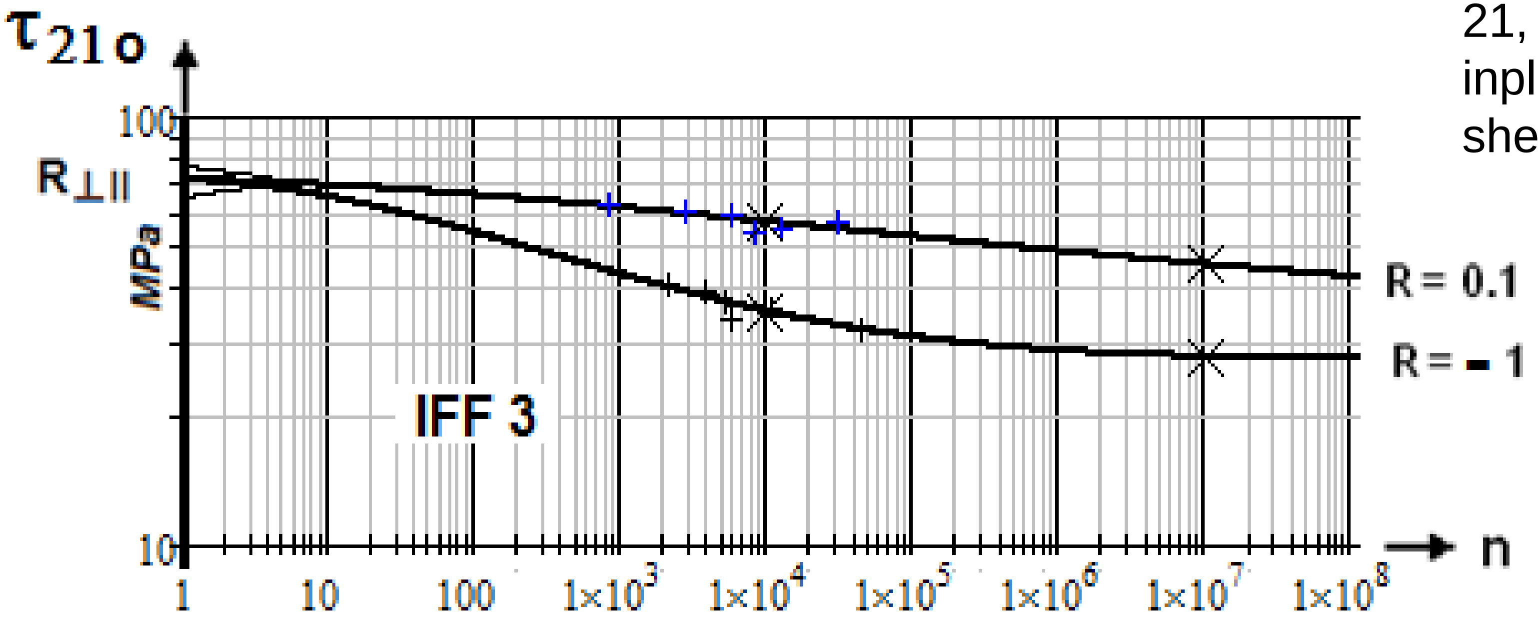
2, ⊥ = across fiber direction

IFF1-FF2 Haigh diagram

displaying the failure mode domains, transition zone *(test data [C. Hahne])*

2, ⊥ =
across fiber
direction

Log-log IFF3-linked S-N curves [data, courtesy C. Hahne]

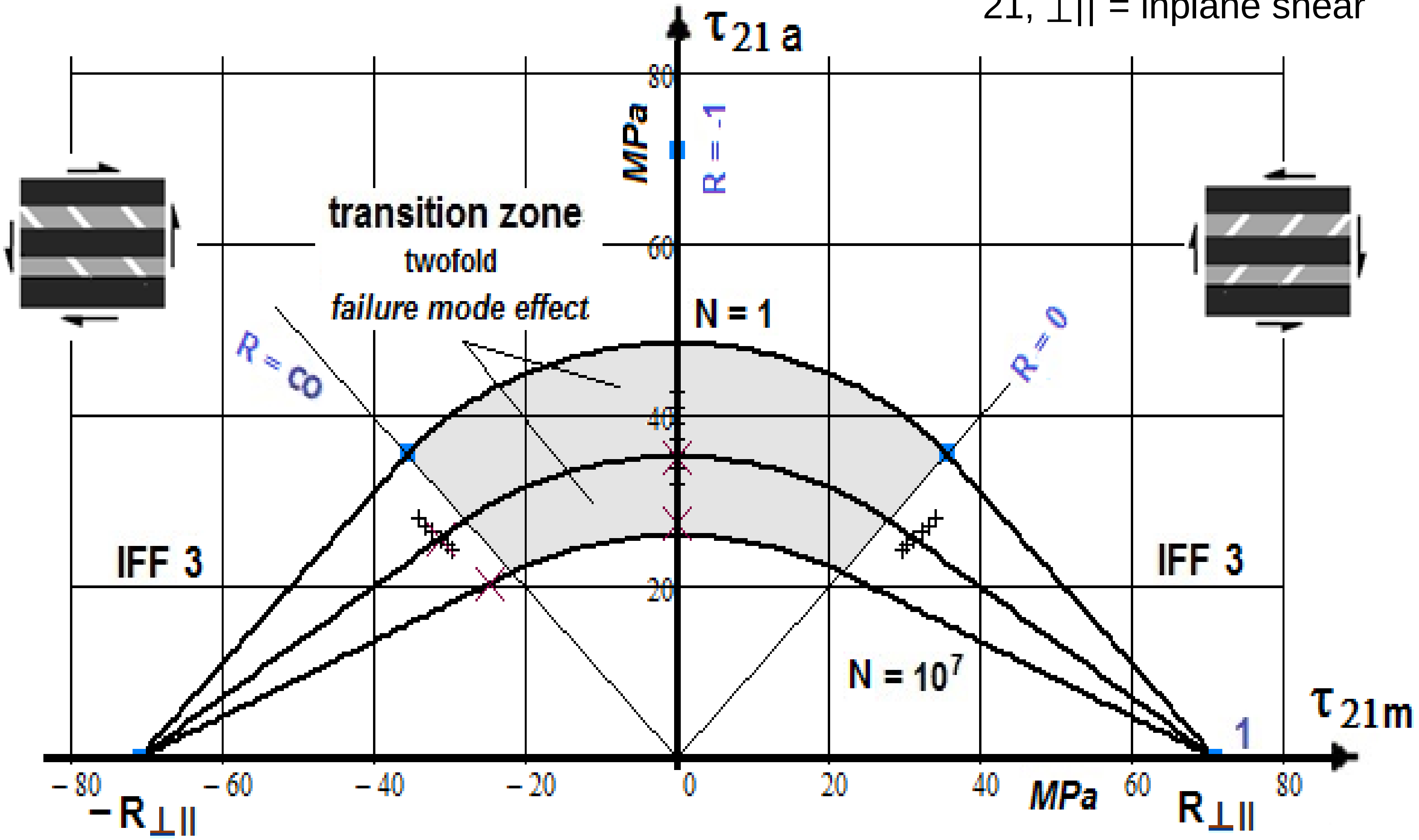


21, ⊥|| = inplane shear

IFF3 Haigh diagram,

Display of a two-fold mode effect (a:= amplitude, m:= mean, N := number of fracture cycles, R := strength and R := $\sigma_{min}/\sigma_{max}$). Test data CF/EP, courtesy [Hah14]

21, ⊥|| = inplane shear



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Objectives of the Method

An engineering, failure modes-linked lifetime prediction method for plain laminates which employs:

1.) Failure mode-linked determination of the cyclic loading

2.) Measurement of just a minimum number of the failure mode-linked representative *mode S-N curves* = master R-curve of each mode

3.) Prediction of other necessary stress-ratio ‘*mode S-N curves*’ on basis of the measured mode master curve one (e.g. R=0.5 *from* R=0.1)

4. Determination of Damaging portions on basis of the static criteria

5.) Accumulation of Damaging Portions using Paömgren-Miner

Novel failure mode-wise modelling of Loading Cycles for high-performance ‘fiber-dominated designed’, UD laminas-composed laminates

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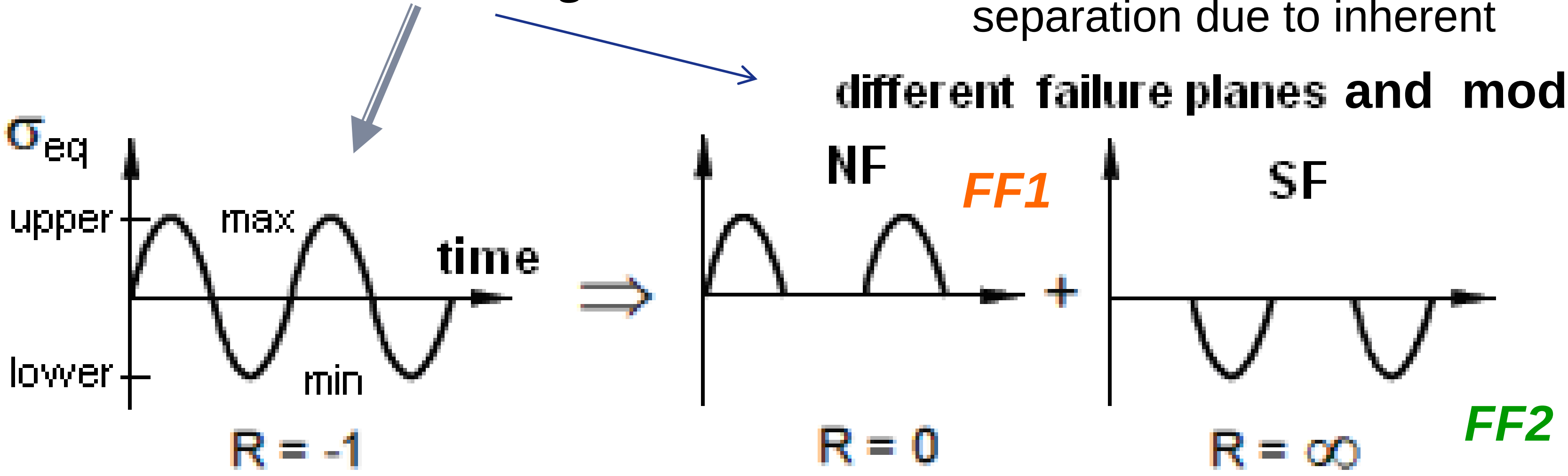
For simply displaying the approach ***it is chosen*** **:**

- **the usually ‘fiber-dominated‘ laminate** and
- ***R = -1 loading***

separation due to inherent

different failure planes and modes



$$\sigma_{mean} = 0$$

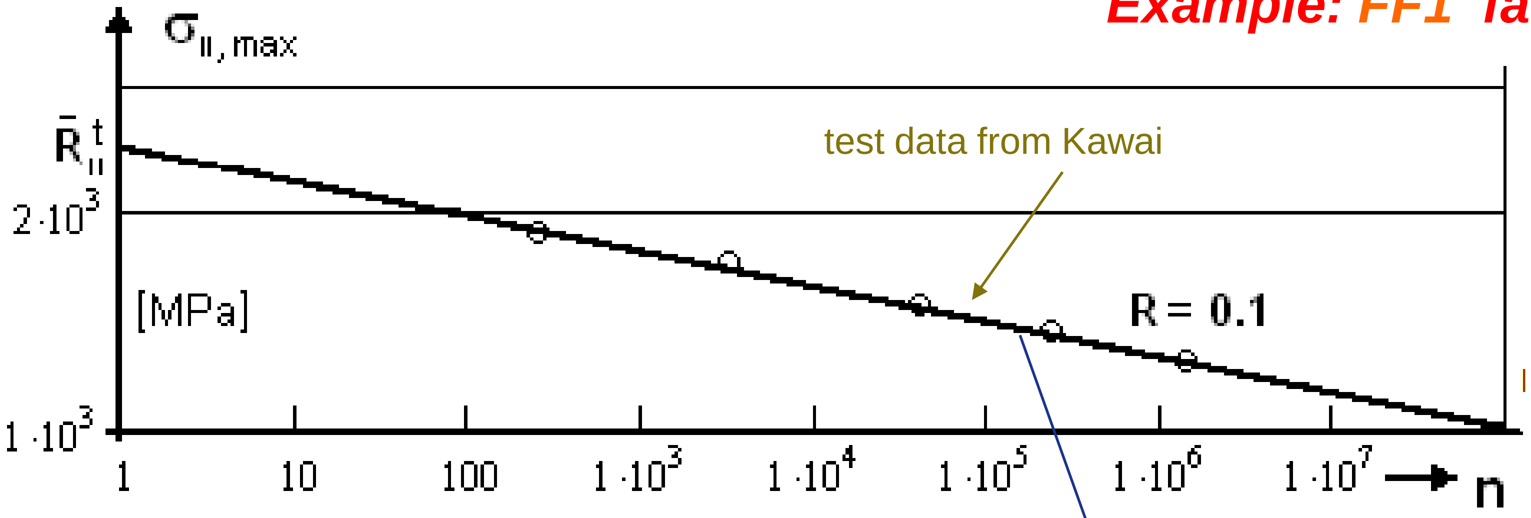
NF := Normal Fracture, SF := Shear Fracture

Step 1 : <u>Failure mode-linked</u> apportionment of cyclic loading (<u>novel</u>)

Specific **rain-fall** procedure to be applied,

Mapping of S-N data and Mode-representative *Master S-N curve*

Example: FF1 failure mode



***Step 2* : S-N curve can be mapped by straight line in a *log-log* graph**

$$\sigma_{\parallel,\ \max}^{Master}(n) \approx \overline{R}_{\parallel}^{t} \cdot n^{c_{Master}}$$

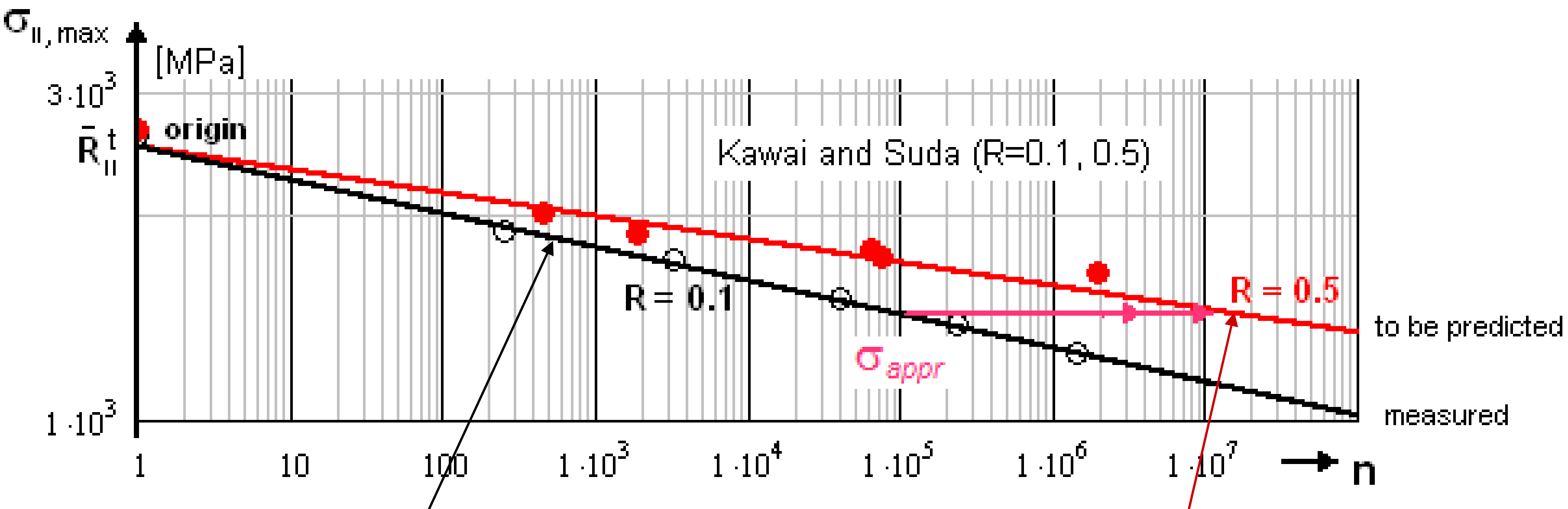
FF1 strength

Measured curve used

as mode-representative ***Master S-N curve*** for ***FF1***

In the general case of variable loading ⟹ Several S-N-curves are needed !

Prediction of needed other *FF1* S-N curves from Master *FF1* Curve



Given : $\sigma_{\|,\ \max}^{Master}(n) \approx \overline{R}_{\|}^{t} \cdot n^{c_{Master}}$ **Searched :** $\sigma_{\|,\max}^{pred} = \overline{R}_{\|}^{t} \cdot n^{c_{pred}}$

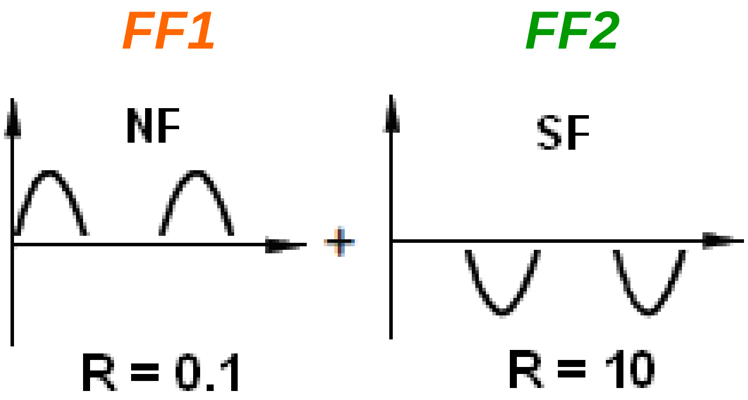
Slope of R = 0.5 ?

Step 3: Application of the Principle of constant strain energy equivalence

A distinct strain energy level will be reached for R > 0.1 at higher cycles.

$$\Delta W^{\|\sigma} \cdot \overline{R}_{\|}^{t\,2} = \sigma_{1,\max}{}^{2} - \sigma_{1.\min}{}^{2} = \sigma_{1,\max}{}^{2} \cdot (1 - R^{2})$$

Application of Miner-‘Rule‘ *simple example*



Loading: again

R = -1

$$D\ (FF1, FF2) = NF : (n_1 / N_1 + n_2 / N_2 + n_3 / N_3) + SF : (n_4 / N_4)$$

$$+ \quad D\ (IFF1, IFF2, IFF3) \ = \ D \leq \ D_{feasible}$$

from test experience

Step 4: Determination of Damaging Portions by Static Strength Criteria

Step 5: Mode-wise Accumulation of Damaging Portions (novel)

Calulation, see [Cun13b]

The presented Novel Lifetime Prediction Method for UD laminas *for the* often ***fibre-dominated designed UD lamina-composed laminates*** employs

1) Failure mode-linked *load modelling* (novel idea)
2) Measurement of a minimum number of Master S-N curves
3) Prediction of other necessary *mode S-N curves* on basis of the master curve by the use of *strain energy equivalence*
4) Accumulation of damaging portions depends on cycles-linked shrinking of failure surface by FMC strength criteria.
In-situ-effect, considered by deformation controlled testing.
5) Failure mode-linked *damaging accumulation* (novel idea)
No mean stress correction to be performed.

To be done: Deeper investigation of the novel method and of the additional damaging caused by mode changes (FF1 to FF2 if *R* = -1).

<u>Aim</u>: Fatigue pre-dimensioning of 'well-designed', UD laminas-composed laminates

just by lamina-dedicated mode-representative Master S-N curves,

derived from *sub-laminate* test specimens,

which capture the embedding (in-situ) effects,

and S-N curves – *due to 3) possible* - from automatically constructed Haigh diagrams.

> Everything in the world
> is terminated
> by **chance** and **fatigue**.
>
> *Heinrich Heine*

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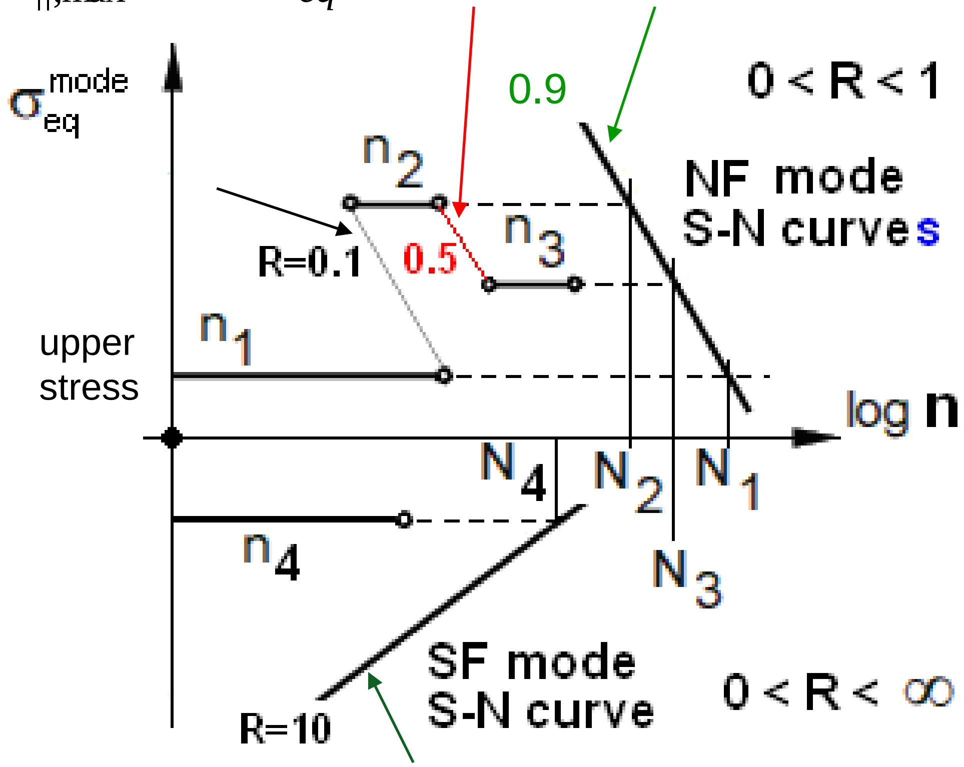
1 Introduction to Static and Fatigue Design
2 Cuntze’s Failure-Mode-Concept-based Strength Criteria
3 Cuntze’s Fatigue Life Estimation Concept
4 Generation and Interpretation of UD Haigh Diagrams
5 Steps of the Fatigue Life Prediction Method Proposed
6 Example: Transversely-isotropic UD-CFRP
Conclusions

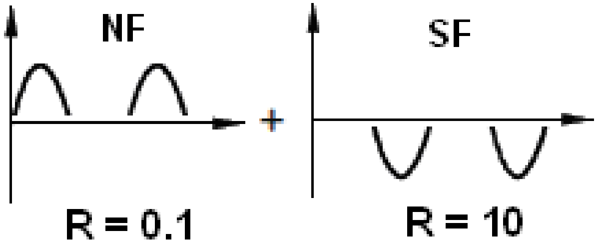
Failure mode-based Lifetime Prediction Method

Schematic Application (principle: for simple isotropic case as example, 4 blocks)

$$\sigma^{mode}_{||,\max} \Rightarrow \sigma^{mode}_{eq}$$



remind



here:

2 master curves

NF: R = 0.1

SF: R = 10

2 predicted curves

NF: R = 0.5, 0.9

Miner application:

$$D = n_1 / N_1 + n_2 / N_2 + n_3 / N_3 + n_4 / N_4$$

Ideas for Experimental Proof

Choice of Test Specimens, Stress Combinations and Loading Types

Demands on test specimens: Consideration of
embedding of ply, ply-thickness effect, fibre volume fraction,
stacking sequence, loadings

1 : Flat coupon material *test specimens* (relatively cheap compared to tubes)

2 : Tension/compression-torsion tube *test specimens* $(\sigma_1, \sigma_2, \tau_{21})$

3 : Sub-laminate *test specimens (with internal proof ply and outer supporting plies)*

4 : Flat off-axis coupons (shortcomings ‘free edge effect‘ + bi-axial stiffness loss not accurately considered)

To be tested: Combinations of stresses (3D or 2D state of stresses)

$$\{\sigma\} = (\sigma_1, \sigma_2, \sigma_3, \tau_{23}, \tau_{31}, \tau_{21})^T \quad \Rightarrow \quad \sigma_{||}^t, \ \sigma_{||}^c, \ \sigma_{\perp}^t, \ \sigma_{\perp}^c, \ \tau_{\perp||}$$ basic stresses

Model VALIDATION: Loading types applied for the *operational lifetime estimation* are

- *Constant-amplitude loading* : delivers S-N curves (Wöhler curve)
- *Block-loading* : (if appropriate) for a more realistic Fatigue Life estimation
- *Random spectrum loading* : Fatigue Life (Gaßner) curve

Assumptions for UD Modelling and Testing and Data Evaluation

- **The UD-lamina is macroscopically homogeneous**.
  It can be treated as a homogenized (‘smeared‘ material)
- **The UD-lamina is transversely-isotropic.**
  On planes, parallel with the fiber direction it behaves orthotropically and on planes transverse to fiber direction isotropically (quasi-isotropic plane)
- **Uniform stress state about the critical stress ‘point‘**
- Test:
  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, edge effects do not exist, …

Load history, variable loading
Smeared (homogenized) composite material macro-scopically modelled.
It is composed of fiber, matrix and interphase

Fatigue model should be applicable for all laminates of the same material kind but different lay-up (stack) in order to further widen the use of composites

Stress (not strain) criteria are applied to determine the subsequent damaging portions:

- capture the combined effect of lamina stresses and
- consider residual stresses from manufacturing cooling down (essential for HCF)

- ***Determination of damaging portions*** *(from diffuse and later discrete damaging)*
- ***Accumulation of damaging portions*** *(cycle-wise, block-wise, or otherwise ?)*

Failure mode-linked Master S-N-curves

For lifetime estimation usually – even in a dictinct failure mode – several S-N-curves are needed

testing requires high effort!

<u>Idea</u>

Measurement of just one failure mode linked Master S-N-curve

- for a fixed stress ratio *R*
- prediction of additionally necessary S-N-curves on basis of the master curve and on the ‘principle of equivalent strain energy‘!

Then, for the often used

all possible load orientations capturing fiber-dominatedly designed, multidirectional laminates, composed of UD plies,

an engineering-like model is derivable.

Its characteristical steps are presented:

steps

S := cyclic stress range $\Delta\sigma$, N := number of cycles to failure, stress ratio R := $min\sigma/max\sigma$

Questions an engineer poses in the case of cyclic design

1. **When does damaging start?**
2. **How can one consider the single (micro-)damaging portion?**
3. **How are the single damaging portions accumulated?**
4. **When do the accumulated damageing portions form a damage?**
5. **When becomes such a damage (delamination, impact) critical?**
6. **How is the damage growth in the 3rd or final phase of fatigue life (fixation of part replacement time, inspection intervals)?**

Driver of damaging: Applicability of Static Strength Failure Conditions?

Proven Assumption:

If the damaging mechanisms (failure modes) are equal, then

- failure parameters that drive cyclic damaging are equal, too, and
- transferability from static failure to cyclic failure is permitted

However, static strength must be replaced by the
fatigue strength = residual strength of the
shrinking failure body.

Therefore,

as necessary static tool, *my*

FMC-based Static Failure Conditions (criteria) shall be briefly derived which

were very successful in the World-Wide-Failure-Exercise (WWFE 1992-2014).

From all the contributors, my *non-funded* Failure Conditions
well mapped the largest number of test data courses in WWFE-I and WWFE–II !

Step 4: Determination of Damaging Portions by Static Strength Criteria