Simulation of Composites - bereit für Industrie 4.0 ?

NAFEMS Seminar: Vortragsblock ***Schädigung***

Oktober 26-27, 2016 ; 20 + 5 min

Progress reached?

Lifetime Prediction for UD-materials by using S-N curves, Strain Energy Equivalence or another Model and Novel Haigh Diagrams

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

Results of a time-consuming, never funded “hobby research work“

Prof. Dr.-Ing. habil. Ralf Cuntze VDI, formerly MAN-Technologie AG

linked to Carbon Composite e.V.(CCeV) Augsburg,

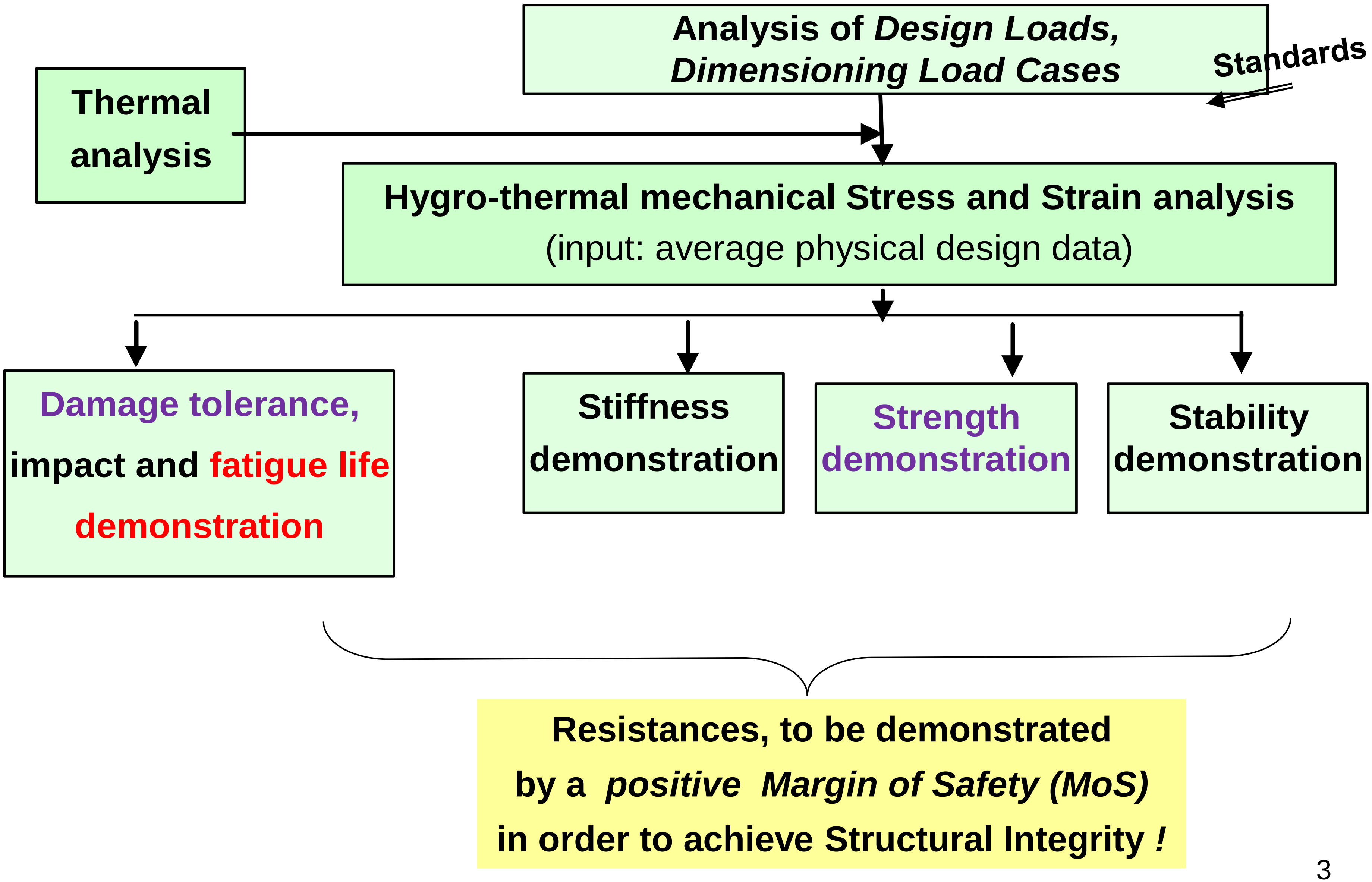
heading the Working Groups „Engineering“ + „Modeling Fiber-Reinforced Concrete“

Since 1970 in CFRP composite business

Aus Zeitgründen ist es nicht möglich,
die komplette Darstellung
dieses vielerlei neuen Ansatzes zu bringen.

Bekanntes zu den anzuwendenden statischen
Festigkeitsbedingungen werde ich deswegen nur
kurz zeigen, um das Wesentliche wenigstens
darstellen zu können - den roten Faden zeigen,
nur das für das Verstehen Wichtige wiederholen..

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, impact and fatigue life demonstration

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 (Werkstoffanstrengung)

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

j = design safety factor

Some Definitions needed for Modeling *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,), a project-defined ‘defect‘

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. Accumulation tool usually used 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

Fatigue Life Stages (1) accumulation of damaging until initiation of a critical damage size (classical fatigue life prediction domain), (2) damage growth until onset of final fracture (damage tolerance concepts domain), (3) separation (not of interest)

Haigh Diagram : involves all S-N curves required for fatigue life prediction.

State of the Art: Static Strength Analysis *of UD laminas*
represent the results of the *World-Wide-Failure-Exercises*

Static strength criteria for high-performance UD composite parts

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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)

Cuntze mapped provided accurate test data sets best, in WWFE-I and in -II !

.. for computation of the damaging portions under cyclic loading

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

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Author's Lesson Learned:

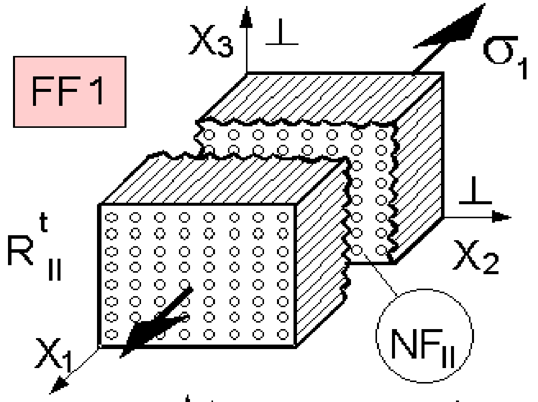
Consider the material's behavior not its type such as *Steel, FRP, Foam, Concrete etc.*

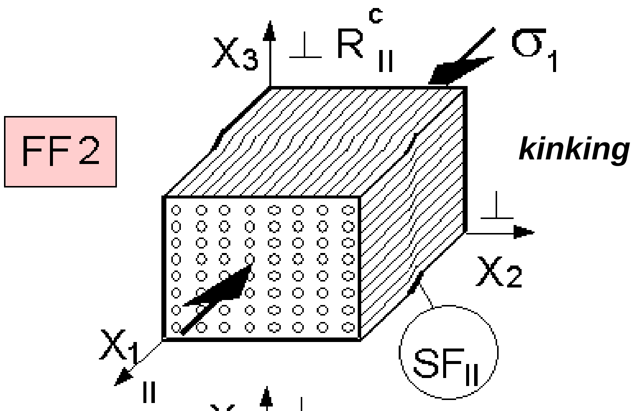
Observed Fracture ‘Planes‘: Transversely-isotropic UD Material

[Cun04]

t = tension

c = compression

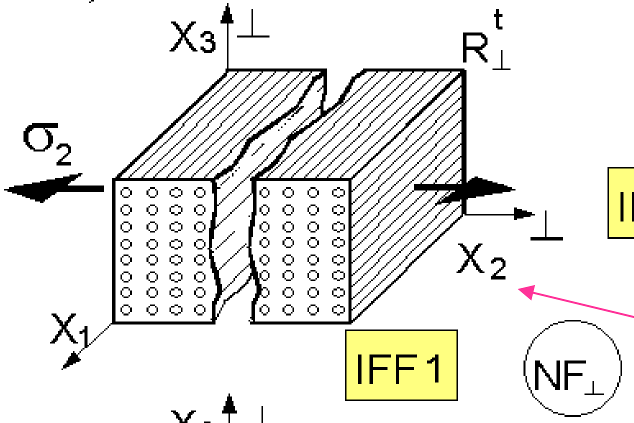


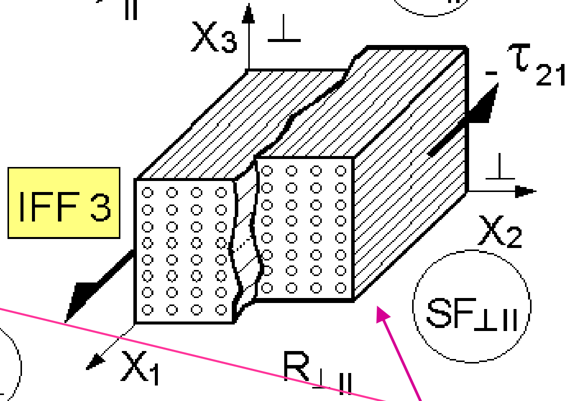


▶ 5 Fracture modes exist

= 2 FF (Fiber Failure)

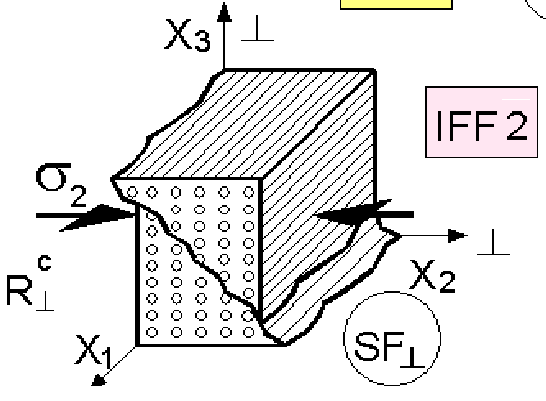
+ 3 IFF (Inter Fiber Failure)



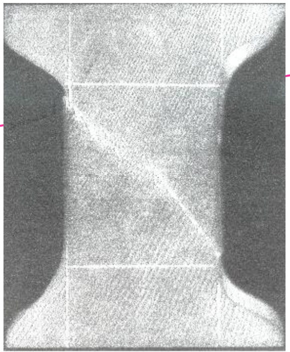


critical in a loaded laminate:
FF1, FF2 + possibly IFF2 !

from the observations follow ..

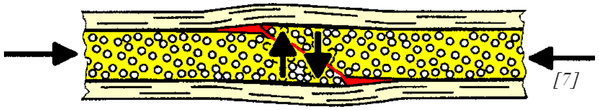


wedge type



NF := Normal Fracture

SF := Shear Fracture



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

plus a confirmation that transversely-isotropic UD Materials exhibit a 5-fold material symmetry characteristic = 5 Strengths, 5 Failure Modes, 5 Es.

- **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 !!

This is of advantage when deriving S-N curves and Haigh diagrams with minimum test effort.

Consequently, the FMC-approach requires :

the *interaction of all 5 Modal (fracture) Failure Modes !*

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

Cuntze = Mises amongst the UD criteria

Invariants replaced by their stress formulations

strains from FEA

[Cun04, Cun11]

FF1 $$Eff^{\parallel\sigma} = \breve{\sigma}_1 / \bar{R}_{\parallel}^{t} = \sigma_{eq}^{\parallel\sigma} / \bar{R}_{\parallel}^{t}, \qquad \breve{\sigma}_1 \cong \varepsilon_1^t \cdot E_{\parallel} \;\; *$$

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

2 filament modes

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

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

3 matrix modes

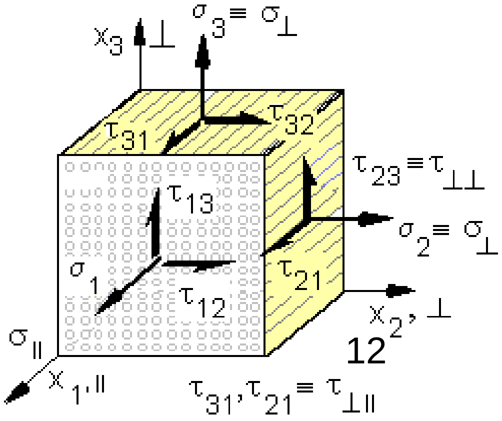
IFF3 $$Eff^{\perp\parallel} = \{[\mu_{\perp\parallel} \cdot I_{23-5} + (\sqrt{\mu_{\perp\parallel}{}^2 \cdot I_{23-5}{}^2 + 4 \cdot \bar{R}_{\perp\parallel}{}^2 \cdot (\tau_{31}^2 + \tau_{21}^2)^2}\,] / (2 \cdot \bar{R}_{\perp\parallel}{}^3)\}^{0.5} = \sigma_{eq}^{\perp\parallel} / \bar{R}_{\perp\parallel}$$

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 :

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

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

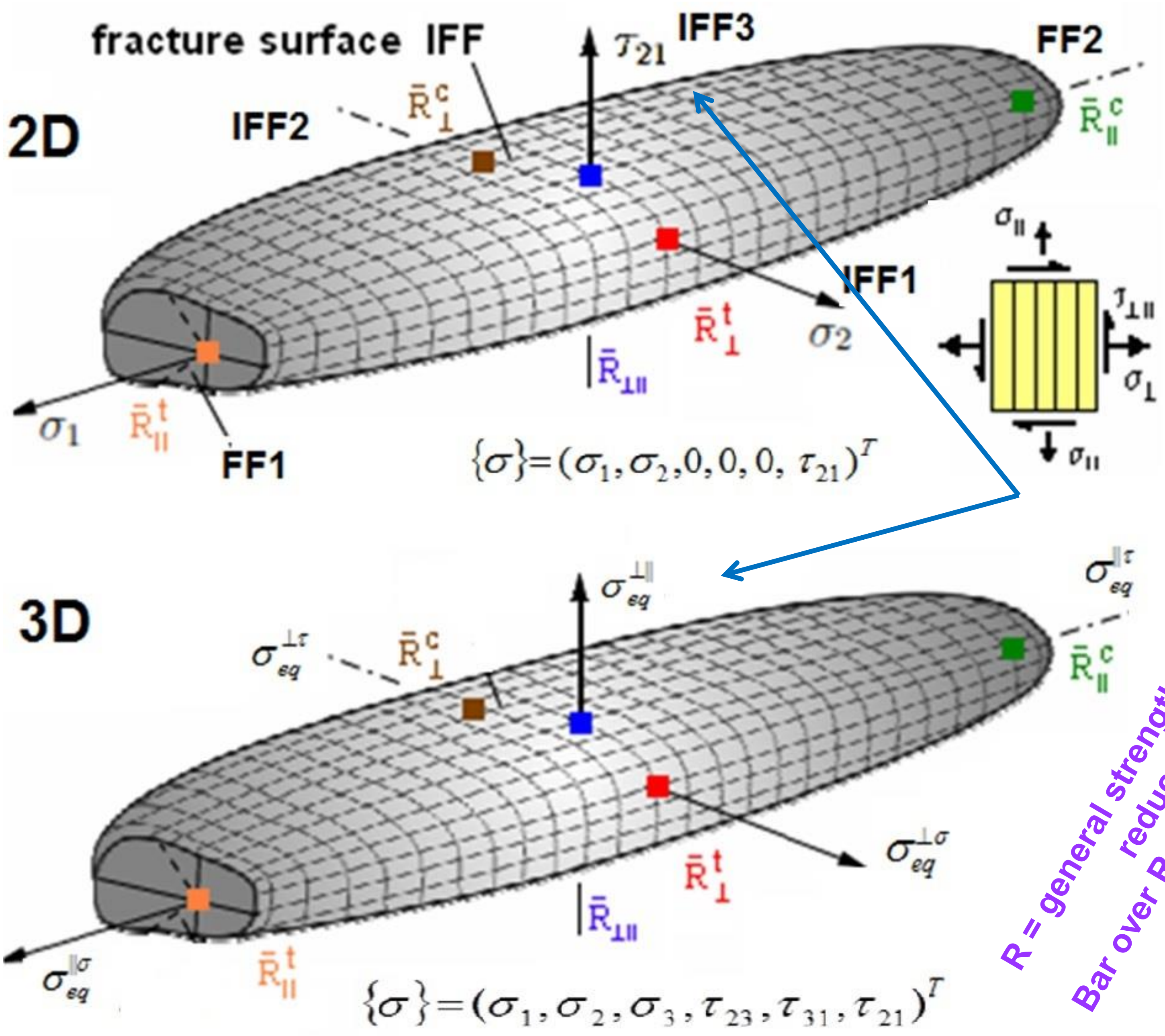


Typical friction value data range: $0.05 < \mu_{\perp\parallel} < 0.3, \quad 0.05 < \mu_{\perp\perp} < 0.2$

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

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

2D ⇨ 3D Fracture surface by replacing the stress by the equival. stress

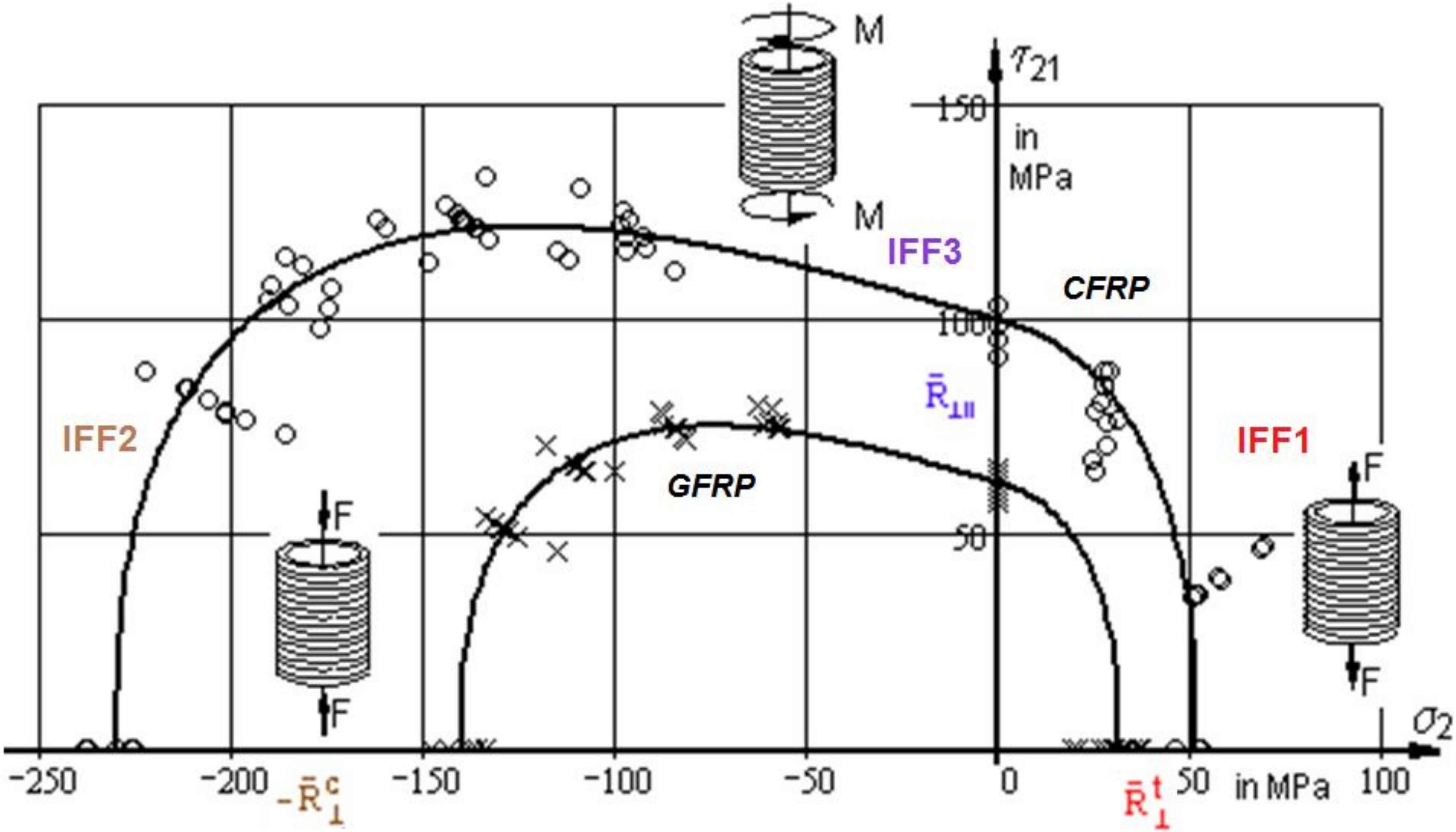


$$\{\sigma\} = (\sigma_1, \sigma_2, 0, 0, 0, \tau_{21})^T$$

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

R = general strength and statistically
reduced ‘strength design allowable
Bar over R means average strength, applied
when mapping .

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



* Above tested were so-called isolated test specimens.

* For the presented fatigue approach embedded laminas are to consider!

Isolated UD-material (generates hardening curve) and embedded (softening curve)

Isolated‘ lamina test specimens

= weakest link results (series failure system)

IFF 1 :

IFF 2 :

unconstrained lamina

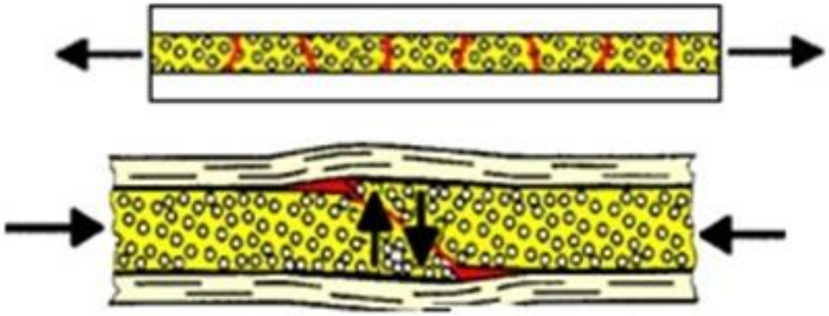
delivers strength property, stress-strain curve

(belongs to hardening)

delivers **basic strength** as analysis input !

‘Embedded‘ laminas experience in-situ effects

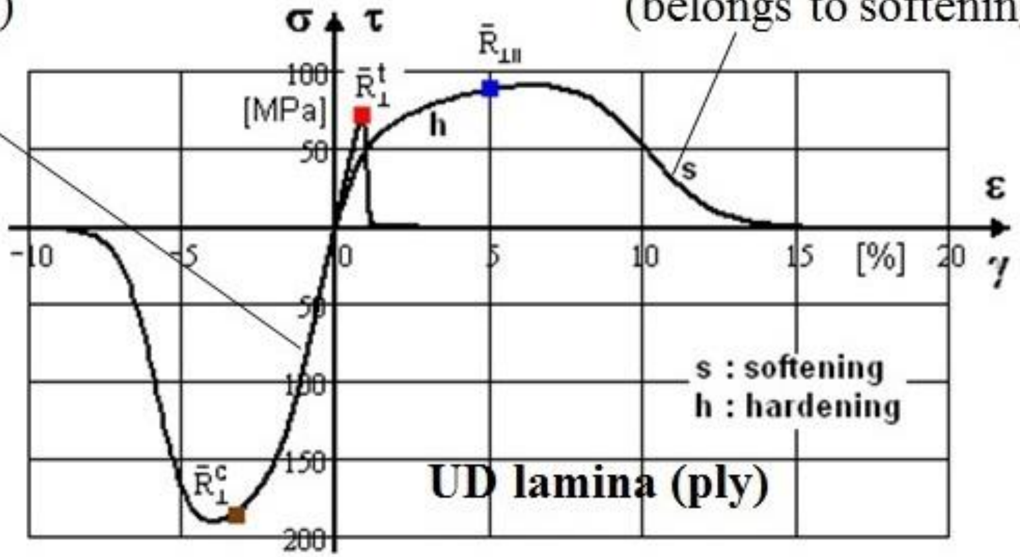
= redundancy result (parallel failure system)



mutually constrained laminas, in laminates

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

(belongs to softening)



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 propert.**
5	**UD**	$R_{\|\|}^{\ t}$ NF	$R_{\perp}^{\ t}$ NF	$R_{\perp}^{\ t}$ NF	$R_{\|\|}^{\ c}$ SF	$R_{\perp}^{\ c}$ SF	$R_{\perp}^{\ c}$ SF	$R_{\|\|\perp}$ SF	$R_{\perp\perp}$ NF	$R_{\|\|\perp}$ SF	$\mu_{\perp\perp},\ \mu_{\perp\|},$
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

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„Fatigue is the black art,

to produce financial black holes“

[J. Draper]

Therefore, in order to reduce very costly cyclic laminate test programs

The German Academic Research Group (BeNa), founded by the author in 2010,

aims at a:

Failure mode-based Lifetime Prediction Method,

lamina-oriented on the embedded lamina in order to capture insitu effects.

Damaging Drivers of Ductile and Brittle behaving Materials

- **Ductile Material Behavior** (example: isotropic metal materials)

  1 damaging mechanism *acts = "slip band shear yielding"*

  drives damaging under cyclic tensile, compressive, shear and torsional stresses:

  Therefore, this single mechanism can be described by one single strength formulation:

  the Mises Yield failure condition!

- **Brittle Behaving Material Behavior :** isotropic Materials

  2 damaging driving mechanisms act = *Normal Fracture failure mode (NF), Shear Fracture failure (SF)*

- **Brittle Behaving Material Behavior : transversely-**isotropic UD Materials

  5 damaging driving Fracture failure mechanisms act ≡ 5 Fracture failure modes

Damaging Determination in Brittle behaving cyclically loaded Composites

Assumption: If failure mechanism (mode) is cyclically the same? Then ..

- the damaging driving failure parameters are the same

- applicability of static stress failure criteria is allowed to quantify the damaging portions .

Thereby, 2D and 3D stress states cause the damaging.

Measurable Damaging Quantities:

Micorcrackdensity, Residual Strength, Residual Stiffness

Which cyclic Quantities are required for Lifetime Estimation ?

- S-N curves for $R = const = \sigma_{unter} / \sigma_{ober}$
- Hypothesis for the accumulation of the damaging portions
- Quantification of damaging portions (- increments) by the

application of static fracture strength criteria if

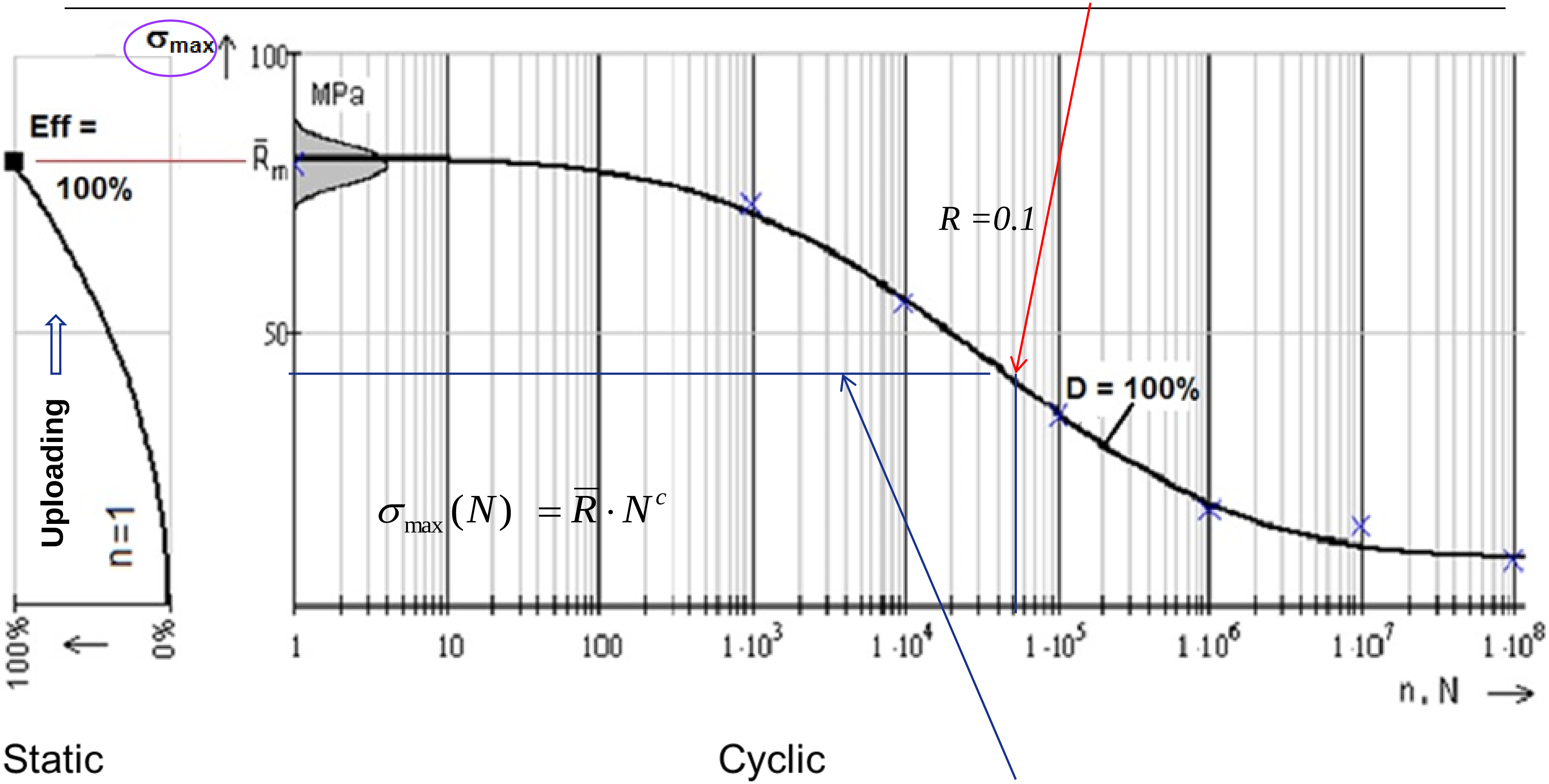
static strength R_m is replaced by the residual strength $\sigma_{res}(N, R)$.

Thereby, the static material stressing effort *Eff* (Werkstoffanstrengungssumme)

is replaced by the accumulated cyclic damaging *D !*

The same letter is used as for the stress ratio R!

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 :

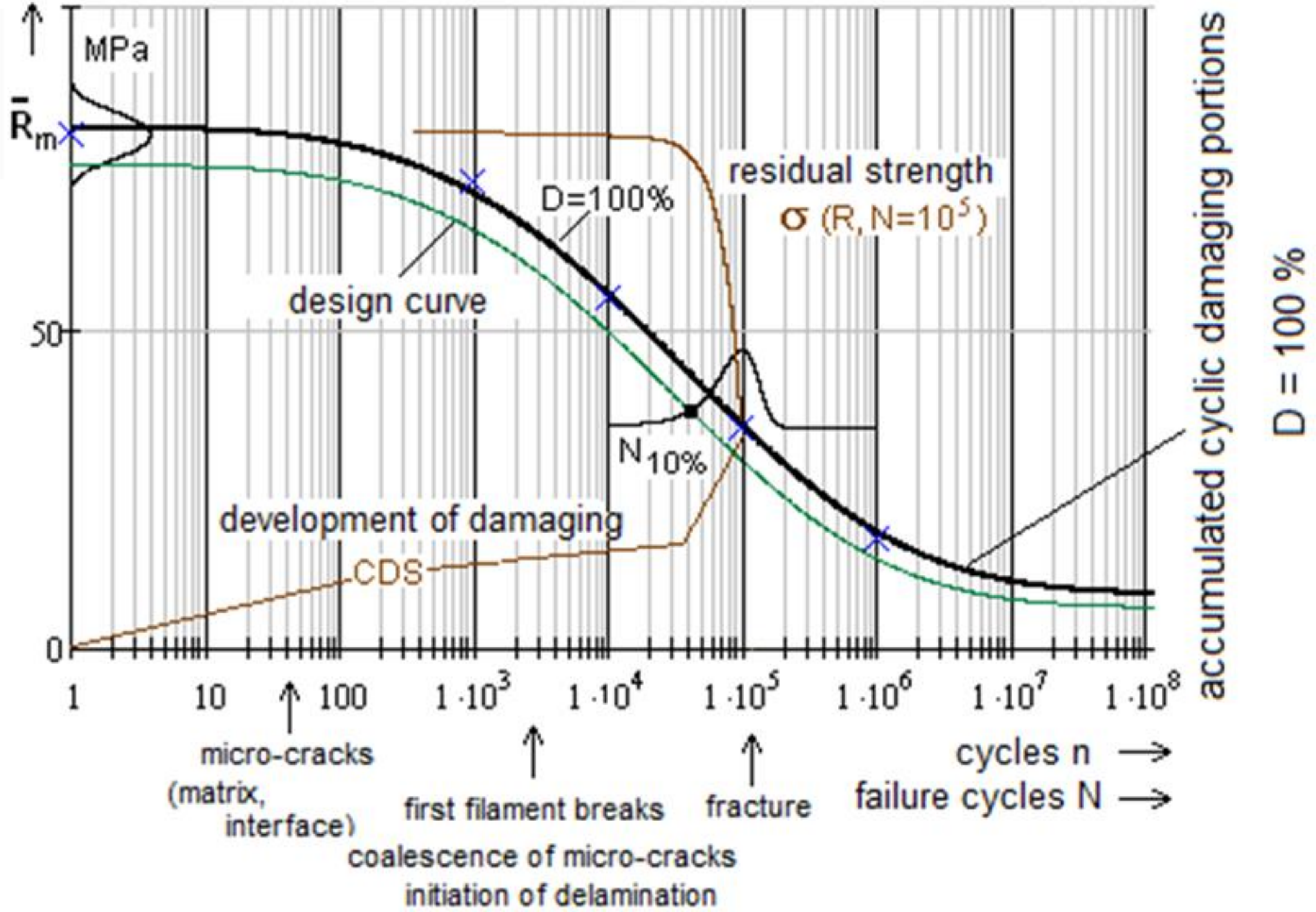
- Static : material stressing effort Eff (N=1) = 100 %
- Cyclic : material damaging sum D (N) = 100 %

= *sum of damaging portions*

When designing brittle behaving materials the use of σ_{max} is helpful compared to $\Delta\sigma$!

Lin-Log S-N Curve: Average Curve (mapping) and Design Curve (verification)

σ_{max} ⇨ $\sigma_{eq,\,max}$ **if more stresses act together within the envisaged failure mode** (like Mises)



FF:= fibre failure. IFF:= Inter Fibre Failure, CDS:= characteristic damage state at the end of diffuse damaging

Schritte bei der Lebensdauerabschätzung

1 Input

Operational Loading: Load time curves (modeling rain flow, ..)

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

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

Safety Concept: Design safety factor Life $j_{Life} = 3 – 4$, or
an Inspection interval, or an replacement time approach

2 Transfer of operational loadings into stresses using structural analysis

3 Domains of Fatigue Analysis

LCF: high stressing,

HCF: intermediate stressing 10.000 < n < 1.000.000

VHCF: low stressing and strains (SPP1466) > 10.000.000

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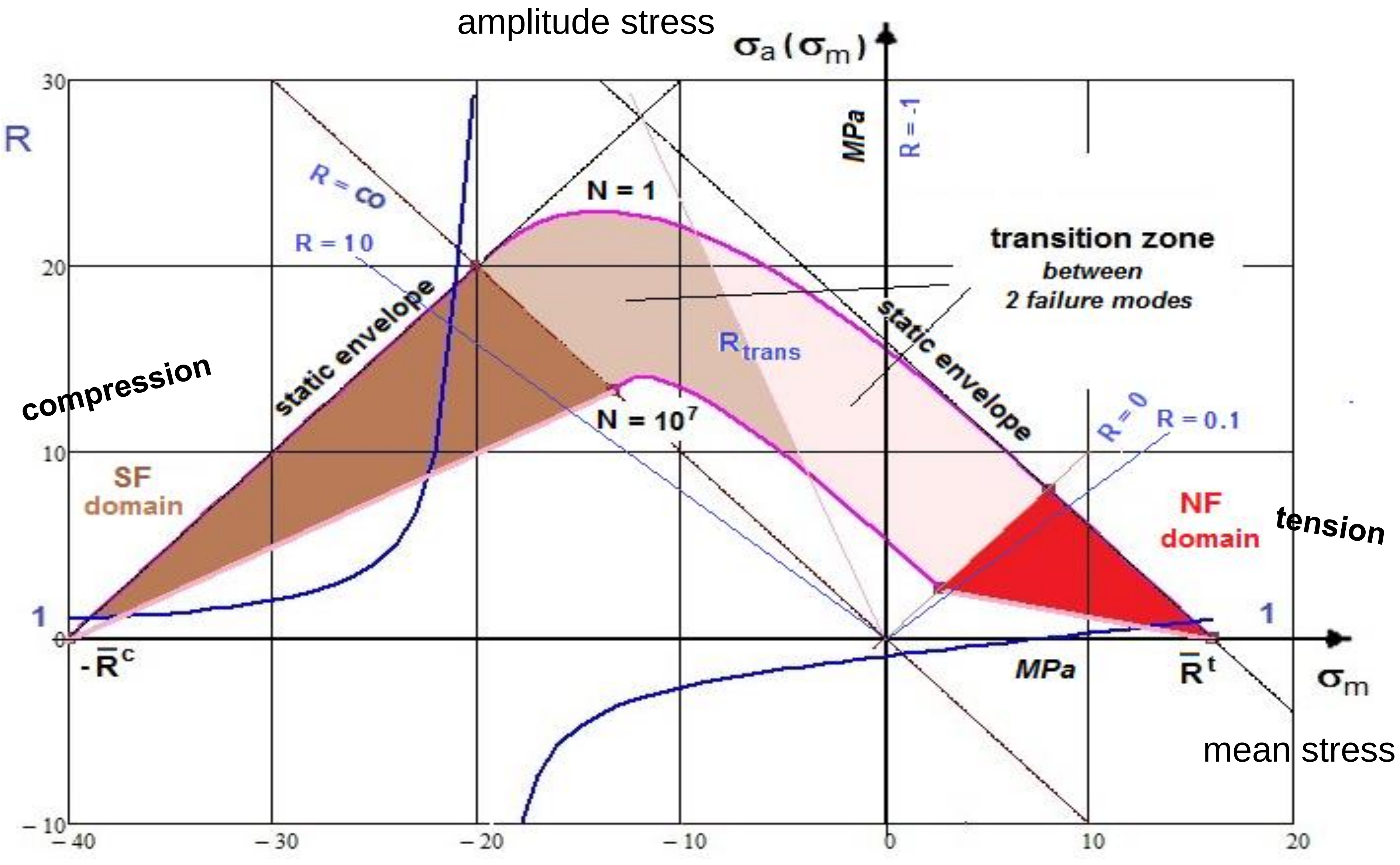
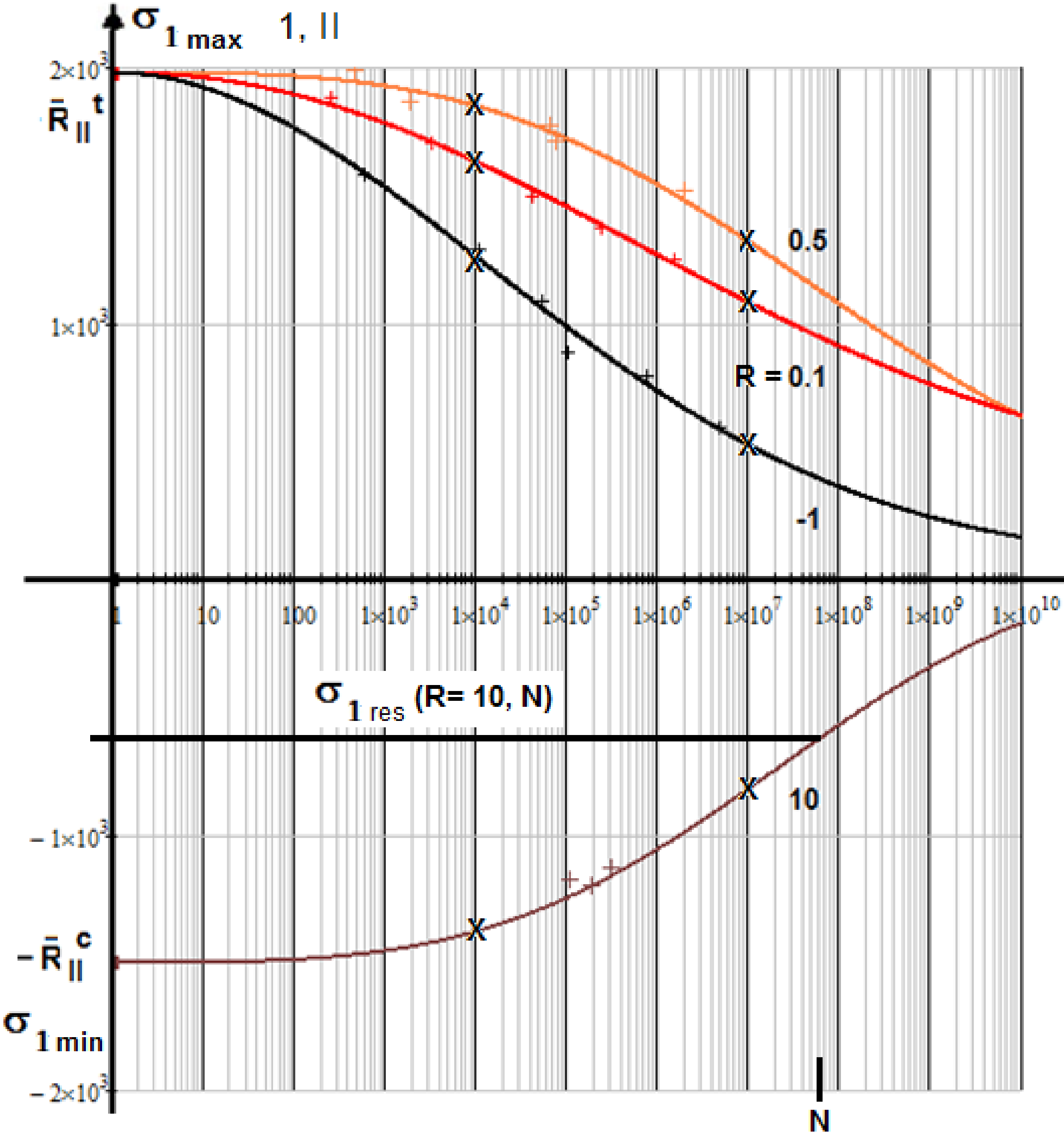
Novel Haigh Diagram of a Brittle behaving Isotropic Material (simple example)



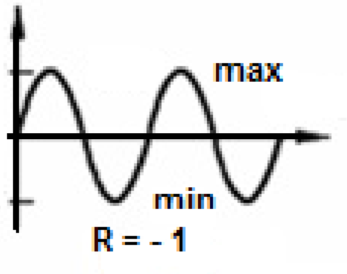
R := stress ratio $\sigma_{min}/\sigma_{max}$

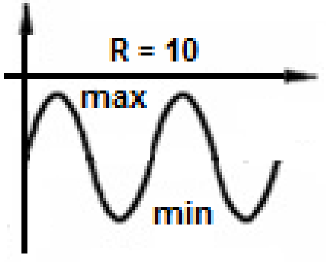
NF = Normal Fracture, **SF** = Shear Fracture, ***N*** = fracture cycle number

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



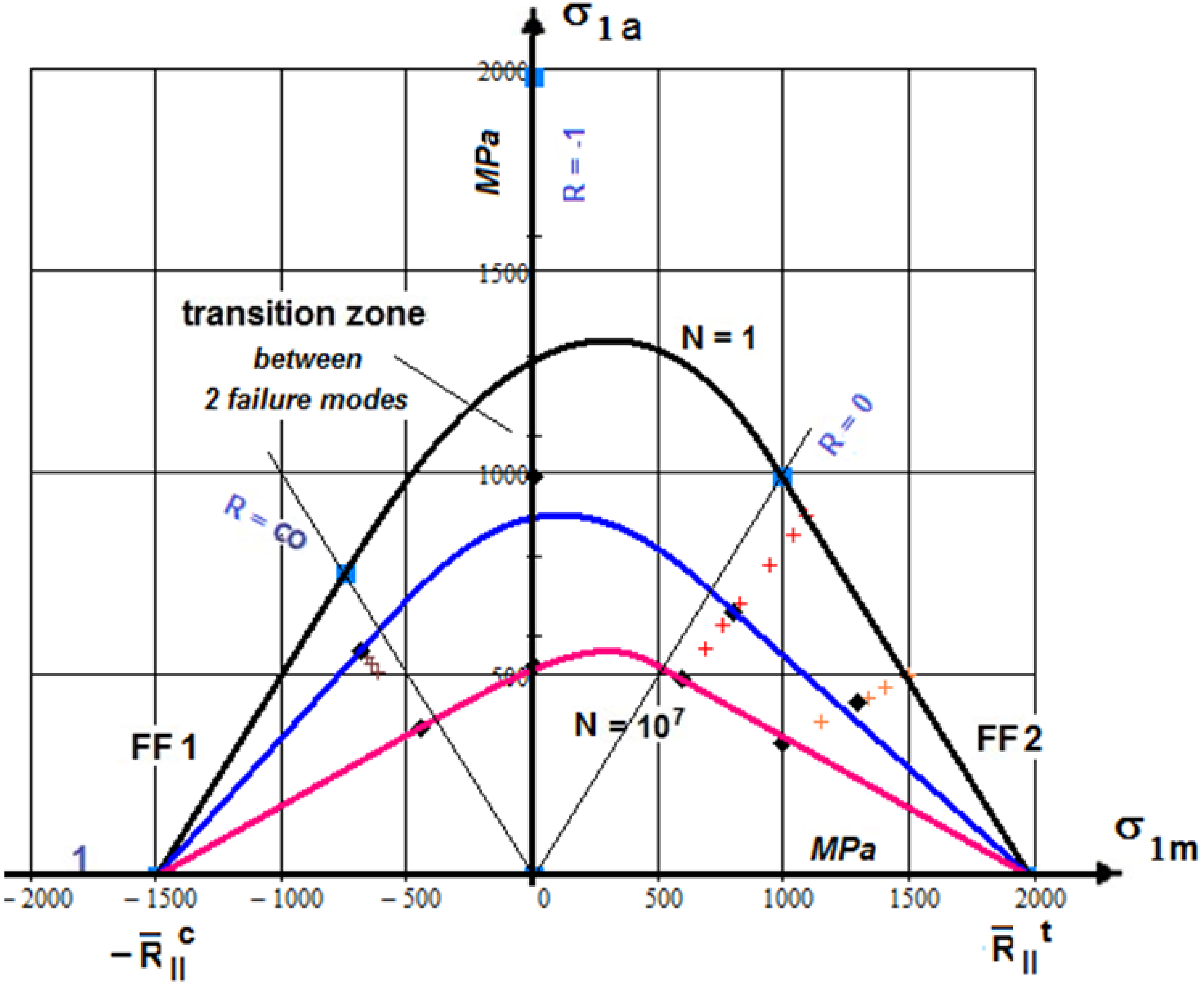
From the mapped test data curve analytically determined are fix points X for the prediction of constant fatigue life (CFL) curves





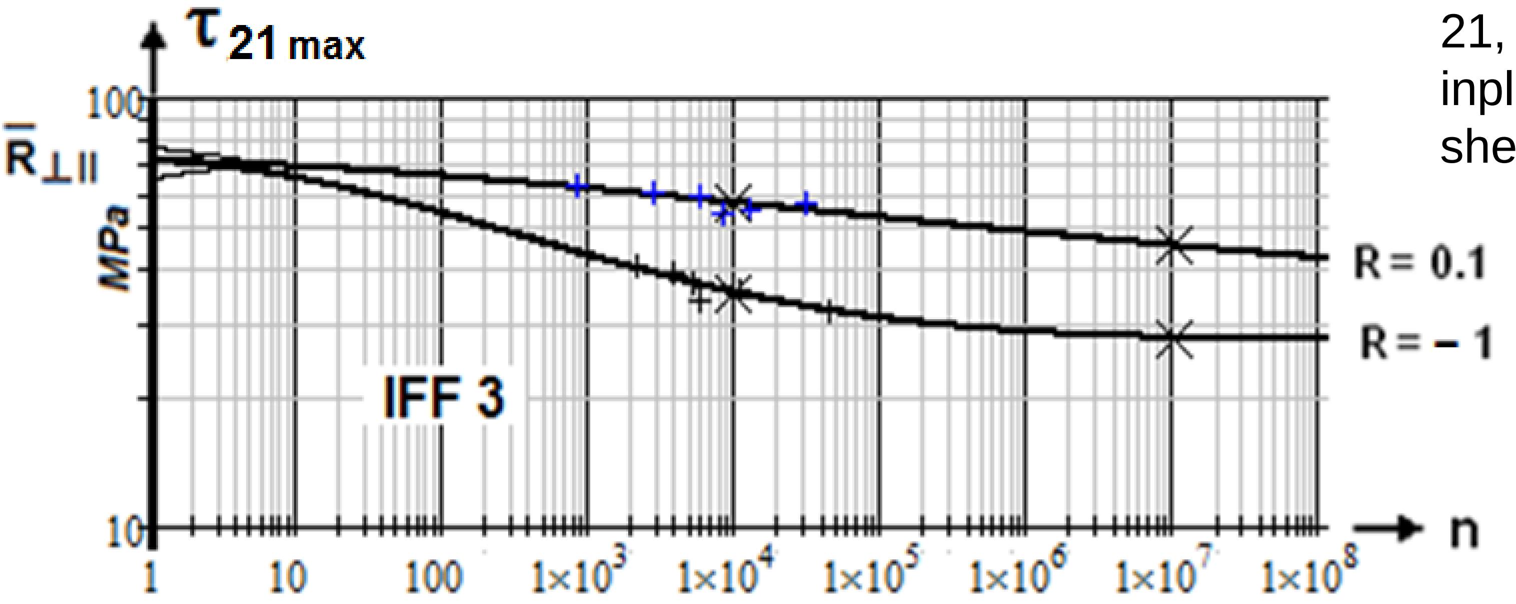
FF1-FF2 Haigh diagram

displaying the failure mode domains, transition zone, test data [Hah14]



1, || = fiber direction

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

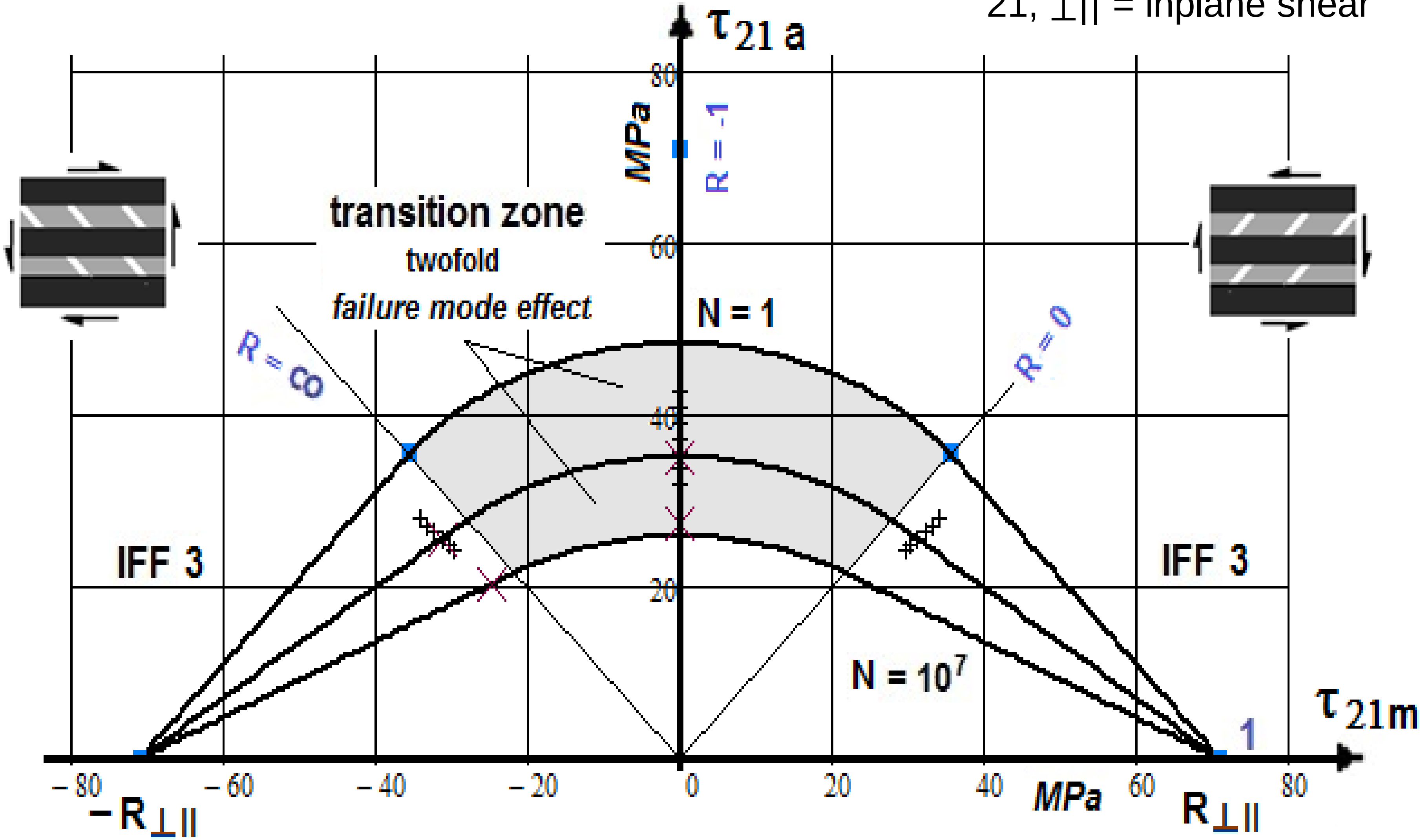


21, ⊥|| =
inplane
shear

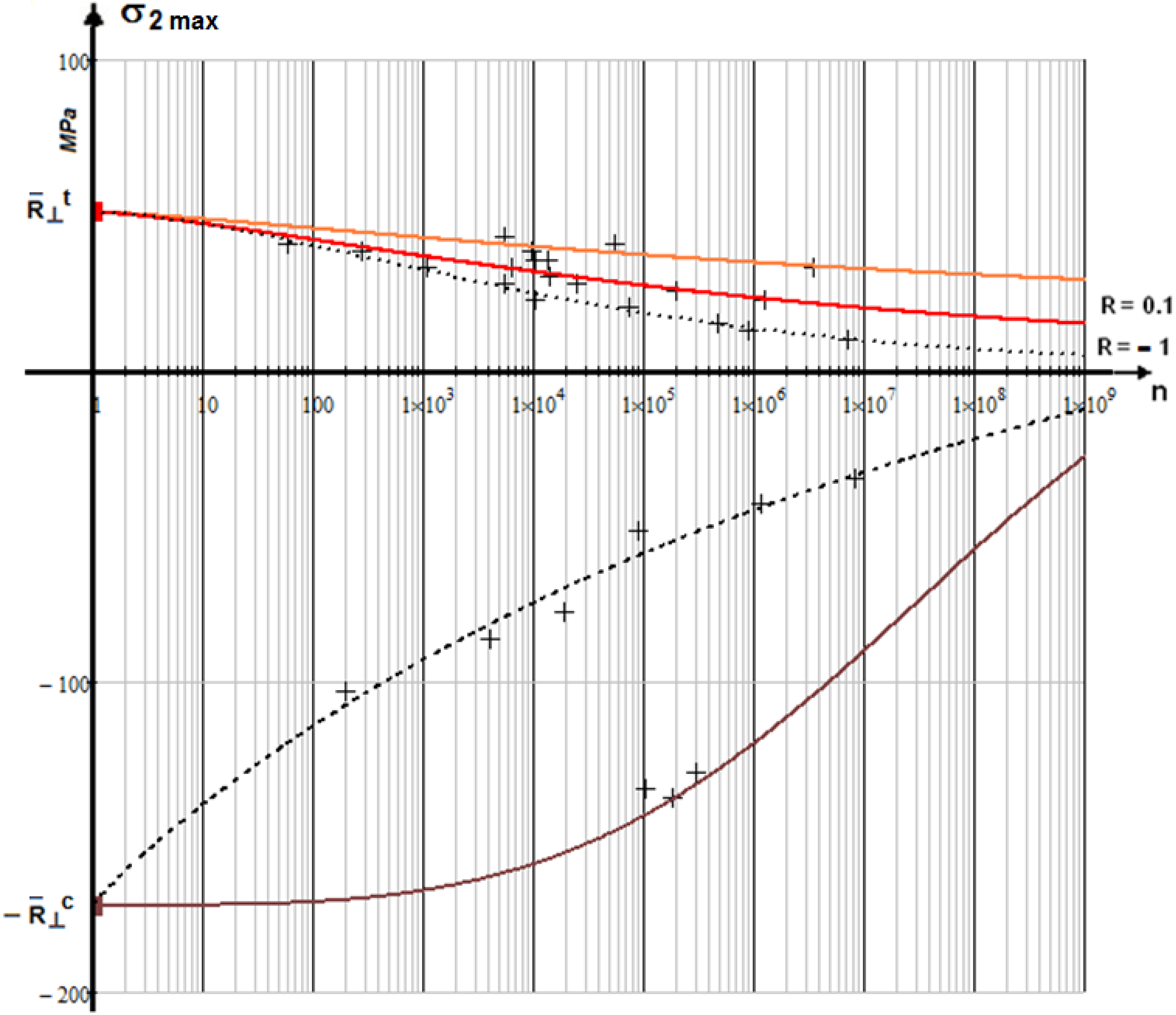
IFF3 Haigh diagram,

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



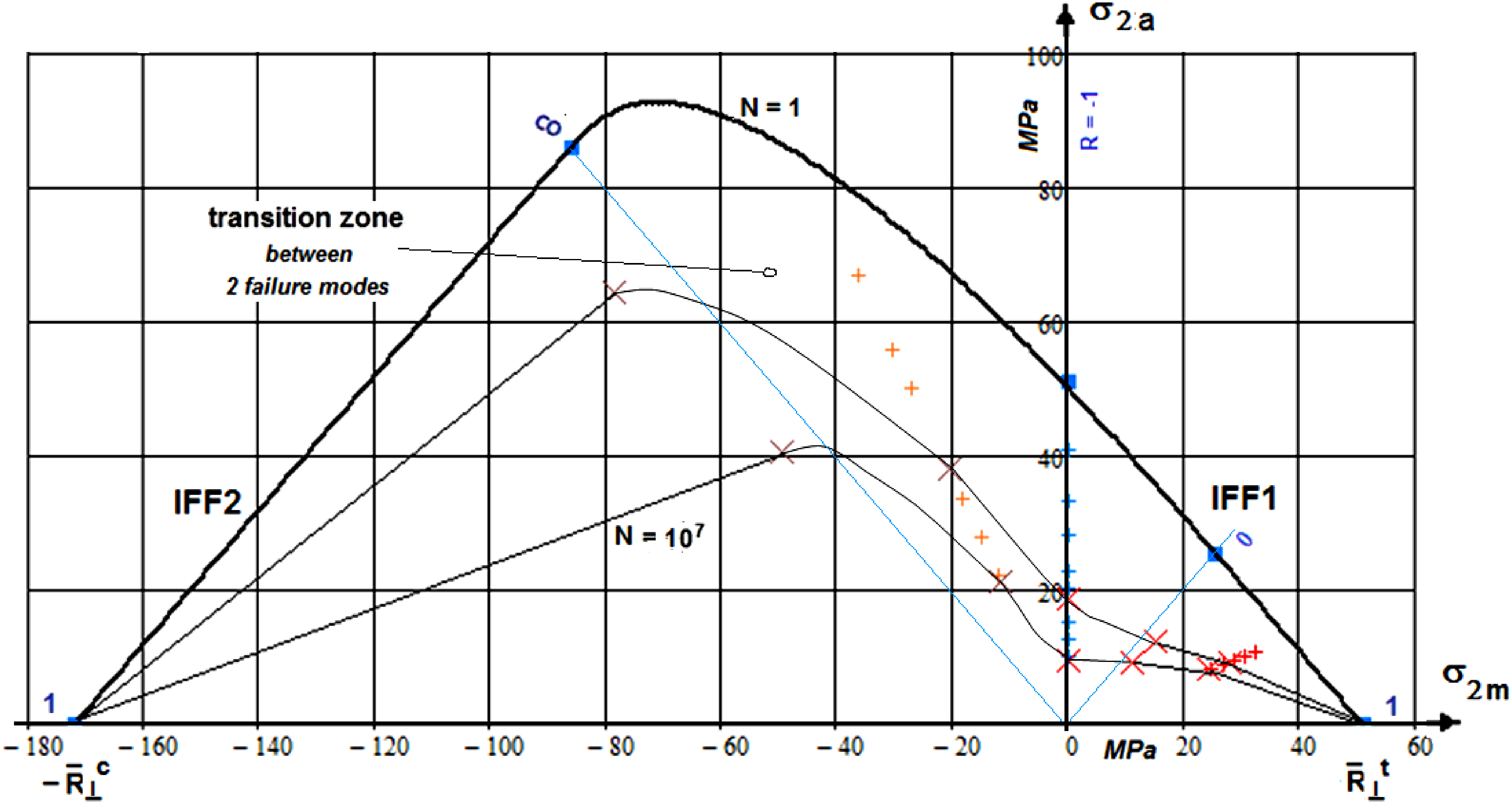
Lin-log IFF1-IFF2-linked S-N curves *[data, courtesy C. Hahne]*



2, ⊥ = across fiber direction

IFF1-IFF2 Haigh diagram

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



The computed S-N curve X-points are mapping fix points for the to be predicted CFL curves

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5 Objectives of the Proposed Method

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

1.) Failure mode-linked *modelling* of the cyclic loading (novel idea)

2.) Measurement of just a minimum number of the failure mode-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)
plus Kawai‘s Model the ‘Modified Fatigue Strength Ratio’

4. Determination of Damaging portions on basis of the static UD strength criteria
considering the residual strength $R_{||}$(R,N))

5.) Failure mode-linked accumulation of Damaging Portions (novel idea) using
Palmgren-Miner

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

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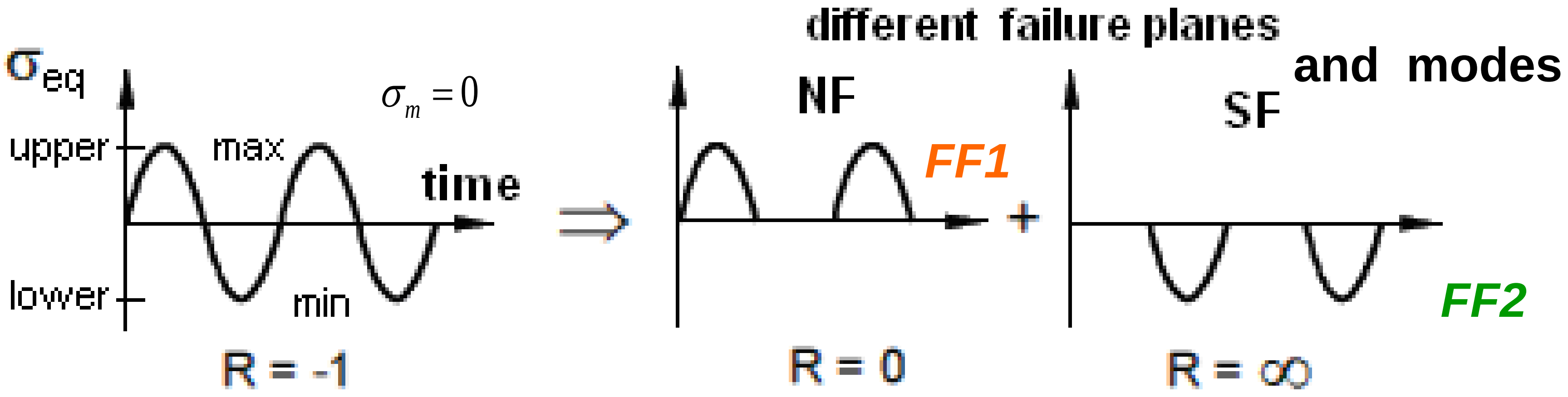
For simply displaying the approach *it is chosen* : - *R = -1 loading*

Separation due to the activated inherent different failure modes



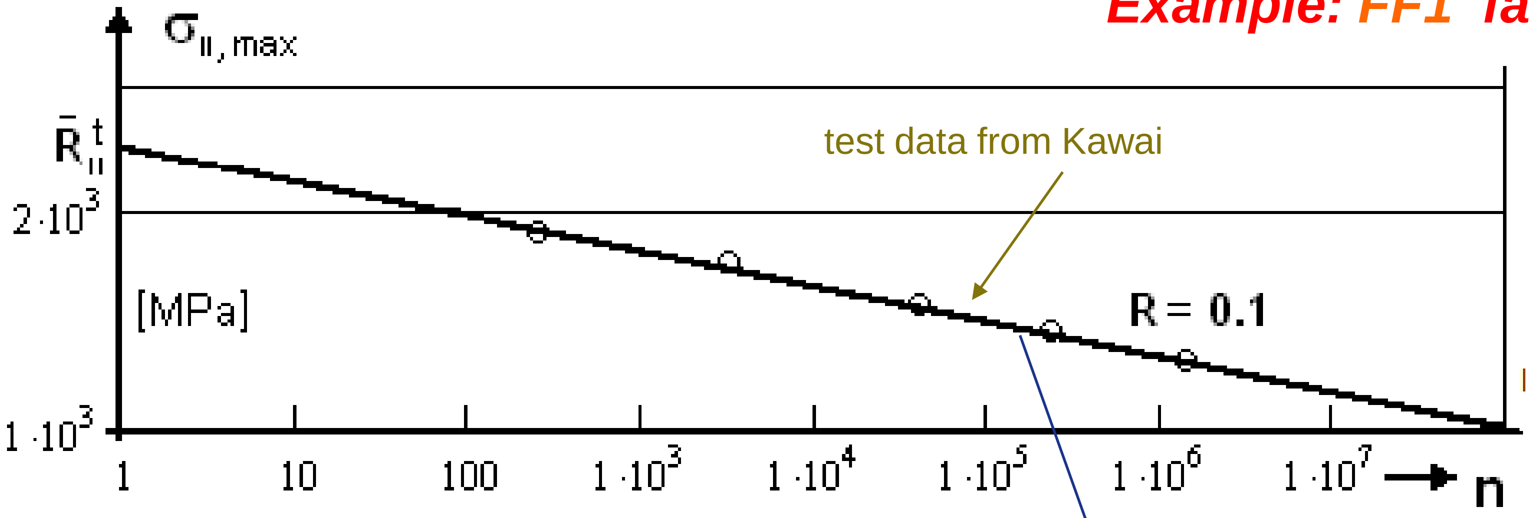
NF := Normal Fracture, SF := Shear Fracture

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**

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

Measured curve used

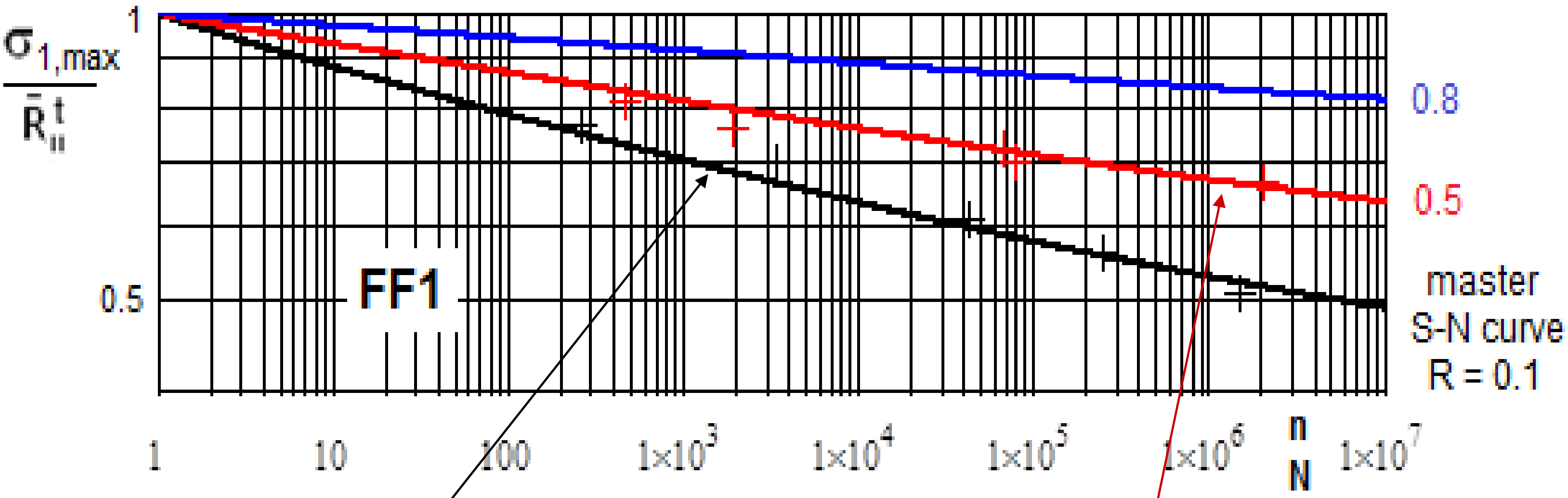
as mode-representative ***Master S-N curve*** for ***FF1***

FF1 strength

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

However, more complicated S-N models may be also applied !

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



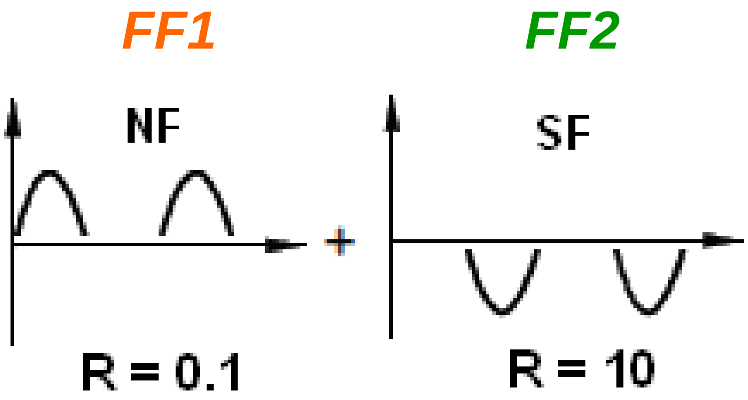
Given : $\sigma_{\|,\ \max}^{Master}(n) \approx \overline{R}_{\|}^{t}\cdot n^{c_{Master}}$ **Searched :** $\sigma_{\|,\max}^{pred} = \overline{R}_{\|}^{t}\cdot n^{c_{pred}}$

Slope of R = 0.5 ?

Step 3: Application of Kawai‘s ‘Modified Fatigue Strength Ratio‘.

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

Application of Miner-‘Rule‘ *simple example*



Loading: again simple

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)

The presented full Lifetime Prediction Approach 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 and the use of Kawai's 'Modified Fatigue Strength Ratio'
4) Detrmination of damaging portions basis of the static UD strength criteria . This depends on cycles-linked shrinking of failure surface by FMC strength criteria. In-situ-effect is considered by deformation-controlled testing.
5) Failure mode-linked *damaging accumulation* (novel idea)

No mean stress correction is performed.

plus the derived Haigh Diagrams.

Cuntze's *5 steps above, including a rigorous failure mode thinking,*

are the main BASIS for the derived Haigh Diagrams.

To be done: Deeper investigation of the behavior in the transition domain and of the additional damaging caused by mode changes (FF1 to FF2 if $R = -1$) including crack-closure effects.

Remind: *What was the main Objective of the Investigation ?*

Fatigue pre-dimensioning of

‘well-designed’, UD laminas-composed laminates

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

derived from *sub-laminate* test specimens,

which capture the embedding (in-situ) effects,

and on S-N curves from automatically constructed Haigh diagrams.

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

Heinrich Heine

Keep in mind !

All is difficult prior to becoming simple!

[Moslik Saadi]

This is my present feeling considering my approach

Some progress is reached.
Further investigations are necessary !

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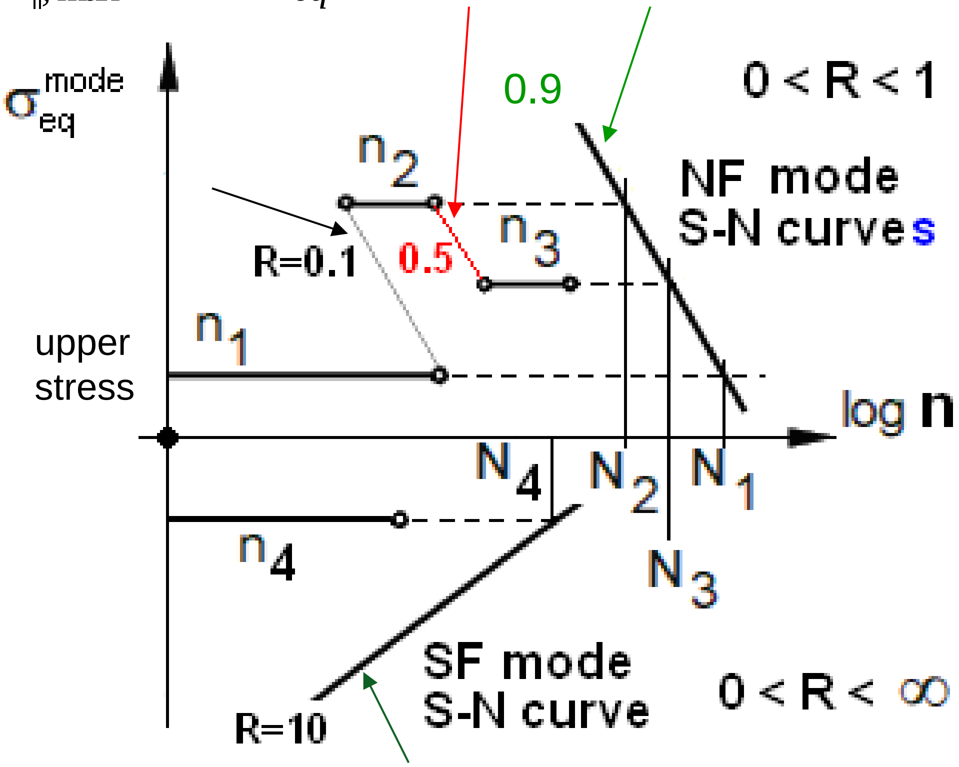
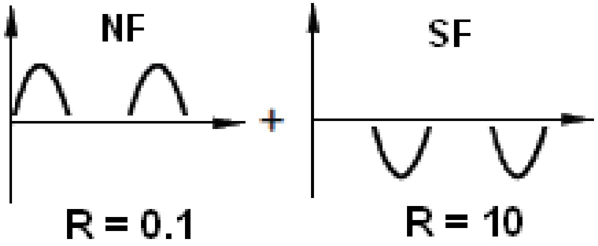
Failure mode-based Lifetime Prediction Method

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

$$\sigma_{\parallel,\max}^{mode} \Rightarrow \sigma_{eq}^{mode}$$



remind



here:

2 master curves

NF: R = 0.1

SF: R = 10

2 predicted curves

NF: R = 0.5, 0.9

Miner application:

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