Increasing use of composites in Aircraft and Automotive Engineering requires a better understanding of its behaviour under static and cyclic loading.

Which are the

How does *Carbon Composites e.V*. support a better understanding?

How did I support it? By one new tool: *Lifetime Prediction of Laminates*

How satisfying is the software situation ?

„Lifetime prediction is a painpoint for a better use of composites in automotive design !“

Industry Requirements & Research State-of-the-Art substantiated by a lifetime prediction for UD lamina-composed laminates

1. **Short Presentation of CCeV + personal activities**
2. **Industrial Requirements with Research State-of-the-Art**
3. **Metal versus Composites** (with some definitions)
4. **Example: *Cuntze's Lifetime Prediction*** *(estimation)* ***) Model for endless fiber-reinforced, fiber-dominated designed Laminates***
5. **Conclusions and Outlook**

Literature and Annex (details on above model and Cuntzes static strength criteria)

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

Carbon Composites eV (CCeV) =

Association of companies and research institutions,

covering the entire value chain of

high-performance fiber reinforced composites

in Germany, Austria and Switzerland.

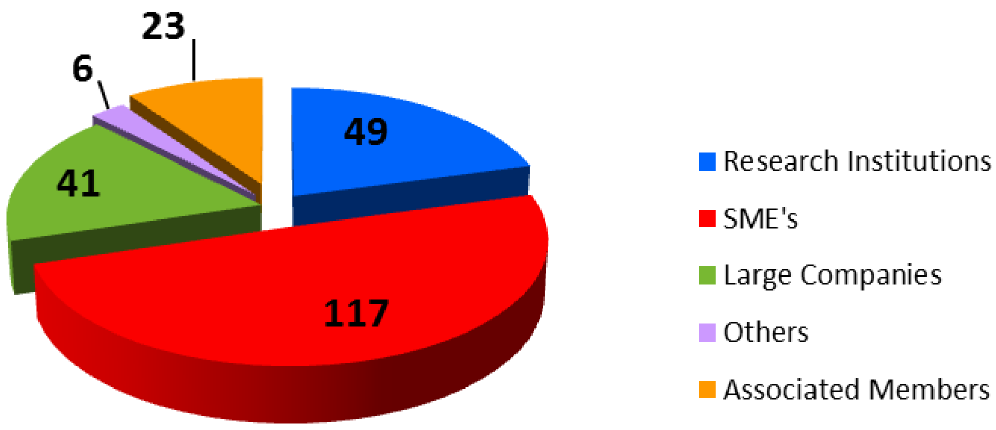
Focus : Promotion of Carbon Fiber Technology

Serving as competence network : to

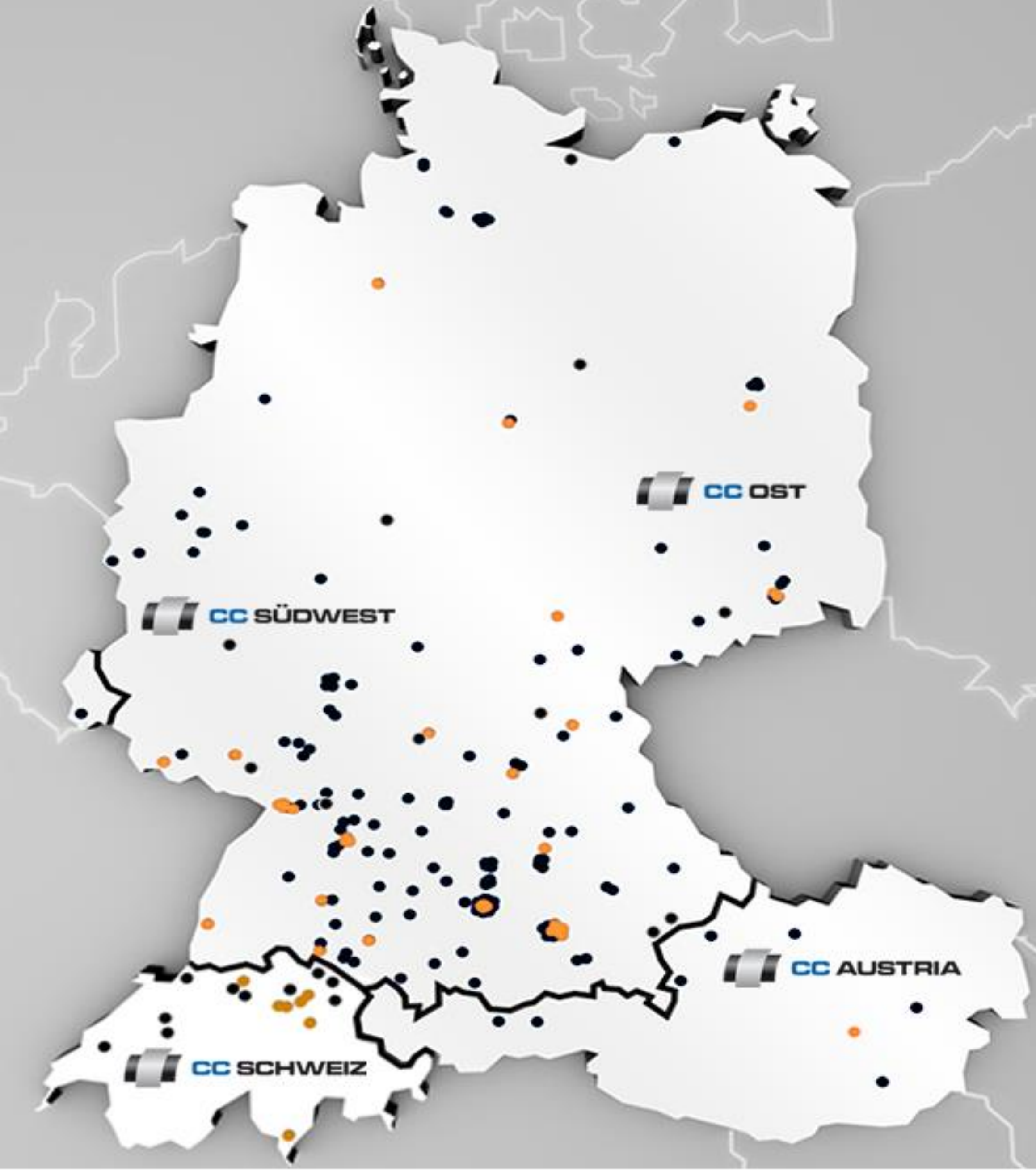
- **support and link collaboration between science, small and large companies**
- **transfer of available know-how and existing competences.**

The CCeV Network

- Organised as an association
- Founded in 2007
- Based in Augsburg
- Financed by membership fees
- The leading Carbon Composites Network in the German-speaking world



An extended presentation with associated literature may be downloaded from the 'free' CCeV-website: http://www.carbon-composites.eu/leistungsspektrum/fachinformationen/fachinformation-2



CARBON COMPOSITES

Regional Departments

CC OST	2012
CC SÜDWEST	2012
CC SCHWEIZ	2012
CC AUSTRIA	2012

Cluster Department

M·A·I CARBON	2012

DACH Area: Specialist Departments

CERAMIC COMPOSITES	2008
CC TUDALIT	2012

Together with TUDALIT e.V.

● = Research Institution ● = Industry

Distribution of the presently 250 members

Sectors

System companies
- Aerospace
- Automotive engineering
- Civil engineering
- Medical technology
- Energy technology
- etc.

Supplier companies
- Fibres, semi-finished products, ancillary materials, coatings
- Assemblies, components
- Tooling machines, processing systems, equipment, plants
- Software and services (e.g. engineering, factory planning)


Bildnachweis: Airbus, ALIEN-Projektteam, KUKA

CCeV‘s Objectives

- ➢ **Pre-competitive cooperation**
- ➢ **Technical information from internal and external contributors**
- ➢ **Initiation of projects**
- **Informal information flow amongst participants**
- **Use of meetings for bilateral and multilateral talks and agreements (“trade fair effect”)**

At present, 35 *technical working groups* live that !

CCeV's activities

Some Technical working groups

… Material

- AG Materialien
- AG Garne und Textilien
- AG Thermoplaste
- AG Biocomposites
- AG Faserbewährte Kunststoffe im Bauwesen
- AG Faserverstärkung im Bauwesen

… Design & Characterisation

- AG Engineering
- UAG Composite Fatigue
- AG Multi-Material-Design
- AG Klebetechnik
- AG Smart Structures
- AG Werkstoff- und Bauteileprüfung
- AG Werkstoffmod./Berechn. im Bauwesen

… Process

- AG Herstellverfahren
- AG Automatisierung
- UAG Herstellprozess-Simulation
- AG RTM Next Steps
- AG Werkzeug- und Formenbau

… Finishing

- AG Bearbeitung
- UAG Absaugtechniken & Schutzmaßnahmen
- AG Oberflächenbeh., Beschichtung, Lackierung
- UAG Roadmap OBL

… Cross Section Issues

- AG Kostenschätzung
- AG Normung und Standardisierung
- AG Roadmap CFK
- AG Umweltaspekte

My Personal Activities in this Field

1. **Foundation of the German Academic Research Group (BeNa) "*Betriebsfestigkeits-Nachweis*" for High-Performance Structures**
   within a Minisymposium for invited specialists as
   Kick-off meeting in March 2010.
   Agreed conditions for Lifetime modeling:
   * *physically-based (on failure modes),*
   * *ply-oriented in order to obtain a generalisation for any UD lamina-composed laminate*

Objective of BeNa group:
Release of a VDI-Guideline

2. **Foundation of a sub-group "*Composite Fatigue*" (2012),**
   of my CCeV-working group 'Engineering',
   managed by the CCeV member company CADCON.

9

my own contribution In this field.

Lifetime prediction of UD Lamina-composed Laminates (such as non-crimp fabrics)

- a lamina-based engineering approach for fibre-dominated laminates -

See my example model later

results of non-funded, private research

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

formerly MAN-Technologie AG, Augsburg, D
now leader of the WG 'Engineering' of Carbon Composites e.V.

Deutsche Arbeitsgruppe BeNa (Betriebsfestigkeits-Nachweis)
'Ermüdung von Bauteilen aus Faserverbundwerkstoff'

CARBON COMPOSITES

Thementag: ***Ermüdung von Bauteilen aus Faserverbundwerkstoff (FVW)***

- Vertiefte Betrachtung von UD Laminaten mit Ausblick Textile Composites -

Zielgruppe: Berechnungsingenieure aus Forschung und Industrie (OEMs, KMUs)

Donnerstag, 14. Februar, 2013. Beginn: 8:00 Uhr , Ende: 17.00 Uhr
Hans-Liebherr-Raum der IHK Schwaben, Stettenstraße 1+ 3, 86150 Augsburg

(zusätzlich Einladung zur ganztägigen Veranstaltung der 3 AGs " *Engineering, NDI, Kleben*" am 15. 2.)

Begrüßung *(P. Horst, TU-Braunschweig, Leiter AG BeNa)*; einführende 'Folien' *(R. Cuntze, CCeV)* (8.10)

Vorträge (20 min + 5 min Diskussion):

Vorstellung und Ziele der AG BeNa. *P. Horst, TU-Braunschweig* (8.25)

1. **Vom Ermüdungsverhalten von Metallen zu dem von FVW.** *G. Kress, ETH Zürich* (8.40)
2. **Lebensdauerabschätzung** (zyklischer Nachweis). *I. Koch (BeNa), ILK Dresden* (9.05)
3. **ZfP und Festigkeit/Ermüdung.** *V. Trappe (BeNa), BAM Berlin,* (9.30)

Kaffee-Pause: (9.55)

4. **Ein neues physikalisch basiertes Ermüdungs-Schädigungsmodell für Faser-Kunststoff-Verbunde.** *R. Rolfes (BeNa), ISD, TU-Hannover* (10.15)
5. **FE-Analyse der Ermüdungsschädigung von FKV.** *M. Magin (BeNa), IVW Kaiserslautern* (10.40)
6. **Anforderungen und Herausforderungen an die Betriebsfestigkeiten für Faserverbundstrukturen bei der A350XWB**. *D. Hartung, Premium Aerotec Augsburg* (11.05)
7. **Composite Fatigue Approach in Airbus.** *W. Göbel / L. Ratier, Airbus.* (11.30)

Mittagsbuffet: (11.55)

8. **Ermüdet Textilbeton?** *F. Jesse, BTU-Cottbus* (12.35)
9. **Fatigue Life Simulat. and Verification of Wind Turbine Rotorblades.** *E. Eyb, Re-Power* (13.00)
10. **Betriebsfestigkeitsbewertung von Faserverbundwerkstoffen – Übersicht und Ausblick.** *M. Hack, LMS Kaiserslautern* (13.25)
11. **Methods for life predict. of comp. materials and adhesively-bonded composite joints.** (13.50) *S. Vassilopoulos, EPFL Lausanne, CH,* editor *"Fatigue life prediction of composites and comp. structures"*,2010

Kaffee-Pause: (14.15)

12. **Lebensdauervorhersage bei BMW**. *P. Wagner, BMW München* (14.40)
13. **Zur Festigkeitsbewertung von CFK-Strukturen unter PKW-Betriebslasten.** (15.05) *C. Hahne/ U. Knaust, Audi Ingolstadt*
14. **Praxiseffekte bei der Schwingfestigkeitsanalyse orthotroper Faserkunststoffverbunde**. (15.30) *Ch. Enke/ J. Eulitz/ R. Grothaus, EAST-4D Carbon Technology Dresden*

10 min Pause

15. **(I) Geschichte der Fatigue-Nachweisführung bei Eurocopter** (seit 1965). *H. Bansemir* (16.05)
(II) Vorgehensweise bei dem Fatigue-Nachweis mit der Bestimmung der Wöhlerkurven und Arbeitskurven. *E. Ahci, Eurocopter Donauwörth*
(III) Die dynamische Festigkeit von Kohlefaser-Verbundstrukturen. *A. Weinert, Eurocopter*

* **Aufnahme von interessierten Industrie- und Behördenmitgliedern in die AG BeNa.** (17.05)

Ausklang im Foyer, Abendbuffet, Zeit für Gespräche

Es freut sich auf eine rege Beteiligung und viele inhaltsreiche interessante Vorträge Ihr Ralf Cuntze

Full day specialists meeting at CCeV Augsburg, February 2013

… and participation at the DVM Congress at Herzogenaurach, Oct. 2013

Workshop "Composite Fatigue (CompoFat)"

- procedures, tackling UD-Laminates through Textile Composites -

Audience: Invited speakers and invited specialists from industry and institutes

Thursday, February 6, 2014. Start: 8:15 Uhr , End: 17.00 Uhr
Fuggersaal, IHK Schwaben, Stettenstraße 1+3, 86150 Augsburg

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Welcome: *R. Cuntze (CCeV) and K. Schulte (TU-Hamburg-Harburg)*

Presentations: (25 min + 5 min Diskussion)

1. (8.30) **Multiaxial Fatigue Phenomena and the Objectives of the Working Group BeNa.** *P. Horst (TU-Braunschweig, leader of BeNa)*
2. (9.00) **Life Time Prediction and Design Verification.** *I. Koch (BeNa), ILK Dresden*
3. (9.30) **Fatigue of Textile Composites.** *N. Kosmann (BeNa), TUHH*

Break: (10.00)

4. (10.30) **Finite element based analysis of fatigue induced damage in fiber reinforced.** *M. Magin (BeNa), IVW-Kaiserslautern*
5. (11.00) **Fatigue Damage in Glass Fibre Reinforced Composites.** *P. Bronsted, Risoe-DTU, Denmark*
6. (11.30) **A link between damage initiation thresholds in static loading and cyclic loading (fatigue strength) of textile composites**. *S. Lomov, Leuven*

Lunch buffet: (12.00)

7. (13.00) **Prediction of Progressive Fatigue Damage in Adhesively-bonded GFRP joints.** *A. Vasilopoulos, EPFL Lausanne, CH,*
8. (13.30) **Fatigue Behaviour of a Carbon Satin Weave Thermoplastic Composite under tension, bending and shear loading.** *W.V. van Paepegem, U-Gent, Belgium*
9. (14.00) **Anisomorphic master diagram approach to fatigue life prediction of composites for any stress ratio at any temperature**. *M. Kawai, Uni-Tsukuba, Japan*

Break: (14.30)

10. (15.00) **Multiaxial fatigue: damage mechanisms and manufacturing defects**. *R. Talreja, Texas A&M University*
11. (15.30 **Multiaxial fatigue: From experimental observations to damage modelling.** *M. Quaresimin, Uni-Padova Italy*)
12. **(16.00). A novel Lifetime Prediction Model for Long Fiber-reinforced Laminates**. *R. Cuntze, CCeV*
13. (16.30) **Discussion round, conclusions and outlook with networking on potential collaboration towards the formation of research groups for the upcoming European HORIZON framework**

17.00 Get Together. Fingerfood, time for linking people and information exchange.

I wish us good discussions and an excellent information exchange.

With best regards Ralf Cuntze

International workshop with invited lecturers, February 2014.

Audience: 130 people

1. Short Presentation of CCeV + personal activities

2. Industrial Requirements with Research State-of-the-Art

3. Metal versus Composites (with some definitions)

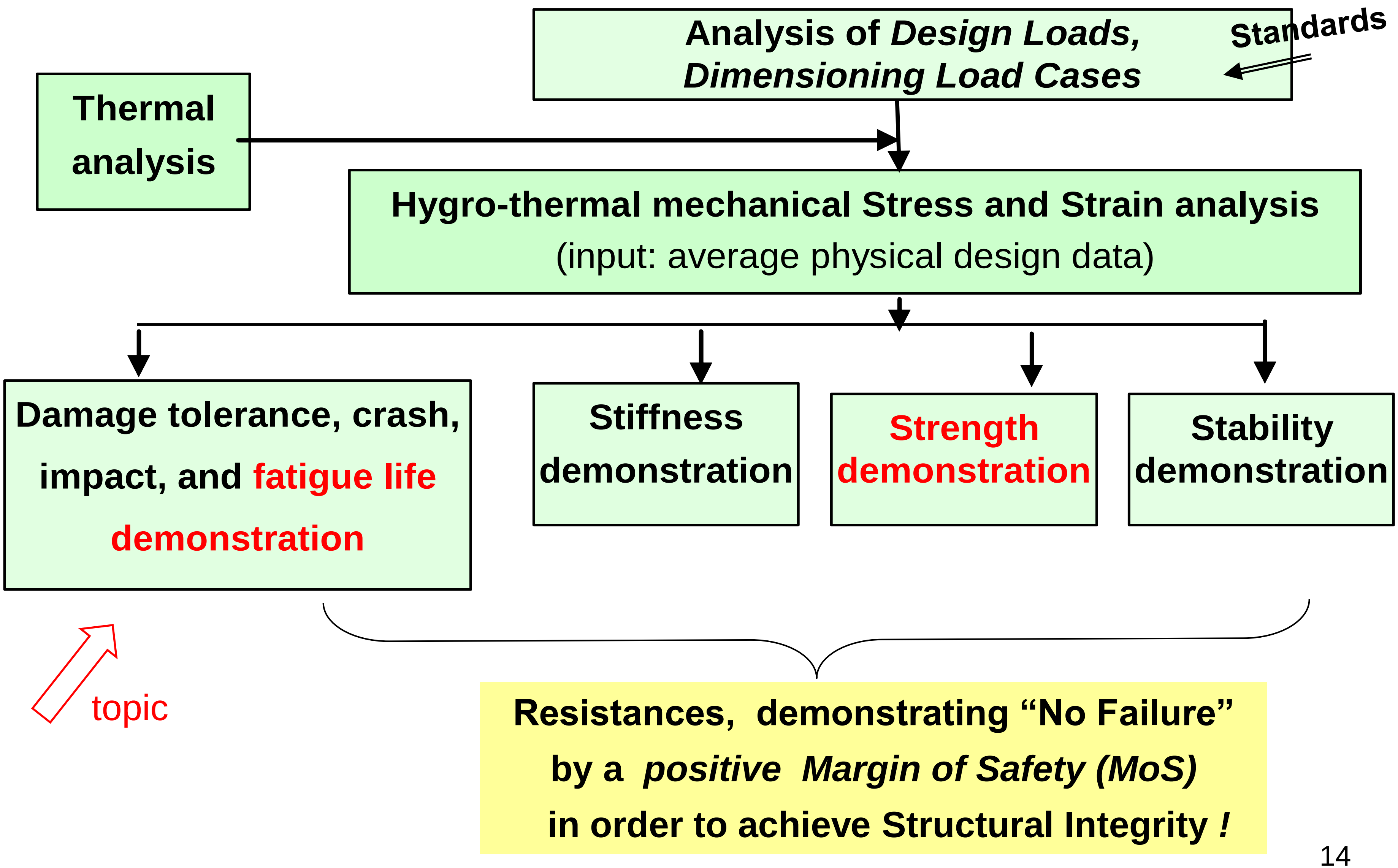
4. Example: *Lifetime Prediction Model for Endless Fiber-Reinforced Laminates*

5. Conclusions and Outlook

Literature

13

Which are the required Analyses in Structural Design and Design Verification ?



Some definitions for a better understanding: *What is ?*

Failure : the structural part does not fulfil its functional requirements

(FF = fiber failure, IFF = inter-fiber-failure (matrix failure, leakage, deformation limit, delamination size limit, etc.)

Fatigue : process, that degrades material properties. 3 fatigue phases exist

Damaging (= Schädigung, is not damage (Schaden), as it is equally used in English): a process wherein the results, the damaging portions, finally accumulate to a technical damage size such as a macro-scopic delamination.

Used as means is the Palmgren-*Miner Damaging Accumulation* model

Damage : damage size that is judged to be critical. *Then Damage Tolerance Analysis is used to predict the damage growth under further cyclic loading*

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

.

Which questions does an engineer pose in the case of cyclic design?

1. **When does damaging start?** 1st phase of fatigue life
2. **How can one quantify the single** (micro-**)damaging portions?**
3. **How can the single damaging portions be accumulated?**
4. **When do the accumulated damaging portions form a real damage?**
5. **When does such a damage (**delamination, impact**) become critical?**
6. **How is the damage growth in the final 3rd phase of fatigue life ?**

    (fixation of part replacement time, inspection intervals)

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

- **No Lifetime Prediction Method available, that is 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**
- **Present: Engineering Approach:**

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

  Design experience proved: No fatigue danger given

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

  We must react!

  Above ε= 0.5% *first filament breaks , diffuse matrix-microcracking* occurs

  in usually *fiber-dominated laminates* used in high-stress applications .

17

Which is the required cyclic design basis? for fatigue characterization

- S-N curves $R = const = \sigma_{unter} / \sigma_{ober}$
- Hypothesis to accumulate the damaging portions (rel. Miner most often)
- Model to quantify the damaging portions under cyclic loading

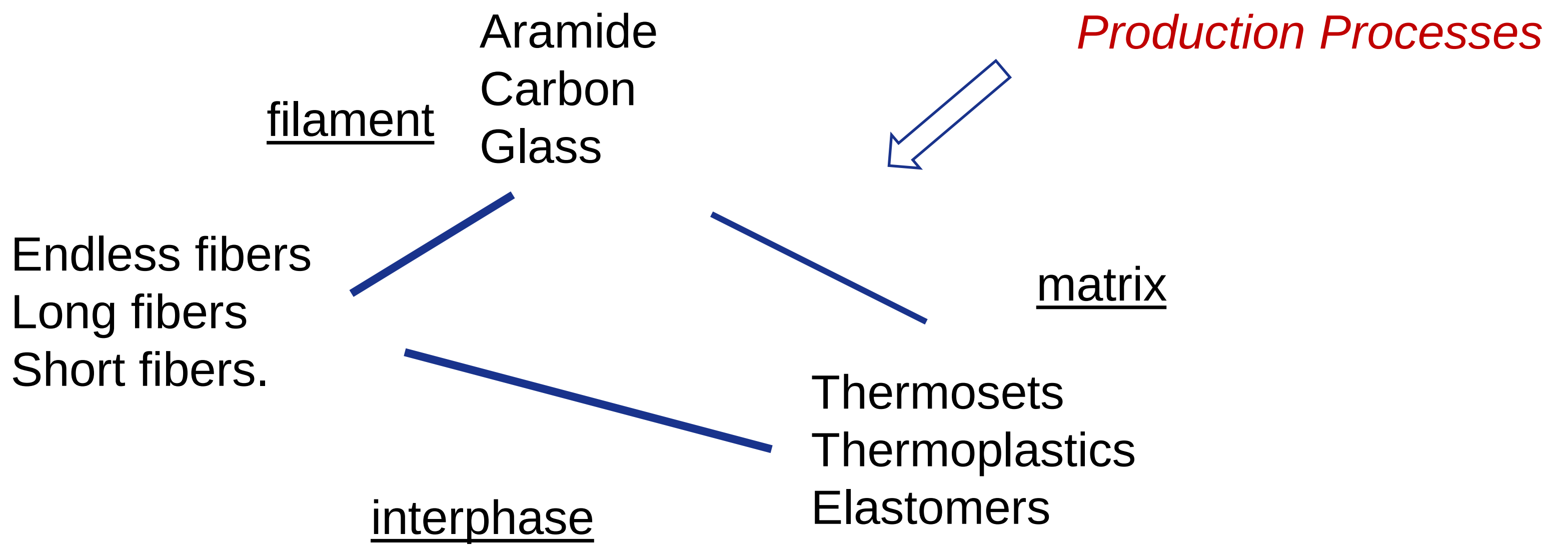
for the determination of above damaging portions:

Experience proved: Static strength failure conditions can be used, if the

Static Strength values are replaced by the

Residual Strength values , associated to the respective lifetime !

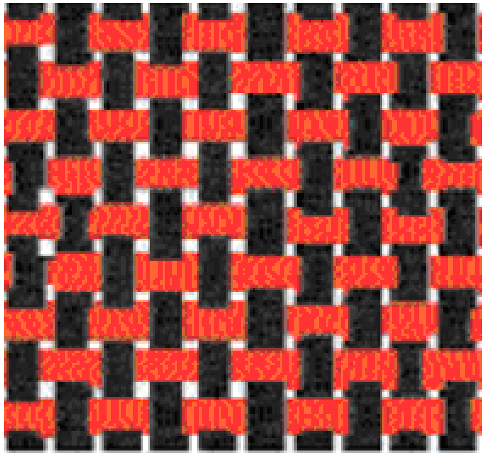
Combinations of different Constituents of polymeric Composites



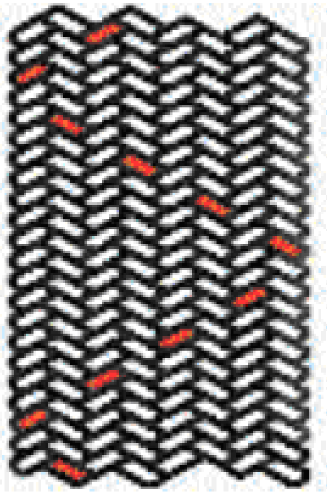
All these combinations

- need a different treatment and
- afford an associated understanding of its internal material behaviour.

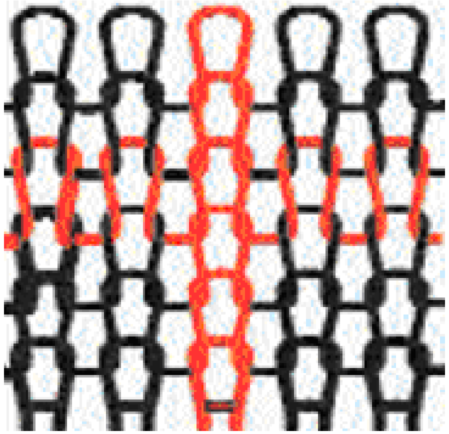
Coming up: The Textile Challenge to achieve Certification



plain weave

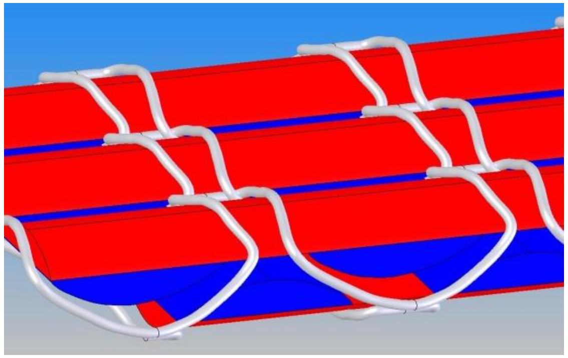


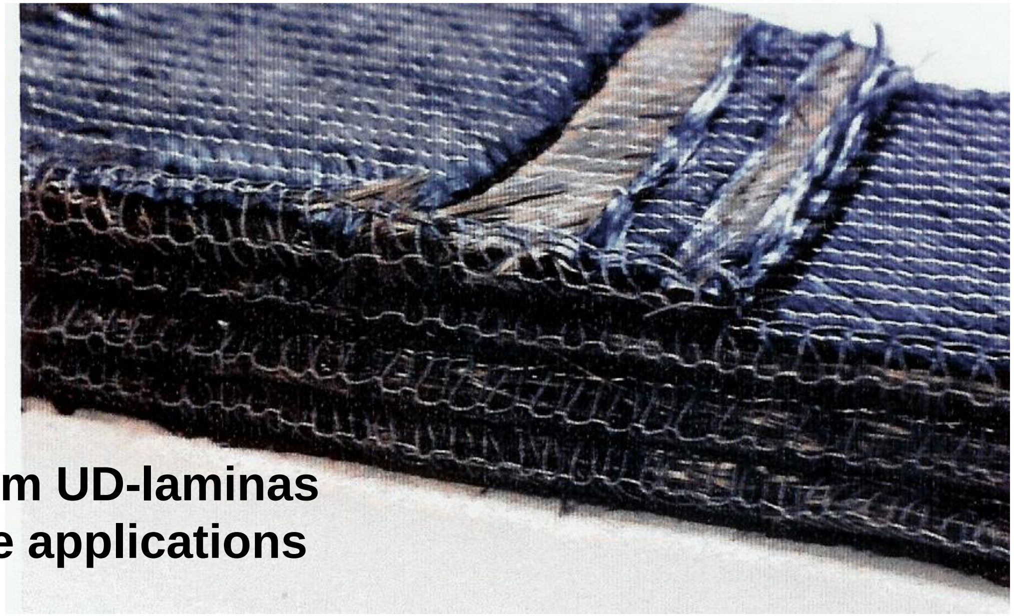
braid



weft knit

warp knit





non-crimp fabrics from UD-laminas for high-performance applications

Static loading:

- Validated 3D strength failure conditions for isotropic (foam), transversely-isotropic UD materials, and orthotropic materials (e.g. textiles) to determine ‘Onset of fracture‘ and ‘Final fracture‘
- Standardisation of material test procedures, test specimens, test rigs, and test data evaluation for the structural analysis input

Cyclic (dynamic) loading : fatigue

- Development of practical, physically-based lifetime-prediction methods. Generation of S-N curve test data for verification of models
- Consideration of manufacturing imperfections (tolerance width of uncertain design variables) in order to achieve a production cost minimum by „Design to Imperfections“ includes defects
- Delamination growth model for duroplastic and thermoplastic matrices
- Consideration of media, temperature, creeping, aging
- Provision of more damping because parts become more monolithic.

21

German Research State-of-the-Art of Fatigue Lifetime Modelling

- Germanischer Lloyd (for windmills, to be reworked)
- VDI 2014, sheet 3: (released by me, as convenor, in 2006. Fatigue to be reworked)
- BeNa group, as university activities (public)
- Company activities, just partly issued

22

Existing Software: As far as (suitable) lifetime prediction models are available

- Company-owned programs: AUDI, AIRBUS?, BMW, …

On this topic will later report:

- HBM GMbH nCode products: Dr. Vervoort
- Magne Powertrain: Mr. Spindelberger
- Safe Technology Ltd: Dr. Sobczak
- LMS, Dr. Hack
- Firehole Composites: (multi-level model
- ….

From the BeNa group, university efforts

for instance:

- ILK, TU-Dresden (UD, textile attempts)
- IVW, TU-Kaiserslautern (thermoplastic UD)
- ISD, TU-Hannover (multi-level model)
- …..

Engineer‘s desires for a fatigue lifetime prediction model

to

- capture multi-axial, variable loadings
- be physically-based
- account for failure of the composite material constituents matrix, fiber and interphase
- deal on the simpler homogenized composite material level (numerical efficency)
- be applicable to any laminate
- set up a fatigue model with clearly measurable parameters
- have them implemented in a standard software.

1. Short Presentation of CCeV + personal activities

2. Industrial Requirements with Research State-of-the-Art

3. Metal versus Composites (with some definitions)

4. Example: *Lifetime Prediction Model for Endless Fiber- reinforced Laminates*

5. Conclusions and Outlook

Literature

25

Which is the Work-Flow of a Fatigue Lifetime Prediction?

1 Input

Operational loadings: Load-time curves (modeling by rain flow, ..)

Safety concept: Design to Life j_{Life} = 3 – 4, inspection interval

Consideration of operational (service) loading:

Time domain: Cycle-by-cycle or collective-by-collective (less computational effort)

Frequency domain: Load spectra (loss of load sequence) or block loadings, etc

2 Transfer of operational loading into stresses by Structural Analysis

3 Output for several S-N regions

Low Cycle Fatigue LCF: high stressing,

High Cycle Fatigue HCF: intermediate stressing

Very High Cycle Fatigue VHCF: low stressing and strains

(DFG Research Program SPP1466, started 2010).

- **Ductile material behaviour** (example: isotropic metal)

  1 Mechanism = "shear stress sliding"

  occurs under all cyclic loadings under:

  tensile stresses, compressive stresses, shear and torsion stresses !

  Therefore this single mechanismus 'shear stress sliding' can be described by a 1 (yield) failure condition !

- **Brittle material behaviour , isotropic material**

  2 *Damaging creating* ***Mechanisms***

- **Brittle material behaviour, UD- material**

  5 *Damaging creating* ***Mechanisms.***

27

Consequence:

5 strength failure condition (criterion) must be employed

… for UD-composed brittle behaving laminates, possessing
5 failure modes, 5 strengths, and
5 strength failure conditions!

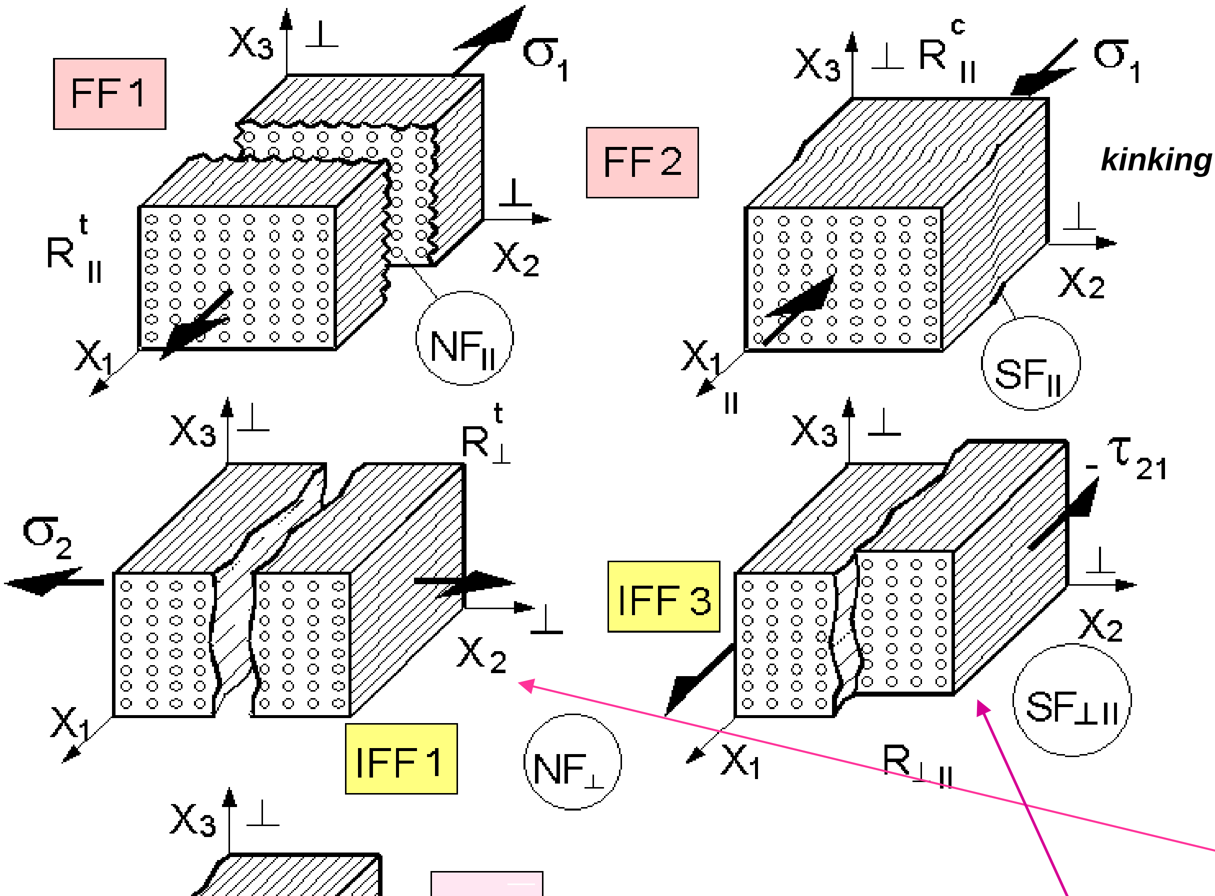
Stress (not strain) criteria are applied to

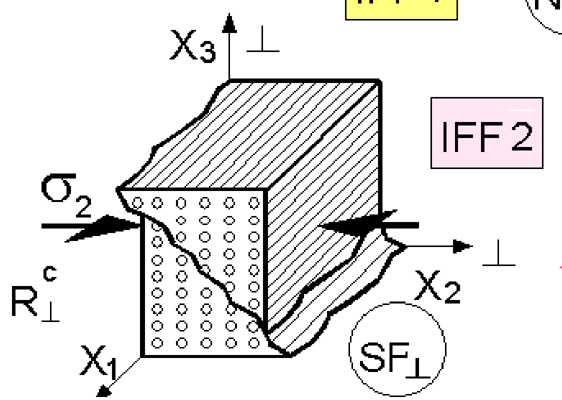
- determine the subsequent damaging portions:
- capture the combined effect of lamina stresses and
- consider residual stresses from manufacturing cooling down (essential for HCF)

PROOF: Fracture Modes of transversely-isotropic UD Material, observed

[Cun04]

t = tension
c = compression





wedge type

- ▶ **5 Fracture modes exist**

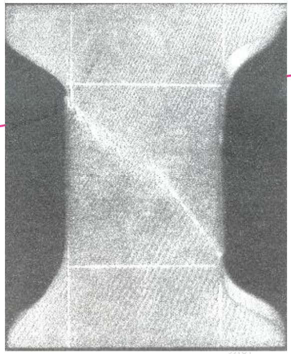
  = 2 FF (Fiber Failure)

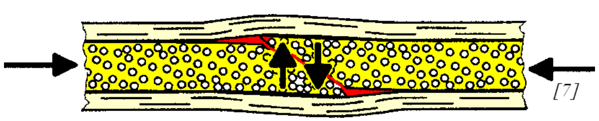
  + 3 IFF (Inter Fiber Failure)

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

NF := Normal Fracture

SF := Shear Fracture





Experience with to-date Composites **from fiber-reinforced plastics**

- behave brittle

- experience early fatigue damage

- show benign fatigue failure behaviour in case of 'well-designed', fiber-dominated laminates until final 'Sudden Death'.

(fiber-dominated:= 0° plies in all significant loading directions,
> 3 fiber direction angles)

30

Quantifying damaging progress: By Static Strength Failure Conditions possible?

Experience-proven Assumption:

If damaging mechanisms (failure modes) in static and cyclic case 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, to obtain quantified damaging portions

my FMC-based Static Failure Conditions (criteria) might be used,

(from my generally applicable Failure-Mode-Concept applied to UD-material)

Measurable quantities within damaging:

Micro-crack density, Residual strength, Resisual stiffness.

Driver for my research work on Strength Failure Conditions (criteria)

Achievement of practical, physically-based criteria under some *pre-requisites* :

- *physically convincing*
- *simple, as much as possible*
- *invariant-based*
- *allow to compute an equivalent stress (very helpful for a distinct failure mode)*
- *rigorous indepent treatment of each single failure mode (2 FF + 3 IFF)*
- *using a material behaviour-linked thinking and not a material-linked one*
- *shall be an engineering approach where all model parameters can be measured*.

Note on UD strength failure conditions:

Puck's action plane approach involves some basic differences to Cuntzes Failure-mode-concept-based approach:
(1) is not invariant-based, (2) interacts the 3 Inter-Fiber-Failure modes (IFF) by a Mohr-Coulomb-based equation, (3) post-corrects the IFF- influence on FF.
Cuntze provides for each failure mode an equivalent stress, that captures the influence of IFF on FF by his interaction equation, uses less model parameters.

32

State of the Art of <u>Static</u> Strength Failure Conditions (SFCs) *for UD laminas:*

Is documented by the results of the *World-Wide-Failure-Exercises 1992-2013*

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

Aim: *' Testing Strength Failure Conditions to the full of Fiber–Reinforced Polymer Composites! '*

(was for transversely-isotropic UD materials, only)

Procedure of the World-Wide-Failure-Exercises-I and -II:

Part A of a WWFE: ***Blind Predictions, based on strengths data, only***

Part B of a WWFE: ***Comparison Theory-Test*** *with not always reliable 'Failure Stress Test Data'*

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

(plain test specimens, no notch)

Cuntzes 3D Strength Failure Conditions (criteria) for UD-material

(top-ranked in the World-Wide-Failure-Exercises-I and –II) [Cun04, Cun11]

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

FF2 $Eff^{\parallel\tau} = -\breve{\sigma}_1 / \bar{R}^c_{\parallel} = +\sigma^{\parallel\tau}_{eq} / \bar{R}^c_{\parallel}$, $\breve{\sigma}_1 \cong \varepsilon^c_1 \cdot E_{\parallel}$ **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 $Eff^{\perp\parallel} = \{[\mu_{\perp\parallel}\cdot I_{23-5} + (\sqrt{\mu_{\perp\parallel}{}^2 \cdot I_{23-5}{}^2 + 4\cdot\bar{R}_{\perp\parallel}{}^2\cdot(\tau_{31}^2 + \tau_{21}^2)^2}\,]/(2\cdot\bar{R}_{\perp\parallel}{}^3)\}^{0.5} = \sigma^{\perp\parallel}_{eq} / \bar{R}_{\perp\parallel}$

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

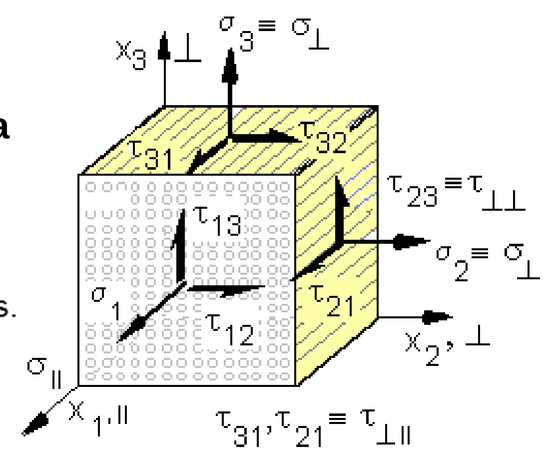
Modes-Interaction $Eff^{\,m} = (Eff^{\parallel\tau})^m + (Eff^{\parallel\sigma})^m + (Eff^{\perp\sigma})^m + (Eff^{\perp\tau})^m + (Eff^{\perp\parallel})^m$

with

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

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

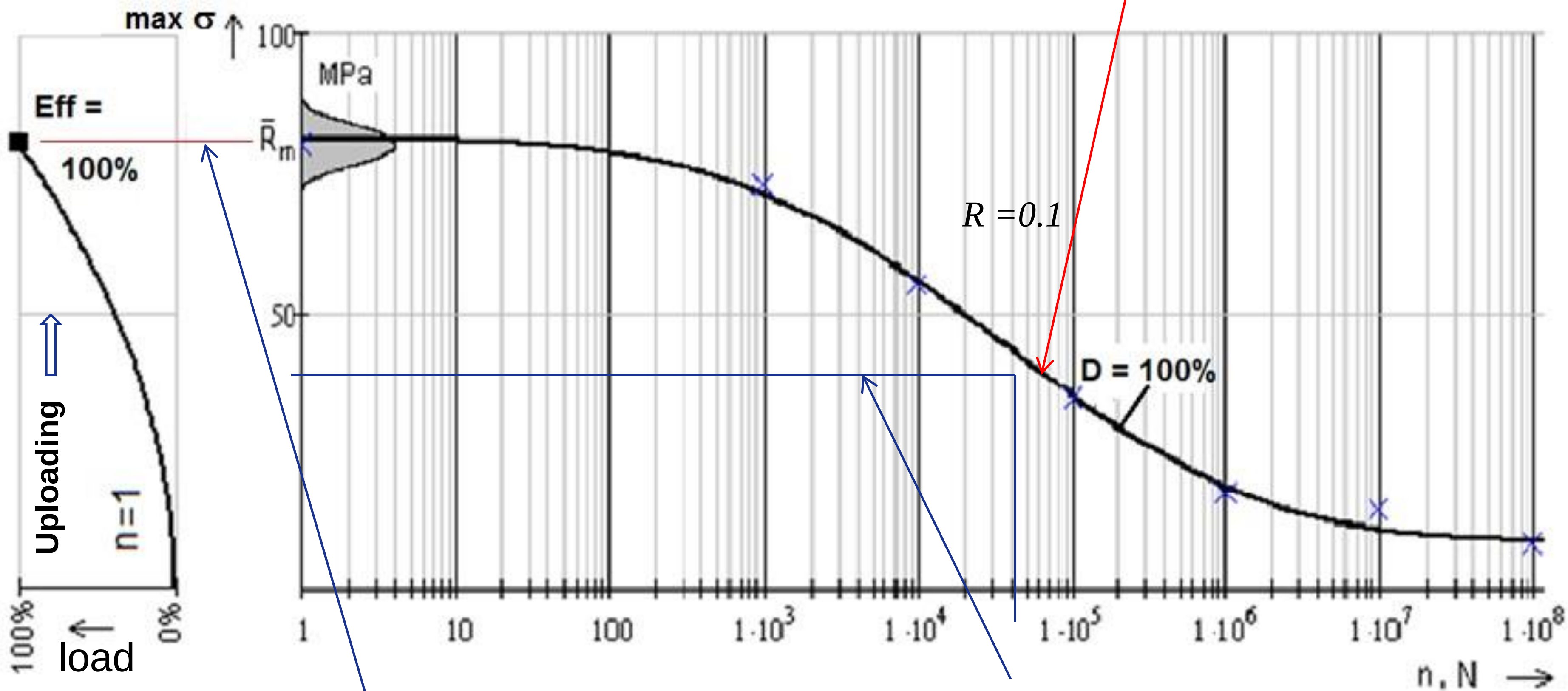
Typical friction value data range: $0.05 < \mu_{\perp\parallel} < 0.3, \quad 0.05 < \mu_{\perp\perp} < 0.2$



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

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

$R = \sigma_{min} / \sigma_{max}$



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 %

The static material stressing effort *Eff* (Werkstoffanstrengung) is replaced by the cyclic *D* !

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

Lifetime Prediction (estimation)

1. Short Presentation of CCeV + personal activities

2. Industrial Requirements with Research State-of-the-Art

3. Metal versus Composites (with some definitions)

4. Example: ***Cuntze's Lifetime Prediction Model for Endless Fiber-reinforced Laminates***

5. Conclusions and Outlook

Literature

36

Failure mode-linked Master S-N-curves to save test costs

For lifetime estimation usually several S-N-curves are needed.

(constant amplitude loading is a seldom case)

<u>Idea</u>

Measurement for each failure mode: just one modal Master S-N-curve

- for a fixed stress ratio *R*
- prediction of additionally necessary S-N-curves of a mode 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 for plain laminates is derivable !

Its characteristical steps are presented:

4 steps

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

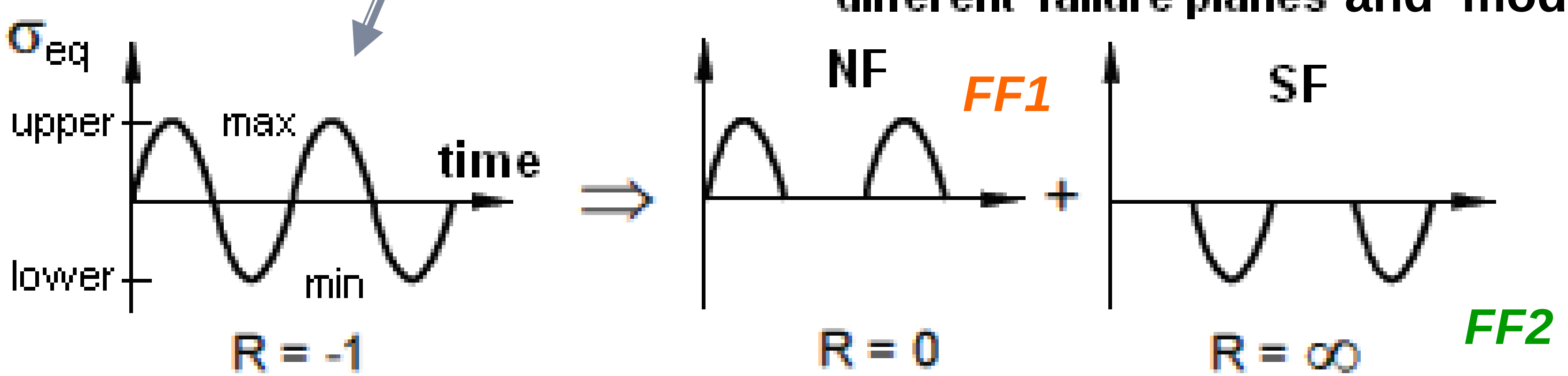
Failure mode-wise Modelling of Loading Cycles for the high-performance ‘fiber-dominated designed’, UD laminas-composed laminates

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

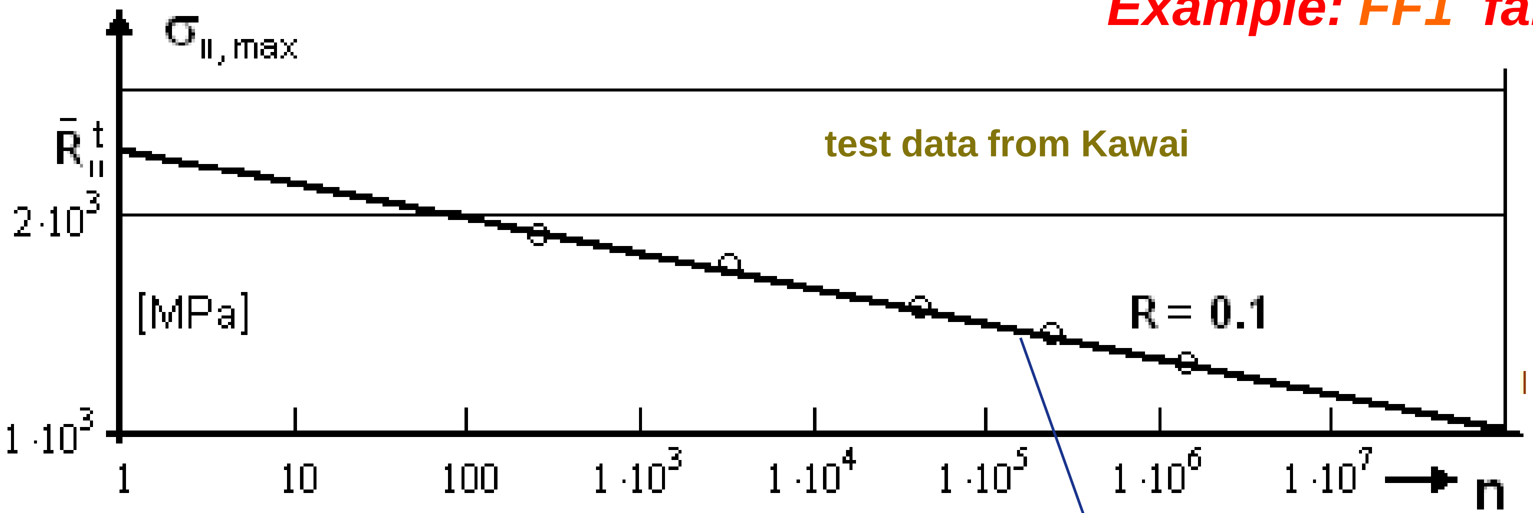
Step 1 : Failure mode-wise apportionment of cyclic loading (novel)

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

FF1:= fiber tensile fracture; *FF2*:= fiber compressive failure

Mapping of Mode S-N data by a representative *Master curve*

Example: FF1 failure mode



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

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

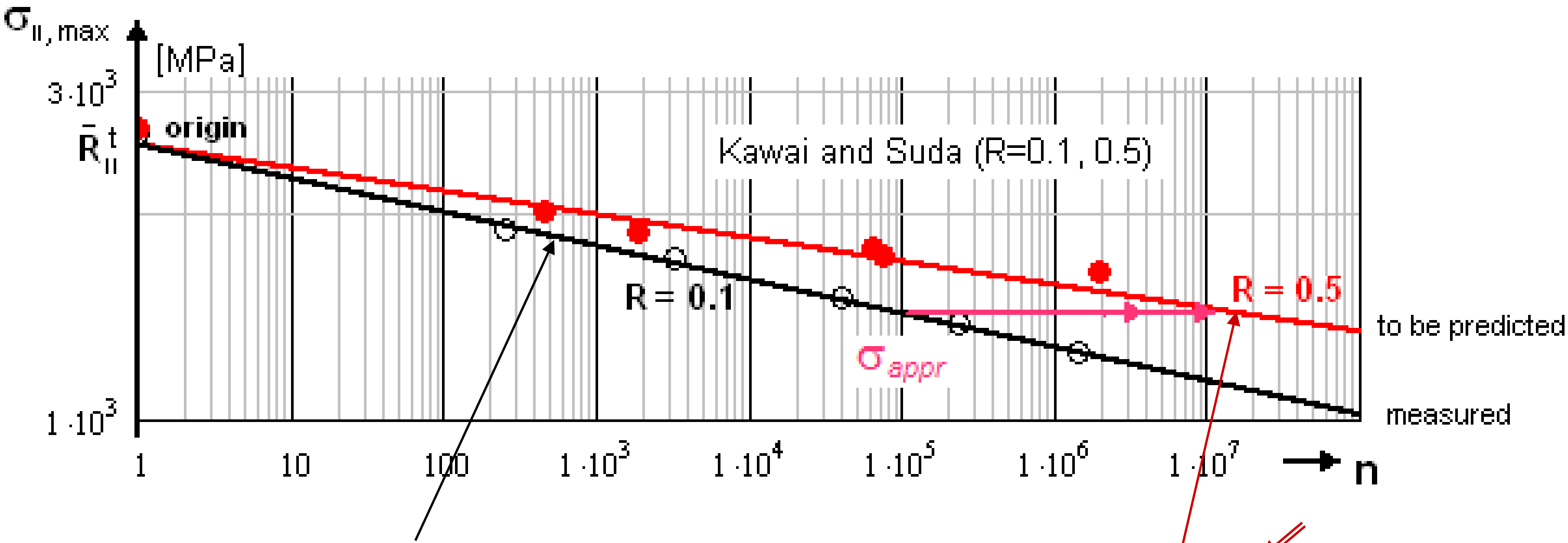
Measured test data mapped by

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

FF1 strength

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



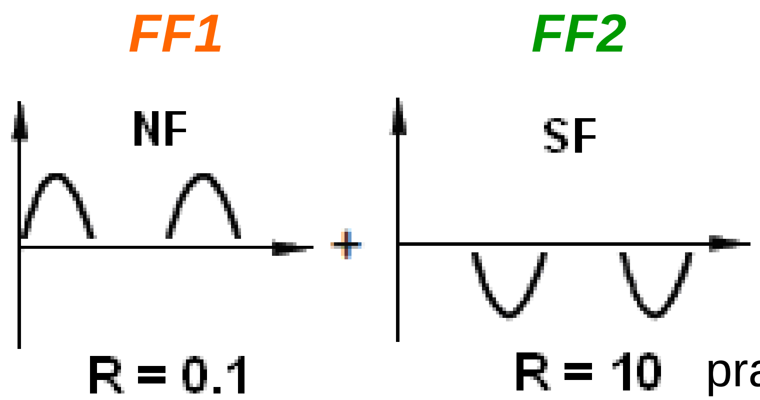
Given : $\sigma_{\|,\ \max}^{Master}(n) \approx \overline{R}_{\|}^{t} \cdot n^{c_{Master}}$ **Searched :** $\sigma_{\|,\max}^{pred} = \overline{R}_{\|}^{t} \cdot n^{c_{pred}}$

Slope of R = 0.5 ?

Step 3: Application of the principle of constant strain energy
A distinct strain energy level will be reached for R > 0.1 at higher cycles.

S := cyclic stress range = Δσ, N:= number of cycles to failure, n:= cycle number

Application of Relative Miner-‘Rule‘



Simple Example: again

R = -1

practically measured curves

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

$$+ \quad D\ (IFF1, IFF2, IFF3) \ = \ D \leq \ D_{feasible} < 100\%$$

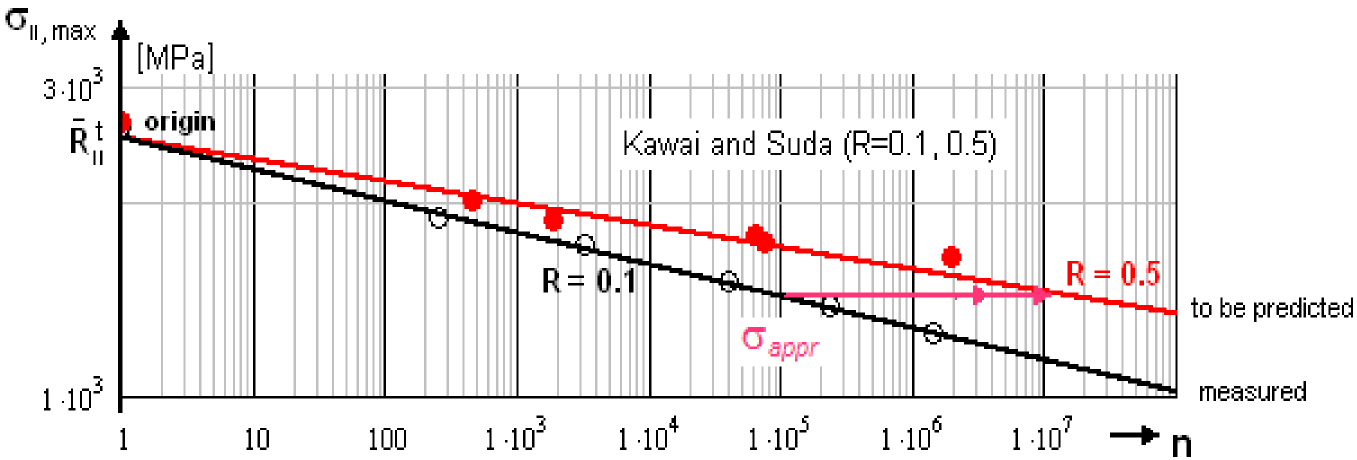
value from test experience

Step 4: Mode-wise Accumulation of Damaging Portions (novel)

Calulation, from [Cun13b], see Annex

FF = Fiber Fracture, IFF = Inter Fiber Fracture

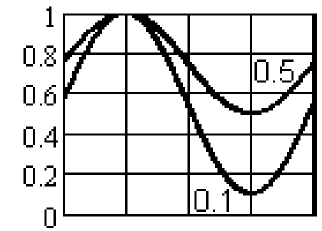
How does it work: Numerical example R0.5 from R0.1



$n_{appr} = 10000$ cycles

$R_{master} = 0.1, \quad R_{pred} = 0.5$

$D_{feasible} = 0.8$



$$f_{pred} = \exp[-\ln(\frac{R_{pred}^2 - 1}{R_{master}^2 - 1}) \cdot \frac{1}{c_2}] = 210$$

$$\sigma_{\|,\max}^{master}(n) \approx \overline{R}_{\|}^{t} \cdot n^{c_{master}} = \overline{R}_{\|}^{t} \cdot n^{-0.049} \quad \Rightarrow \quad \sigma_{1,\max}^{pred}(n) \approx \overline{R}_{\|}^{t} \cdot n^{c_{pred}}.$$

$$c_{pred} = -\ln(\overline{R}_{\|}^{t} / \sigma_{appr}) / \ln(n_{appr} \cdot f_{pre}) = -0.034$$

Loading $n_3(R = 0.1) = 0$

$n_1(R = 0.1) = 100000\ cycles, \quad \sigma_1^{(1)} = 12500\ MPa, \quad N_1(R = 0.1) = 2300000\ cycles,$

$n_2(R = 0.1) = 1600\ cycles, \quad \sigma_1^{(2)} = 1500\ MPa, \quad N_2(R = 0.1) = 55000\ cycles,$

$n_4(R = 10) = 6000\ cycles, \quad \sigma_1^{(4)} = -1150\ MPa, \quad N_4(R = 10) = 5000\ cycles,$

$n_5(R = 0.5) = 600000\ cycles, \quad \sigma_1^{(5)} = 1550\ MPa, \quad N_5(R = 0.5) = 2600000\ cycles.$

Miner application

$D = \sum n_i/N_i$) =100000/2300000 + 1600/55000 + 6000/5000 + 600000/2 600000 = 0.43

$$MoS = \frac{\frac{D_{feasible}}{D}}{j_{life} \cdot D_{\square}} - 1 = \frac{0.8/0.43}{3 \cdot 0.43} - 1 = 0.4 > 0.$$

$\{\overline{R}\} = (2560, 1590, 73, 185, 90)^T$ MPa

$\sigma_{\max} = 2 \cdot \sigma_a / (1 - R) = \Delta\sigma / (1 - R)$ with $\Delta\sigma$:= stress range

Lifetime Estimation of Endless Fiber-reinforced Composites - a failure mode-based approach – *full procedure*

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Technical status (2013)
A general and reliable method to estimate composites‘ lifetime does not exist.

Proposal for a partial domain
Creation of an engineering-like method ‘fiber-dominated-ly‘ designed laminates composed of UD laminas (plies).

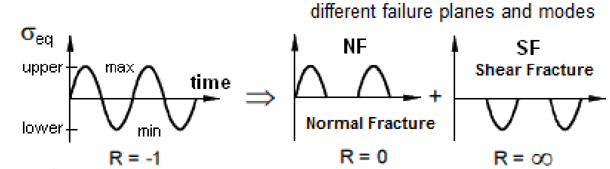
Steps of the approach ‘lifetime estimation‘

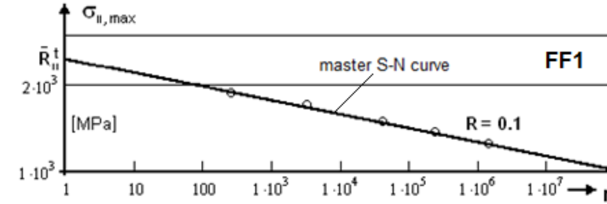
1. Failure mode-linked modeling of the stressing e.g. R = 0.1 (tensile), 10 (compressive) *novel idea*
2. Application of a failure mode-representative master s-n-curve
3. Determination of further necessary s-n curves of the envisaged mode on basis of the “mode master s-n-curve“ and the often applied principle of “equality of strain energy“ (saves test costs)
4. Accumulation of damaging portions using Miner.

Static strength failure conditions and modelling of damaging portions

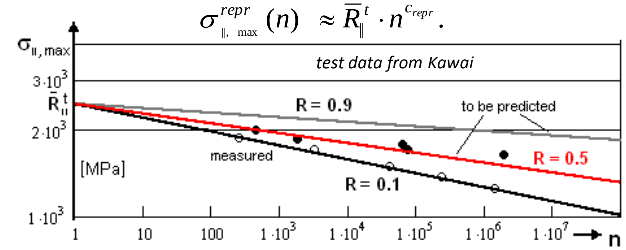
Static failure conditions for brittle behaving UD materials can be taken for cyclic applications, when replacing the static strength by the fatigue (residual) strength. σ_{eq} (similar to ‘Mises‘) represents the multi-axial stress state acting in a distinct mode and is the tool to determine the associated mode fracture failure cycle N. Used are Cuntze‘s *Failure Mode Concept-based* strength failure conditions (criteria), top ranked in the World-Wide-Failure-Exercises-I and -II (1992-2012).

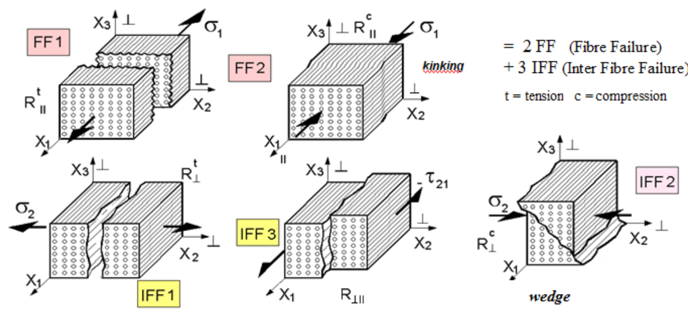
Static damaging (Werkstoffanstrengung Eff = D(n=1)) und zyklische Schädigung D(n)

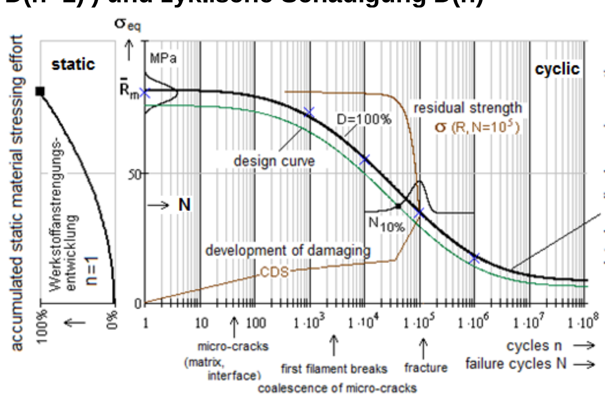


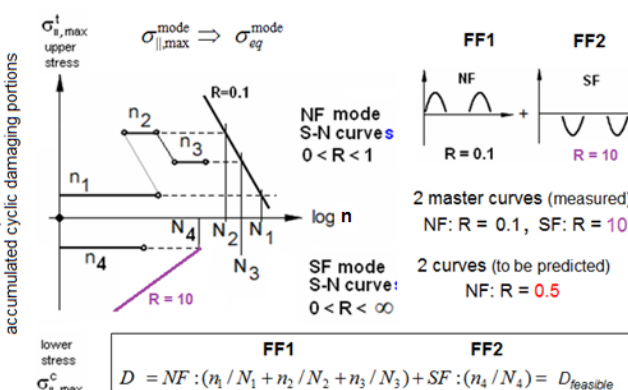


$$\sigma^{repr}_{\parallel,\ max}(n) \approx \bar{R}^t_\parallel \cdot n^{c_{repr}}.$$









FF1	FF2

$D = NF : (n_1/N_1 + n_2/N_2 + n_3/N_3) + SF : (n_4/N_4) = D_{feasible}$

Miner (Relative) application: $D_{feasible}$ - calibration from test experience

Conclusions for the presented UD Lifetime Prediction Method

Idea recalled**:** *It employs for the* ***often fibre-dominated designed laminates***

1) Failure mode-linked load modelling and damaging accumulation (Miner)
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. These depend on cycles-linked shrinking of the static failure surface. In-situ-effect consideration by deformation-controlled testing that captures the embedding (in-situ) effects

5) No mean stress correction to be performed? Probably

To be done:

Deeper investigation of the novel idea and of probable additional damaging caused by mode changes (FF, IFF, mixed).

44

General Conclusions on lifetime prediction models and Outlook

- Generally applicable, practical lifetime prediction models are not available
- For UD-materials the model situation is promising
- For 'higher' textiles the model situation is not satisfying
- The implementation of available models into Software is in progress.

45

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Drafts (permission) of the WWFE contributions and of additional literature are CCeV-website-uploaded and may be downloaded from http://www.carbon-composites.eu/leistungsspektrum/fachinformationen/fachinformation-2

ANNEX

Verification Levels of the Structural Part with

- Local Stress 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)

is valid, statically and cyclic.

STATIC :

Reserve Factor is load-defined : *RF = Failure Load / applied Design Load*

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

Material Reserve Factor : f_{Res} = *Strength / Applied Stress*

If linear situation: $f_{Res} = RF = 1 / Eff$

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

CYCLIC :

$$MoS_{Life} = (\text{predicted lifetime}) / (j_{Life} \cdot \text{design lifetime}) - 1 > 0$$

Cuntze's Pre-design Input

Test Data Mapping | Design Verification

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

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

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

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

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

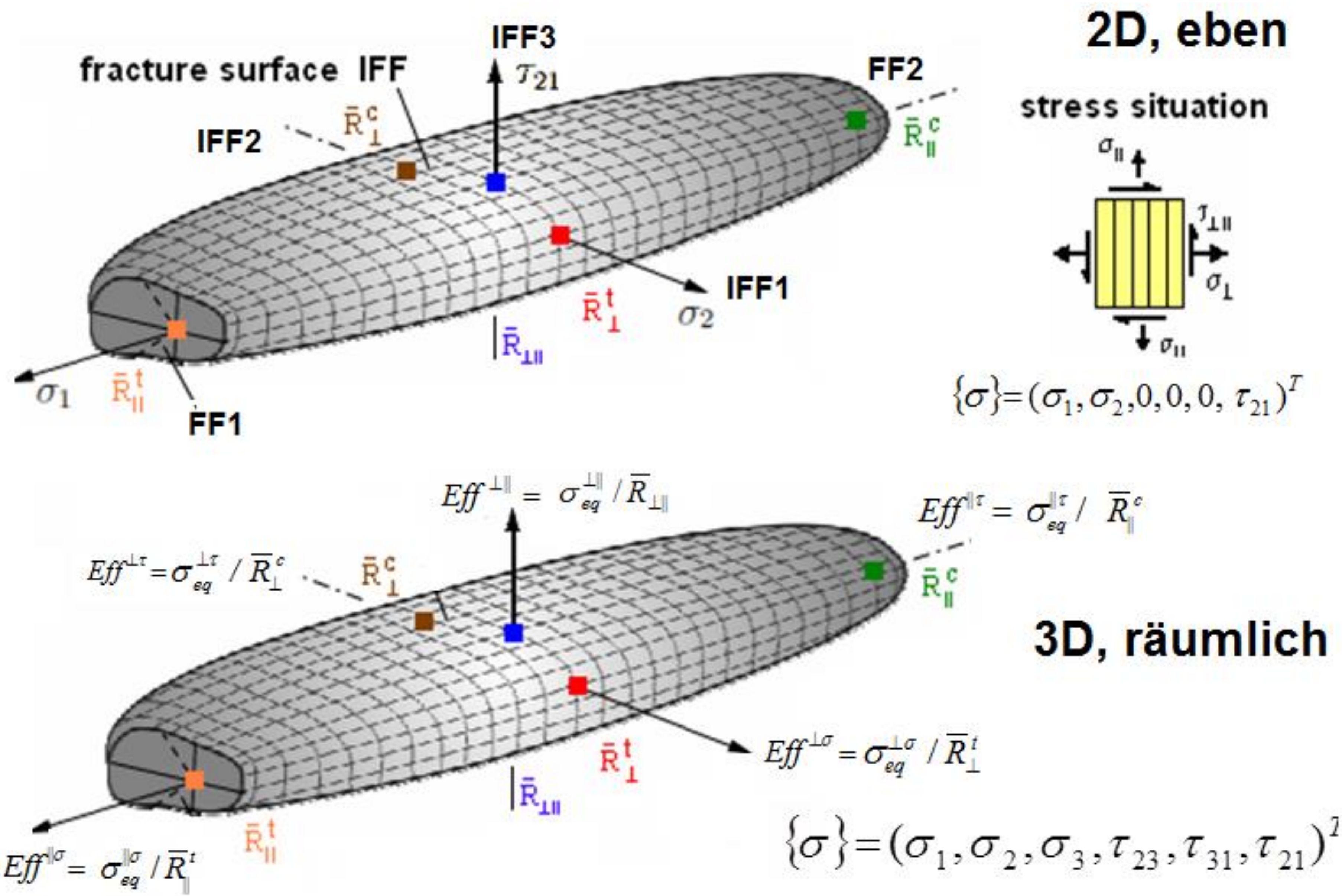
values, recommended for pre-design

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

* No more input required than for the usually applied *<u>global</u> strength failure conditions* , except of a guess of the friction value for brittle behaving materials

* Have not the short-comings of the global conditions that do not use the physically necessary friction !

2D und 3D-Bruchversagenskörper für UD-Werkstoff



The same failure surface is valid for 2D (stresses) and 3D (equivalent stresses) !

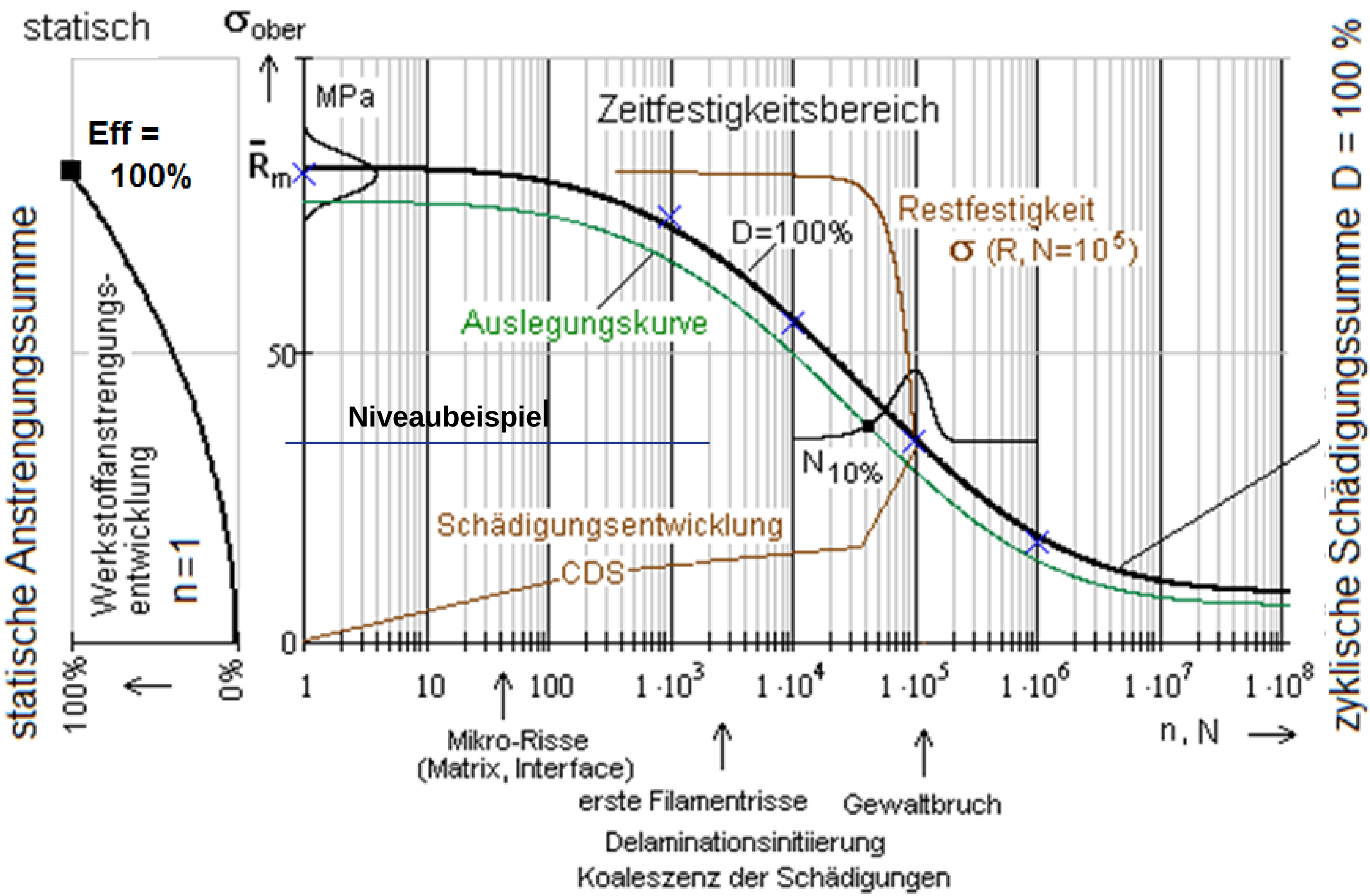
Assumptions for UD Modelling and Testing and Data Evaluation

- **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

Statische und zyklische Schädigungsentwicklung, sowie Wöhlerkurve *R = 0*



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

Cyclic fatigue life consists of three phases:

Phase I: Increasing damaging in embedded Laminas up to discrete damage onset
(determination of accumulating damaging portions (= Schädigungen), initiated at end of elastic domain and dominated by diffuse micro-cracking + matrix yielding, and finally micro-delaminations)

Phase II: Stabile local growth of discrete damaging in Laminate up to delamination
(growth of dominating discrete micro-crack widths incl. micro-delaminations)

Phase III: Final in-stabile fracture of Laminate initiated by FFs, IFF2 of any lamina
+ possible delamination (= Schaden) criticality of the loaded laminate

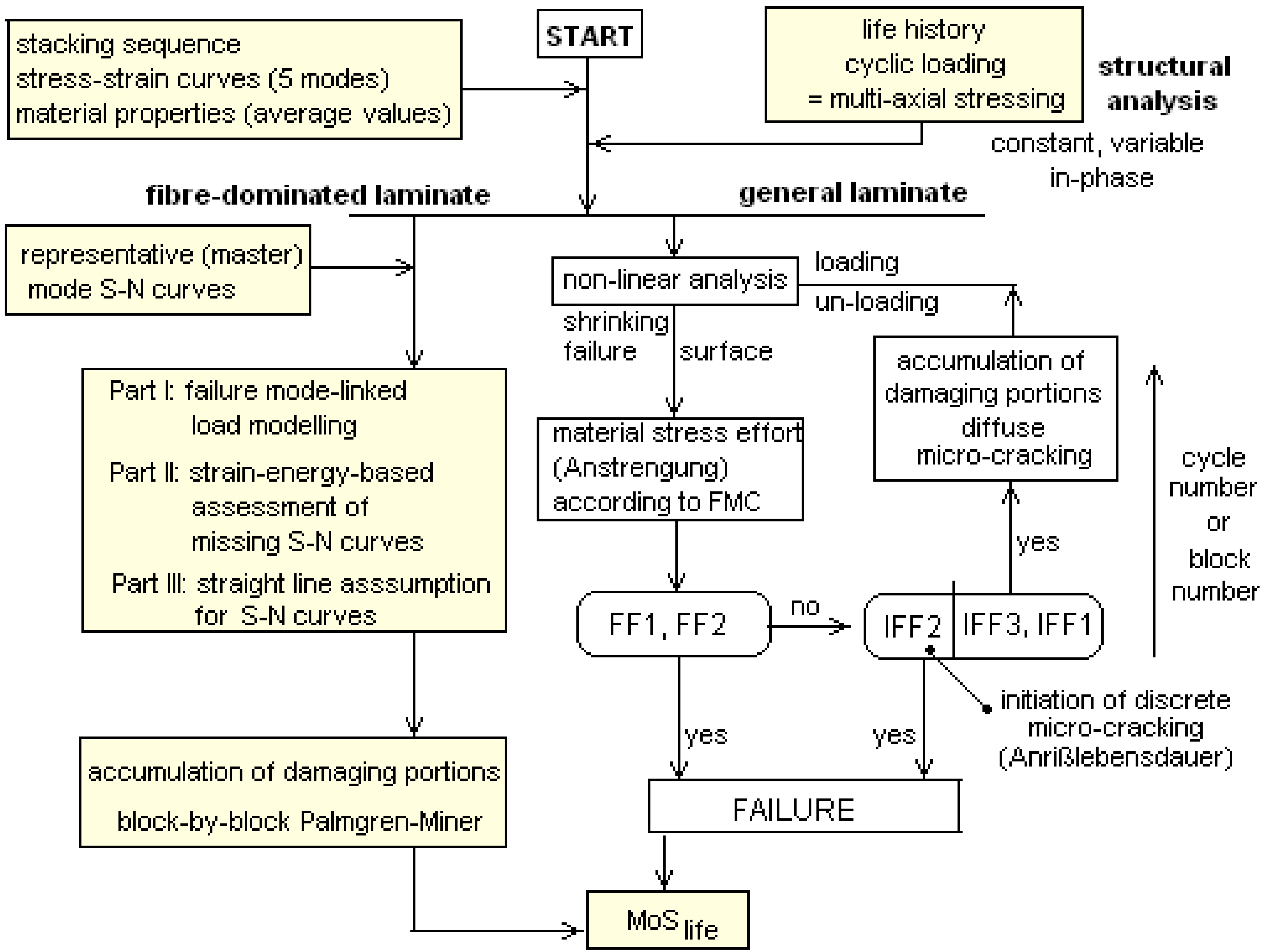
FF:= fibre failure. IFF:= Inter Fibre Failure

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

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

54

Failure-Mode-Concept-based Lifetime Prediction



Approach incl. Accumulation of Damaging Portions

Logic behind: Fatigue strain energy, required to generate a distinct damage state is equal to the strain energy, which is necessary under monotonic loading to obtain the same damage state.

$$\Delta W = \sum_{1}^{5} \Delta W^{modes}$$

strain energy of all mode contributions (5 in the UD case)

Idea demonstrated for simple case of 'well-designed, laminates under tension, where the change of strain energy between maximum and minimum loading for FF1 reads:

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

Solving for the maximum stress delivers:

$$\sigma_{1,\max}(n) = \bar{R}_{\|}^{t} \cdot \sqrt{\Delta W^{\|\sigma}(n) / /(1 - R^2)}.$$

From experiment known:

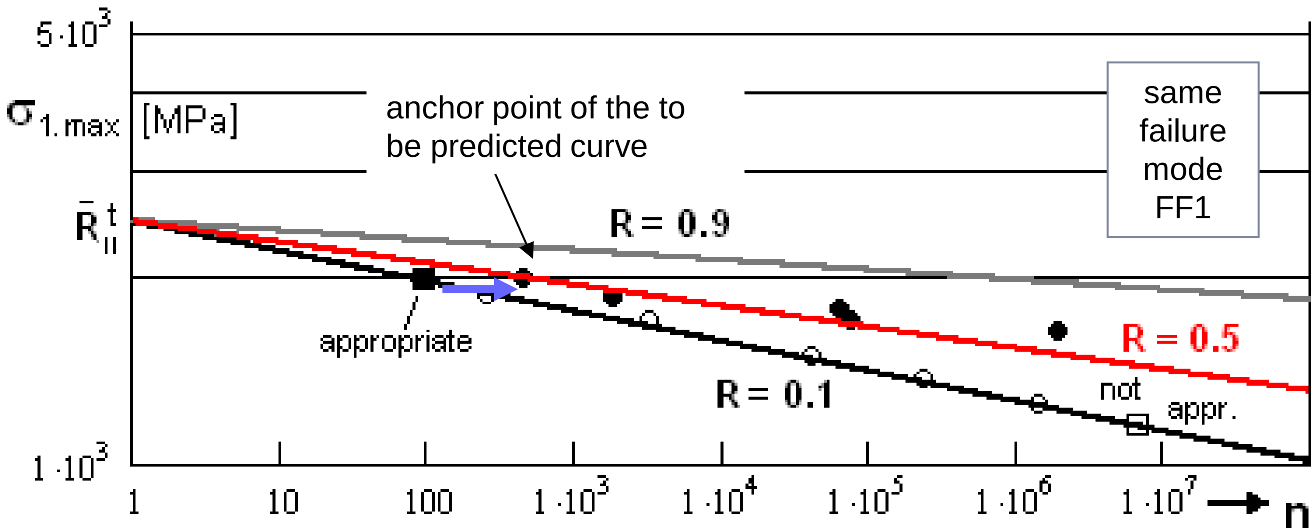
- Max stress + tensile strength + stress ratio *R;* and thereby the *fatigue strain energy*.
- Course of strain energy can be described by a simple power law function, forming a straight line in a log-log diagram:

$$\Delta W^{\|\sigma}(n) = c_1 \cdot n^{-c_2}$$ [Hwang] .

56

Failure mode-based Lifetime Prediction Method

Procedure for the Prediction of S-N curves (test-based Example)



to predict

given

Given:

Test points +

$$\Delta W_{R=0.1}^{\parallel\sigma}(n) = c_1 \cdot n^{-c_2} = 0.89 \cdot n^{-0.097}$$

$n_{appr} = 100 cycles$

.

III : S-N curve may be mapped by a straight line in a log-log graph (safe side)

Given: normalized mode-representative curve (R = 0.1); to be predicted curve: (R > 0.1)

$$\sigma_{1,\max\ repr}(n) = \bar{R}_{\parallel}^t \cdot \sqrt{\frac{\Delta W_{R=0.1}^{\parallel\sigma}}{1-R_{repr}^2}} = \bar{R}_{\parallel}^t \cdot \sqrt{\frac{c_1 \cdot n^{-c_2}}{1-R_{repr}^2}} = \bar{R}_{\parallel}^t \cdot n^{c_{repr}(n)} \approx \bar{R}_{\parallel}^t \cdot n^{c_{repr}},$$

$$\sigma_{1,\max\ pred}(n) \approx \bar{R}_{\parallel}^t \cdot n^{c_{pred}}$$

Example *R=0.5* : Procedure to determine c_{pred} *(one anchor point needed besides the strength point)* is depicted below:

$$\sigma_{1,\max\ repr}(n_{appr}) = \bar{R}_{\parallel}^t \cdot \sqrt{\frac{c_1 \cdot n_{appr}^{-c_2}}{1-R_{repr}^2}} = \sigma_{appr}$$

shift from representative curve to predicted curve $\rightarrow$

$$\sigma_{appr} = \bar{R}_{\parallel}^t \cdot \sqrt{\frac{c_1 \cdot (n_{appr} \cdot f_{pred})^{-c_2}}{1-R_{pred}^2}}$$

$$c_{pre} = -\ln(\bar{R}_{\parallel}^t / \sigma_{appr}) / \ln(n_{appr} \cdot f_{pre}) = -0.034 \quad \Leftarrow \quad f_{pred} = \exp[-\ln(\frac{R_{pred}^2 - 1}{R_{repr}^2 - 1}) \cdot \frac{1}{c_2}] = 17.5$$

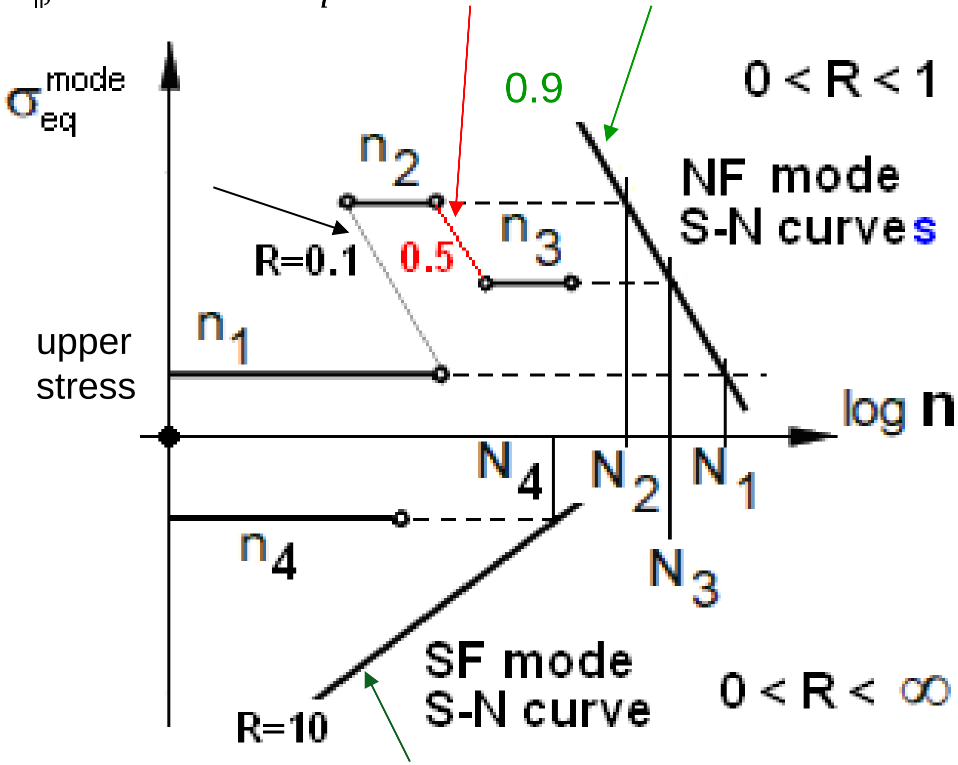
R = 0.5

57

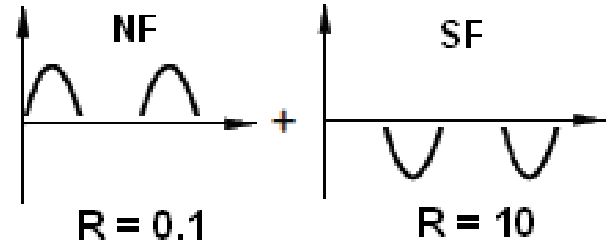
Failure mode-based Lifetime Prediction Method

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:

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

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)

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