SURVEY:

UD-Material Properties and Model Parameters, necessary for the Analysis of Static & Cyclic Stress States

1 Design Dimensioning in Structural Design, some Definitions

2 Modelling of Materials (elasticity, strength) and Analysis

3 Material Properties (matrix, fiber, interphase, composite)

4 Special Material Properties and Model Parameters

5 Test Methods and Material Sheets

6 Design Verification

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

Formerly: *Engineer at MAN-Technologie and hobby material modeller .*

Convenor of CCeV working groups : 'Engineering' (Mechanical Eng.) & 'Modelling Fiber Reinforcement in Civil Engineering'

Reliable material properties are an essential key

to achieve this effectiveness and fidelity

because

i.e. a neccesary new flight certification costs more than 50 millions €.

Now**:**

Certification of composite parts is *dominated by tests aided by analysis*

Future:

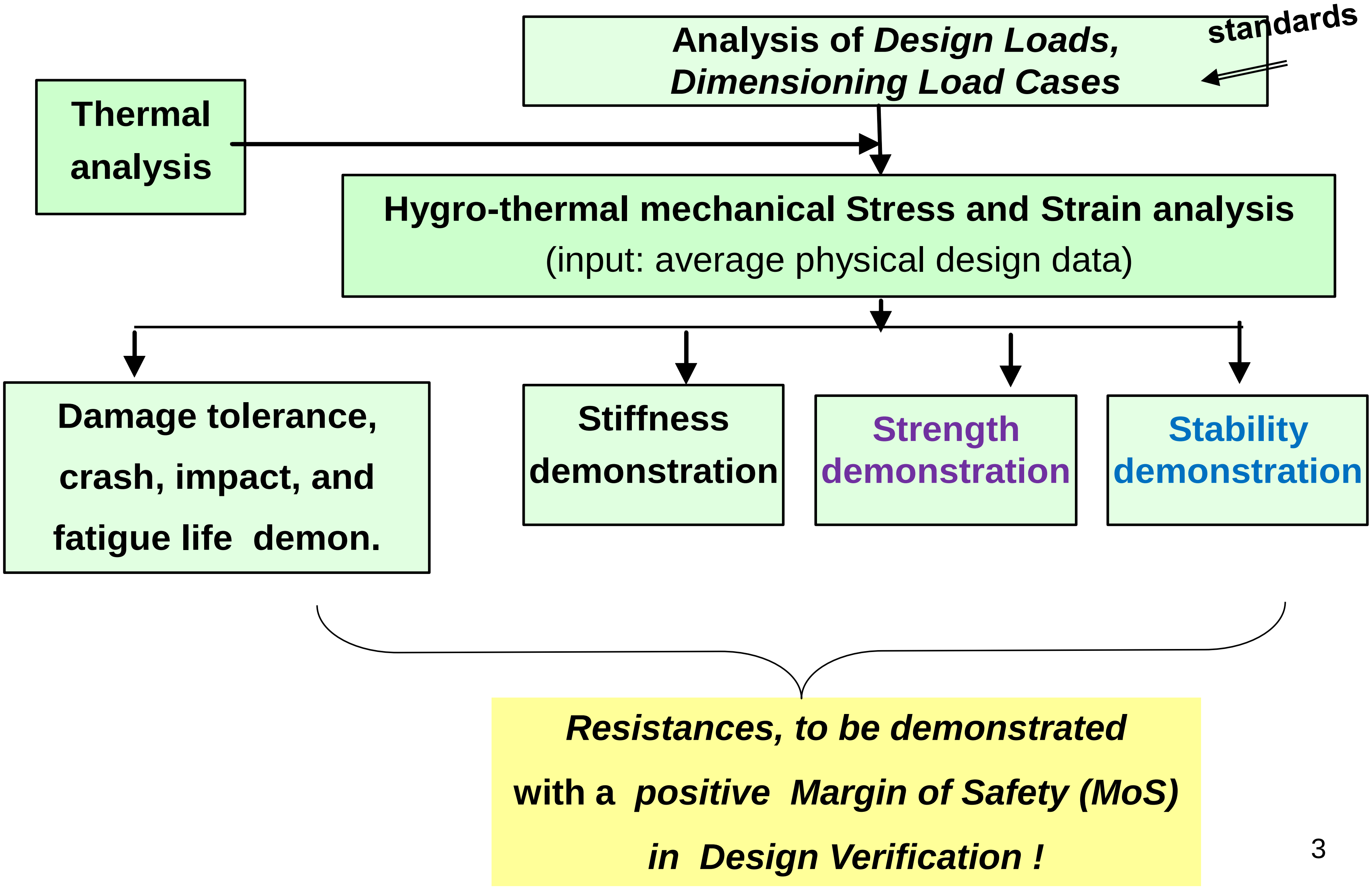
Certification of comp. parts *driven by models substantiated by tests* !

Main Topics here:

- High-performance Laminates, - Structural Properties

Outline of my talk

Which Analyses are mandatory in Structural Design ?



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, impact, and fatigue life demon.

Stiffness demonstration

Strength demonstration

Stability demonstration

Resistances, to be demonstrated
with a *positive Margin of Safety (MoS)*
in Design Verification !

AIM in Development :

Certification of products in a manner

that allows for analysis and processing and

to be adjustable without re-certification (costs),

and besides

Understanding the origins of **property uncertainty**

and control them !

Aspects in Product Development

- **All designed products should be manufacturable, testable, and maintainable**
- **Sustainability and Life-Cycle-Cost Assessment are now demands**

*** Materials used must have known, reliable, and reproducible properties and shall have proven resistance to the environment envisaged**

*** It has to be shown by:**

- Analyses that the *design meets the requirements*,

- Manufacturing with Quality Assurance that the *product meets the requirements*,

- Structural Test that the *requirements are verified*.

Definitions for Mutual Understanding

TOOLS, needed during the development of a product (full process chain):

Analyses **=** generation of abstract models for the examination of the physical behaviour

Simulation **=** procedure, incl. Analyses *plus* transfer of the simulation results to the system
plus Adjustment of the (virtual test) simulation results to the physical results.

Special terms:

Damaging portion (Schädigung), *investigated by ‘damaging mechanics tools‘*
*(**Schädigungsmechanik**)*

Damage (Schaden) = *accumulation of damaging portions of an engineering critical size.*
investigated in Damage Tolerance Analysis by fracture mechanics tools ***(Schadensmechanik)***

Definitions: see Glossary, CCeV-Website !

Some Further Definitions

Material: ‘homogenized‘ model of the envisaged solid or material combination which principally may be a metal, a lamina or a laminate *analysed with effective anisotropic properties*

Composite Material: material made from constituent materials, that when combined, produce a material with characteristics different from the individual component (Fiber Reinforced Plastic, Concrete, Glare, Ceramic Matrix Composites, etc.

Failure: structural part does not fulfil its functional requirements such as *onset of* yielding, brittle fracture, Fiber-Failure FF, Inter-Fiber-Failure IFF, leakage, deformation limit, delamination size limit, frequency bound, ……

= ***project-fixed Limit State*** with F = Limit State Function or Failure Function

Failure Criterion: $F >=< 1$, Failure Condition : $F = 1 = 100\%$ ***This is what we write!***

Failure Theory: tool, to predict failure danger of a structural part

Strength Failure Condition (SFC): subset of the strength failure theory

tool, to assess a ‘multi-axial failure stress state ‘ in a **critical** location of the homogenized material. Should consider, that failure occurs at a lower level, e.g. micromechanically.

IFF (Inter-Fiber-Failure) a failure occurring in the matrix, the interphase, or along a non-bonded filament interface

Criticality *depends on the generally required function the composite is designed to, and not only on the inability to carry further loads.*

Static Verification Levels

* **Stress** at a local material ‘point‘:

verification by a *basic strength* or a *multi-axial failure stress state*

Local stresses are acting and used in the Strength Criteria models

* Stress concentration at a notch (stress peak at a joint):

verification by a *notch strength (usually Neuber-like, Nuismer, etc..)*

‘Far‘-field stresses are acting, not directly used in the notch strength analysis

* Stress intensity (at tip of delamination crack):

verification by a *fracture toughness (energy –related).*

Applied stresses are used as ‘far‘-field stresses.

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Modelling Composites of laminated, high-performance Composites

**** Lamina-based, sub-laminate-based*** *(e.g. for non-crimp fabrics)* ***or laminate-based !***

*** Is performed, if applicable, *according to the distinct symmetry of the envisaged material***

*** For the chosen material model, if material symmetry-based, *the number of the***

to be measured   inherent   Strengths and Elasticity Properties

is the same as the observed number of Failure Modes !! *Test costs = minimum*

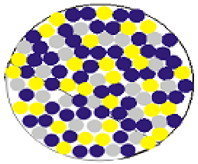
Lesson-Learned: As far as the failure mode or failure mechanism remains ,

Static Strength Criteria can be used for Cyclic Loading , too !

Variety of possible Composites Types

Filaments: **glass, aramide, carbon, ceramics, .. (**short, long fibers → endless fibers)

Fiber preforms **(+ sizing)** **from** ***roving, tape, weave, braid, knit, stitch***
dry or wet ***(2D and 3D),*** **or mixed as in a** ***preform hybrid***
non-crimp fabric laminates



PP/glass/aramidePEEK/
glass –filament-yarn

Matrices **(resin + hardener):** **polymers, thermoplastics, ceramics, concrete, ..**

Polymers (crystalline and amorphous)		
Plastics		**Elastomers**
thermo-plastics	**thermo-sets**	
Acrylic, polycarbonat, polyimide, polypropylene	**epoxy, phenolic, polyurethane, silicon**	**natural rubber, polyurethan, thermoplastic elastomer**

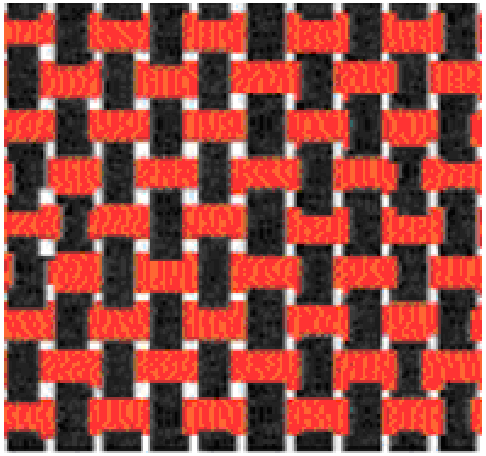
← *polymers*
are also
bonding materials
(3D understanding)

Manufacturing processes : **pre-pregging, wet winding, RTM, fiber placement, ..**

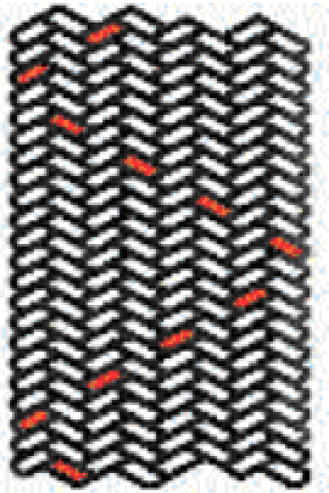
Rovings: 2k through 48 k

Some Types of Fabrics (textiles)

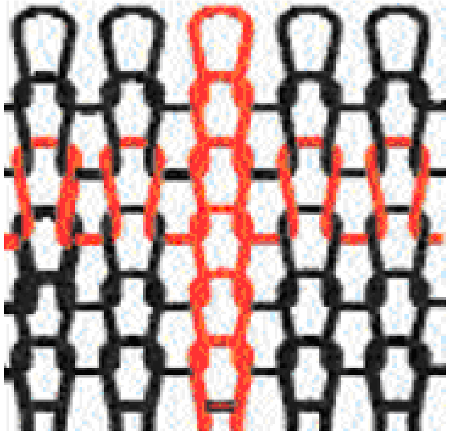
UD = simpler



plain weave



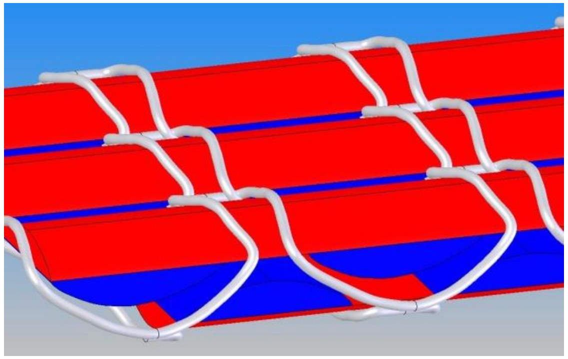
braid



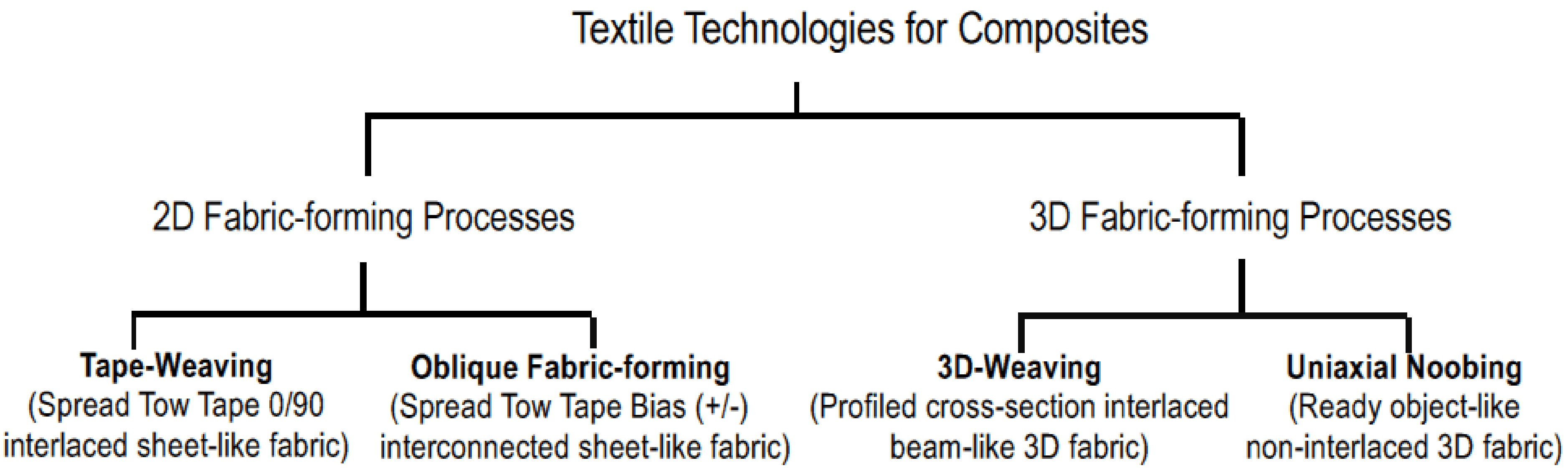
weft knit

warp knit

non-crimp fabric



Question: How may we optimally model composites generated with …?



Textile Technologies for Composites

- 2D Fabric-forming Processes
  - **Tape-Weaving** (Spread Tow Tape 0/90 interlaced sheet-like fabric)
  - **Oblique Fabric-forming** (Spread Tow Tape Bias (+/-) interconnected sheet-like fabric)
- 3D Fabric-forming Processes
  - **3D-Weaving** (Profiled cross-section interlaced beam-like 3D fabric)
  - **Uniaxial Noobing** (Ready object-like non-interlaced 3D fabric)

Further: How can we effectively model specific high-performance Composites ?

KOBLEDER NCK Non Crimp Knit - Now available based on MLG (Multi-Layer-knitted fabric)

Kobleder has developed non crimp knit (NCK) with integrated reinforcing fibers, which can absorb maximum mechanical tensile forces. The straight reinforcement threads knitted in 0° and 90° direction are held in place by loops so that no damage is caused to the reinforcement fibers. This construction guarantees a high level of drapeability at nearly 100% utilization of the reinforcing fiber strength. In addition to high tensile strength, these knitted fabrics also feature very good impact behavior.

KOBLEDER NCK - 3 Arguments in comparison

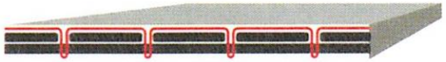
The textile has a plain weave construction

Threads are crimped

Biaxial textile through stitch-bonding technology

Damaged fibers – punctured reinforcement threads

KOBLEDER NCK



NCK with biaxial reinforcement are currently available as continuous plain fabrics in widths up to 900 mm and in tube form with a diameter of 200 mm. The reinforcement materials can be varied in type and dimension according to customer requirements and can even be somewhat customized within their

….. or a 3D Brick, connections may be milled from

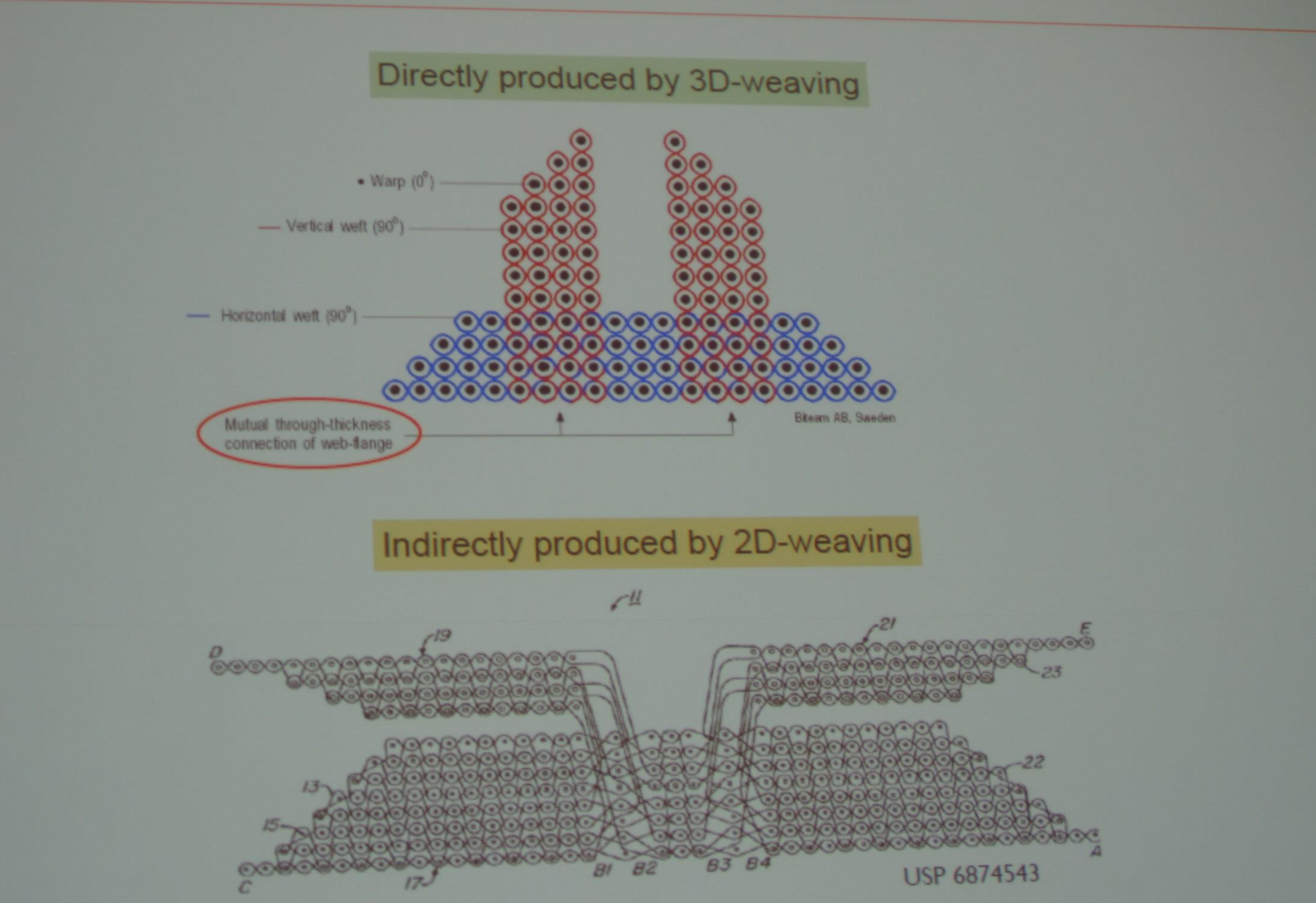
Infusion Solution for Thick Carbon Fiber Spar Caps

SAERTEX®

Steven Bakker

29/10/2014

or this joint, produced with a cutting-edge manufacturing process



Directly produced by 3D-weaving

Indirectly produced by 2D-weaving

Modelling: ‘Simple‘ UD material = Lamina (ply)

1 Lamina = Layer of a Laminate, e.g. UD-laminas = “Bricks“

- ***Homogenisation of a solid to a material brings benefits*.**
- ***Then Knowledge of Material Symmetry applicable : number of required material properties are minimal, test-costs too***

UD-lamina, modelled a homogenised (‘smeared‘) material requires in:

Material Characterisation f (Temp, Moisture, time, etc.)

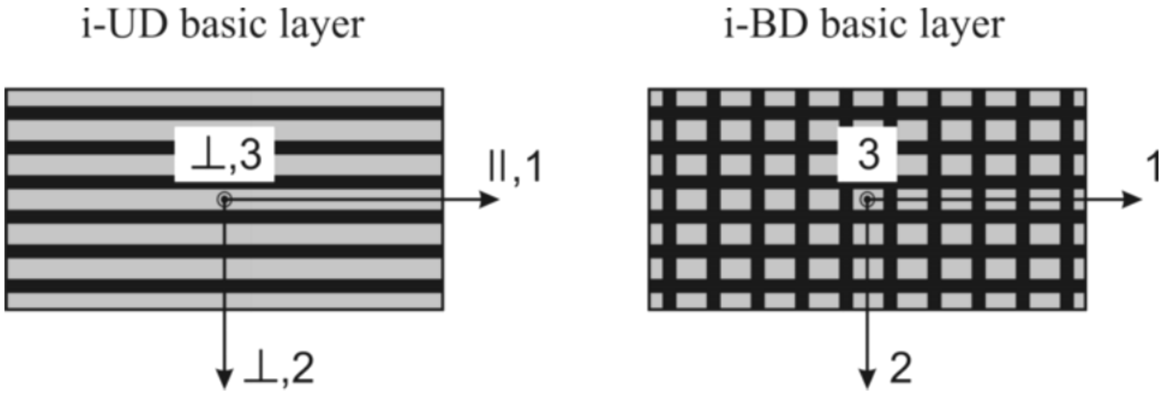
Modelling Fabrics with ‘Basic Layers‘: Homogenization and De-Homogenization

Basic layers of a laminate:

Increasing complexity ⟹

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

Use of equivalent basic layers



Modelling of textiles depends on their texture:

- **2D-textiles are relatively simple,**
- **3D-textiles are effortful (binding threads, 3D weaving, etc.)**

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3 **Material Properties** (matrix, fiber, interphase, composite)

4 Additionally Required Material Information (i.e. model parameters)

5 Standardized Test Methods

6 Design Verification

The production process ‘bakes‘ the composite material

FEA-Codes:

Designing engineers have problems with using the correct properties!

Hence, what do we firstly need ???

> **A general system**
> **of signs and symbols is of**
> **high importance for**
> **a logically consistent universal language**
> **for scientific use !**
>
> **Gottfried Wilhelm Leibniz (about 1800)**

What do we further need ?
Accurately <u>denoted</u> properties

Elasticity Properties *(homogenised materials)*, self-explaining denotations !

Considered in my VDI 2014 Guideline, proposed to ESA-Hdbk

		Elasticity Properties									
	direction or **plane**	1	2	3	12	23	13	12	23	13	
9	***general orthotropic***	E_1	E_2	E_3	G_{12}	G_{23}	G_{13}	ν_{12}	ν_{23}	ν_{13}	**comments**
5	***UD, $\cong$ non-crimp fabrics***	$E_{\parallel}$	$E_{\perp}$	$E_{\perp}$	$G_{\parallel\perp}$	$G_{\perp\perp}$	$G_{\parallel\perp}$	$\nu_{\parallel\perp}$	$\nu_{\perp\perp}$	$\nu_{\parallel\perp}$	$G_{\perp\perp} = E_{\perp}/(2+2\nu_{\perp\perp})$ $\nu_{\perp\parallel} = \nu_{\parallel\perp} \cdot E_{\perp} / E_{\parallel}$ *quasi-isotropic 2-3-plane*
6	***fabrics***	E_W	E_F	E_3	G_{WF}	G_{W3}	G_{W3}	ν_{WF}	ν_{W3}	ν_{W3}	*Warp = Fill* *W=warp, F=Fill= weft*
9	***fabrics general***	E_W	E_F	E_3	G_{WF}	G_{W3}	G_{F3}	ν_{WF}	ν_{F3}	ν_{W3}	*Warp $\neq$ Fill*
5	***mat***	E_M	E_M	E_3	G_M	G_{M3}	G_{M3}	ν_M	ν_{M3}	ν_{M3}	$G_M = E_M/(2+2\nu_M)$ *1 is perpendicular to quasi-isotropic Mat plane*
2	***isotropic*** *for comparison*	E	E	E	G	G	G	ν	ν	ν	$G=E/(2+2\nu)$

Lesson Learned: - *Unique, self-explaining denotations are mandatory*
my experience - *Otherwise, expensively generated test data cannot be interpreted and go lost*

Hygrothermal Properties

		Hygro-thermal properties					
	direction	**1**	**2**	**3**	**1**	**2**	**3**
9	**general orthotropic**	α_{T1}	α_{T2}	α_{T3}	α_{M1}	α_{M2}	α_{M3}
5	**UD, $\cong$ non-crimp fabrics**	$\alpha_{T\parallel}$	$\alpha_{T\perp}$	$\alpha_{T\perp}$	$\alpha_{M\parallel}$	$\alpha_{M\perp}$	$\alpha_{M\perp}$
6	**fabrics**	α_{TW}	α_{TW}	α_{T3}	α_{MW}	α_{MW}	α_{M3}
9	**fabrics general**	α_{TW}	α_{TF}	α_{T3}	α_{MW}	α_{MF}	α_{M3}
5	**mat**	α_{TM}	α_{TM}	α_{TM3}	α_{MM}	α_{MM}	α_{MM3}
2	**isotropic** for comparison	α_{T}	α_{T}	α_{T}	α_{M}	α_{M}	α_{M}

.. analogous for heat flux λ, thermal capacity c

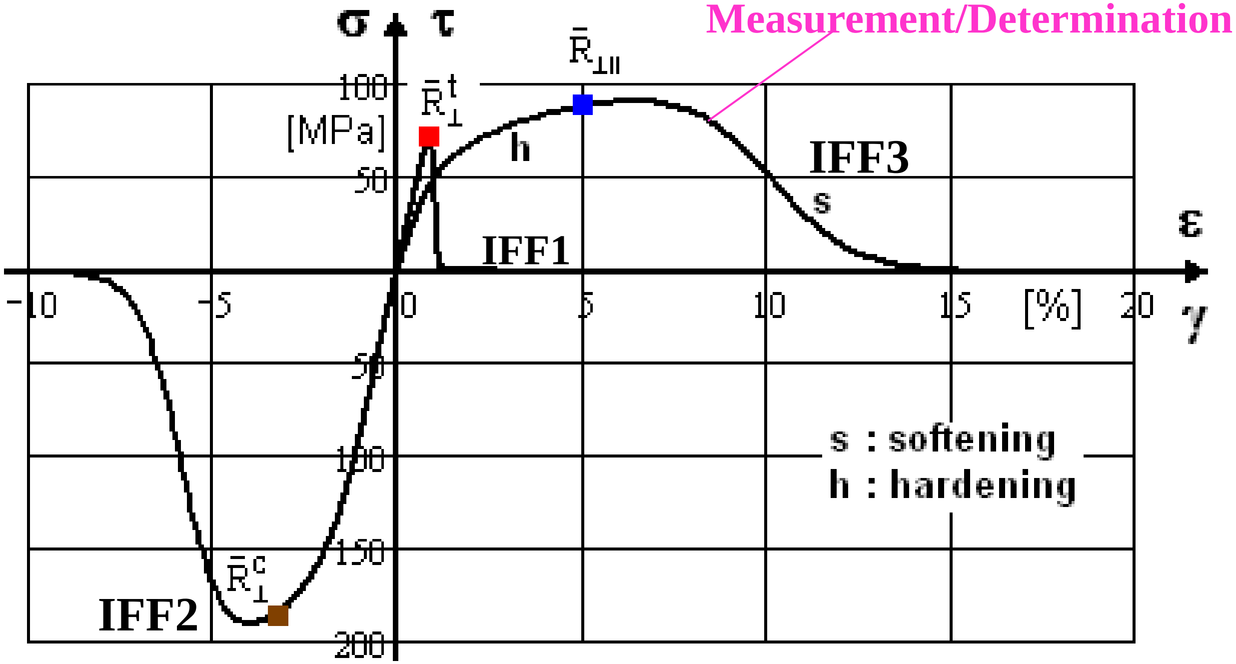
NOTE: Despite of annoying some people, I propose to rethink the use of α for the CTE and β for the CME. Utilizing α_T and α_M automatically indicates that the computation procedure will be similar.

Strength Properties self-explaining symbolic notations

		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}	**with friction**
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)*
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**

What else is required for **Non-linear Structural Analysis ?**



Measurement/Determination of strain softening curve ?

IFF = Inter-Fiber-Failure

Example: UD Laminates

h load-controlled *strain hardening*
branch, data from isolated lamina
(i.e. tests on hoop wound tube specimen)

s deformation-controll. *strain softening*
branch, (assumed engin. curve for
the embedded lamina material):

Assumed engineering-like
or by damaging mechanics tools,
or by fracture mechanics tools
(G values)

- *D*egree of non-linearity in ***strain hardening*** regime essentially depends on the degrading matrix material. This affects the secant moduli $E^c_{\perp}, G_{\parallel\perp}$
- Mapping (fitting) for instance by the Ramberg/Osgood equation

Lesson Learned: for consideration — *In the Post-IFF regime the embedded lamina experiences no sudden death but still has residual strength and stiffness due to in-situ effect!*

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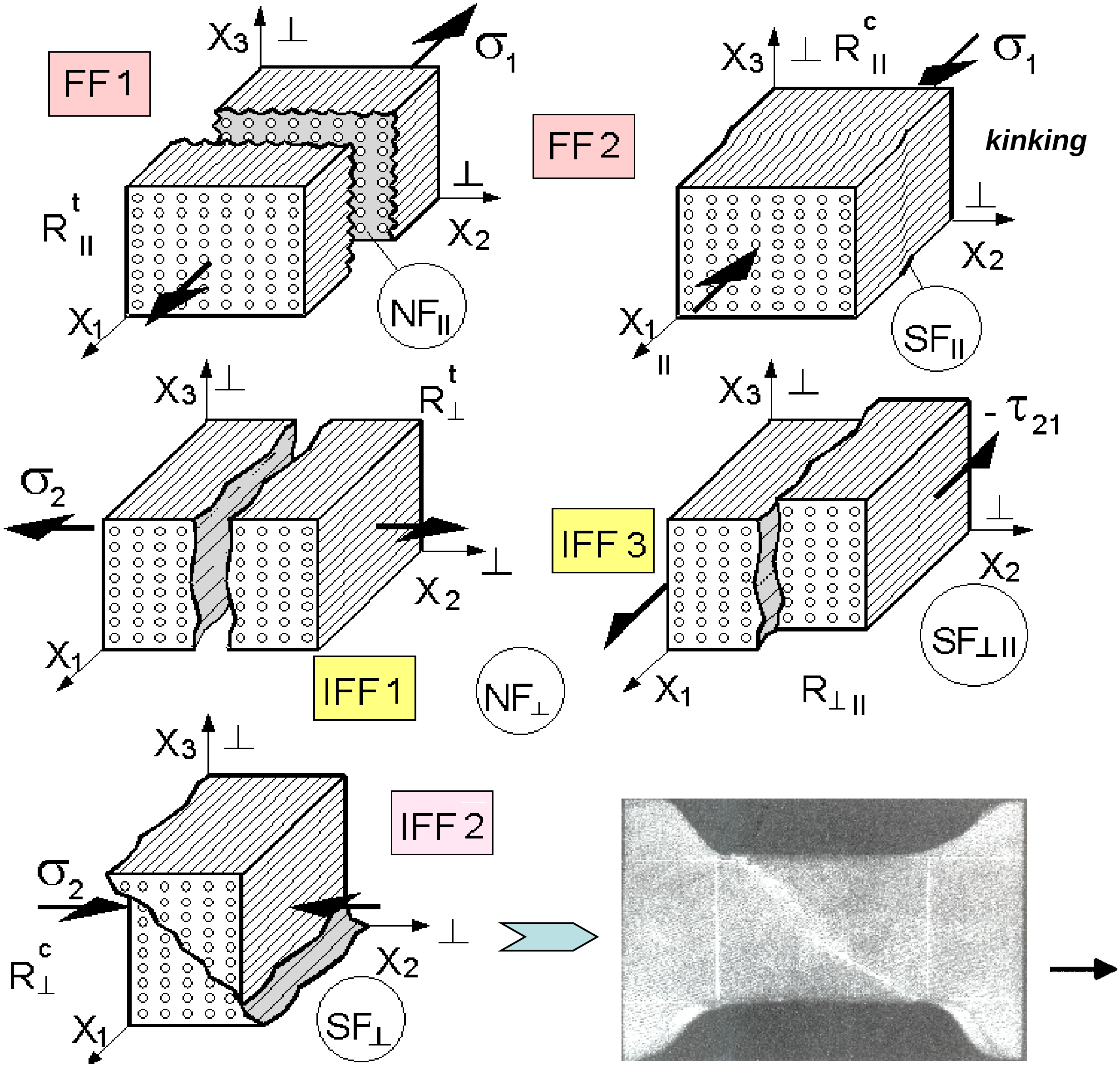
Example UD-Material: Strengths and Observed Strength Failure Modes



wedge failure type

t = tension

c = compression

- ► **5 Fracture modes exist**

= 2 FF (Fibre Failure)

+ 3 IFF (Inter Fibre Failure)

Fracture Types:

NF := Normal Fracture

SF := Shear Fracture

Friction occurs in IFF2 and IFF3 !

Example: Cuntze‘s Pre-design Input for his 3D UD strength criteria

Test Data Mapping | **Design Verification**

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

  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

model parameter

Mohr-Coulomb –required further ‘strength‘ parameters

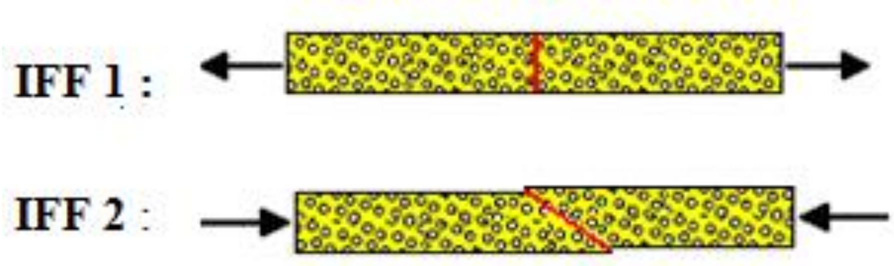
Mind the difference in analysis ! Isolated and embedded Properties

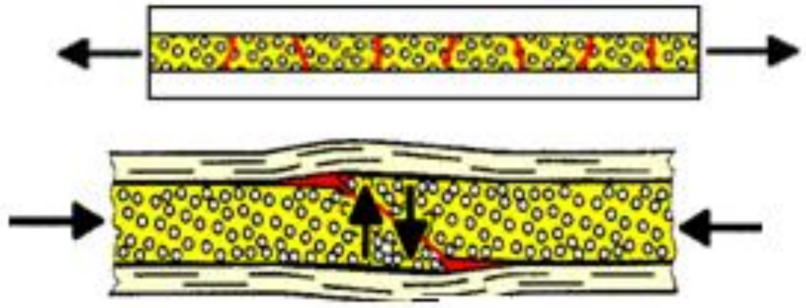
‘Isolated‘ lamina test specimens

= weakest link results (series failure system)

‘Embedded‘ laminas experience in-situ effects

= redundancy result (parallel failure system)





unconstrained lamina

mutually constrained laminates

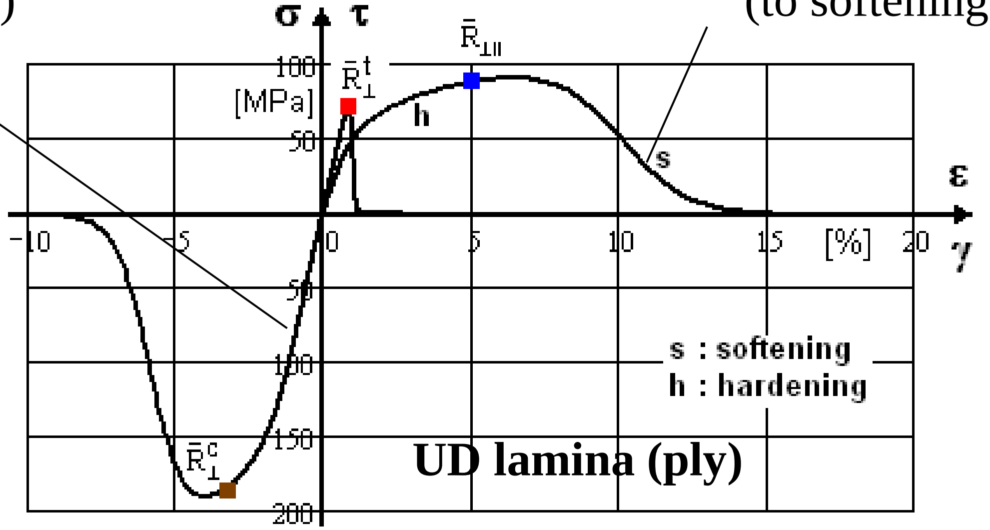
delivers strength property, stress-strain curve

(belongs to hardening)

= standard property
as analysis input !

in non-linear laminate analysis

(to softening)



UD lamina (ply)

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Aim of a Standard: To obtain Comparable Values

- **Test data depend on test method, test rig, specimen size, measurement, evaluation, etc.**
- **Therefore, so-called “exact“ values do not exist.**

The values are the result of a ‘convention‘.

- **Test-required knowledge for properties:**
  Scatter, average (mean) value, statistical distribution
- **If applicable? Damaging quantities to be also measured:**
  microcrack-density, residual strength, residual stiffness

UD lamina (ply) : Micro-mechanical Properties [WWFE, HSB sheets]

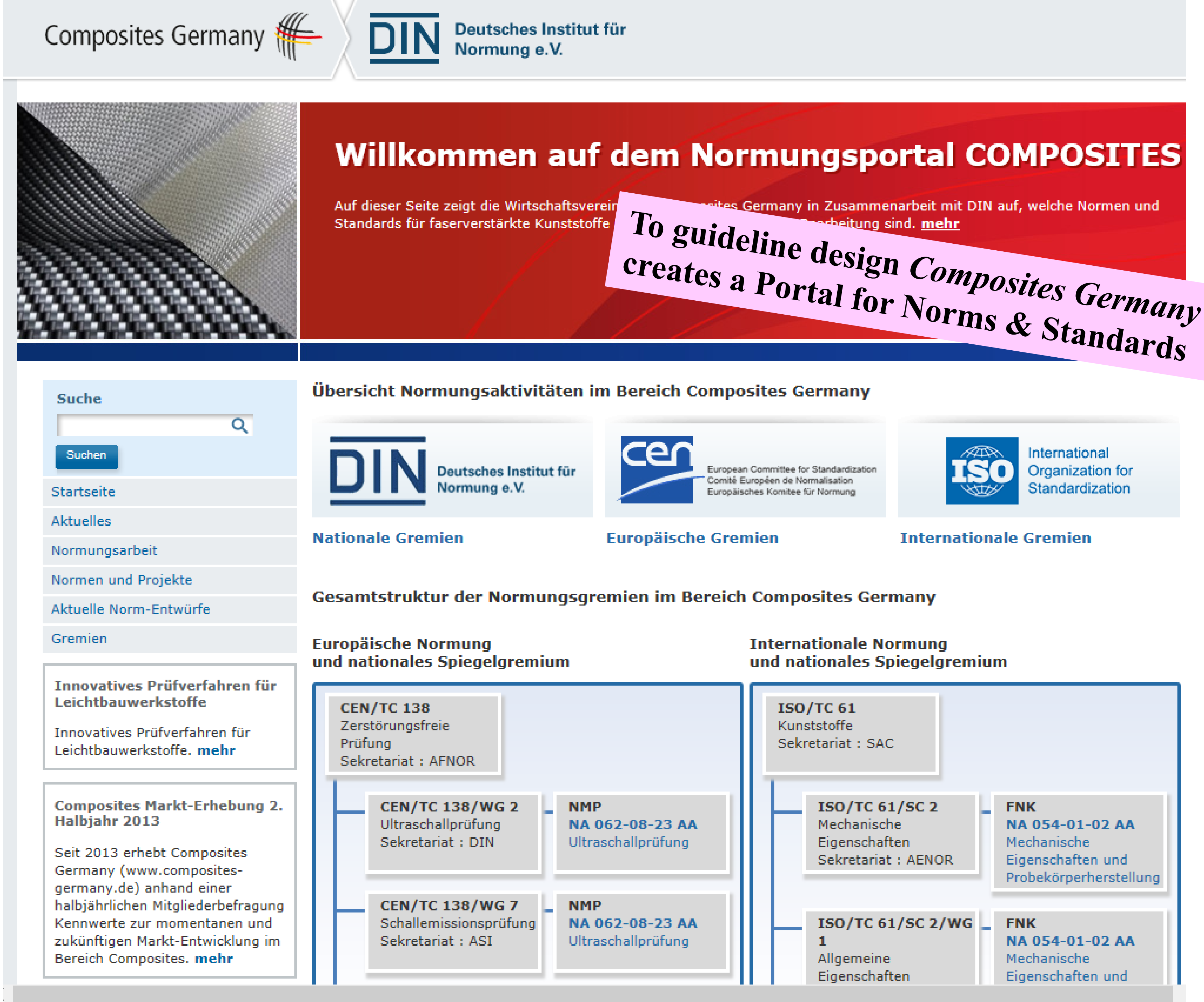
Some lamina analyses require a micro-mechanical input:

Problem: Not all micro-mechanical properties can be measured.

Solution: Micro-mechanical equations are calibrated by macro-mechanical test results (lamina level) = an *inversal parameter identification*

Pre-sumption: **Micro-mechanical properties can be used only together with the equations they have been determined with !!!**

e.g. not done in the WWFE ! Unbelievable



Composites Germany

DIN Deutsches Institut für Normung e.V.

Willkommen auf dem Normungsportal COMPOSITES

Auf dieser Seite zeigt die Wirtschaftsverein sites Germany in Zusammenarbeit mit DIN auf, welche Normen und Standards für faserverstärkte Kunststoffe arbeitung sind. mehr

To guideline design Composites Germany creates a Portal for Norms & Standards

Suche

- Startseite
- Aktuelles
- Normungsarbeit
- Normen und Projekte
- Aktuelle Norm-Entwürfe
- Gremien

Innovatives Prüfverfahren für Leichtbauwerkstoffe

Innovatives Prüfverfahren für Leichtbauwerkstoffe. mehr

Composites Markt-Erhebung 2. Halbjahr 2013

Seit 2013 erhebt Composites Germany (www.composites-germany.de) anhand einer halbjährlichen Mitgliederbefragung Kennwerte zur momentanen und zukünftigen Markt-Entwicklung im Bereich Composites. mehr

Übersicht Normungsaktivitäten im Bereich Composites Germany

DIN Deutsches Institut für Normung e.V.

cen European Committee for Standardization
Comité Européen de Normalisation
Europäisches Komitee für Normung

ISO International Organization for Standardization

Nationale Gremien

Europäische Gremien

Internationale Gremien

Gesamtstruktur der Normungsgremien im Bereich Composites Germany

Europäische Normung und nationales Spiegelgremium

CEN/TC 138
Zerstörungsfreie Prüfung
Sekretariat : AFNOR

CEN/TC 138/WG 2
Ultraschallprüfung
Sekretariat : DIN

NMP
NA 062-08-23 AA
Ultraschallprüfung

CEN/TC 138/WG 7
Schallemissionsprüfung
Sekretariat : ASI

NMP
NA 062-08-23 AA
Ultraschallprüfung

Internationale Normung und nationales Spiegelgremium

ISO/TC 61
Kunststoffe
Sekretariat : SAC

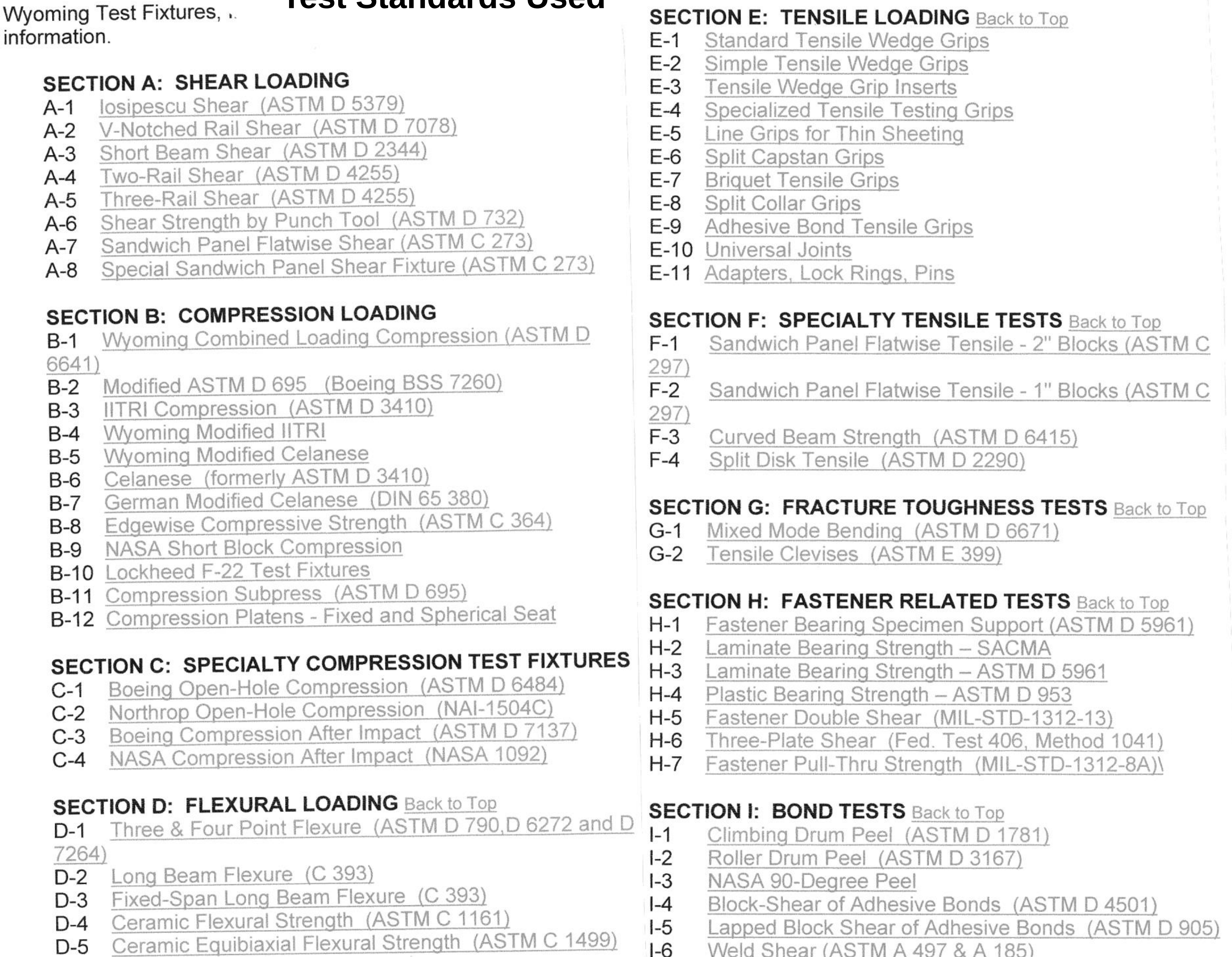
ISO/TC 61/SC 2
Mechanische Eigenschaften
Sekretariat : AENOR

FNK
NA 054-01-02 AA
Mechanische Eigenschaften und Probekörperherstellung

ISO/TC 61/SC 2/WG 1
Allgemeine Eigenschaften

FNK
NA 054-01-02 AA
Mechanische Eigenschaften und

Test Standards Used



Wyoming Test Fixtures,
information.

SECTION A: SHEAR LOADING

A-1 Iosipescu Shear (ASTM D 5379)
A-2 V-Notched Rail Shear (ASTM D 7078)
A-3 Short Beam Shear (ASTM D 2344)
A-4 Two-Rail Shear (ASTM D 4255)
A-5 Three-Rail Shear (ASTM D 4255)
A-6 Shear Strength by Punch Tool (ASTM D 732)
A-7 Sandwich Panel Flatwise Shear (ASTM C 273)
A-8 Special Sandwich Panel Shear Fixture (ASTM C 273)

SECTION B: COMPRESSION LOADING

B-1 Wyoming Combined Loading Compression (ASTM D 6641)
B-2 Modified ASTM D 695 (Boeing BSS 7260)
B-3 IITRI Compression (ASTM D 3410)
B-4 Wyoming Modified IITRI
B-5 Wyoming Modified Celanese
B-6 Celanese (formerly ASTM D 3410)
B-7 German Modified Celanese (DIN 65 380)
B-8 Edgewise Compressive Strength (ASTM C 364)
B-9 NASA Short Block Compression
B-10 Lockheed F-22 Test Fixtures
B-11 Compression Subpress (ASTM D 695)
B-12 Compression Platens - Fixed and Spherical Seat

SECTION C: SPECIALTY COMPRESSION TEST FIXTURES

C-1 Boeing Open-Hole Compression (ASTM D 6484)
C-2 Northrop Open-Hole Compression (NAI-1504C)
C-3 Boeing Compression After Impact (ASTM D 7137)
C-4 NASA Compression After Impact (NASA 1092)

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D-1 Three & Four Point Flexure (ASTM D 790,D 6272 and D 7264)
D-2 Long Beam Flexure (C 393)
D-3 Fixed-Span Long Beam Flexure (C 393)
D-4 Ceramic Flexural Strength (ASTM C 1161)
D-5 Ceramic Equibiaxial Flexural Strength (ASTM C 1499)

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E-1 Standard Tensile Wedge Grips
E-2 Simple Tensile Wedge Grips
E-3 Tensile Wedge Grip Inserts
E-4 Specialized Tensile Testing Grips
E-5 Line Grips for Thin Sheeting
E-6 Split Capstan Grips
E-7 Briquet Tensile Grips
E-8 Split Collar Grips
E-9 Adhesive Bond Tensile Grips
E-10 Universal Joints
E-11 Adapters, Lock Rings, Pins

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F-1 Sandwich Panel Flatwise Tensile - 2" Blocks (ASTM C 297)
F-2 Sandwich Panel Flatwise Tensile - 1" Blocks (ASTM C 297)
F-3 Curved Beam Strength (ASTM D 6415)
F-4 Split Disk Tensile (ASTM D 2290)

SECTION G: FRACTURE TOUGHNESS TESTS Back to Top

G-1 Mixed Mode Bending (ASTM D 6671)
G-2 Tensile Clevises (ASTM E 399)

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H-1 Fastener Bearing Specimen Support (ASTM D 5961)
H-2 Laminate Bearing Strength – SACMA
H-3 Laminate Bearing Strength – ASTM D 5961
H-4 Plastic Bearing Strength – ASTM D 953
H-5 Fastener Double Shear (MIL-STD-1312-13)
H-6 Three-Plate Shear (Fed. Test 406, Method 1041)
H-7 Fastener Pull-Thru Strength (MIL-STD-1312-8A)\

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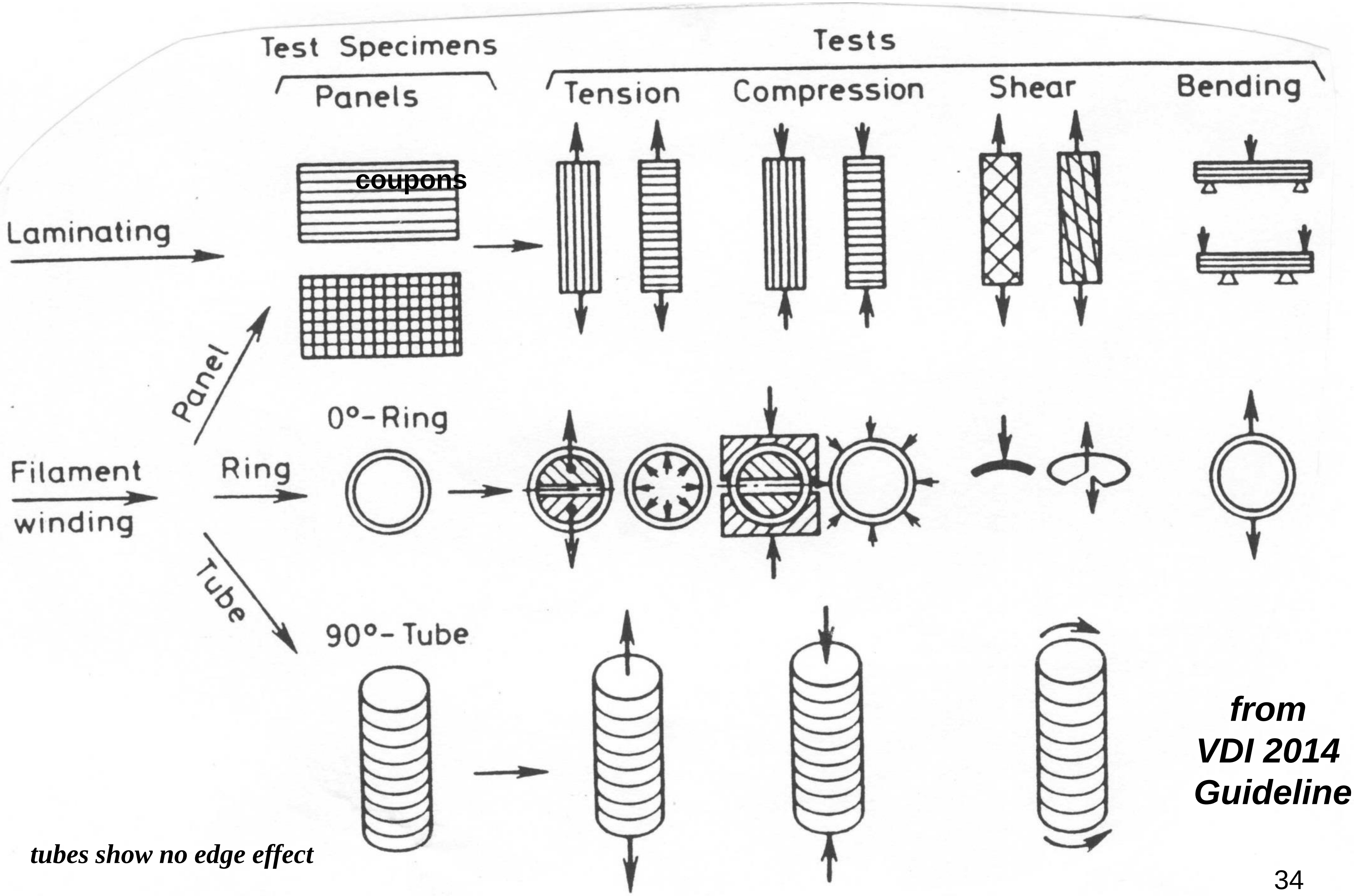
I-1 Climbing Drum Peel (ASTM D 1781)
I-2 Roller Drum Peel (ASTM D 3167)
I-3 NASA 90-Degree Peel
I-4 Block-Shear of Adhesive Bonds (ASTM D 4501)
I-5 Lapped Block Shear of Adhesive Bonds (ASTM D 905)
I-6 Weld Shear (ASTM A 497 & A 185)

Measurement of UD Strengths

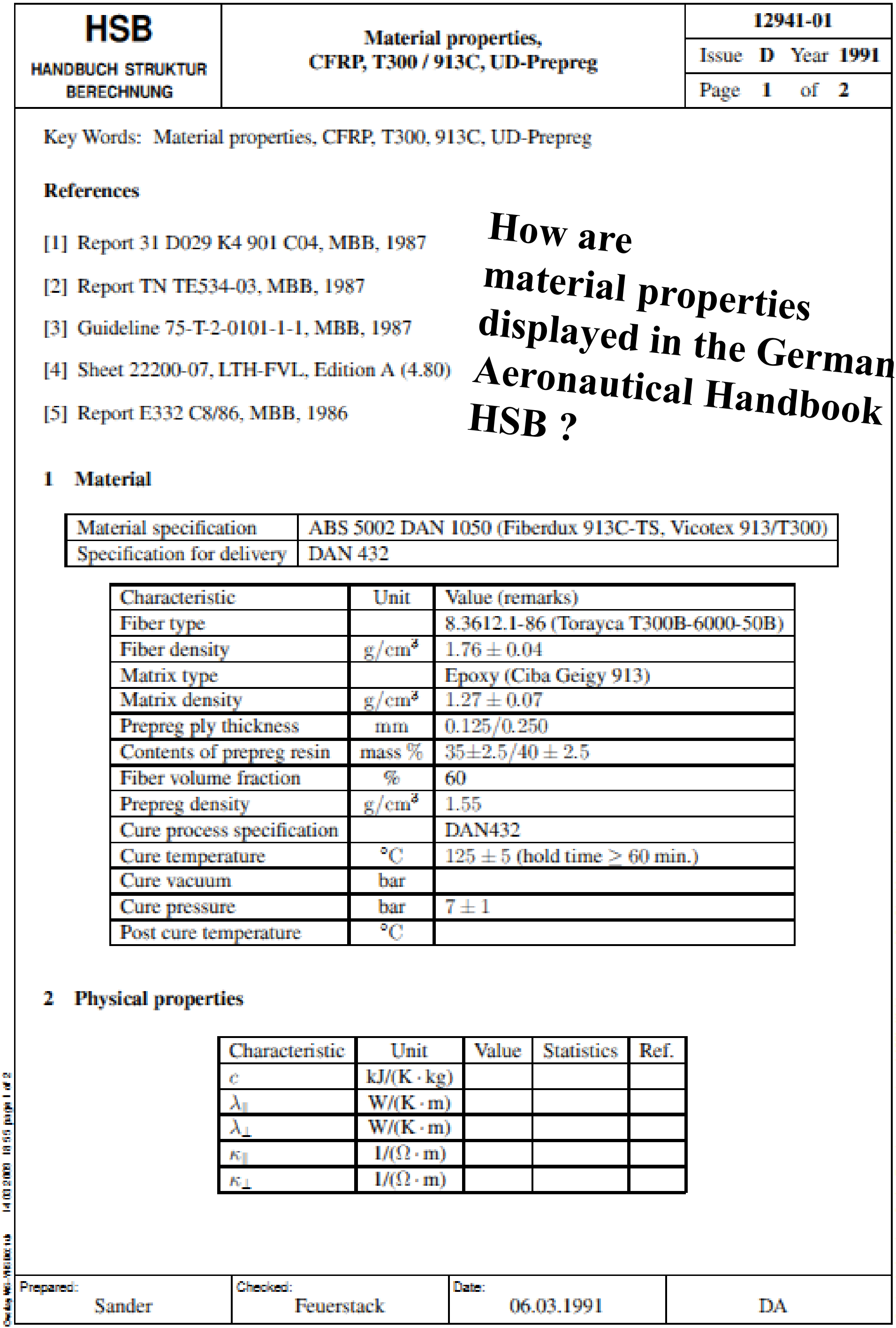
$$\{R\} = (R_\parallel^t, R_\parallel^c, R_\perp^t, R_\perp^c, R_{\perp\parallel})^T$$



tubes show no edge effect

from VDI 2014 Guideline

How are material properties displayed in the German Aeronautical Handbook HSB ?



Key Words: Material properties, CFRP, T300, 913C, UD-Prepreg

References

[1] Report 31 D029 K4 901 C04, MBB, 1987

[2] Report TN TE534-03, MBB, 1987

[3] Guideline 75-T-2-0101-1-1, MBB, 1987

[4] Sheet 22200-07, LTH-FVL, Edition A (4.80)

[5] Report E332 C8/86, MBB, 1986

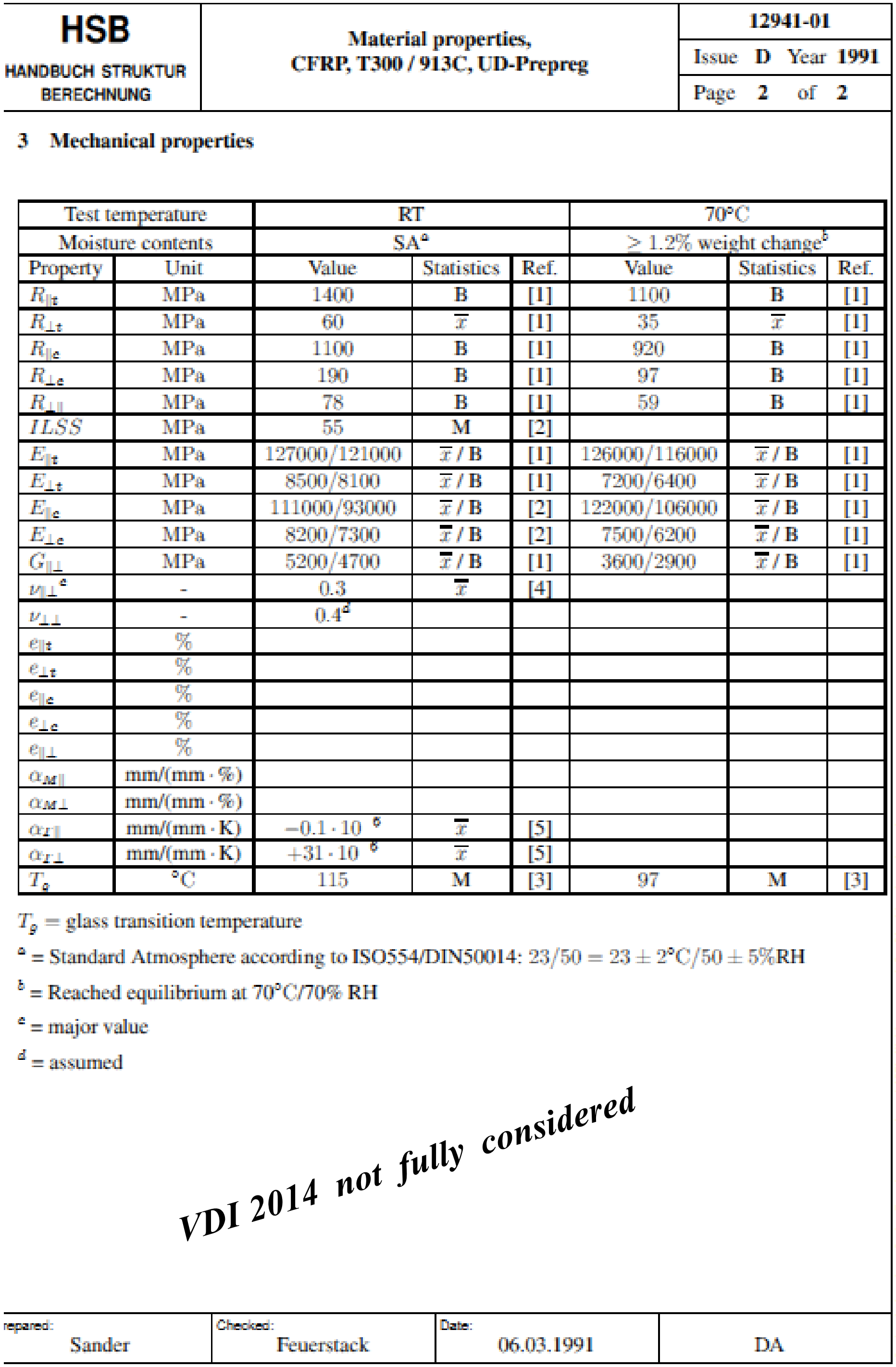
1 Material

Material specification	ABS 5002 DAN 1050 (Fiberdux 913C-TS, Vicotex 913/T300)
Specification for delivery	DAN 432

Characteristic	Unit	Value (remarks)
Fiber type		8.3612.1-86 (Torayca T300B-6000-50B)
Fiber density	g/cm^3	1.76 ± 0.04
Matrix type		Epoxy (Ciba Geigy 913)
Matrix density	g/cm^3	1.27 ± 0.07
Prepreg ply thickness	mm	0.125/0.250
Contents of prepreg resin	mass %	$35 \pm 2.5 / 40 \pm 2.5$
Fiber volume fraction	%	60
Prepreg density	g/cm^3	1.55
Cure process specification		DAN432
Cure temperature	°C	125 ± 5 (hold time $\geq$ 60 min.)
Cure vacuum	bar	
Cure pressure	bar	7 ± 1
Post cure temperature	°C	

2 Physical properties

Characteristic	Unit	Value	Statistics	Ref.
c	$kJ/(K \cdot kg)$			
$\lambda_{\parallel}$	$W/(K \cdot m)$			
$\lambda_{\perp}$	$W/(K \cdot m)$			
$\kappa_{\parallel}$	$1/(\Omega \cdot m)$			
$\kappa_{\perp}$	$1/(\Omega \cdot m)$			



3 Mechanical properties

Test temperature		RT			70°C		
Moisture contents		SA[a]			$\geq$ 1.2% weight change[b]		
Property	Unit	Value	Statistics	Ref.	Value	Statistics	Ref.
$R_{\parallel t}$	MPa	1400	B	[1]	1100	B	[1]
$R_{\perp t}$	MPa	60	$\bar{x}$	[1]	35	$\bar{x}$	[1]
$R_{\parallel c}$	MPa	1100	B	[1]	920	B	[1]
$R_{\perp c}$	MPa	190	B	[1]	97	B	[1]
$R_{\perp\parallel}$	MPa	78	B	[1]	59	B	[1]
$ILSS$	MPa	55	M	[2]			
$E_{\parallel t}$	MPa	127000/121000	$\bar{x}$ / B	[1]	126000/116000	$\bar{x}$ / B	[1]
$E_{\perp t}$	MPa	8500/8100	$\bar{x}$ / B	[1]	7200/6400	$\bar{x}$ / B	[1]
$E_{\parallel c}$	MPa	111000/93000	$\bar{x}$ / B	[2]	122000/106000	$\bar{x}$ / B	[1]
$E_{\perp c}$	MPa	8200/7300	$\bar{x}$ / B	[2]	7500/6200	$\bar{x}$ / B	[1]
$G_{\parallel\perp}$	MPa	5200/4700	$\bar{x}$ / B	[1]	3600/2900	$\bar{x}$ / B	[1]
$\nu_{\parallel\perp}{}^{c}$	-	0.3	$\bar{x}$	[4]			
$\nu_{\perp\perp}$	-	0.4^{d}					
$e_{\parallel t}$	%						
$e_{\perp t}$	%						
$e_{\parallel c}$	%						
$e_{\perp c}$	%						
$e_{\parallel\perp}$	%						
$\alpha_{M\parallel}$	$mm/(mm \cdot \%)$						
$\alpha_{M\perp}$	$mm/(mm \cdot \%)$						
$\alpha_{T\parallel}$	$mm/(mm \cdot K)$	$-0.1 \cdot 10^{-6}$	$\bar{x}$	[5]			
$\alpha_{T\perp}$	$mm/(mm \cdot K)$	$+31 \cdot 10^{-6}$	$\bar{x}$	[5]			
T_g	°C	115	M	[3]	97	M	[3]

T_g = glass transition temperature

[a] = Standard Atmosphere according to ISO554/DIN50014: $23/50 = 23 \pm 2°C/50 \pm 5\%RH$

[b] = Reached equilibrium at 70°C/70% RH

[c] = major value

[d] = assumed

VDI 2014 not fully considered

Key Words: Material properties, CFRP, T300, 913C, satin-fabric

References

[1] Report 31 D029 K4 901 C04, MBB, 1992

[2] Report TN TE534-03/87, MBB, 1987

[3] Guideline 75-T2-0110-1-1, MBB, 1990

[4] DIN65147 part 1, 04.87

[5] ACJ25.603 2.Definitions

1 Material

Material specification	ABS 5003 DAN 1208 (Fiberdux 913C-815, Vicotex 913C/G815)
Specification for delivery	DAN 432

Characteristic	Unit	Value (remarks)
Fiber type		8.3540.80-1 (T300-3K-135-8HS) Ref.[4]
Fiber density	g/cm^3	1.76 ± 0.04
Matrix type		Epoxy (Ciba Geigy BS 913C)
Matrix density	g/cm^3	1.27 ± 0.07
Prepreg ply thickness	mm	0.35
Contents of prepreg resin	mass %	35±2.5/40 ± 2.5
Fiber volume fraction	%	60
Prepreg density	g/cm^3	1.55
Cure process specification		DAN432
Cure temperature	°C	125 ± 5 (hold time > 60 min.)
Cure vacuum	bar	
Cure pressure	bar	7 ± 1
Post cure temperature	°C	

2 Physical properties

Characteristic	Unit	Value	Statistics	Ref.
c	kJ/(K · kg)			
$\lambda_\parallel$	W/(K · m)			
$\lambda_\perp$	W/(K · m)			
$\kappa_\parallel$	1/(Ω · m)			
$\kappa_\perp$	1/(Ω · m)			

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3 Mechanical properties

Test temperature		RT			70°C		
Moisture contents		SA^a			$\geq$ 1.2% weight change^b		
Property	Unit	Value	Statistics	Ref.	Value	Statistics	Ref.
R_{Wt}	MPa	635	B	[1]	575	B	[1]
R_{Ft}	MPa	575	B	[1]	410	B	[1]
R_{Wc}	MPa				390	B	[1]
R_{Fc}	MPa	480	B	[1]	325	B	[1]
R_{WF}	MPa				61.5	B	[1]
$ILSS$	MPa	50	^{c}	[2]			
E_{Wt}	MPa	69000	$\overline{x}$	[1]	65000	$\overline{x}$	[1]
E_{Ft}	MPa	64000	$\overline{x}$	[1]	62000	$\overline{x}$	[1]
E_{Wc}	MPa	60000	$\overline{x}$	[1]	73500	$\overline{x}$	[1]
E_{Fc}	MPa	56000	$\overline{x}$	[1]	65000	$\overline{x}$	[1]
G_{WF}	MPa	5050	$\overline{x}$	[1]	4200	$\overline{x}$	[1]
ν_{WF}	-						
e_{Wt}	%						
e_{Ft}	%						
e_{Wc}	%						
e_{Fc}	%						
e_{WF}	%						
α_{MW}	mm/(mm · %)						
α_{MF}	mm/(mm · %)						
α_{TW}	mm/(mm · K)						
α_{TF}	mm/(mm · K)						
T_g	°C	140	$\overline{x}$	[3]	100	$\overline{x}$	[3]

Subscripts: W = Warp, F = Fill

T_g = glass transition temperature

^{a} = Standard Atmosphere according to ISO554/DIN50014: $23/50 = 23 \pm 2$°C$/50 \pm 5$%RH

^{b} = Reached equilibrium at 70°C/70% RH

^{c} = minimum mean value of a sample of 6 test specimens at stock receipt

Note:

Due to material symmetry, it requires independent 9 strength and 9 elastic properties for 3D-Analyses. Practically, just in-plane properties are available which can provide the input for 2D-Analyses, only. The remaining unknown properties have to be assumed for 3D-Analyses.

What do we really measure when determining Material Properties ?

for **Stress and Strain Analysis + Strength Analysis**

Stress States are judged by a **Strength = ultimate (fracture) stress !**

Property values are the Result of no direct measurements:

Stress: force /area

Strain : length increase/ measurement length .

Further Required Cyclic and Fracture Mechanical Properties

- **S-N (Wöhler) curves** $R = const = \sigma_{unter} / \sigma_{ober}$
- **Tools to quantify the damaging portions (micro-crack density etc.)**
- **G_{Ic}, G_{IIc}, G_{IIIc} (strain) energy release rates for the treatment of delaminations**
- **Residual strengths**

1 Design Dimensioning in Structural Design, some Definitions

2 Modelling of Materials (elasticity, strength) and Analysis

3 Material Properties (matrix, fiber, interphase, composite)

4 Special Material Properties and Model Parameters

5 Test Methods and Material Sheets

6 Design Verification

Analyses needs Provided Properties and Manufacturing Process Information

Analytical, semi-analytical and numerical procedures for

- **Process-Simulation (CAD, FEM, CFD, etc.)**

  (draping, flow front, fusion weld, fiber orientation, curing, Tg value, curing stresses etc.) and the intensively linked

- **Structure-Analysis (FEM, BEM, pre- and post-processing)**

Thereby, epistemic Uncertainties to achieve a Robust Design must be tackled:

- Certification must focus an uncertainty quantification.
- Reduction of the Coefficient of Variation is of higher importance than increasing the average value a bit
- Design to Imperfections in manufacturing
- Provide ease-of-use and ease-of-interpretation of the results.

Aleatoric Uncertainty: play at dice (Würfel), number by chance, cannot be influenced !

Epistemic Uncertainty: reduced knowledge from too few tests etc.

Which property value is mandatory as Input in Structural Analysis ?

- The best prediction of the typical behaviour of the structure is performed with typical values = avarage values

- In the design verification – *dependent on the requirements* - the average, the upper or the lower value of the property is used.

Keep in mind:

Be similarly certain/reliable in the design with applied equations, properties, etc. !!

Design Objective: Achievement of a Reserve against a Design Limit State

For each distinct Load Case with its single Failure Modes must be computed:

Reserve Factor (load-defined !) :

determinisitic or semi-probabilistic

$$RF = \frac{\textbf{\textit{Failure Load}}\ \textit{at Eff} = 100\%}{\textbf{\textit{applied Design Load}}}$$

valid in linear and non-linear analysis

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

$f_{Res} = RF = 1 / Eff$, valid in linear analysis

Material Stressing Effort : *Eff = 100% if RF = 1* ***material exhausted***

(Werkstoff-Anstrengung)

applied Design Load = Factor of Safety j x Design Limit Load

Final Comments

- Properties are ‘agreed’ values to achieve a common and *comparable* design basis
- Properties must be provided with average value and coefficient of variation
- Changing a certified material is economically seldom possible
- Sources of uncertainty should be investigated
- Model parameters should be measurable and physically self-explaining
- Variety of Composites: Many properties for design and manufacturing not yet available
- For brittle behaving materials, multi-axial stress assessment is not possible on basis of the uni-axial strength values alone. Knowledge of material internal friction values, *following Mohr-Coulomb*, is mandatory
- Theory ‘only’ creates a model of the reality, an Experiment is ‘just’ one realisation of the reality.
  Experimental results can be far away from reality like an inaccurate theoretical model.
  Therefore, put sufficient effort into both, analysis and test,
  to achieve the desired FIDELITY.

DANKE

Ralf Cuntze: ***Retired engineer*** and ***hobby material modeller***

Formerly: MAN-Technologie AG Augsburg, Head of Main Department ’Structural and Thermal-Analysis’
Now: linked to Carbon Composites e.V. (CCeV) Augsburg and Founder and Leader of the CCeV- working groups ‘Engineering’ (2009) and ‘Modeling Fiber-Reinforcement in Civil Engineering’ (2011).

- 1959 - 1964 Study of Civil Engineering at Hannover
- 1968 Dr.-Ing. in Structural Dynamics
- 1978 Dr.-Ing. habil. in Mechanics of ***Lightweight Structures***
- 1980 - 2003 Lecturer at ’Universität der Bundeswehr’ München on fracture mechanics and ***lightweight structures*** from Fiber Reinforced Plastics (FRP)

<u>Professional career:</u>

1968 - 1970 DLR (German aerospace center: finite element analysis programming)
1970 - 2004 MAN-Technologie, Munich/Augsburg: involved in the *Development of :*

- ARIANE 1-5 Launcher family: Components of central stage + Boosters, high pressure vessels, etc.
- Windenergy rotors (Growian Ø103m, WKA 60, Aeroman). ***Since 1970 in Carbon Comp. business***
- Satellite components, Space Antennas; FRP light weight structures, IRAM antenna, SOFIA telescope (in Boeing 747); Automated Transfer Vehicles (ATV1 Jules Verne) + Crew Rescue Vehicle CRV (for ISS) + NASA X38 Demonstrator space plane
- CMC body flap for Crew Rescue Vehicle (2002), Spacelab mission D1 (1985): material experiments,
- Apogee solid propellant motor cases MAGE and IRIS, water-tanks for AIRBUS
- Heat exchanger for gas cooled Solartower GAST(20 MW) and Solarfield constructions (Almeria)
- Gasultra-Centrifuge, Fly wheels (for ship "Trans Swartow", MAN-Buses), Diesel engine parts in metal and in monolithic ceramics for trucks, Structural calculations for MAN buses
- Fusion reactor WENDELSTEIN VII: toroidal ring chamber.

Material applications in the range: 20 K through 2000 K (FRP, CMC, metals, concrete).

<u>Co-author and Convenor of various Handbooks and Working Groups</u>

- German Aircraft Structural Handbook HSB (> 2000 pages): since 1972 (WG IASB) author and co-author of some hundreds of design sheets. Member of the HSB-Handbook’s ‘transfer’ team into English
- VDI 2014 Guideline “Development of Fibre Reinforced Plastic Components”, Sheet 3 “Analysis” (co-author, convenor), VDI-WG 4.3 "Reliability of Structural Components" (1980ies, WG member)
- ESA/ESTEC, since 1978: Structural Requirements Standards, co-author in the 3 working groups: Structural Analysis, High Pressure Vessels (metal and composites), Safety Factors; Contributor to Handbooks: PSS and follower Structural Materials Handbook SMH; Buckling Handbook (first convenor, contributor to several chapters); ECSS (European Cooperation for Space Standardization)
- was involved in EU projects (BRITE, BRITE-EURAM), and BMFT and BMBF research projects.

<u>Miscellaneous</u>

- Civil Engineering experience: Armouring plans, builder of 5th German climbing garden,.statics of supermarkets, pile foundation.
- Surveyor/advisor (since 1980) for German Ministry BMFT + BMBF on R&D Material Programmes (MaTech, MatFo, LuFo, German Material Modelling competence centres). Advisor to EU-project MAAXIMUS (Airbus Toulouse: On improving Aircraft sizing)
- Advisor for German Research Foundation DFG (SFBs, SPPs on modelling structural textiles)
- Originator of the (never funded) successful Failure Mode Concept (FMC), a general invariant-based foundation for the derivation of failure mode-linked *strength failure conditions* for isotropic, transversely-isotropic (UD), and orthotropic (fabrics) materials applicable for FRP, CMC, metals, concrete, etc. Winner of the World-Wide-Failure-Exercise-I on “UD composites strength failure theories” (WWFE-I, bi-axial stress states). Now, top-ranked in WWFE-II on “UD, tri-axial stress states” considering hydrostatic pressures > 700 MPa
- Numerous ‘single-author’ publications in different structural fields
- Founder (2010) and co-worker of the working group ‘Fatigue of Composites’ (only group, world-wide) of all respec. German universities. Member of the world-wide NAFEMS Composite Working Group

Assumptions for Material Modelling (example: UD material) and **Test**

- **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‘** (location)
- **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, …**
- **From engineerring point of view Macro-mechanical SFCs are desired.**
  However, the SFCs should consider that failure starts in constituents

Failure Analysis Flow Path (multi-level 2-scale approach)

isotropic or a
quasi-isotropic continuum

Constituent materials: fiber, matrix, interphase of the interface

build up a **layered continuum**

failure usually occurs at micro-level

Isotropic Matrix

Micro-mechanical (scale) Model

Transversely-isotropic Lamina (ply)

calibration by macromechanical properties *elasticity, strength*

Meso-Model (RVEs, Voxel)

maufacturing 'significances'
flaws, waviness, matrix-nests,

calibration by macromechanical properties

Ply-by-Ply analysis of the Laminate

merely non-degraded material **strain-hardening**

degrading material **strain-softening + non-linear analysis beyond IFF**

Failure Conditions for the Homogenized Solid = Material

Strength Failure Conditions for the Material

validation of strength failure conditions by strength test series on material level

Macro-mechanical (scale) Model

Orthotropic Laminate

Fracture Mechanics Failure Conditions for the Structural Part

final failure: FF in an lamina or delamination in a laminate

arbitray crack in an isotropic or a
quasi-isotropic continuum

delamination crack in a layered
continuum (laminate)

Meso-level is no scale, per definitionem !

RVE:Representative Volume Element, voxel : volumetric pixel

Evaluation of Strength Design Values & Design Allowables (Airbus, HSB)

Material Supplier	**Customer**			
Manufacture *1* raw data, T99 / T90 data	**In-house tests** raw data, T99 / T90 data	**Pooling of T data,** **S-value adjustment, Material Procurement** **Determination of *Strength Design Values***	**Determination of *Strength Design Allowables*** *(A-, B-values)* based on statistical rules in MMPDS Hdbk (formerly MIL Hdbk 5)	**approval** by handbook committee , agency etc.
Manufacture *2* raw data, T99 / T90 data				
Manufacture *n* raw data, T99 / T90 data				
		for **design + analysis**	for **design verification**	

S-value: Procurement value

A-, B-value: Strength *Design Allowables. Statistically defined like T99/T90 –values. Number of different batches is required, on top.*

T99/T90-values: *Material* strength allowables. The determination follows the same statistical procedure as with the Strength Design Allowables. However, the data volume and batch requirements are less stringent.

A > S, only allowed if premium selection of material is applied. Normally ***A* < *S*.**

Mechanisms of Interest when considering Property Measurement

Yielding versus quasi-yielding:
In ductile behaving materials the failure mechanism *yielding* is active for the loadings tension, compression and shear whereas in case of brittle behaving composites the diffuse damaging as *quasi-yielding* belongs to different macroscopic failure mechanisms in tension (NF) and shear (SF)..

Diffuse Damaging:
damaging, occurring fro onset of micro-cracking until onset of discrete local macro-cracks, often indicated by whitening (for ductile thermoplastics it is connected to void intiation and void growth)

Discrete Damaging:
localization of diffuse damaging which sometimes ends with CDS (characteristic damage state)

Micro-mechanical ‘notching’:
- onset of micro-cracks degrade the matrix in a transversely stressed lamina the more the thicker the lamina is (‘thin-layer effect’ ; energy release rate becomes larger)
- onset of filament breaks causes 3D stress states resulting in growth of lateral micro-cracks and lamina-parallel micro-delaminations (more critical in general)

Helpful Information available when Generating SFCs and Testing Materials

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

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

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

(for isotropic materials the respective numbers are 2 and 1)

2 Mohr-Coulomb requires for the <u>real</u> crystal another inherent parameter,

- **the *physical parameter 'material friction' : UD*** $\mu_{\perp\|}, \; \mu_{\perp\perp}$ ***; Isotropic*** μ

3 Fracture morphology witnesses:

- **Each strength corresponds to a distinct *failure mode***

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

Lessons Learnt:

** Above information helps to generate a SCF model with a minimum number of <u>measurable</u> parameters!*

** When mapping, such a model sorts out whether test data are accurate (testing, evaluating) in contrast to a multi-parameter model!*

World-Wide-Failure-Excercise

In den beiden Teilen WWFE-I und WWFE-II wurden Festigkeitsbedingungen für UD-Werkstoff evaluiert und konnten aufgrund unvollständiger zuverlässiger Testdaten nur teilweise validiert werden.

- WWFE-I (1993-2004): *2D-Validierung von Festigkeitsbedingungen*
  - 14 Test Cases
  - Ebene Beanspruchung bzw. 2D-Spannungszustände
  - Nichtlineares Spannungs-Dehnungsverhalten

- WWFE-II (2004-2013): *2D-Validierung von Festigkeitsbedingungen*
  - 12 Test Cases
  - Reines Matrixmaterial neben UD-Werkstoff
  - Hydrostat. Beanspruchung ($\sigma_1 = \sigma_2 = \sigma_3$) mit überlagerten Spannungen
  - Nichtlineares Spannungs-Dehnungsv. unter hydrostatischer Beanspruchung.

Die “non-funded“ erzeugten Festigkeitsbedingungen von Puck und Cuntze haben die Spitzenplätze belegt.

Die FMC-basierten Festigkeitsbedingungen für UD-Werkstoff

$$FF1 : Eff^{\|\sigma} = \sigma_1^* / R_\|^t = \sigma_{eq}^{\|\sigma} / R_\|^t \qquad \text{mit} \quad \sigma_1^* = \sigma_{1f} \cdot V_f,$$

$$FF2 : Eff^{\|\tau} = \sigma_1^* / R_\|^c = \sigma_{eq}^{\|\tau} / R_\|^c \qquad \sigma_{1f} = \varepsilon \cdot E_\|^{t,c}.$$

berücksichtigt Faserbruch unter bi-axialer Pressung

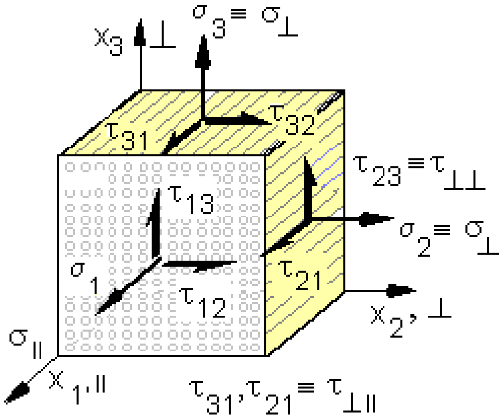
$$IFF1 : \quad Eff^{\perp\sigma} = \left[(\sigma_2 + \sigma_3) + \sqrt{(\sigma_2 - \sigma_3)^2 + 4\tau_{23}^2} \right] / 2R_\perp^t = \sigma_{eq}^{\perp\sigma} / R_\perp^t$$

$$IFF2 : \quad Eff^{\perp\tau} = [\frac{1}{1-\mu_{\perp\perp}} \cdot \sqrt{(\sigma_2 - \sigma_3)^2 + 4\tau_{23}^2} + \frac{\mu_{\perp\perp}}{1-\mu_{\perp\perp}} \cdot (\sigma_2 + \sigma_3)] / R_\perp^c \qquad = \sigma_{eq}^{\perp\tau} / R_\perp^c$$

$$0.05 < \mu_{\perp\|} < 0.3, \quad 0.05 < \mu_{\perp\perp} < 0.2$$

$$IFF3 : \quad Eff^{\perp\|} = \left\{ \left[\sqrt{\mu_{\perp\|}^2 \cdot I_{23-5}^2 + 4 \cdot R_{\perp\|}^2 \cdot (\tau_{31}^2 + \tau_{21}^2)^2} + \mu_{\perp\|} \cdot I_{23-5} \right] / (2 \cdot R_{\perp\|}^3) \right\}^{0.5} \qquad = \sigma_{eq}^{\perp\|} / R_{\perp\|}$$

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

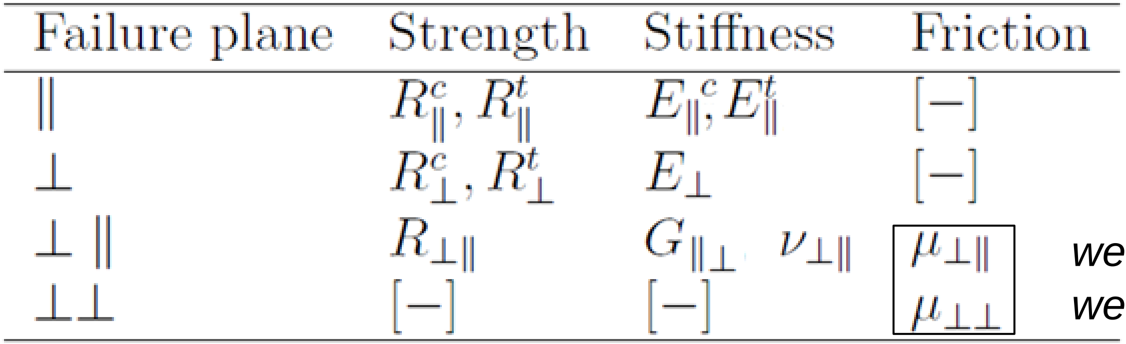


Formel zur Interaktion der Bruchmoden über die Werkstoffanstrengung *Eff* :

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

$$2.5 < m < 3$$

Benötigte Parameter für die transversal isotrope UD-Schicht



Failure plane	Strength	Stiffness	Friction
$\parallel$	$R^c_{\parallel}, R^t_{\parallel}$	$E^c_{\parallel}, E^t_{\parallel}$	[–]
$\perp$	$R^c_{\perp}, R^t_{\perp}$	$E_{\perp}$	[–]
$\perp\parallel$	$R_{\perp\parallel}$	$G_{\parallel\perp}$ $\nu_{\perp\parallel}$	$\mu_{\perp\parallel}$
$\perp\perp$	[–]	[–]	$\mu_{\perp\perp}$

wegen Mohr-Coulomb notwendige 2 Reibungswerte

$$\sum 5+5+2=12\ \textbf{Werkstoffparameter}$$

Woher?

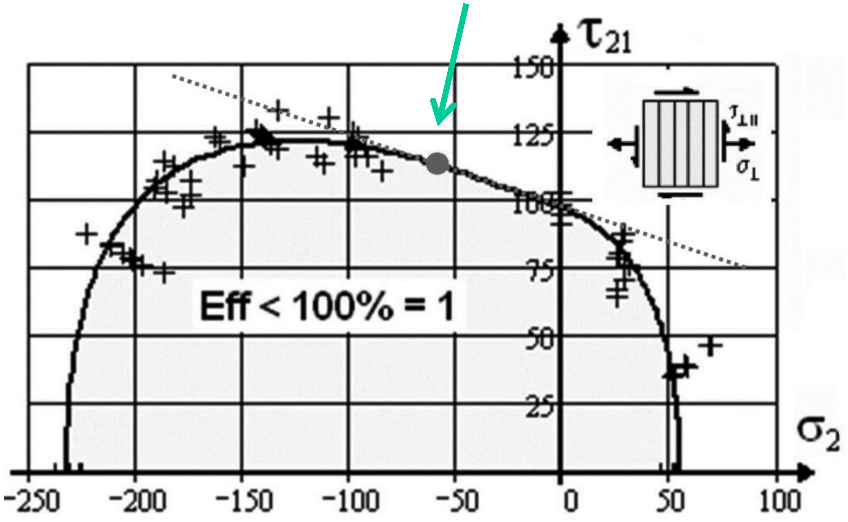
$\Rightarrow$ Experimentelle Bestimmung der festigkeitsbezogenen Parameter ***R*** (hier das Wesentliche, nicht ***E***) und $\boldsymbol{\mu}$

Für die Anwendung des FMCs wird noch der Interaktions- Exponent m benötigt, um die 5 einzelnen Festigkeitsbedingungen zu interagieren.

3. Abschätzung der UD-typischen Reibungswerte $\mu_{\perp\parallel}$, $\mu_{\perp\perp}$

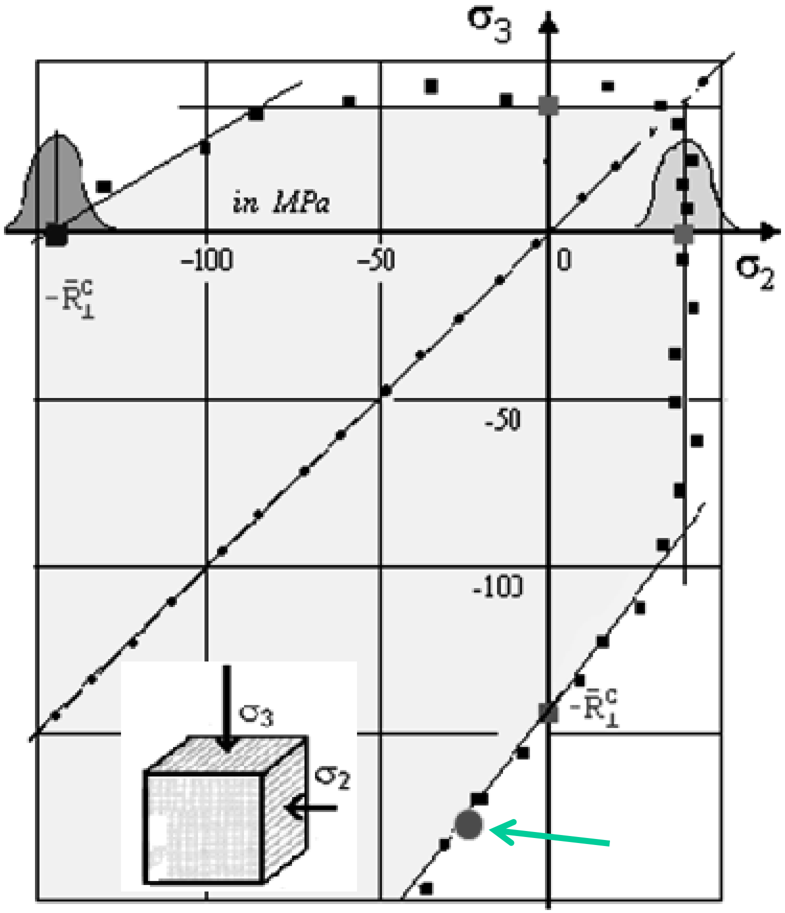
$\mu_{\perp\parallel}$: mit der Zug-Druck-Torsions-Prüfeinrichtung und zugehörigem Probekörper *(Prüfvorrichtung beim DLR nicht vorhanden*)

$\mu_{\perp\perp}$: mit zweiachsigem Druckfestigkeitsversuch ***(aufwendig)***



$$\mu_{\perp\parallel} = \frac{\bar{R}^4_{\perp\parallel} - \tau^4_{21}}{2\sigma^c_2 \cdot \tau^2_{21} \cdot \bar{R}_{\perp\parallel}}$$

Eff := Werkstoffanstrengung

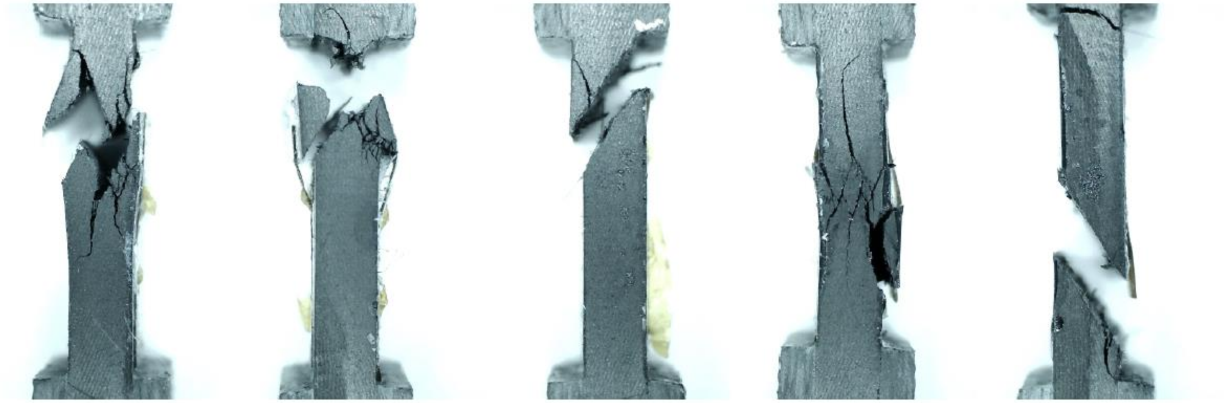


Nur einfache lineare Formeln angeben

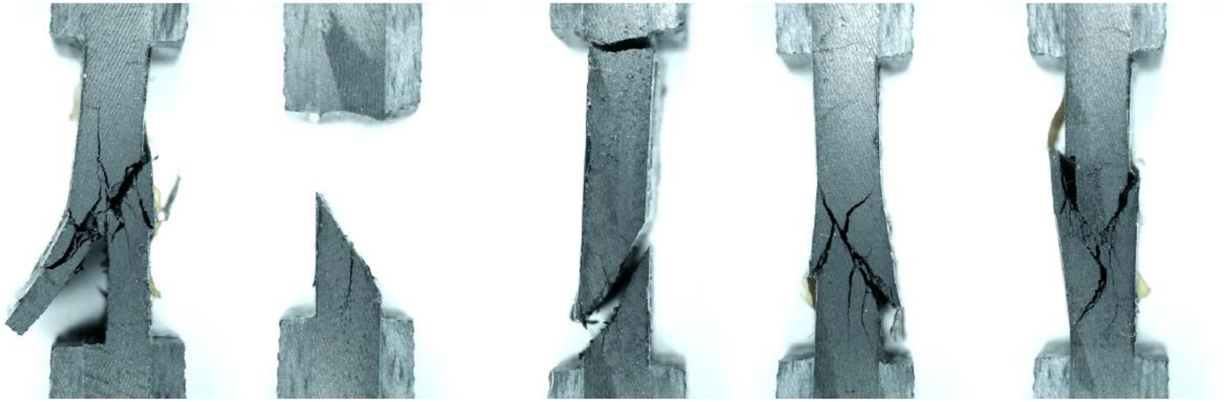
$$\mu_{\perp\perp} = \frac{1-\sqrt{(\sigma^c_2-\sigma^c_3)^2/\bar{R}^c_\perp}}{(\sigma^c_2+\sigma^c_3)/\bar{R}^c_\perp+1}$$

Alternative 1: Abschätzung eines typischen Wertes $\mu_{\perp\perp}$ über den Bruchwinkel θ_{fp}

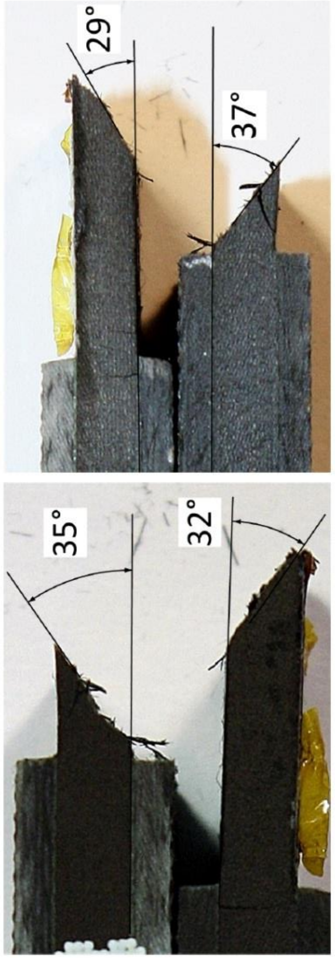
$$\mu_{\perp\perp} = -\cos\frac{2\cdot\theta_{fp}}{180°}\cdot\pi$$



(a) $\theta_{fp} = n.m.$ (b) $\theta_{fp} = n.m.$ (c) $\theta_{fp} = 56°$ (d) $\theta_{fp} = n.m.$ (e) $\theta_{fp} = 56°$



(f) $\theta_{fp} = n.m$ (g) $\theta_{fp} = 59°$ (h) $\theta_{fp} = 60°$ (i) $\theta_{fp} = n.m.$ (j) $\theta_{fp} = n.m.$



aus uniaxialem Querdruck-Versuch, streut ziemlich