THE WORLD-WIDE-FAILURE-EXERCISES-I AND –II FOR UD MATERIALS - VALUABLE ATTEMPTS TO VALIDATE FAILURE THEORIES ON BASIS OF MORE OR LESS APPLICABLE TEST DATA -

Ralf Cuntze
D-85229 Markt Indersdorf, Matthaeus-Guenther-Straße 32
Tel 0049 8136 7754, Ralf_Cuntze@t-online.de,
formerly MAN-Technologie, now linked to Carbon Composites e.V (CCeV), Augsburg

ABSTRACT

There was a lack of really validated 2D and 3D strength failure conditions (SFC) for unidirectional (UD) laminas. In the World-Wide-Failure-Exercises WWFE-I (2D stress states) and II (3D stress states), organized by QinetiQ (UK) in the past 20 years, it was extensively attempted to fill this gap. The author participated in both these exercises with a set of 'modal' failure conditions for the brittle behaving, transversely-isotropic UD lamina material composed of endless fibre-reinforced polymers. These conditions base on his so-called Failure Mode Concept (FMC). In the paper the provided, more or less applicable or even not reliable test data sets - provided for the Test Cases (TC) - are discussed with the aim of a better exploitation. There are no further data sets available. Therefore the interested designer must get sufficient knowledge about the quality of the data sets. With a better understanding the designer will be able to perform design verification with a remaining minimum amount of costly test work. To achieve this, the author presents his personal WWFE assessments, provides lessons learnt and draws conclusions.

1. INTRODUCTION

This paper addresses a reader who intends to look deeper at the two WWFE books [Hin04, Kad13] in order to get more insight. With respect to the number of pages the TC-associated figures cannot be presented here but can be downloaded from the website [CCeV as other associated literature like [Cun04, 11, 13].

The situation in strength assessment lacked of methods sufficiently well describing strength failure. Therefore, in order to reduce the expensive ‘Make and Test' approach confidential and robust models were intensively searched to predict failure of the high-performance UD lamina-composed laminates. The UD lamina model is a homogenized transversely-isotropic material.

In 1992, QinetiQ in the UK began to set up the well-known World-Wide-Failure-Exercises-I, -II and the still ongoing –III. QinetiQ aimed at an independent assessment of the currently available failure theories. The WWFEs should sort out the capability to predict failure of the laminas and laminates above. In addition, the limit of a theory's applicability was to depict. Leading failure theories were tested wrt their general applicability, against each other, and against experimental evidence. At the end of each WWFE conclusions shall be drawn for the following WWFE and for further research.

Some definitions might help to better understand the following context: Failure: If the structural part does not fulfil its functional requirements (FF:= Fibre Failure, IFF:= Inter-Fibre Failure (matrix failure), leakage, deformation limit, delamination size limit. Failure theory as used in the WWFE comprises: (1) UD strength failure conditions to predict interactive IFF and IFF; (2) Non-linear modelling of the lamina material (hardening with softening for post-IFF modeling); (3) Implementation of SFCs into a computer code for non-linear analysis so, that large strains in laminas and multi-directional laminates can be captured; (4) Consideration of the so-called 2nd-Tg effect, a stiffness and strength weakening of the matrix material beyond p_{hyd}> 200 MPa = 2000 bar; and of (5) Birch effect, which represents the elastic stiffening under hydrostatic pressure p_{hyd}. Multifold failure mode, a failure mode which acts several times (i.e. if $\sigma_2 = \sigma_3$, twofold).

Main objective was: Prediction of a ‘multi-axial failure stress state ‘of the UD lamina material. Specific task was: Mapping courses of test data for endless fibre-reinforced polymers with the various strength failure conditions (criteria) of the contributors.

2. FAILURE-MODE-CONCEPT-BASED STENGTH FAILURE CONDITIONS (SFC)

2.1 The Failure-Mode-Concept (FMC)

The author and contributor applied his so-called Failure-Mode-Concept. This is an invariant-based macro-mechanical concept which however considers failure of the constituents matrix and fibre. It relies on Beltrami, Mises and Mohr-Coulomb and uses the UD-lamina as building block in a ply-by-ply laminate analysis. The formulation of the strength failure conditions of the homogenized lamina material follows the material symmetry requirements of a transversely-isotropic UD material. This means that five UD strengths and two friction values are to be considered. Fracture morphology outlines that each single strength reigns one associated failure mode of the five independent modes. There are three IFF and two FF strength failure conditions (SFCs).

Two different formulations are possible: A Global one (like Tsai-Wu) and a Modal one (like Puck, Cuntze). Fig.1 depicts that in a global formulation all strengths are included whereas one modal formulation involves just one strength. The vector of stresses and the strengths, collected in a vector, read

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

1 Global ***strength*** **failure condition** :

$\mathbf{F}(\{\sigma\},\{R\}) = 1$ (usual formulation)

Set of Modal **strength failure conditions** :

$\mathbf{F}(\{\sigma\},R^{mode}) = 1$ (addressed in FMC)

Figure 1 : Global and modal SFCs

From above follows: The FMC may be termed a 'Modal Formulation', whereas most of the other formulations may be termed 'Global Formulations'. A Global Formulation has the physical bottleneck that it mathematically connects independent failure modes in one equation. Then, a change in one mode has an effect in an independent mode and this effect is not always on the safe side [Cun03]. Of-course, the five modal conditions must be interacted..

Benefits of choosing modal strength failure conditions are ***: (1)*** Less input is required than for the usually applied *global strength failure conditions*, except of a guess of the friction value for brittle behaving materials. (2) Have not the short-comings of the global conditions that do not directly apply physically necessary friction.

Basic features of the modal FMC are:

- Each failure mode represents 1 independent failure mechanism and 1 piece of the complete *failure surface*
- Each failure mechanism is governed by 1 basic strength. Therefore, for the single modal SFC advantageous equivalent stresses can be determined displaying in which mode the design key must be turned. Fracture morphology witnesses: Each strength R corresponds to a distinct failure mode and to a fracture type such as Normal Fracture (NF) or Shear Fracture (SF)
- Each failure *mechanism* is represented by 1 failure *condition* (interaction of stresses). A clear failure mode identification is possible and the associated degradation is determinable
- From Beltrami, Mises (HMH) and Mohr/Coulomb (friction) can be concluded: Invariants, used in the formulation of a SFC can be dedicated to one physical mechanism in the solid (or cubic material element), whether the element's volume changes or its shape change (analogous to Mises). An invariant is a combination of stresses, the value of which does not change when altering the coordinate system
- Material symmetry requires for an *ideal* UD material crystal 5 basic strengths (5 elastic constants, 5 basic invariants) and 2 physical parameters. This means for the *real* crystal – due to Mohr-Coulomb - 2 material internal friction values μ
- Interaction of 5 Failure Modes: Probabilistic-based 'series system failure model' that directly delivers the (material) reserve factor in linear analysis
- Basic strengths are weakest link data (see Fig. 2) from isolated lamina test specimens. Isolated laminas just show hardening behaviour before IFF, whereas the embedded, redundant laminas do not fully lose their load carrying capacity after IFF and show softening in the failure progression domain.

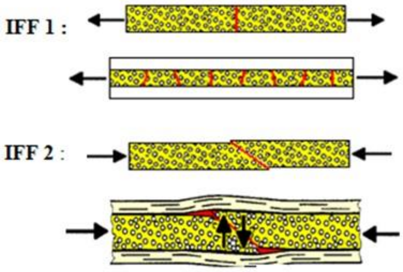

Figure 2: Isolated and embedded (in-situ) laminas

FF1 $\breve{\sigma}_1/\bar{R}_\parallel^t = \sigma_{eq}^{\parallel\sigma}/\bar{R}_\parallel^t$,

2 filament modes

FF2 $-\breve{\sigma}_1/\bar{R}_\parallel^c = +\sigma_{eq}^{\parallel\tau}/\bar{R}_\parallel^c$,

with strains from FEA

$$\breve{\sigma}_1 \cong \varepsilon_1^t \cdot E_\parallel\,,\ \breve{\sigma}_1 \cong \varepsilon_1^c \cdot E_\parallel$$

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

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

3 'matrix' modes

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

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

Interaction of modes: $Eff = \sigma_{eq}/\bar{R}$

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

mode-interaction exponent

$2.5 < m < 3$

Typical friction value data range:

$0.05<\mu_{\perp\parallel}<0.3,\ 0.05<\mu_{\perp\perp}<0.2$

t:= tensile, c: = compression,

$\parallel$: = parallel to fibre, $\perp$:= transversal to fibre

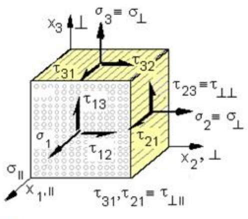

Figure 3: Collection of Cuntze's 3D modal SFCs

2.2 The FMC-based strength failure conditions

In Fig.3 the SFCs used in WWFE-II are collected.

Fig.4 depicts the 2D fracture failure body of the UD material. Replacing the mode dominating stresses by the associated equivalent stresses the same body is applicable as 3D fracture failure body (surface), too.

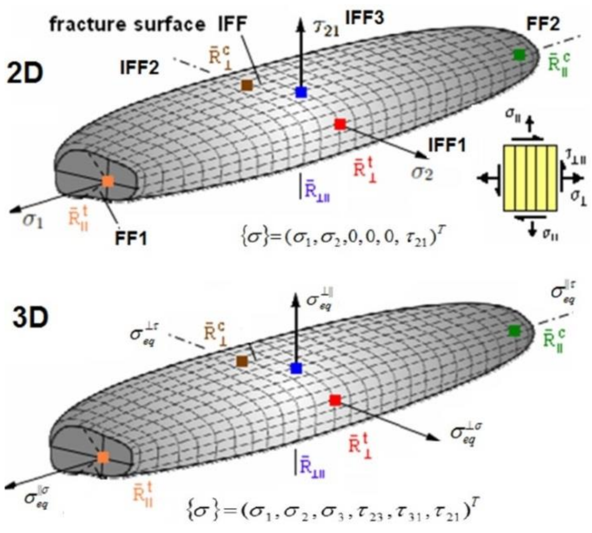

Figure 4: 2D and 3D Fracture failure bodies

3. SURVEY ON THE WORLD-WIDE-FAILURE-EXERCISES (WWFEs)

Assumptions for UD modeling and test evaluation in the WWFEs are: 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 fibre direction it behaves orthotropic and on planes transverse to fibre direction isotropic (quasi-isotropic plane). A uniform stress state should be about the critical stress 'point', where failure occurs.
And for the test: Pore-free material, specimen surfaces polished, well-sealed (WWFE-II), fibre volume content V_f is constant, tube specimens show no warping and do not bulge (used in Part A prediction), perfect bonding, no layer waviness, edge effects do not exist.

Whereas WWFE-I served for the validation of failure theories on the 2D stress state level the WWFE-II should do that on the 3D level. A 3D validation is necessary due to the upcoming necessary 3D analysis efforts (examples, see [Cun12]) and the associated required design verification. Each WWFE was subdivided into two parts: (1) Part A described the individual theory and contained a blind theoretical prediction (of the failure surface or of strains) for specified Test Cases (TCs) on the basis of provided strengths and no friction value, only. (2) Part B included possible modifications or refinements of the theory and a comparison of the Part B theoretical results with test data provided in Test Case-dedicated data packs. In addition, reasons for differences and recommendations had to be given.

Main idea of Part B was to demonstrate: How well can a distinct theory predict failure? Of course, this requires the presumption: all provided test data packs are 'good', and the original data source was accurately evaluated. But unfortunately, this could not be fulfilled neither in WWFE-I nor in WWFE-II. As test data packs were provided:

- WWFE-I: *2D in-plane loading for 14 TCs,*
- WWFE-II: *3D loading for 12 TCs.*
- The still ongoing WWFE-III contains the application of advanced failure models based on Continuum Damage and Fracture Mechanics Models. Deals with validating and benchmarking failure theories that are capable of predicting damage, such as (1) matrix crack initiation and development, (2) delamination initiation triggered by transverse cracks, and (3) deformation up to final fracture. The author contributed to I and II.

The objectives of the WWFEs were:
I: 2D-Validation with 2D Failure Stress Test Data
- TC1-TC3 UD lamina: validation of UD models
-TC4-TC14 UD-composed Laminates (quasi-isotropic, angle-ply, cross-ply): verification of laminate design by multi-axial failure stress surfaces and stress-strain curves.
II: 3D–Validation with <u>3D</u> Failure Stress Test Data *involving hydrostatic pressures up to > 14000 bar = 1400 MPa*
- TC1 *Epoxide matrix: validation of isotropic model,*
- TC2-TC7 *UD lamina: validation of UD model,*
-TC8-TC12 *Laminate*: *verification of laminate design.*

Used for modeling are micro-mechanics-based models, meso models and the engineering-like macro-mechanical models on the homogenized UD material level. Predicting crack density was desired.

4. DISCUSSION OF MODIFICATIONS AND QUALITY OF TEST DATA PACKS

In order to better understand the following chapters the WWFE-II assessment of the author's FMC-based SFCs by QinetiQ (see [Kad13]) shall be cited: *"The theory performed very well overall and seems to have provided a good fit with large number of test data. Some of the improvement in performance offered in Part B were partly as a result of altering the lamina stress-strain input curves, assuming degradation profiles of the lamina stress-strain curves and (to a lesser extent) by a suitable choice of the curve fitting parameters embedded in the theory. Certain other modifications, made in Part B, were offered as a means of simplifying the computation and appear to have no physical basis. The readers should form his/her own view as to the fidelity of these revisions".* This needs to be discussed.

4.1 Critics from QinetiQ on Modifications from WWFE-II Part A to Part B

Basically, the step from insufficient Part A information to an improved Part B information level made modifications of the theoretical model necessary. These modifications were mandatory, primarily, because test data sets were modified by the organizer (in Part A even provided strengths were changed) and because additional Part B information was given. Therefore, it makes not much sense to compare the contributors' blind predictions if data provision in Part A does not contain all material parameters, i.e. the two material internal friction values, which are physically necessary (brittle behaving materials follow Mohr-Coulomb and therefore exhibit friction). It further makes no sense to provide sample data generated by different test specimens, i.e. torsion tests of a hoop wound 90°-tube together with a 0°-tube, as the latter twists and the stress state must be transformed by the twisting angle in order to obtain the lamina stress state which then can be judged by the SFCs, see [Cun04, 13].

In the following paragraph details on each TC are given to inform the reader why modifications had to be made:

TC1: *Part-model modification, necessary due to an information change*

(1) Part A information: Matrix failure is yielding. This practically means no friction. A low friction value was assumed according to "matrix failure is yielding". Part B information: matrix failure is fracture (significant friction). This caused the author to change to friction modelling because the material behaviour in B is different to A and this has a strong influence. From the newly provided data a friction value could be computed.

(2) Part A: According to available knowledge, matrix material was assumed in Part A to possess the 2ndTg-effect (the author gave this effect a name). Therefore, all 2ndTg-affected TCs (6 and 7) have been programmed to consider this effect, but lacking of Part A data for the kink at -200MPa the effect was not computed. Part B: The 2ndTg-effect is inherent in the epoxide matrix of TC1 but was not shown by Part B TC test data! Hence, this effect could never be considered by a computation.

Comment: Effect is significant for TC6, TC7. Unfortunately, it was never discussed that the provided matrix data did not demonstrate the well-known matrix material inherent 2ndTg-effect.

TC2, TC3: *No model modification but data change due to provision of all fracture strain data.*

- Part A: 0° tubes and 90°-wound tubes inherently have different failure stress states (see old comments in WWFE-I [Cun04]). Therefore, they should not have been provided in one common diagram (apples and oranges) in WWFE-II again, where both specimen type results were provided in one diagram. In Annex 5 of [Cun13] the big difference in the failure states is shown by an approximate analysis. The author never received any reviewer comment on adding the 0°-test data and on twisting of the 0° tubes, neither in WWFE-I nor in -II.

Comment: One should use the same specimen type in a diagram, and then perform an accurate evaluation of test data and analyse the shear stress distribution over the thickness over the not really thin-walled tube.

- It is physically accurate to differentiate 'weakest link' (isolated test specimens) behaviour and 'redundant behaviour' of 3D-loaded tubes under hydrostatic pressure. Hence, my treatment of TC2, 3 and 4 is a novel idea. Using the distinction of redundant and isolated behaviour no mapping problems existed anymore in the vicinity of $\sigma_2 = 0$
- Mandatory is the idea with the determination of the average stress-strain curve. This made it possible that in all the three curves a 'check point' is given (see the open square in each figure of [Cun13].

TC4: No model modification, but data change due to be able to compute the needed average curve to be applied for TC2 and TC3.

Part A: The contributors were asked to predict the τ-γ $(p_{hyd} = 600MPa)$ −curve. Enough information to predict the desired shear stress-shear strain curve could not be provided by the organizers. The author had to use results from Parry [Par90], when employing the engineering standard mapping function, the '4 points approach' of Ramberg-Osgood. Further, to perform this task, an upper τ-γ-curve for $p_{hyd} = 0$ was provided. This was one single curve of the Part B-distributed test series and was not correct because the to be predicted TC2- and TC3-curves are p_{hyd}-depending average curves. Part B, with its information about all measured stress-strain curves enabled the author to determine the physically necessary average curve.

TC5: *No model modification, but data change due to be able to compute the in Part A missing friction value with the Part B information*

TC6, TC7: *No model modification*

TC8: *No model modification, but data change due to be able to compute the missing friction value.*

TC9: *No model modification, but data change being enabled to compute the missing friction value*

TC10, TC11: *No model modification, but data change due to be able to compute the missing friction value.* The author's engineering-like approach (described in the WWFE-II body text) was the following: Stress state and distribution at the critical location was investigated and it was found that the consideration of the 3 interlaminar stresses in the FMC conditions will deliver a good failure prediction. And the result was simple and good, A sophisticated stress analysis would require a 3D FEA. This means that the FMC should have to be implemented into a source deck. After the FEA, the obtained FE-stress results found for TC10 and TC11 must be transferred into stresses, which can be assessed by strength conditions, because the stack does not 'produce' a non-uniform stress distribution. This violates the presumption of a necessary homogeneous stress state at the critical location! Further, the provided fracture compressive strength $\max\sigma_z = -1400 MPa$ was not a measured value dedicated to the stacks of TC10 or TC11. As it was the result of a 'similar' stack, it could just serve as a guess. The author reduced this value according to his view how differently TC10 and TC11 will fracture in comparison to the 'similar' stack.

TC12*: The author did not perform a progressive filament-by-filament analysis, as seen by QinetiQ*. He has just used phenomenological facts to explain the deformation process. Therefore, the author's methodology is *not a self-fulfilling one.*

4.2 'Calibration of models' in II-TCs 2,3,4,12 - seen by QinetiQ as an undesirable feature

TC4: The task was to predict TC2 and TC3 which are linked to TC4. TC4 delivers the needed stress-strain curve. Mapping the average course of data points of TC2 and TC3 must be the result of an "average" stress-strain curve (behaviour) from TC4 and not of an "upper curve" as delivered in Part A. The 3 TCs are only fully linked if an average stress-strain curve is used. This was first possible by the full fracture strain information provided in Part B. Then in all 3 figures - as a fidelity control - a common check point with the coordinates (phyd = 600 MPa, tau21 = 140 MPa, gamma = 14,2°) was determined. The reviewers seem not to have picked up both the points: the necessity to use an average τ-γ-curve, and that redundant and isolated material behaviour should be discriminated when the embedded material is hydrostatically compressed.
Comment: Applying an average curve is a physical 'must'. This has nothing to do with calibration.

TC12: After having corrected a sign mistake of Part A, curve (a) was obtained (unfortunately the author had made this mistake in Part A). However, also the better Part B information-based curve (b) did not fully map the provided course of test data points despite of the fact that the Birch effect was considered. The remaining small difference to the provided course of test data was then fitted on basis of a physical fact: With increasing compression in thickness direction filaments are more and more pressed upon another. And therefore, the stiffness in z-direction increases into the direction of the lateral filament Young's modulus value. This further means that a strength failure condition of the homogenized UD material has surpassed its applicability limit.
Comment: Therefore, the complete TC12 approach cannot be simply marked by a reviewer as fitting. If the physical argument, leading from (b) to (c), is wrong the author would be very pleased to obtain a response correcting the approach. This would benefit the designing engineer to better understand composites.

4.3 Highlighting specific gaps and shortfalls in the experimental data of some TCs

WWFE-I:
Even here not all test data sets (2D stress states, only) were reliable. For instance, see [CCeV] download:
I-TC1, buckling failure occurred in one multi-axial failure stress domain. However, buckling of a test specimen cannot be described by a strength failure (material) condition but by a structural (stability) condition. No mapping in this domain possible
I-TC2: Part A: Provision of strength data, no friction value μ given. Part B: Strength points altered!, 2 doubtful single failure stress points (marked by a ?). A much too high friction had to be considered to map this case, unrealistic, as own and other measurements prove [Cun14]. On top it is 'Not on the safe side'.
I-TC13 could be first mapped after having full test information for Part B (the right failure strain was not given for Part A prediction, a discrepancy was found).

WWFE-II:
Addressed are brittle behaving UD materials. These are materials with inherent friction - due to Mohr-Coulomb. Therefore global and modal SFCs cannot be based on uni-axial strength data only. The conditions must consider a friction parameter to accurately map the material behaviour. If the organizer cannot provide a friction parameter, then a good Part A prediction is not possible, in general. One has to estimate a value (required is the knowledge of a fracture angle or of multi-axial compression test data, see [Cun13, Pet14].
In several test cases - for the used matrix materials - the physically existing stiffness and strength lowering '2nd-Tg effect' is active. In TC1 (isotropic matrix test specimen), however, this is unfortunately not demonstrated by the well-known kink of the provided course of test data beyond a hydrostatic compression of -200 MPa. Question: Why is this true physical effect not

shown and never discussed somewhere throughout the WWFE-II? The '2ndTg-effect' would have been of highest impact for TC6 and TC7. (By the way, why should the 2ndTg- effect be my novel idea as a reviewer said. I just gave this effect a name.) This effect is standard knowledge when performing tests under high hydrostatic pressures, executed for instance by Parry, DeTeresa etc., and QinetiQ, too!

The author integrated the impact of this effect into his MATHCAD program. This took much time. Unfortunately in Part B, the author could not perform a calculation to show this kink because the matrix data in TC1 did not show the effect and because the change of the failure curve of the two branches in TC 6 and 7 beyond -200 MPa is opposite.

The cases TC10, TC11 (thick-walled tube, milled from a laminated rectangular thick plate) did not show a uniform (smooth, homogeneous) stress state with a small stress gradient in the failure critical location. This multi-site failure situation increases the joint failure probability of the full test specimen, that turns to be a very complicated 'failure system'. More material volume is stressed in the vicinity of the fracture stress state which results – following Weibull - in a lower fracture failure stress and thereby in a higher failure risk. The specimen encounters multi-site damaging and failure within each lamina and multi-fold failure modes in all laminas. The pre-requisites are violated in TC10 and TC11.

Principally, just the lamina test cases TC2 through TC7 are directly applicable for validating the UD-FMC-based strength failure conditions. The laminate test cases TC8 through TC12 can 'only' serve as benchmarks for verification of the full failure theory. In each TC the investigation of the influence of wall-thickness on hoop stress is mandatory.

5. SOME CONCLUSIONS, PRACTICAL RELEVANCE AND LESSONS LEARNT

We must try our best with the test data sets we have! In WWFE-II again the provided test data packs were seen to give evidence. No discussion where this is not and where it might be not the case! So, the author draws the following conclusions from the two WWFEs:

- So-called physically-based modal criteria (failure mode- based such as with Puck and Cuntze) need friction values. Standard Gobal criteria do more data fitting and do not need a friction value because they mathematically combine different failure modes, with friction and without friction. A prediction, in general, is physically not possible and not correct on basis of strength values alone. Otherwise the Mohr-Coulomb theory would not exist. In order to capture friction the global criteria need more test data points in the shear failure prone compression domain, than the modal criteria require. Modal criteria estimate a friction value instead and need just a few points within each pure failure mode domain.
- A physically based modal strength condition maps just one single failure mode
- Providing micro-mechanical properties (necessary to capture the '2ndTg-effect') is obsolete without providing the associated micromechanical formulas where these properties were determined with. It is a closed system! The organizers did not pick up this point, from my response. That made the author much fitting work because he had to use own micro-mechanical formulas. Adjusting them, of course, was no full success.
- A physically-based model cannot map a course of false test data! However, fitting procedures used in simulation can fit nearly 'every' course of test data. It just depends on the number of free parameters. So, even good mapping of a course of test data does not guarantee 'validation of a theory'.
- Full validation of a theory is possible with reliable test data, only
- To apply a SFC means to address material failure. If material failure behaviour is terminated and its presumption violated, then the application of a structural failure condition is required, for instance in TC12 a (micro)-mechanical structural failure condition
- Ranking the contributing criteria on basis of insufficient test data input is not helpful, like for the II-Part A contributions. One can just compare Part B-mappings of the *reliable* Test Cases and further recognize each contributor's enhancements to improve mechanical understanding which shall support further scientific progress. And, adding Part A predictions to Part B results on the same graph makes no sense if a change occurred to B. And further not, if necessary parameters such as the friction parameters have not been provided in A
- Each UD criterion must fulfil the material symmetry requirements for a transversely-isotropic UD material, see paper in [CCeV]. This seems to be not the case for some contributing criteria
- UD-lamina test results, only, can be taken for a *validation* of strength conditions. The results of multi-axial laminate tests serve for *verification* of the full failure theory, where the SFCs are one part of
- Preliminary design: Modal SFCs require a few test data points in each pure mode domain. The interaction exponent *m* can be estimated on the safe side. Global SFCs need sufficient test data in the pure and the interaction domains to perform fitting

- Material symmetry requires the use of separate SFCs for isotropic (matrix, TC1) and transversely-isotropic UD materials!
- Counting parameters of the failure theories is a compareon of apples and oranges. If an author employs more theoretical subjects than another contributor, then, one counts more parameters. Of interest is: Which SFC is the most reliable one and which has a minimum number of parameters, and, can all model parameters be measured? The FMC counts 5 UD strengths, 2 friction values, and the assessable interaction exponent. In contrast to a dense isotropic material a dense UD material might fracture under a very high hydrostatic compression stress ($\sigma = -p_{hyd}$), according to the Poisson effect which makes the filament strain (TC5) to reach the fracture strain $e_{||}^{c} = p_{hyd} \cdot (1 - 2 \cdot \nu_{\perp ||}) / E_{||}$ under the pre-requisite $2 \cdot \nu_{\perp ||} < 1$. The failure surface is therefore closed
- Open or closed failure surface: The ends of a failure surface (body) are always the result of the acting multi-axial stress state. In the tensile domain this always leads to a closed surface wherever for multi-axial compression this may happen or not happen. Modal strength criteria do just capture one failure mode and in the closing usually the same failure mode acts two-fold or three-fold. This has to be considered! Otherwise it is a global test data fit and not a physical mapping. If the material has no pores, which is the assumption in the WWFEs for UD-material then it is differently treated to a porous material where the ends are always closed. Therefore, any judgement whether the surface is open or closed cannot be performed if the specimen consistency is not clearly given. TC1: closed; TC2, TC3: closed, by material failure 'kinking' FF2 leading to real structural (instability) failure; TC4: not applicable; TC5: closed; TC6, TC7: theoretically open; TC8: closed; TC10, TC11: closed; TC12: not applicable.
- The nominal higher load carrying capacity or – more accurate – the higher multi-axial resistance, obtained under p_{hyd}, is the result of the favourably p_{hyd}-affected, *lowered* equivalent stress σ_{eq}. It does not rise from an *increased* uni-axial technical strength $\overline{R}$ and therefore cannot be called 'Increased strength' as often done
- Test results of a test series vary around the average value. In consequence, the course of test data points varies around an average curve, e.g. TC3, τ_{21}(phyd)
- A theory shall well capture the material behaviour in the technical application domain. For instance, the TC9 Cuntze model is valid for fracture strains smaller than 0.5%. This is still larger than usual design limit strain of 0.3%
- Experimental results can be far away from the reality like a bad theoretical model. Theory creates a model of the reality, 'only' and one experiment is 'just' one realisation of the reality
- The failure index FI = |F| only gives an information on the reserve of a material if the failure condition F is mathematically homogeneous
- The failure index FI = | F| only gives an information on the reserve of a material if the failure condition F is mathematically homogeneous
- Most engineers assume that FF in at least one lamina of a laminate means final failure of the laminate. Therefore, the bi-axial (non-)failure envelopes for final failure of laminates predicted by the various authors do not differ that much, as long as the laminates are 'well-designed and have three or more fibre directions. The multi-axial 'strength', better resistance, of these laminates is 'fibre dominated'. Further, the predicted stress-strain curves of such laminates look very similar because the fibres, being much stiffer than the matrix carry almost the full loading. Different degradation procedures after the onset of inter-fibre failure (IFF) do therefore not influence the predicted strains very much. This is especially true for CFRP laminates
- And, as the author learned, one should fully indicate the test information (test specimen, test rig, etc.). The author for instance had thought about another test rig (ARCAN scissor test) in Part II A for TC10 and TC11 which led to another failure curve because another layer became failure-critical in Part A than in Part B (deTeresa torque test).

Some final remarks:

- Experimental results can be far away from the reality like a bad theoretical model. Theory creates a model of the reality, 'only' and one experiment is 'just' one realisation of the reality
- Conclusions, after having personally spent -as a single, non-funded author- about 2 man years of my 'vacant' time in 17 years of contribution: If we simply accept physically not plausible test data then we do undermine the excellent WWFE efforts. Did we really exploit costly 3D test data sets for the sake of the designing engineers? Why did we not discuss obviously not reliably looking test curves? Probably the only reason is, as experienced with II-TC5, that just the hydrostatic stress was not correctly considered. For TC5, the original input test data set

was re-evaluated. Might the evaluation of the basic test data of TC6 and TC7 be not also partly wrong?

- For in-elastic analysis non-linear stress-strain curves are needed with a yield surface. The growing yield surface is confined by the fracture failure surface
- The FMC-based conditions could be also 3D-validated as far as reliable data sets were provided. They were again successful in WWFE-II. Unfortunately, some physically-based reasons - used in mapping - seem not to have been understood by the reviewers. In this context in addition: The existing but missing 2nd Tg-effect of matrices (II TC1 beyond -200MPa) was never questioned. *The needed fidelity for 2D- and 3D-laminate design will be obtained after provision of the missing test data sets*. Therefore Professor Hashin's remark at a conference at Brussels (1998) “I must say to you that I personally do not know how to predict the failure of a laminate and furthermore, that I do not believe that anybody else does" will not become true for the designing engineer from industry. We have made good progress! However, some final missing test data must be delivered by reliable tests and data evaluation.

6. REFERENCES

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