THE WORLD-WIDE FAILURE EXERCISES: HOW CAN COMPOSITES DESIGN AND MANUFACTURE COMMUNITIES BUILD THEIR STRENGTH

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Abstract

In a manner reminiscent to establishing the 'periodic table', researchers and keen material scientists/engineers have been engaged in intensive activities trying to identify their own characteristic model or discover a unique aspect/failure mode in a composites material. No tangible progress could have possibly been achieved without the relentless efforts made by some 40 dedicated developers of advanced methods for failure criteria for composites. They have been at the core of an international initiative, referred to as the World-Wide Failure Exercise (WWFE). It is aimed at establishing the maturity of existing method and the remaining challenges of building the best method to accurately predict the strength of composites materials.

The paper deals generally with the three exercise (WWFE, WWFE-II and WFE-III) which have been conducted over the last 20 years. The focus is on some of the lessons emanating from the latest exercise (WWFE-III).

1 Introduction

Despite the heavy use of composites in leading industries (aircraft, automobile, wind turbines, ships), composite design and manufacture communities are, nonetheless, still facing numerous and real challenges. These challenges include (a) shorter life cycles (b) automated manufacture (c) production of high volumes (d) integrating 3D structures into 3D architectures (e) development of alternative materials and (f) meeting climate change targets. For instance, it is anticipated that meeting CO2 emission reduction targets will drive toward lighter transports. ACARE (The Advisory Council for Aeronautics Research in Europe) calls for a 50% reduction in CO2 emissions by 2020 versus 2000. To meet these targets, it is estimated that 200kg will be taken out of the medium size cars (family cars) by 2020 and further 200 kg by 2030.

These challenges are becoming harder to meet due to the continuous lack of validated simulation tools/ standards. Reliable tools capable of predicting the linear and nonlinear behaviour, including manufacturing, damage and failure, are at the heart of those challenges.

We will focus here on design. The existence of a myriad of failure/damage theories with no clear consensus as to their accuracy can potentially lead to confusion and a misrepresentation of what is possible and what is impossible to achieve within the current state-of-the-art in the field. One direct consequence of the lack of consensus is the prospect of hampering progress and slowing down the development of robust analytical or numerical computational tools. Ultimately, this tends to lead to over-conservative and cost-ineffective design of composite materials. Hence, there is a gap to be bridged between theoreticians and design practitioners on the maturity of the current models for prediction of failure, especially when embedded within analytical and numerical tools, such as commercial FE codes.

It is clear that a neutral, independent and internationally-based effort is needed to promote confidence in the use of failure criteria and in the deployment of robust modelling capabilities for fibre reinforced polymer composites as a cost-effective means of designing light weight structures.

In response to the above challenges, the authors, since 1992, began a series of coordinated studies (known as the 'World-Wide Failure Exercise (WWFE)) to provide a comprehensive description of the foremost failure theories for fibre reinforced plastic (FRP) laminates that were available at the time, a comparison of their predictive capabilities directly with each other, and a comparison of their predictive capabilities against experimental data. In the 'exercise', selected workers in the area of fibre composite failure theories, including leading academics and developers of software/numerical codes, were invited to submit papers to a strictly-controlled format. Some of the strong features of the WWFE are

- It involved those theoreticians and designers who are the originators of known failure approaches,
- The originators are given the opportunity to describe their design method in detail,
- The originators are given the chance to indicate the limitations of their methods and specified steps to improve the predictive capability of their theories,
- The originators are encouraged to provide their recommendations on how their methodology could be used in design applications,
- Each participating group was restricted and requested to comment only on their <u>own</u> theory thus fulfilling one of the basic and important objectives of the exercise.

This objective was set out so that the originators of the methods are best placed to provide a true and unambiguous interpretation of their own work and thus eliminating and negating any second guessing by a third party. To this end, their recommendations are judged to be focused and targeted and, consequently, rendering them to be potentially very useful to those wishing to adopt one of the methodologies.

The first World-Wide Failure Exercise (WWFE), Ref[1], started in 1996 and came to a fruitful end in 2004 with the publication of comprehensive reference book about failure criteria in fibre reinforced polymer composites under two dimensional (2-D) stresses. It contained a detailed assessment of 19 theoretical approaches for predicting the deformation and failure response of polymer composite laminates when subjected to complex states of stress. One of the striking results is that designers can only expect a few theories to give acceptable correlation with test data for 75% of the test cases proposed in the exercise. In the extreme, some of the theories consistently gave predictions away from the test data and these theories require a fundamental change in order to bring them to the degree of the maturity the other theories exhibited. The first WWFE proved to be a groundbreaking effort with many achievements:-

- It established, for the first time, an open and objective way of working in order to compare, contrast and challenge disparate theories from around the world.
- It exposed the strengths and weaknesses of the current theories.
- As a result of carrying out the first exercise, some 50% of the theories were improved and modified. In some cases, the modifications were made for the first time in over 40 years
- It provided a stimulus for researchers to build upon the accurate theoretical features whilst making improvements to deal with the shortfalls that were exposed.
- It highlighted gaps in experimental data and in theoretical understanding, and preliminary recommendations were made in terms of prioritisation and approach to their resolution.
- It provided design engineers (the ultimate beneficiaries for such research knowledge) with recommendations on the preferred theories to use, together with evidence of the level of confidence and bounds of applicability.

Unfortunately, the first exercise provided no clue or guidance on the maturity of failure criteria in the following two important areas:

Area (1): The behaviour of materials under triaxial stresses and

Area (2): Damage/matrix crack development, initiation of matrix-driven delamination and ultimate failure.

In order to fill in the gap knowledge and to assess the maturity of the current predictive models in those two areas, the authors have launched two new exercises, referred to as:

2 The Second World-Wide Failure Exercise (WWFE-II)

This has tackled Area (1) above, where twelve groups took part and they represented a wide range of 3D failure criteria. WWFE-II involves posing a set of 12 challenging test cases to validate and benchmark the triaxial failure theories. The cases cover the following areas: (a) behaviour of an isotropic polymeric resin material, without fibres under triaxial loading, (b) triaxial behaviour of a fibre-reinforced polymer UD lamina, made of various fibres and resins, and (c) 3-D and through-thickness strength and deformation behaviour of multi-directional laminates under various triaxial stresses. The loadings considered include: (1) Effect of hydrostatic pressure on the tensile and compressive strength of an isotropic material (polymer), UD lamina and multi-directional laminates. (2) Effects of hydrostatic pressure on shear strength, shear strain and shear stress strain curves. (3) Effects of in-plane loading on the through- thickness shear. (4) Behaviour of composite laminates under through-thickness loadings. The results were published in Refs [2][3].

3 The Third World-Wide Failure Exercise (WWFE-III)

This aims at addressing issues with Area (2) above. This paper is concerned with the process of conducting WWFE-III.

3.1 Description of the WWFE-III Test Cases

A total of 13 Test Cases have been chosen carefully to stretch each theory to the full in order to shed light on their strengths and weaknesses. They are focused on a range of classical, continuous fibre, laminated, reinforced polymer composites subjected, in the presence of stress concentrations, to a variety of in-plane loading conditions, see **Table 1**. The key issues being explored are:

- Basic understanding and differences between damage in an isolated and that in an embedded lamina, under combined transverse and shear loadings.
- Effects of ply thickness and constraints on matrix cracks and fibre failure.
- Effects of lay-up and ply orientation and constraints on damage of isotropic laminate.
- Damage and cracking development under bending and repeated loading.
- Effects of matrix cracking on thermal expansion coefficients.
- Size effects and ply blocking effects on strength of laminates with a central open hole under tension and compression.
- Types of damage and cracking and failure mechanism employed and the way that each is implemented within any given theory.
- The accuracy and bounds of applicability of each theory.
- The maturity and accuracy of the full range of the employed theories.

Table 1 shows that cases were selected covering eight different lay-ups consisting of 0°, [0°/90°/0°], [0°/90$_8$°/0°], [0$_2$°/90$_2$°]$_s$, family of [0°/45°/90°/-45°]$_s$ quasi-isotropic, [±45°]$_s$, [±50°]$_s$, and [30°/90°/-30°/90°]$_s$ laminates. Four different materials, as described in **Table 2**, are used and these are: AS4/3501-6 carbon/epoxy material, E-glass/epoxy material, G4-800/5260 carbon/epoxy materials and IM7/8552 carbon/epoxy material.

Figure 1 shows a schematic of the laminates and the loading conditions for all the 13 Test Cases. Five different types of loadings are covered:

-Uniaxial monotonic tension (Test Cases 3, 4, 6-8, 12-13),
-Biaxial stresses on a lamina and a laminate (Test Cases 1, 2, 10),
-Loading and unloading ((Test Cases 11),
-Bending (Test Case 9), and
-Thermal loading (Test Case 5).

The cases also involved laminates with a central circular hole (Test Cases 12 and 13).

3.2 Methodologies employed in WWFE-III

A list of contributors currently taking part in WWFE-III is shown in **Table 3**. The participants represent some twelve institutions /groups /individuals from seven countries. Their contributions cover a good spectrum of available methodologies that have been employed, mainly, by their originators. Full details of the models can be found in Ref[4]. A brief summary is shown below.

Carrere, Laurin and Maire's model	**M**icromechanical based **H**ybrid **M**esoscopic (MHM) 3-D approach, is uded to predict damage and failure. It introduces viscosity of the matrix in order to obtain non-linearity under shear loading. The failure criterion introduces micromechanical aspects (e.g. local debonding) at the mesoscopic scale. The approach implemented in an implicit finite element code in order to predict the strength of composite structures, exhibiting different levels of complexity (open-hole plates) and subjected to complex loadings (membrane or bending loadings). All the 13 Test Cases solved.
Chamis' model	The model, referred to as GENeral Optimization Analyzer (GENOA), uses Multi-scale (Micro-Macro) Progressive Failure Analysis (PFA). Based on commercial software developed by AlphaStar Corporation (USA). Multiple failure criteria were utilized. The critical damage events/indexes predictions tracked trans-laminar and inter-laminar composite failures namely: matrix

	cracking/crack density, damage initiation/propagation delamination initiation/growth and their interaction with fiber failure. All of the 13 Test Cases solved.
Ladeveze's model	The model provided a detailed description of a new damage mesomodel and examined its application to solve material and structural problems. The model deals with various damage scenarios and mechanisms of degradation, including diffuse intralaminar damage, diffuse interface damage, localised delamination, fibre and plasticity and can predict the evolution of a laminate's response until final failure.
Soutis-Kashtalyan's model	The model describes an analytical approach to predict the effect of intra- (matrix cracking and splitting) and inter-laminar (delamination) damage on the residual stiffness properties of the laminate. It is based on a two-dimensional shear lag stress analysis and the Equivalent Constraint Model (ECM) of the damaged laminate with multiple damaged plies. 2 of the 13 Test Cases solved.
McCartney's model	Based on an energy methodology that requires knowledge of the dependence of thermoelastic constants on damage. Crack density in the 90° plies was modelled using ply refinement technique.
Pettermann's model	The model considers stiffness degradation and plastic strain accumulation for the the prediction of stress strain curves and failure envelopes. Predictions were presented in terms of stress–strain curves and curves presenting the evolution of brittle damage and the formation of plastic strains. All the test cases were solved
Pinho's model	The model is based on plasticity theory (with new yield function and nonlinear kinematic hardening rule). The failure criteria distinguish between matrix failure and fibre failure (kinking, microbuckling, tension). In-situ strengths are used for matrix failure. Propagation of failure takes into consideration the fracture energy associated with each failure mode and, for matrix failure, the accumulation of cracks in the plies. It is implemented in an explicit finite element code. 12 of the 13 Test Cases solved.
Sapozhnikov's model	The model, known as Generalized Daniels' Model (GDM), describes the process of micro-damage accumulation, deformation and failure. The model considers three independent types of ply micro-damage: longitudinal, transverse and shear. Nonlinear analysis, taking into account scissoring effects, is used. For the prediction of notched strength of laminates, the model is used with a nonlocal approach based on the specific size of ply microstructure and Neuber's hyperbola of specific deformation energy. All of the 13 Test Cases solved.
Soutis' model	Cohesive zone models have been successfully applied to predict the damage from notches in engineering materials loaded in tension. They have also been used to determine the growth of fibre microbuckling from a hole in composite laminates under compression. A plastic fibre kinking analysis and a linear reduced (softening) relationship are used for the prediction of the unnotched and open hole compressive strength.
Talreja's model	A synergistic damage mechanics (SDM), based on micromechanics and continuum damage mechanics (CDM), is used to predicts the overall mechanical response of composite laminates with ply cracking in multiple orientations. The material constants needed in the CDM formulation are calculated from stiffness property changes incurred in a reference laminate. For other laminate configurations, the stiffness changes are derived using a

	relative constraint parameter which is calculated from the constraint on the opening displacement of ply cracks within the given cracked laminate evaluated numerically by a finite element analysis of an appropriately constructed representative unit cell. The method was used to generate stress-strain response of the laminates by combining stiffness property changes and evolution of crack density.
Varna's model	In the model, the reduction of thermo-elastic constants of laminates and their nonlinear behavior due to intralaminar cracking and nonlinear shear response of the composite are analyzed using a global-local approach. The initiation and evolution of the intralaminar damage is analyzed using strength based approach for laminates with thick layers and fracture mechanics approach for thin layers. Statistical failure properties, distribution parameters and transition point (thickness) from strength to fracture mechanics applicability, were assumed. 9 out of the 13 Test Cases solved.
Pousatrip-Vaziri's model	The methodology/modeling framework is best suited for non-linear structural analysis of large scale laminated composites whose boundaries do not interfere/interact with the damage zone that develops and grows within the structure. The new CODAM2 addresses the deficiencies in both the numerical and material objectivity of the original version of CODAM. It introduces a non-local regularization scheme to alleviate both the spurious mesh dependency and mesh orientation problems that plague all local strain-softening models. 2 of 13 Test Cases solved, related to specimens containing open hole.

3.3 Comparison between the WWFE-III models

In order to assess the relative differences between the predictions of the various models, 44 different properties were selected from the 13 Test Cases. For each property, the ratio between largest and lowest predictions from the various models was taken. If the ratio is equal to 1, then all the 12 models give an identical prediction. The results from all of the theories for the 44 selected properties are recorded and listed in **Table 4**. These properties vary from one Test Case to another. For instance, in Test Case 1, the properties selected (see row number 1 and 2) were the shear failure stress and shear failure strain of a unidirectional lamina. For Test Case 8, five properties were selected (see row number 25 to 29) and these were (a) final failure strength, (b) axial failure strain, (c) transverse failure strain, (d) failure strain at initiation of damage and (e) maximum crack density in a quasi-isotropic laminate.

The comparison between the data shown in **Table 4** has revealed similarities and more importantly differences between the predictions of the models. This is normal as the various models used different assumptions and made different simplifications to provide solutions for the 13 Test Cases. The data presented in **Table 4** revealed the following:

(i) -The ratio between the highest and the lowest predictions ranged from 1.14 (for the shear strength of a lamina) to approximately 20. The latter ratio was observed in the following situations:

-Crack density in Test Case 8.
-Initial strain in Test Case 3.
-Ultimate transverse failure strain in Test Case 11.

(ii) -One of the models gave consistently higher predictions than the other models where the 'highest' value was noted in 14 of the 44 properties listed in **Table 4**.

(iii) -Two of the models gave consistently lower predictions than the other models in 25% of the 44 cases (i.e. in 11 of the 44 cases).

(iv) -The ratio for 50% of the properties is less than 4.5 whereas that for the other 50% was between 4.5 and 20. This is clear from the graph in Figure 2.

4 Design and manufacture communities' requirements

It is recognised that a model giving consistently higher and lower predictions than others does not normally make it wrong or physically unrealistic. Equally, a model which gives consistently moderate predictions in relation to extreme predictions produced by other models does not necessarily make it correct and more reliable than any other for every prediction outside the scope of the current exercise.

However, certain physical and mathematical limiting features in some of the models are worth exposing so that appropriate actions could be taken regarding how they can be improved in the future. Sources for the differences between the various WWFE-III models could be attributed to one or more of the following factors:

- Limitations of damage parameters of the models
- Calibration of crack density curves/ Crack density saturation
- Final strength prediction (four of the models were incapable of predicting final failure)
- Material nonlinearity(a few models were based on linear material behaviour)
- Thermal residual stresses
- Size effects (a few models took those into account)
- Over-simplifications
- Accurate mode of failure

Ref [4] gives an account of the influence of some of these factors on the predictions of the various models. The results of Part B of WWFE-III, Ref[5], showing a comparison between the theories ad experiments will shed more light on the importance of the above factors.

For the design and manufacture communities, it is important learn the lessons from Part B of the WWFE-III, together with the lessons emanating from Part B of the previous exercises (WWFE and WWFE-II), Refs [1,3].

Ultimately, a designer is seeking to have a tool which can be reliably used to predict the response of a **material** or a **structure** in one of more of the stages shown in Figure 3. Hence, one of the outcomes of the exercises is to provide the community with recommendations on the best methodology for predicting the correct features in Zone A, Zone B, Zone C, Zone D and Zone E where:
Zone A: Elastic behaviour
Zone B: Onset of damage
Zone C: Evolution of Damage
Zone D: onset of final failure
Zone E: Final failure (Note D and E could be the same)

The recommendations will be published as a part of the WWFE activities.

5 Conclusions

- The 12 models employed in the Part A of the WWFE-III varied in their complexity, maturity and their treatment of final failure. No two models gave identical predictions for any of 13 Test Cases.
    - Four models did not provide a clear definition of final failure of a laminate.
- None of the models predicted cracking or damage for an isolated lamina under combined shear and transverse loading (tension or compression).
- Even in those laminates in Test Cases 3, 4, 6-8, whose failure is controlled by tensile failure of the fibres, large differences in predicting the strength and failure strains were observed between the various models.
- In a few cases, the ratio between the highest and lowest predictions reached 20.
- From manufacture and design point of view, the models are broadly immature and there was a lack of consensus regarding:
    - Effects of ply thickness and lay-up sequence
    - Interaction between cracks in differently oriented adjacent layers
    - Effects of unloading and reloading behaviour
    - Size effects (effects of hole diameter to thickness ratio and effects of laminate thickness for a given hole size)
    - Matrix cracking and delamination under pure bending
    - Delamination driven by matrix cracking

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Test Case	Laminate lay-up	Material	Ply thickness. mm	Description of Required Prediction
1	$[0°]_8$	AS4/3501-6	0.125	Shear stress strain curve with the presence of transverse tension stress of 14MPa.
2	$[0°]_8$	AS4/3501-6	0.125	Shear stress strain curve with the presence of transverse compression stress of -34.5MPa.
3	[0°/90°/0°]	Glass/epoxy	0.125	Stress strain curves and crack density variation**.
4	$[0°/90_8°/0°]$	Glass/epoxy	0.125	Stress strain curves and crack density variation**.
5	$[0_2/90_2]_s$	AS4/3501-6	0.125	Variation of thermal expansion coefficient with crack density.
6	$(0°/90°/-45°/+45°)_s$	Glass/epoxy	0.5	Stress strain curves and crack density variation**.
7	$[0°/-45°/+45°/90°]_s$	G4-800/5260	0.14	Stress strain curves and crack density variation**.
8	$[45°/0°/90°/-45°]_s$	G4-800/5260	0.14	Stress strain curves and crack density variation**.
9	$(+30°/90°/-30°/90°)_s$	Glass/epoxy	0.25	Bending stress versus axial and transverse strains and crack density**.
10	$[\pm 45°]_s$	Glass/epoxy	0.25	Biaxial failure stress and strain envelopes, maximum crack density, delamination level and location.
11*	$[\pm 50°]_{3s}$	Glass/epoxy	0.2	Loading and unloading curves under uniaxial loading.
12	$[45°/90°/-45°/0°]_s$	IM7/8552	0.5	Tension strength versus laminate hole diameter**.
13	$[45_m°/90_m°/-45_m°/0_m°]_s$	IM7/8552	0.125***	Tensile and compressive strengths versus laminate thickness**.

* For Test Case No 11, please apply a stress of 120MPa, then unloading followed by re-loading up to final failure.

** Additional information required includes maximum crack density, delamination level and location.

*** In order to study the size effects, the thickness of the 8 ply laminate is increased by increasing the value of m (=1, 2, 3 etc..) where m is the number of plies blocked together and where each ply is 0.125mm thick.

Table 1 *Details of the Test Cases used in WWFE-III.*

Fibre type	IM7	G40-800	AS4	Glass
Matrix	8552	5260	3501-6	LY556
Fibre volume fraction V_f (%)	60	60	60	60
Fibre diameter (μm)	4.5	8	7	11
Longitudinal modulus E_1 (GPa)	165*	173	126*	45.6
Transverse modulus E_2 (GPa)	9	10	11	16.2
Through-thickness modulus E_3 (GPa)	9	10	11	16.2
In-plane shear modulus G_{12} (GPa)	5.6*	6.94*	6.6*	5.83*
Transverse shear modulus G_{13} (GPa)	5.6*	6.94*	6.6*	5.83*
Through-thickness shear modulus G_{23} (GPa)	2.8	3.355	3.618	5.7
Major Poisson's ratio υ_{12}	0.34	0.33	0.28	0.278
Major transverse Poisson's ratio υ_{13}	0.34	0.33	0.28	0.278
Through-thickness Poisson's ratio υ_{23}	0.5	0.49	0.52	0.4
Longitudinal tensile strength X_T (MPa)	2560	2750	1950**	1280
Longitudinal compressive strength X_C (MPa)	1590	1700	1480	800
Transverse tensile strength Y_T (MPa)	73	75	48	40
Transverse compressive strength Y_C (MPa)	185**	210**	200**	145**
Through-thickness tensile strength Z_T (MPa)	63	65	48	40
Through-thickness compressive strength Z_C (MPa)	185**	210**	200**	145**
In-plane shear strength S_{12} (MPa)	90**	90**	79**	73**
Transverse shear strength S_{13} (MPa)	90**	85**	79**	73**
Through-thickness shear strength S_{23} (MPa)	57	57	55	50
Longitudinal tensile failure strain ε_{1T} (%)	1.551	1.59	1.38	2.807
Longitudinal compressive failure strain ε_{1C} (%)	1.1	0.98	1.175	1.754
Transverse tensile failure strain ε_{2T} (%)	0.81	0.75	0.436	0.246
Transverse compressive failure strain ε_{2C} (%)	3.2	3	2.0	1.2
Through-thickness tensile failure strain ε_{3T} (%)	0.7	0.85	0.436	0.246
Through-thickness compressive failure strain ε_{3C} (%)	3.2	3	2.0	1.2
In-plane shear failure strain γ_{12u} (%)	5	5	2.0	4
Transverse shear failure strain γ_{13u} (%)	5	5	2.0	4
Through-thickness shear failure strain γ_{23u} (%)	2.1	1.699	1.52	0.88
Strain energy release rate Mode I G_{IC} J/m^2	200	240	220	165
Strain energy release rate Mode II G_{IIC} J/m^2	800	900	650	1500
Longitudinal thermal coefficient α_1 (10^{-6}/°C)	-1	-0.6	-1	8.6
Transverse thermal coefficient α_2 (10^{-6}/°C)	18	36	26	26.4
Through-thickness thermal coefficient α_3 (10^{-6}/°C)	18	36	26	26.4
Stress free temperature (°C)***	177	195	177	120

* Initial modulus

** Nonlinear behaviour and stress-strain curves and data points are provided

*** Ambient temperature =20°C

Table 2 *Mechanical properties for four unidirectional laminae.*

	Name	Organisation	Approach used	Designation
1	Laurin, Carrere, Huchette and Maire	ONERA (France)	Multi-scale hybrid damage and failure	Carrere
2	Chamis, Abdi, Garg Minnetyan, Baid, Huang and Housner	NASA (USA), Alpha-star Corporation (USA) and Delft University	Micro-mechanics based model	Chamis
3	Kashtalyan and Soutis	Aberdeen University, Manchester University (UK)	Shear lag and Equivalent Constraint Model	Kashtalyan
4	Ladeveze and Daghia	LMT.ENS-CACHAN (France)	Enhanced damage mesomodel	Ladeveze
5	McCartney	NPL (UK)	Energy methodology	McCartney
6	Flatscher, Schuecker and Pettermann	Vienna University (Austria)	Constitutive damage model	Pettermann
7	Pinho, Vyas and Robinson	Imperial College (UK)	Plasticity-based theory	Pinho
8	Sapozhnikov and Cheremnykh**Error! Reference source not found.**	South Ural State University (Russia)	Classical damage model	Sapozhnikov
9	Soutis**Error! Reference source not found.**	Manchester University (UK)	Cohesive zone model	Soutis
10	Talreja and Singh	Texas University (USA)	Synergistic damage mechanics (SDM)	Talreja
11	Varna	Lulea University (Sweden)	Global-local cracking approach	Varna
12	Forghani, Zobeiry, Poursartip and Vaziri	The University of British Columbia (Canada)	Structural damage modelling Framework	Vaziri

Table 3 *A list of the participants and approaches represented in WWFE-III.*

No	Test Case	Selected Property	Ratio(*)	Remarks
1	1	Strength	1.2	
2		Failure strain	3.4	
3	2	Strength	1.14	
4		Failure strain	2.4	
5	3	Strength	1.3	
6		Axial strain	1.5	
7		Transverse failure strain	>8.1	
8		Initial failure strain	18.5	
9	4	Strength	3.9	
10		Axial failure strain	3.7	
11		Transverse failure strain	>8.2	
12		Initial failure strain	2.8	
13		Max crack density	15	
14	5	Crack density	2.7	At α_x=0.0
15	6	Strength	4.3	
16		Axial strain	2.9	
17		Transverse strain	3.2	
18		Initial failure strain	4.6	
19		Max crack density	9.5	
20	7	Strength	1.32	
21		Axial failure strain	1.96	
22		Transverse failure strain	2.96	
23		Initial failure strain	7.75	
24		Max crack density	10.8	
25	8	Strength	1.34	
26		Axial failure strain	2.57	
27		Transverse failure strain	4.6	
28		Initial failure strain	7.7	
29		Max crack density	>17	
30	9	Bending moment	2.72	
31		Axial strain	10.6	
32		Transverse failure strain	13.8	
33		Initial failure strain	3.1	
34		Max crack density	8.6	
35	10	Final failure stress	10.3	At SR= = 1:1
36		Final failure stress	1.8	At SR = -1:-1
37		Initial failure stress	5.2	at SR = 1:0
38		Initial failure stress	4.2	at SR = 1:1
39	11	Axial strain at 120MPa	6.6	
40		Unloading strain	>10	
41		Transverse failure strain	21.9	At final failure
42		Axial failure strain	11.2	At final failure
43	12	Strength at d=3.14 mm	1.9	
44	13	Strength at h=2mm	2.29	

(*) These ratios did not include values corresponding to those with small strains, stresses or crack density.

Table 4 *Summary of theoretical results showing extreme cases of predictions.*

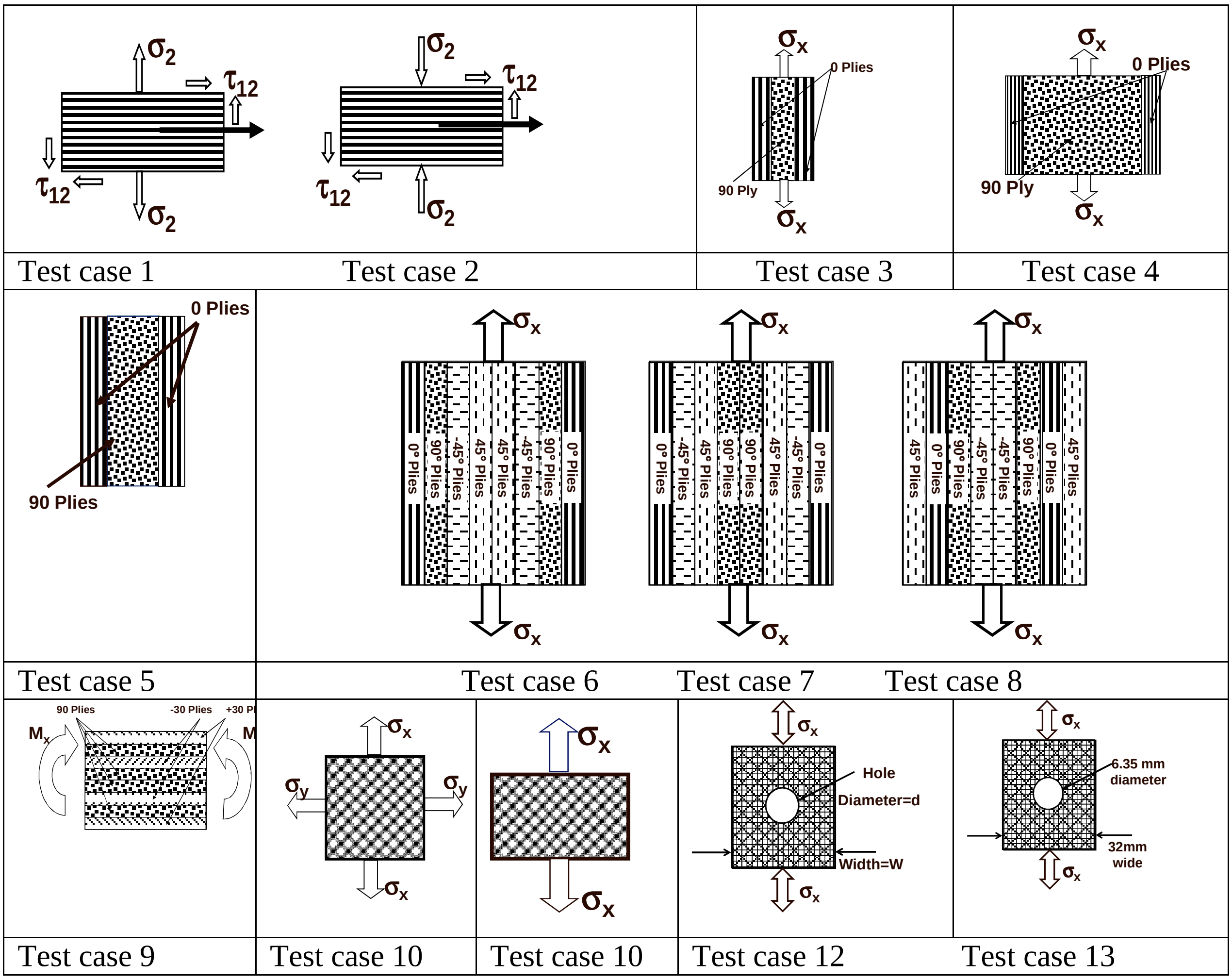

Figure 1 *Schematics of the 13 Test Cases used in WWFE-III: 2 UD laminae (Test cases 1 and 2) and 11 multi-directional laminates (Test cases 3 to 13), see Table 1 for details.*

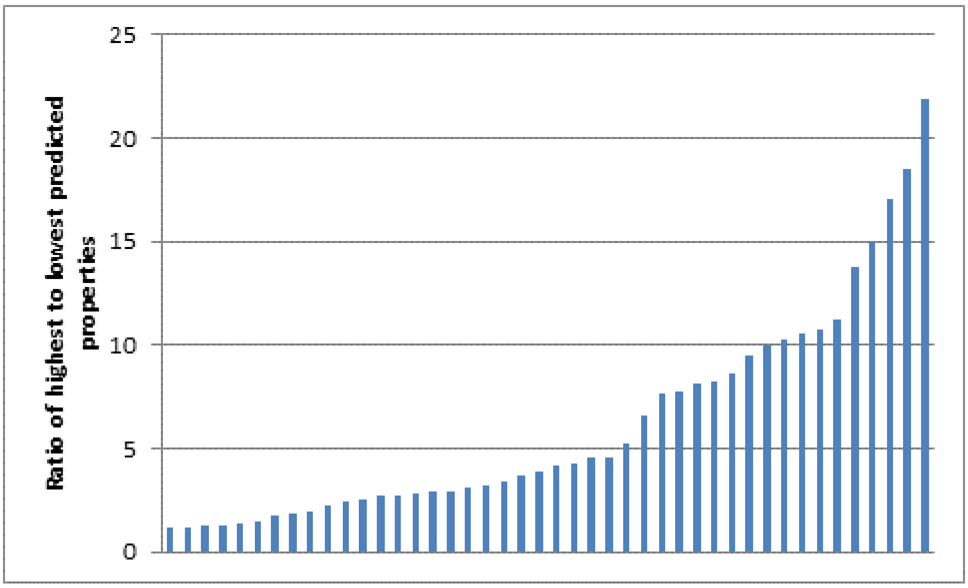

Figure 2 *A graph showing the ratio of highest to lowest predicted value for the 44 properties listed in* ***Table 4****.*

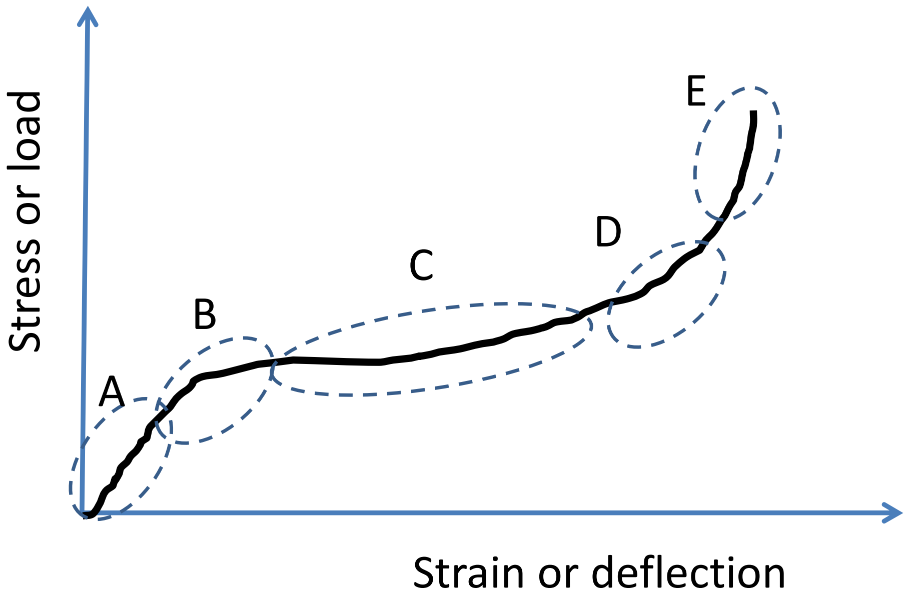

Figure 3 *Idealised stages of failure in a composites material or a composite structure*.