THE SECOND WORLD-WIDE FAILURE EXERCISE: BENCHMARKING OF FAILURE CRITERIA UNDER TRIAXIAL STRESSES FOR FIBRE-REINFORCED POLYMER COMPOSITES

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Abstract

An international activity, called the Second World-Wide Failure Exercise (WWFE-II), is currently underway to assess the current understanding of the failure behaviour of fibre-reinforced polymer composites under triaxial loads. Competing and unique world theories, employed by their originators who have been vetted and invited to participate in the exercise, will be validated and benchmarked against challenging test data. This paper gives a summary of the input data and a description of 12 Test Cases and the associated composite laminates provided to all participants. The input data include the three dimensional (3D) elastic constants, 3D ultimate strains and strengths and some of the nonlinear stress strain curves for five unidirectional laminae and their constituents. Five types of laminates, chosen for the analysis, are described, together with the lay-up, layer thicknesses, stacking sequences and the loading conditions. The detailed instructions issued to the contributors are available upon request.

1 Introduction

For more than a decade, and shortly before the ICCM-10 in Vancouver (Canada), the authors have been making attempts to enhance the faith in the use of fibre-reinforced composites by bridging the gaps between academia, traditionally associated with providing excellent theoreticians and modellers, and industry, traditionally associated with designing and making lightweight composite components. To achieve that, they organised and coordinated an international activity, called the World-Wide Failure Exercise (WWFE), aimed primarily at benchmarking and validating failure theories and design methodologies under uniaxial and biaxial loadings: see Ref[1] for details.

The findings of the first WWFE, completed in 2004, identified a number of gaps in the ability of current failure theories and failure models to accurately predict the deformation and strength of composite laminates. Some of these gaps are concerned with areas for which either no sufficiently challenging test cases existed or no representative failure models were involved. In particular, and of interest to the present paper, there was a lack of robustness and an uncertainty in the maturity of the current models dealing with the following two significant topics:

(a) The behaviour of materials under triaxial stresses. Although the first exercise contained a number of potentially powerful

failure theories capable of predicting failure under triaxial loads, there were no direct test cases to challenge these theories and, hence, their validation remains incomplete.

(b) Continuum damage and fracture mechanics, crack development and initiation of matrix-driven delamination. The first exercise, Ref[1], contained only two theories (Sun and McCartney) that were able to deal with only some aspects (matrix crack density evolution) of this subject.

The present authors, together with two other colleagues, have started organising two new exercises to deal with the above two subjects and these are referred to hereafter as the second world-wide failure exercise (WFFE-II) and the third world-wide failure exercise (WWFE-III). In both exercises, and as before, theoreticians, designers, originators of failure theories and software houses will be selected and invited to participate. They will make a prediction of failure, using their own methodology, for a set of challenging Test Cases using the same input data. Their predictions will be compared with reliable experimental results.

The present paper is concerned with progress made so far regarding WWFE-II, in the area of the triaxial behaviour of composites. A companion paper will deal with the WWFE-III, Ref[2].

A thorough understanding of the triaxial failure behaviour of composites is undoubtedly important in many scenarios and applications, including:

- thick and thin composites,
- lightweight fighting vehicles,
- rotor blades in wind turbines, helicopters and others,
- deep underwater structures,
- bolted joints,
- indentations of shells and panels,
- impact and dynamic loadings,
- ballistic penetration,
- high pressure applications
- composite manufacturing, and thermal stress build-up.

On a wider level, triaxial failure theories are important tools for providing fundamental understanding of anisotropic metal forming, rock science and powder compaction technology, for example.

For anisotropic materials (e.g. composites), nine different strengths are normally required to characterise overall behaviour. Six strength data are related to in-plane loading and three to through-thickness loading. Generating reliable testing methods and analysis for generating 3-D stresses, including those in the through-thickness direction, are not generally well established. Difficulties are normally encountered in obtaining all the required information from the tests. Consequently, accurate data representing the behaviour of composites under 3-D states of stress are relatively scarce. As a direct consequence of the above deficiencies, reliable predictive methods, if any exist at all, have not been subjected to thorough benchmarking and remain largely invalidated

The paper describes a set of challenging test cases proposed to validate and benchmark triaxial failure theories. The cases are aimed at tackling the following issues/problems:

- How would a polymeric resin material behave under triaxial compression.
- Behaviour of a fibre-reinforced polymer UD lamina, made of the same resin as above.
- Behaviour of a multi-directional laminate of the same resin as above.

The loadings considered include:

- Effect of hydrostatic pressure on the tensile and compressive strength of an isotropic material (polymer).
- Effect of hydrostatic pressure on the longitudinal (along the fibres) tensile and compressive failure of a

unidirectional lamina and multi-directional laminates.
- Effects of in-plane loading on the through- thickness shear behaviour.
- Behaviour of composite laminates under through-thickness loadings.

2. Selection of Participants

Efforts were made to obtain a true representation of the widely used 3D failure theories. Consequently, their originators, and occasionally their colleagues, were invited to take part. A list of those who agreed to take part and their respective institutions are shown in Table 1. A significant number of the theories, Refs[3-17], that were benchmarked under 2D state of stress in the first exercise will be employed in the current exercise. These theories remain widely used in academia, software houses and industry.

3. Material selection

Many different types of composite materials are available and these include woven, non-woven, braided, stitched, z-pinned and many other composites. To make the exercise manageable, consideration was limited to continuous fibre- reinforced polymer composites. Taking into consideration the availability of suitably extensive experimental data for laminates, two important and widely used classes of fibres (carbon and glass) and one group of resin systems (epoxy resins) were selected for the exercise.

A unidirectional (UD) lamina made of continuous fibres in a softer matrix was considered to be the basic building block for the multidirectional laminates. The properties of the laminate depend very much on the properties of the laminae. The behaviour of each lamina is, in turn, governed by its constituents, i.e. the properties of the fibres, the surrounding matrix, the interface and the relative amount of fibres and matrix in the lamina.

For performing theoretical analysis of the mechanical behaviour of multidirectional laminates under various loadings, most theories require the properties of each of the individual layers in the laminates. The properties required include: elastic constants and thermal properties, strengths, failure strains and, in some cases, the full stress-strain curves. Some methods of analysis require information on the properties of the constituent fibres and matrix.

The three dimensional elastic constants for an orthotropic UD lamina consist of the following independent in-plane and through-thickness properties: Longitudinal (along the fibre) modulus $\mathbf{E_1}$, Transverse (perpendicular to the fibre) modulus $\mathbf{E_2}$, Through-thickness (perpendicular to the fibre) modulus $\mathbf{E_3}$, In-plane shear modulus $\mathbf{G_{12}}$, Transverse shear modulus $\mathbf{G_{13}}$, Through-thickness shear modulus $\mathbf{G_{23}}$, Major in-plane Poisson's ratio $\boldsymbol{\upsilon_{12}}$, Transverse Poisson's ratio $\boldsymbol{\upsilon_{13}}$ and Through-thickness Poisson's ratio $\boldsymbol{\upsilon_{23}}$. The subscripts 1, 2 and 3 refer to the three mutually perpendicular principal material directions. Fig 1 shows schematic diagrams of a UD lamina with the co-ordinate system used. The rest of the Poisson's ratios can be obtained by applying the reciprocal Maxwell relations, which give $\boldsymbol{\upsilon_{ij}/E_i = \upsilon_{ji}/E_j}$. Four of these constants ($\mathbf{E_1}$, $\mathbf{E_2}$, $\boldsymbol{\upsilon_{12}}$ and $\mathbf{G_{12}}$) pertain to the in-plane behaviour of thin laminae and the rest are related to the through-thickness (direction 3) behaviour. It is usually assumed that a unidirectional fibre-reinforced lamina can be treated as transversely isotropic. For a transversely isotropic lamina, the independent elastic constants may be reduced to five because $\mathbf{E_2{=}E_3}$, $\mathbf{G_{12}{=}G_{13}}$, $\boldsymbol{\upsilon_{12}=\upsilon_{13}}$ and $\mathbf{G_{23}=E_2/2(1+\boldsymbol{\upsilon_{23}})}$.

Orthotropic composites generally possess nine strengths and nine failure strain values. These are longitudinal tensile and compressive properties $\mathbf{X_{1T}}$, $\boldsymbol{\varepsilon_{1T}}$, $\mathbf{X_{1C}}$ and $\boldsymbol{\varepsilon_{1C}}$, transverse tensile and compressive properties $\mathbf{X_{2T}}$, $\boldsymbol{\varepsilon_{2T}}$, $\mathbf{X_{2C}}$ and $\boldsymbol{\varepsilon_{2C}}$, through-thickness tensile and compressive properties $\mathbf{X_{3T}}$, $\boldsymbol{\varepsilon_{3T}}$, $\mathbf{X_{3C}}$ and $\boldsymbol{\varepsilon_{3C}}$ and in-plane and through-thickness shear properties $\mathbf{S_{12}}$, $\boldsymbol{\gamma_{12u}}$, $\mathbf{S_{13}}$, $\boldsymbol{\gamma_{13u}}$, $\mathbf{S_{23}}$ and $\boldsymbol{\gamma_{23u}}$.

4. Materials properties and lay-ups

Five types of fibres were selected in the analysis; two types of glass fibres and three types of carbon fibres. They were chosen for consistency with data for particular laminates. The fibres used are:

- E-Glass fibres,
- S2-Glass fibres,
- T300 carbon fibres,
- AS carbon fibres and
- IM7 carbon fibres.

Five types of epoxy matrices were used in the analysis. These are:
(1)- MY750,
(2)- Epoxy1,
(3)- Epoxy2,
(4)- PR-319, and
(5)- 8551-7.

Using the above matrices and fibres, five types of laminae were used and these are:
(1)- E-Glass/MY750,
(2)- S2-Glass/epoxy,
(3)- AS carbon/epoxy,
(4)- IM7/8551-7 carbon/epoxy, and
(5)- T300/PR319 carbon/epoxy.

Five different lay-ups were chosen in the exercise and these are:
(1)- Pure resin matrix,
(2)- 0° unidirectional lamina,
(3)- Quasi-isotropic (0°/±45°/90°)s laminate,
(4)- Angle ply (±35°)s laminate and
(5)- Cross-ply (0°/90°)s laminate.

Details of the material properties and stress strain curves were supplied to the participants and are available upon request.

5. Test Cases

A number of considerations have been given to the choice of the Test Cases. These considerations include:

1. The cases should tackle fundamental issues covering both isotropic material (matrix) and anisotropic materials (composites).
2. The cases should cover the behaviour of a lamina and that of a laminate
3. The cases should illustrate extreme loading conditions
4. The cases should include peculiar behaviour of composites
5. The cases should include a loading (stress) component in the through-thickness direction.
6. The existence of experimental results that may be used to compared the theories with.
7. Various types of fibres and matrices and various lay-ups
8. Lay-ups of practical and industrial use
9. Loadings encountered in real applications
10. Behaviour of linear and nonlinear nature
11. Ability to differentiate between competing theories.
12. Prediction of complete failure strength envelopes
13. Prediction of strengths and deformations.

Twelve test cases were selected to challenge the theories. Table (2) summarises laminate type, material type and the graphical results requested for each of these Test Cases. Instructions were sent to the participants to specify how loads were to be applied and how results were to be presented in their papers.

Schematic diagrams showing the loading directions, layer and laminate dimensions and stacking sequence of the laminates are shown in Fig 1. Note that the angles of the fibres in each layer are measured from the x direction as shown in Fig 2. A total of 12 Test Cases were selected. The majority of these cases were related to providing full failure envelopes and only three were related to providing stress strain curves.

Test Case (1) is aimed at assessing how the composite failure theories predict the compressive strength of an isotropic polymer material in the presence of hydrostatic pressure compression. This represents the simplest form of triaxial failure of isotropic materials.

Test Cases (2) to (4) are dealing with the shear behaviour of a unidirectional lamina in the presence of a hydrostatic compressive stress.

Test Cases (5) to (7) are concerned with assessing the enhancement (or reduction) in the transverse or longitudinal strengths of a unidirectional lamina with the presence of stresses in the perpendicular direction.

Test Cases (8) to (12) look into the behaviour of multi-directional laminates under stresses containing one in the through-thickness direction.

6. Conclusions

The present paper has provided an up-to-date report on the progress made in co-ordinating the second World-Wide Failure Exercise (WWFE-II). Details of 12 challenging Test Cases, together with their corresponding materials and lay-ups have been described. A list of the names of the participating groups, together with the methods, has been presented. At the time of writing this paper, the participants are engaged in making the blind predictions for Part A of the exercise; expected to be completed by December 2007.

7. References

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Table 1: A list of contributors currently taking part in WWFE-II.

	Group/name	Country	Organisation	Method/ failure criteria
1	Banks	UK	Strathclyde Uni	Simplified failure criterion
2*	Bogetti, Ref[14]	USA	U.S. Army Research Laboratory	Maximum strain failure criterion
3	Carrere / Maire, Ref[24]	France	ONERA	Chaboche’s anisotropic damage
4*	Cuntze, Ref[15]	Germany	Germany	Failure Mode Concept (FMC)
5	Pinho/Robinson/ Camanho/Davila, Ref[20]	UK/UK/ Portugal/ USA	Imperial College/Imperial College/ University of Porto/ NASA	Improved failure criterion
6*	Hansen, Ref[16]	USA	Wyoming University	Multi-continuum micro-mechanics theory
7*	Hart-Smith, Ref[6]	USA	Boeing	Maximum shear failure criterion
8*	Huang, Ref[17]	China	Tongi University	Generalised max stress
9	Iannucci, Ref [21]	UK	Imperial College	Damage based failure criterion
10	Klintworth	UK	Simulayt software	Software integrated failure criteria
11	Kostopoulos, Ref [23]	Greece	Patra University	Theocaris’s interactive failure criterion
12*	Kroeplin/ Puck, Ref [18]	Germany	Institut für Statik und Dynamik (ISD) der Luft- und Raumfahrtkonstruktionen, Stuttgart university	Puck’s phenomenonlogical failure criteria
13*	Rotem, Ref[9]	Israel	Technion University	Interactive matrix and fibre failure theory
14*	Schuermann, Ref[8]	Germany	Darmstade University	Modified Puck’s phenomenonlogical failure criteria
15	Tessmer / Rohwer, Ref[22]	Germany	DLR	Improved 3D failure criterion
16*	Tsai and Ha, Ref[10]	USA	Stanford University	Tsai’s interactive failure theory
17	Wierzbicki, Ref[25]	USA	Massachusetts Institute of Technology (MIT)	Triaxiality-dependent failure criterion
18*	Wolfe-Butalia, Ref[12]	USA	Ohio State University	Maximum strain energy failure theory
19	Ye, Ref[19]	UK	Leeds University	3D elastic stress analysis

* Theories benchmarked against two dimensional stress state in the first exercise, Ref[1].

Table 2 Details of the Test Cases proposed in the WWFE-II.

Test Case	Laminate lay-up	Material	Description of Required Predictions
1	Resin	MY750 epoxy	σ_x versus σ_z (with $\sigma_y = \sigma_z$) envelope
2	0°	T300/PR319	τ_{12} versus σ_2 (with $\sigma_1 = \sigma_2 = \sigma_3$) envelope
3	0°	T300/PR319	γ_{12} versus σ_2 (with $\sigma_1 = \sigma_2 = \sigma_3$) envelope
4(a)	0°	T300/PR319	Shear stress strain curves (τ_{12}-γ_{12}) (for $\sigma_1 = \sigma_2 = \sigma_3$ =-600MPa)
5	90°	E-glass/MY750 epoxy	σ_2 versus σ_3 (with $\sigma_1 = \sigma_3$) envelope
6	0°	S-glass/epoxy	σ_1 versus σ_3 (with $\sigma_2 = \sigma_3$) envelope
7	0°	A-S carbon/epoxy	σ_1 versus σ_3 (with $\sigma_2 = \sigma_3$) envelope
8	±35°	E-glass/MY750 epoxy	σ_y versus σ_z (with $\sigma_x = \sigma_z$) envelope
9(b)	±35°	E-glass/MY750 epoxy	Stress-strain curves (σ_y -ε_x and σ_y -ε_y) at $\sigma_z = \sigma_x$ =-100MPa
10	(0°/90°/±45°)s	IM7/8551-7	τ_{yz} versus σ_z (with $\sigma_y = \sigma_x = 0$) envelope
11	(0°/90°)s	IM7/8551-7	τ_{yz} versus σ_z (with $\sigma_y = \sigma_x = 0$) envelope
12	(0°/90°)s	IM7/8551-7	Stress-strain curves (σ_z -ε_z, σ_z -ε_x and σ_z -ε_y) for $\sigma_y = \sigma_x = 0$

(a)- Please first apply $\sigma_1 = \sigma_2 = \sigma_3$ =-600MPa to the lamina. Then apply the shear loading, until final failure takes place.
(b)- Please first apply $\sigma_y = \sigma_z = \sigma_x$ =-100MPa and record the resulting strain values. Then increase the stress σ_y (beyond -100MPa) gradually until final failure takes place. Please plot the full stress-strain curves (σ_y -ε_x and σ_y -ε_y).

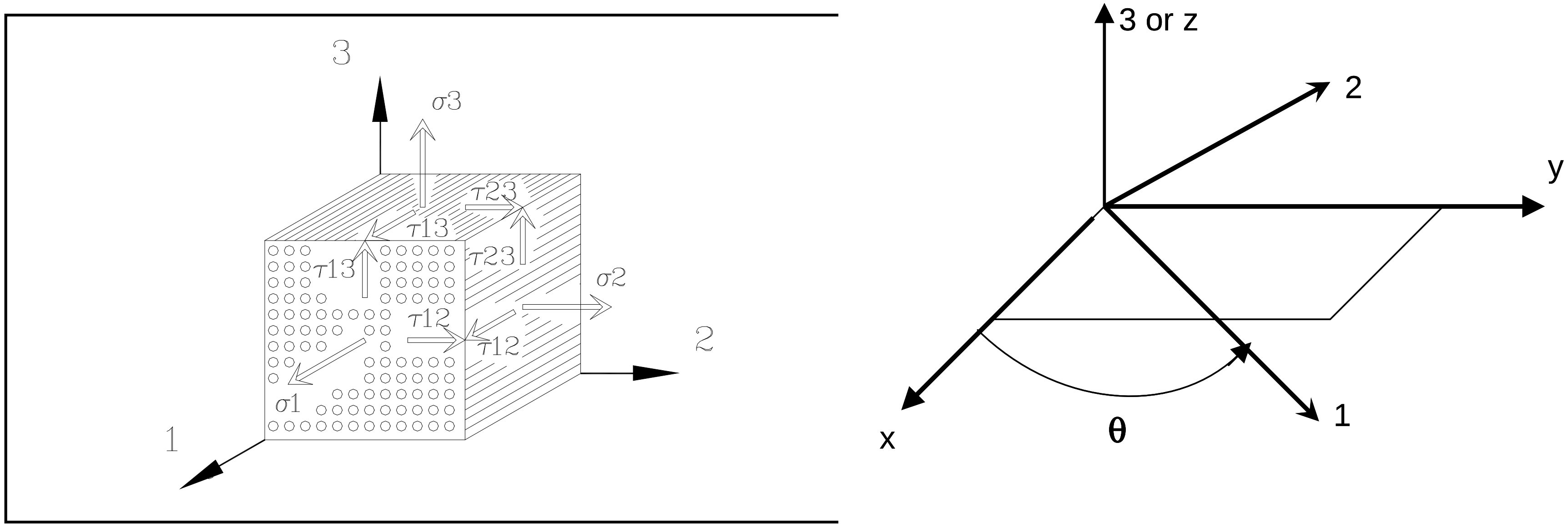

Figure 1 A schematic of a composite lamina under a general state of 3-D stresses (left) and fibre orientation convention (right).

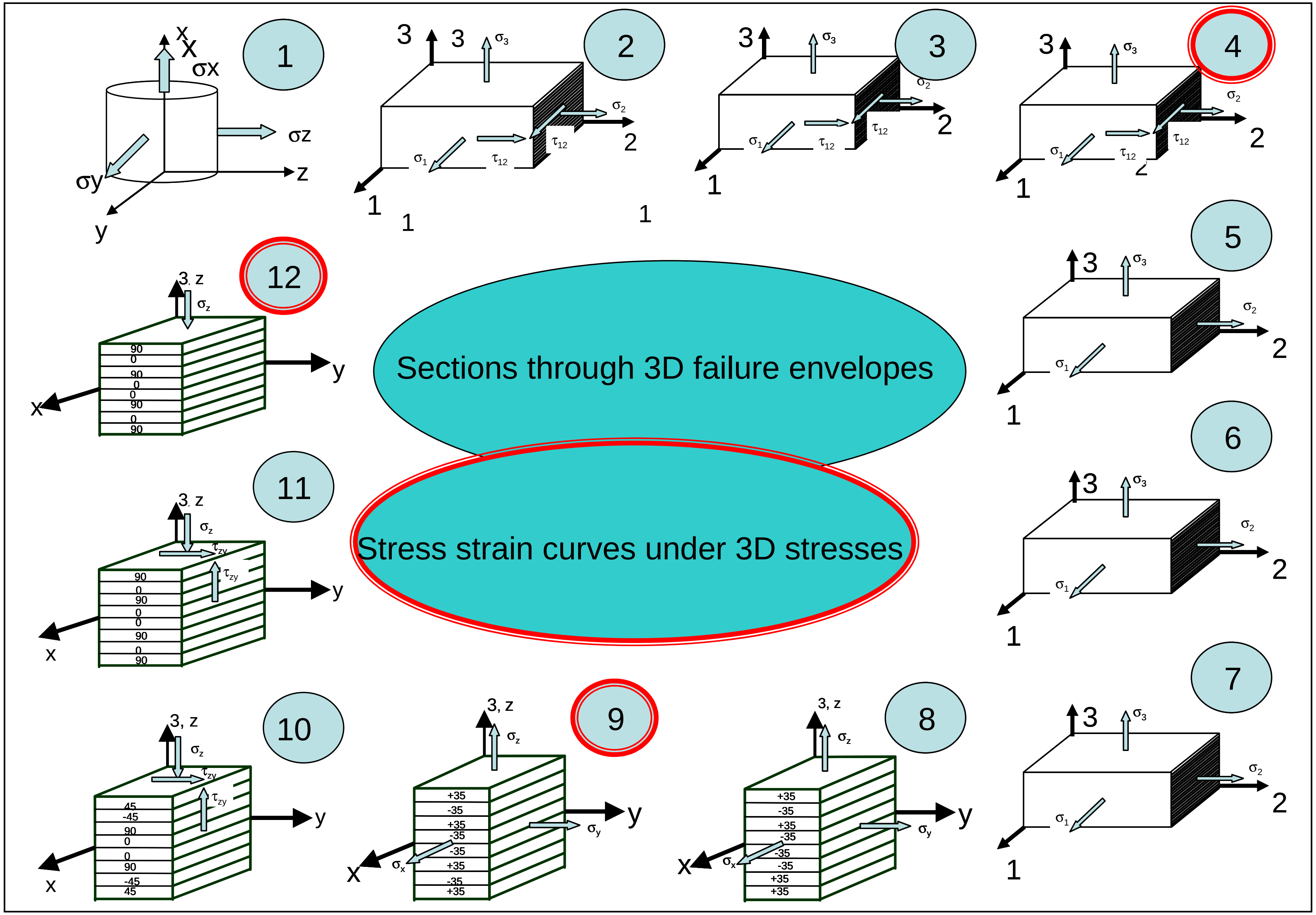

Figure 2: Schematics showing the lay-ups and loading patterns for the twelve Test Cases used in WWFE-II.