DAMAGE THEORIES FOR FIBRE-REINFORCED POLYMER COMPOSITES: THE THIRD WORLD-WIDE FAILURE EXERCISE (WWFE-III)

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Abstract

This paper is concerned with the launch of a new international activity, called the Third World-Wide Failure Exercise (WWFE-III). The aim of this exercise is to validate and benchmark current failure models capable of handling cracks and damage development in multi-directional fibre-reinforced polymer composite laminates. The paper gives details of the rationale behind coordinating this activity and the technical challenges facing the composite community in this specific area. A set of problems that should be used to test current models is proposed.

1 Introduction

Having established the maturity of a wide range of conventional failure criteria for fibre-reinforced polymer composites, it is, as a natural progression, crucial to tackle the maturity of advanced failure criteria; i.e. those related to the modelling of sub-critical damage. Such approaches include continuum damage mechanics and fracture mechanics models. It is widely accepted that, in designing composites, one is faced with the problems of damage initiation, damage propagation and ultimate fracture; all being facets related to describing the state of stress, strain, stiffness, deformation and modes of failure in fibre-reinforced laminated composite materials and structures. One of the commonest forms of damage is the accumulation of multiple matrix micro-cracks and these cracks may play a role in the subsequent development of other modes of damage, such as delamination along ply interfaces. Fibre breakage or occasionally fibre buckling, on the other hand, is a mode of failure normally associated with the ultimate strength of a composite. A damage state can develop either from a uniform loading on a virtually virgin laminate or can be created as a result of local and concentrated loadings, e.g. an impact damage site or a stress concentration.

By way of examples, it was noted in ref.[1] that the use of composite material tanks offers a cost- effective way for making re-usable launch vehicles for space transportation systems. The use of a carbon/epoxy sandwich panel construction to make tanks for liquefied hydrogen led to a catastrophic failure as a result of matrix cracking in the inner skin of the sandwich panel. It was reported that hydrogen permeated the inner skin of the composite tank through the matrix cracks and accumulated inside the honeycomb core. A subsequent pressure increase in the core, combined with a rise in temperature, caused the separation of the skin laminates from the core materials. The matrix cracks in the tank were induced due to the large thermal strains associated with the cryogenic environment.

Similar problems were also apparent back in the 1980s and 1990s, when extensive work was carried out by the authors at QinetiQ (then DERA) and Manchester University (then UMIST) in order to characterise the static and dynamic mechanical properties of composite materials using a thin tubular specimen as the test piece. One of the problems identified by the work was that leakage of the internally pressurised specimen tended to take place at relatively low pressures (and low associated circumferential stresses). The occurrence of leakage prevented further loading of the specimens and hence the failure stresses were well below those expected *on the basis of the fibre strength*, ref. [2]. The problem was more apparent under conditions of quasi-static pressurization than under dynamic loading (internal explosive pressurisation). In the latter situation the problem was muted and almost non-existent, as the strain rate modified the rate of crack propagation through the thickness of laminates.

It is widely recognised that leakage of pressurised tubes and tanks is caused by an accumulation of intra- and inter-laminar matrix cracks making a path for the liquid to penetrate from the inner surface to the outer surface. The occurrence of matrix crack leads to modified local and global stress and strain distributions. Arguably, local stress concentration close to the tip of a matrix crack may cause the initiation of local delamination or possibly fibre failure. It should be noted that leakage in composites is not confined to tubes and tanks but can take place also in planar specimens.

More generally, damage levels and damage modes are very important in the final optimisation of light weight composite components subjected to multi-axial loads. The presence of matrix cracking and delamination is known to alter the dynamic characteristics of a structure and also to reduce the strength, particularly under compressive loading. Hence it is noted that for a proper evaluation of a composite structure, as well as understanding short term behaviour, it is necessary to understand the way that different modes of damage develop under cyclic loading. In many situations, the fatigue crack growth in composite laminates tends to take place in three stages (a) initiation (b) steady-state crack growth and (c) crack interaction and saturation. All the plies, whether they are off-axis plies or longitudinal plies, will probably be subjected to matrix cracks, delamination and eventual ultimate failure.

The need for a comprehensive understanding of these issues is driven not only by the steady increase in the use of composites in current and future aerospace and other industries, but also by the lack of robust design criteria for predicting accurately the level of their occurrence and subsequent significance. The existence of a myriad of failure theories with no clear consensus as to which theory is good can potentially lead to confusion and a misrepresentation of the current state-of-the-art in the field. One direct consequence of the lack of consensus is that it hampers and retards the development of robust computational tools, analytical or numerical, and this tends to lead to over-conservative and cost-ineffective design. Hence, there is a gap to be bridged between theoreticians and design practitioners on the maturity of the current damage models for prediction of failure, especially when embedded within analytical and numerical tools, such as commercial FE codes.

For more than a decade, two of the authors (Hinton and Kaddour), together with founders and leading members of the composites community, have been making a major effort to establish the current level of maturity of theories for predicting the failure response of fibre- reinforced plastic (FRP) laminates and to close the knowledge gap between theoreticians and design practitioners in the area of conventional failure criteria. As a consequence of that, and in parallel to these two aims, the composites community has been stimulated into providing design engineers with more robust and accurate failure prediction methods, and the confidence to use them.

The results of this extensive study, termed the first World-Wide Failure Exercise (WWFE-I), are reported in ref. [3]. The investigation encompassed nineteen conventional failure methodologies as applied to continuous fibre-reinforced polymer composites subjected to uniaxial or biaxial states of stress. The associated publication provides details of all the theories and a comparison between the theories and test data, together with a section on recommendations for designers. There were many important outcomes but, in particular, the study highlighted significant shortfalls in predicting the strength and deformation response of polymer composite structures under biaxial states of stress.

The shortfalls from WWFE-I were discussed in a paper presented at ICCM-15 [4]. Since then, the present authors have started organising two new exercises to bridge some of the gaps identified during WWFE-I. The new exercises are (a) the Second World Wide Failure Exercise (WWFE-II), which will consider triaxial failure and associated theories, and (b) the Third World Wide Failure Exercise (WWFE-III), which will deal with damage and associated modelling techniques.

This paper is concerned with WWFE-III, for which the motivation is to validate and benchmark failure theories capable of predicting damage (including matrix crack initiation and development; delamination initiation triggered by transverse cracks) and deformation up to final fracture. The WWFE-III will involve a large number of challenging Test Cases, to cover a wide range of fundamental problems and an appropriate industrial application.

The Test Cases will contain damage processes involving some of the following areas: a single mode of damage; multiple modes of damage; transverse tension-dominated, shear-dominated and mixed mode matrix cracking; ply staggering and thickness effects; effects of ply location and ply constraints; effects of initial damage on the loading and subsequent unloading characteristics; effects of material nonlinearity; effects of geometrical nonlinearity, effects of resin characteristics; effects of fibre characteristics and different architectures and manufacturing processes.

Reliable test data are a very important part of any such exercise. Ideally the following information will be available:

- a full description of the type and properties of fibres and matrix used together with the required property data at the (isolated) lamina level
- details of the manufacturing processes for the test samples, including cure data

Table 1 A summary of some of the major issues addressed in the first exercise, Ref[4].

Designation	Approach represented	Initial failure	Nonlinear	Post failure	Crack density	Delamination	Ply constraint	Fibre splitting	Loading path	Probabilistic	Deterministic
-Chamis(1) -Chamis(2)	-ICAN (micro-mechanics based) -CODSTRAN	•		•							•
Hart-Smith(1)	Generalised Tresca theory										•
Hart-Smith(2)	Maximum Strain Theory										•
Eckold	British Standard pressure vessel design codes										•
Edge	British Aerospace, In-house design method	•	•	•		•					•
McCartney	Physically based 'Damage Mechanics'	•			•		•			•	•
Puck	Physically based 3-D phenomenological models	•	•	•							•
Wolfe	Maximum strain energy method	•	•	•							•
Sun(L)	Linear analysis	•		•							•
Sun(NL)	Nonlinear analysis (nonlinear is FE based)	•	•	•	•						•
Zinoviev	Development of Maximum stress theory	•		•					•		•
Tsai	Interactive progressive quadratic failure criterion	•		•	•						•
Rotem	Interactive matrix and fibre failure theory	•	•	•							•
Hart-Smith(3)	Ten-Per-Cent rule										•
Cuntze	Failure mode concept (FMC)	•	•	•						•	•
Bogetti	3-D Maximum strain	•	•	•							•
Mayes	Multi-continuum micro-mechanics theory	•	•	•							•
Huang	Anisotropic plasticity and generalised max stress	•	•	•							•

- assessment of initial defects and imperfections
- assessment of the statistical nature of measured properties and failure occurrence

It would be anticipated that a full description of testing techniques and the way that the test data were measured should be supplied; ideally there should be macro and micro photographic information, showing modes of failure during and after testing.

2 Gaps in the previous exercise

Table 1 shows a list of the failure theories that were involved in the first exercise. Column (1) shows the designation of the theories and column (2) shows the method employed in each of these theories.

The rest of the columns provide an indication as to whether the theories were capable of addressing particular (important) issues. These issues are itemised below:

- Initial failure prediction
- Nonlinear material modelling
- Post-failure mechanisms
- Crack density computation
- Delamination prediction
- Ply constraints effects
- Fibre splitting
- Loading path
- Probabilistic failure modelling
- Deterministic failure.

This information is displayed quantitatively in Figure 1 in the form of a plot of the proportion of the (nineteen) failure theories which explicitly treat each of these phenomena - the vertical axis shows the percentage number of the theories which treat the phenomenon on the horizontal axis.

The table clearly indicates that a reasonable proportion (greater than around 50 %) of the theories appear to have the capability to handle the following

- Deterministic nature of failure,
- Initial failure prediction,
- Post failure modelling, and
- Nonlinear analysis.

Fewer appear to be able to deal with the remaining aspects:

- Crack density computation,
- Delamination prediction,
- Ply constraints effects,
- Fibre splitting,
- Loading path, and
- Probabilistic failure modelling

Clearly, the limitations in these areas present a potential difficulty and hence there is a need to solve these problems in an orderly manner. The test cases proposed in this exercise are aimed at focusing on these issues.

3 Potential theories

There are a number of theories in the literature, e.g. refs. [5-14], that have distinct features and that will be considered in the exercise as they appear to handle explicitly some of the issues highlighted in the previous section. The organizers are currently inviting the originators of these and other models, together with representatives from the industry and software houses, to take part in the new project. Potential participants bring a range of approaches and methods, mainly based on fracture mechanics and continuum damage mechanics – in some cases incorporating a probabilistic element. Approaches of interest include:

Fracture mechanics methods

- Nairn, e.g. ref. [10], analysed matrix cracking phenomena using a variational stress analysis coupled with a fracture mechanics formulation for crack formation and multiplication.

- McCartney developed a methodology for matrix crack prediction based on a stress transfer model with probabilistic fracture mechanics to handle crack initiation and multiplication

- Soutis *et al*., e.g. ref[5], used a relatively simple modified shear-lag model to treat the stress transfer coupled with a fracture mechanics based failure criterion and extended this approach to predict delamination initiating from existing transverse cracks.

- Hashin [7] proposed an analytical model for the analysis of cracked laminates based on variational principles. A probabilistic element was incorporated into the model to simulate the crack multiplication process.

Damage Mechanics methods

- Talreja [7] developed a continuum damage approach, applied to single and multiple modes of damage,
- Ladeveze, Ref[5], formulated a continuum damage model, incorporating damage evolution laws

Incorporation into FE for structural analysis

- Wisnom, e.g Ref[15], incorporated physically based models into a detailed finite element analysis to assess damage in composites, including damage growth from a notch.

The ability of these theories to predict crack density formulation has not been fully validated; in particular against common experimental data sets. An example of the trend that is expected from some of these theories in a relatively simple problem (crack accumulation in a cross-ply laminate) is shown in Figure 2. While the initial rate of matrix crack development is captured fairly well, the particular theories shown tend to diverge significantly as the crack density increases further. One implication of this divergence is that the prediction of initiation of delamination between plies will vary considerably.

4 Initial set of Test Cases

Schematics of the proposed set of test cases are shown in Figures 3 to 8. They are broadly classified as follows:

4.1 Category (I):

This test case considers cracking and damage in unidirectional laminae (0° and 90° degree) under combined loadings, the 90^{o} under shear and transverse tension (or transverse compression) loading and the 0^{o} under shear and longitudinal compression, see Figure 3. The aim is to explore the effect of applying a shear stress on the failure of a lamina under either transverse tension, transverse compression or longitudinal compression. The first exercise attempted to solve this problem from a strength point of view. The 19 conventional failure theories employed in Ref[1], gave a wide range of predictions for this test case.

4.2 Category (II)

This case is designed to study the effect of increasing the thickness of the central 90° plies on the cracking and damage of $(0/90_n/0)$ laminates under tension; see Figure 4. Failure is normally associated with Mode I (crack opening).

4.3 Category (III)

In this category, Cases are proposed to study the differing constraints on transverse layer cracking as a result of the plies being located in the interior or on the surface of the laminate; see Figure 5.

4.4 Category (IV)

The presence of matrix cracks is known to change the residual thermo-elastic properties of a laminate and this test case will consider the thermal expansion coefficient of a cracked laminate; see Figure 6, in which the matrix cracks could have developed under thermal or mechanical loading.

4.5 Category (V)

This category is related to Test Cases dealing with cracks and damage development in quasi-isotropic laminates; see Figure 7. Quasi-isotropic laminates are widely used in aircraft structures. The theories employed in the first exercise have given a wide range or prediction for the initial damage (failure). Hence, it is important to pose the same problem for newer theories. Although many aspects of the mechanical behaviour (including longitudinal stiffness and ultimate strength) are dominated by the fibre properties, the damage evolution in these laminates is affected by the location of the 90° and the off-axis (45° and -45°) plies. Hence, specific cases have been selected to explore this aspect of crack development.

4.6 Category (VI)

Cases dealing with crack and damage in laminates under dominant shear loading; see Fihure. 8. Unlike those cases in Categories (I) to (III) above, this Test Case enables the damage and crack growth resulting from a dominant Mode II (crack shearing under interlaminar shear) to be considered.

4.7 Category (VII)

A Test Case is proposed to assess how the models predict the unloading behaviour of laminates; see Figure 8. A repeated loading and unloading is common in fatigue characterisation of composites. The challenging issue here is to begin to understand the loading path dependency of the behaviour of composites under multi-axial loading.

5 Stages of the exercise

As before, the intention is that the exercise will be carried out mainly in two distinct parts: Part A and Part B. Figure 9 shows a chart of the various stages of the exercise. The first stage, referred to as 'Establish Frame' is a preparatory stages to establish the challenging problems and select the contributors.

6 Conclusions

The current paper has provided details of the background to a proposed new international activity, known as the Third World-Wide Failure Exercise (WWFE-III), which is aimed at benchmarking damage and fracture mechanics approaches for fibre-reinforced polymer composites. The paper has identified a set of challenging test problems and also some of the potential theories, that have been used previously for tackling cracks and damage development in uniaxial and multi-directional laminates. The complete work is planned to take place over two years or so.

7 References

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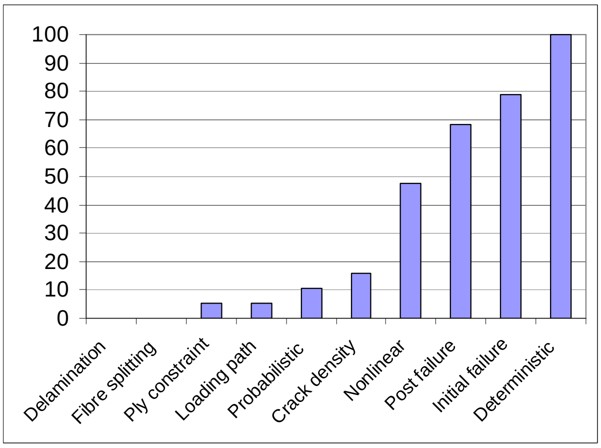

Fig 1 showing the percentage number of theories, employed in the first exercise (WWFE-I), as a function of the problems solved by all these theories. Note 100% corresponds to a total of 19 theories

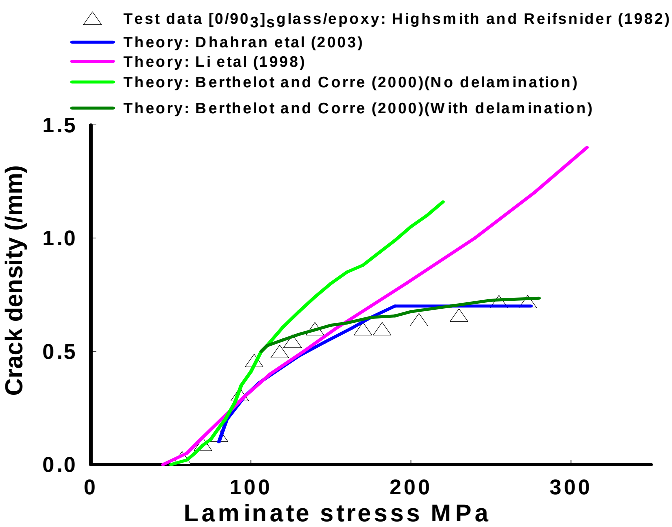

Fig 2 Competing theoretical predictions

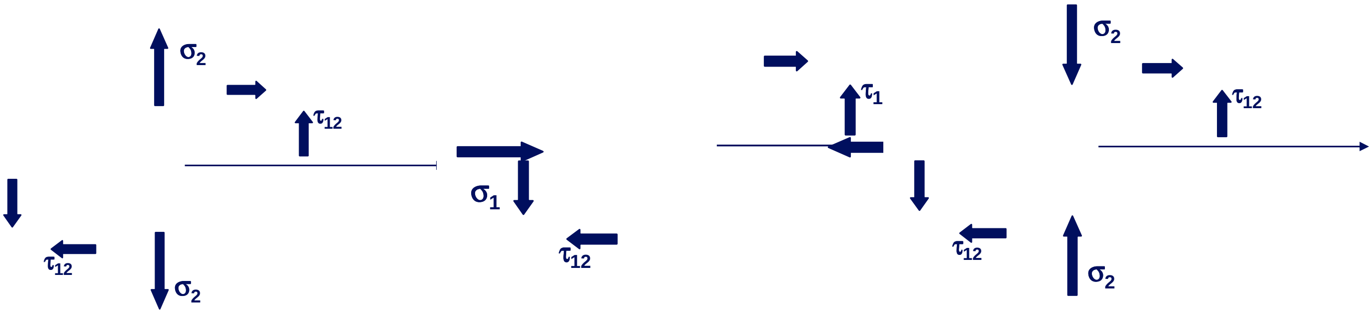

Figure 3 Cases for damage development in unidirectional lamina under biaxial loads

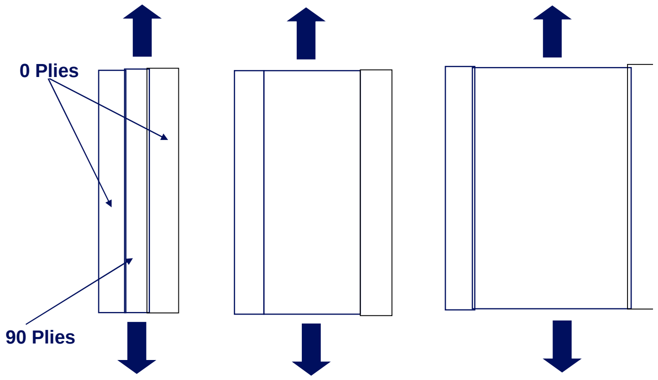

Figure 4: Cases for the effects of 90 deg ply thickness on crack and damage development in (0°/90°$_n$/0°) laminates under tension.

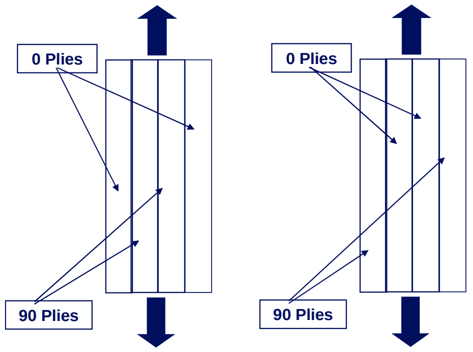

Figure 5: Cases for the effects of ply constraints on the cracking and damage development in (a) (0°/90°/90°/0°) and (b) (90°/0°/0°/90°) laminates. All plies of the same thickness

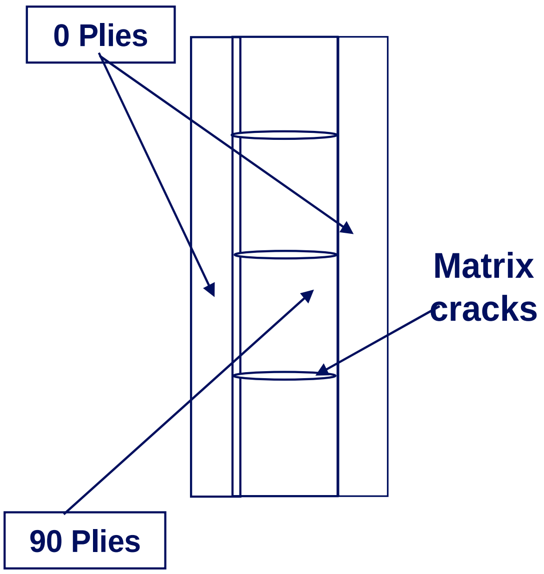

Figure 6: Cases for the effects of matrix cracking on thermal expansion coefficients of (0°/90°/90°/0°) laminates

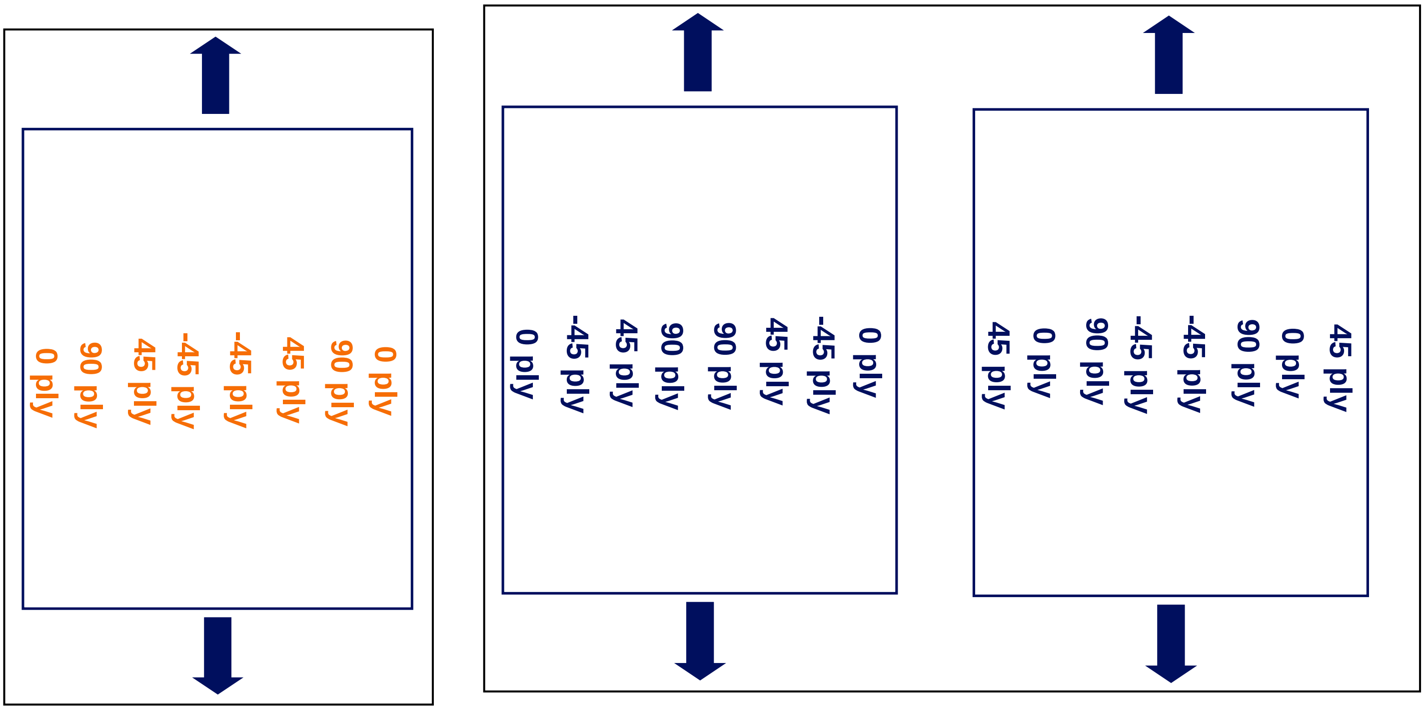

Figure 7: Cases for the effects of material and ply sequence of the damage development in quasi-isotropic laminates

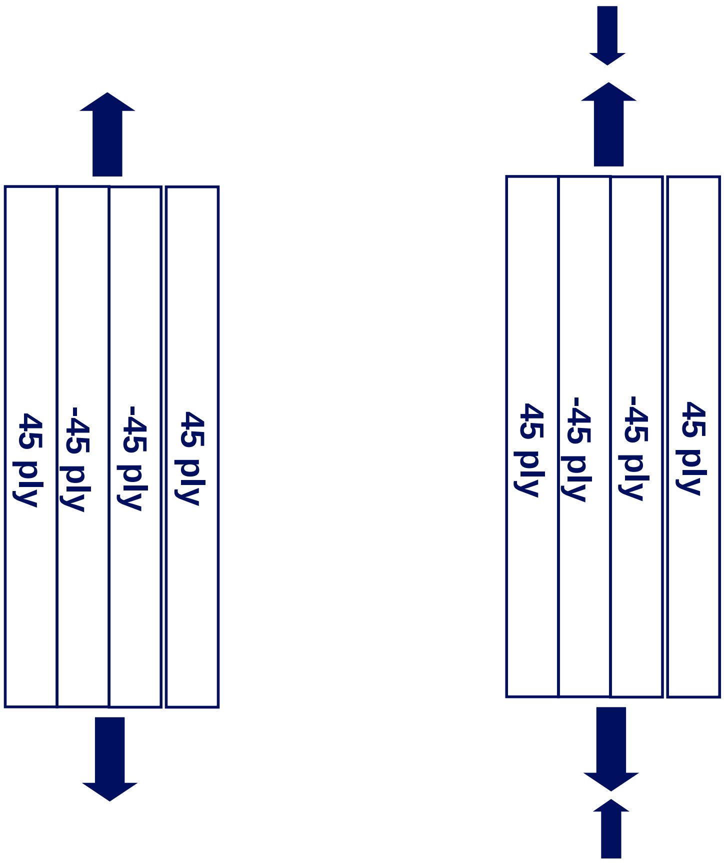

Figure 8: Cases for the development of cracks and damage under shear loading. Left: Uniaxial loading of +45/-45 laminate under monotonic tension and Right: Loading and unloading of +45/-45 laminates under tension

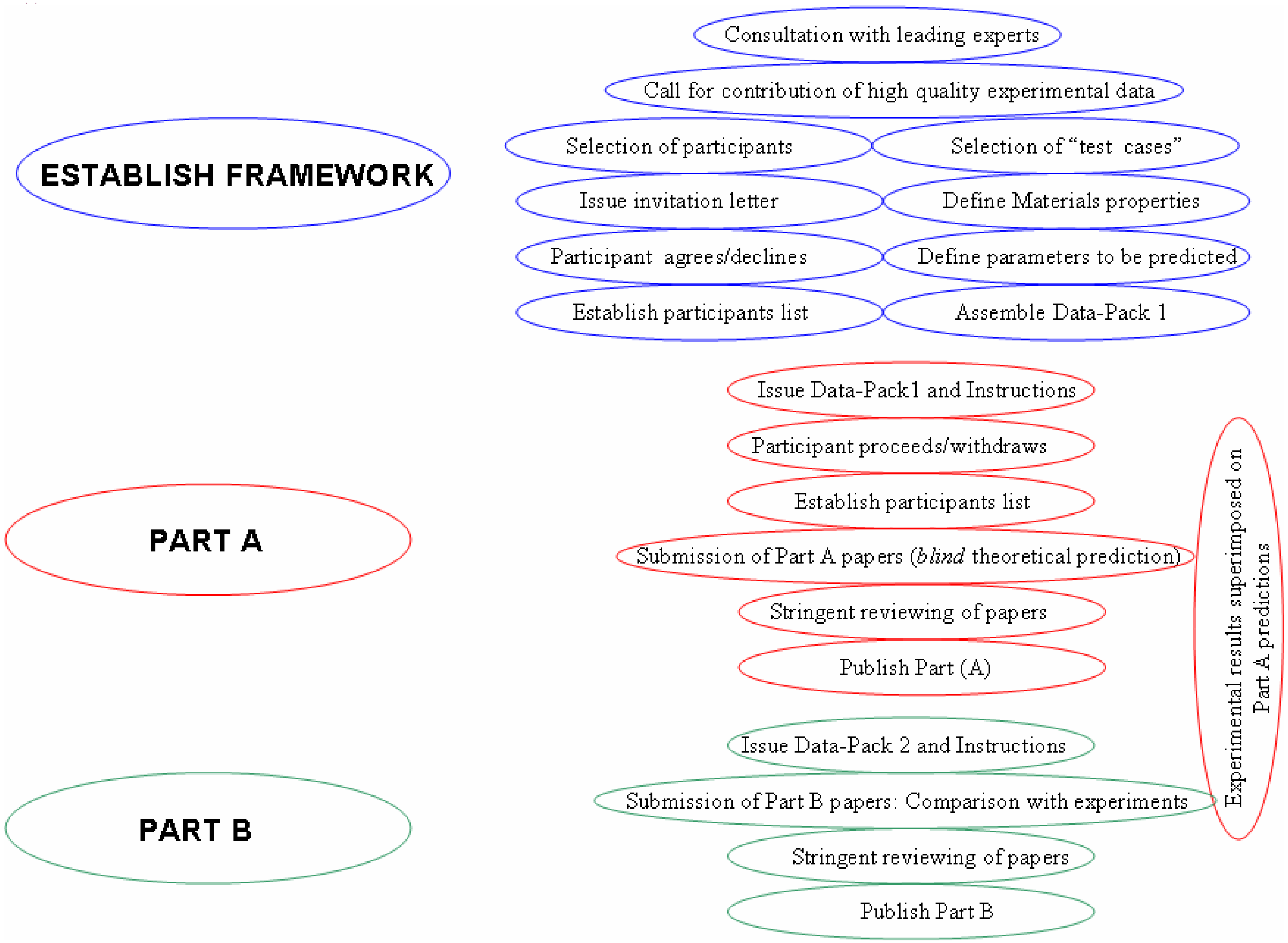

Figure 9: A chart of the major stages for completing Part A and Part B of the exercise