

# DAMAGE PREDICTION IN POLYMERIC COMPOSITES: UP-DATE OF PART(A) OF THE THIRD WORLD-WIDE FAILURE EXERCISE (WWFE-III)

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## 1. ABSTRACT

A high profile international activity is currently underway to assess the maturity of well established methodologies for the prediction of damage (matrix cracking and delamination) and ultimate failure in composite laminates. The activity is known as the 3<sup>rd</sup> World-Wide Failure Exercise (WWFE-III). The predictions are made 'blindly' by the originators of those well established methodologies, who accepted an invitation to take part in the exercise. The organisers of the WWFE-III have provided the participating groups (originators) with comprehensive material property data and a full description of 13 challenging Test problems to be solved and used in their analysis. In this paper, an up-date is given regarding the progress made by the participants for applying their models to solve the specified Test Cases. A wide variety of approaches have been implemented and some of the results are described briefly.

## 2. Introduction

Since the early 1970s, numerous researchers have been battling their way to win a status within the composite community in relation to understanding the development of micro-cracking, delamination, fracture and failure in composite laminates. There are many associated publications and software codes that have been generated for educational and design purposes. The philosophical arguments developed by key and renowned individuals, groups, software houses have been good and useful to the advancement of science. However, it is perhaps premature to conclude that the individual activities act alone as a panacea to the needs and requirement of designers and industry.

It is partly against that background that collective efforts are needed to reach a consensus as to what has been achieved to date and how wide the gaps are.

Based on their previous experience, the authors of the present paper have taken the lead in establishing an international collaborative activity known as the Third World-Wide Failure Exercise, WWFE-III [1]. The WWFE-III is concerned with highlighting the degree of maturity of the current capabilities of internationally recognised methods for modelling various aspects of damage in composite materials. Such problems include matrix cracks due to thermal and mechanical loads; delamination; ply constraint and stacking sequence effects; loading and unloading phenomena; failure due to stress gradients (in particular the hole size effect). The topics addressed within the WWFE-III represent an extremely important and crucial area for advanced modelling and virtual testing of composites.

## 3. Establishing a framework

The main players are those who have developed their own failure theory/modelling capability and who have published their work widely in the open literature. Those have been hand picked by the organisers and invited to take part. They have agreed to participate in a two step process, known as 'Part A' and 'Part B' stages, [1]. Part A is devoted to making a comparison between the predictions of all the models involved and Part B is aimed at making a comparison between all the predictions and relevant experimental data, supplied by the organisers. The WWFE-III is organised to run logically through a series of activities, as follows:

### Part A

- (1)-Definition of the scope of WWFE-III (Selection of Test Cases and supporting data).
- (2)-Identifying suitable participants and gaining their agreement to participate.
- (3)-Issuing Part A data to participants.
- (4)-Receipt of Part A submissions. Stringent reviewing process is adopted for each submission.

### **Part B**

- (5)-Issuing Part B experimental data to participants.
- (6)-Publication of Part A in special edition of a suitable journal.
- (7)-Receipt of Part B submissions. Stringent reviewing process is adopted for each submission.
- (8)-Publication of Part B in special edition of a suitable journal.
- (9)-Publication of WWFE-III in a text book.

Thirteen different cases [2] were selected covering eight different lay-ups consisting of  $0^\circ$ ,  $[0^\circ/90^\circ/0^\circ]$ ,  $[0^\circ/90^\circ/0^\circ]_s$ ,  $[0^\circ/90^\circ]_s$ , family of  $[0^\circ/45^\circ/90^\circ/-45^\circ]_s$ ,  $[\pm 45^\circ]_s$ ,  $[\pm 50^\circ]_s$ , and  $[30^\circ/90^\circ/-30^\circ/90^\circ]_s$  laminates.

Four different materials are used and these are:

- AS4/3501-6 material,
- E-glass/epoxy material,
- G4-800/5260 carbon/epoxy materials and
- IM7/8552 carbon/epoxy material.

Five different types of loadings are covered:

- I -Biaxial direct stresses,
- II -Uniaxial monotonic tension,
- III-Loading and unloading,
- IV -Bending and
- V -Thermal loading.

### **Details of models**

A wide variety of models has been employed by the participants of the WWFE-III, Ref[4] to Ref[15]. A total of 12 methods are currently being benchmarked. The names of the participants, together with their organisations, are listed in Table 1. They range from a simple model, analysing

stiffness reduction with crack density for a limited number of Test Cases, Ref[6], to a sophisticated model targeting damage development in realistic size structures. In the latter case, the modelling capability is designed to simulate the damage progression and its effect on the behaviour of composite laminates at the structural level. The ultimate goal was to provide a computationally robust, yet simple framework that can be applied to model damage development in realistic size structures while adhering to the physics of the damage mechanisms and ensuring the relevance of the model parameters to experimentally observed and measured phenomena, Ref[8]. Figure 1 shows a bar chart illustrating the number of Test Cases, in percentage terms, that were attempted by the various participants. It is clear from this graph that not all the participants were able to solve all the Test Cases.

### **4. Initial results**

In order to show typical results emanating from Part A of the WWFE-III, selected predictions have been compiled for two Test Cases, as shown in Figures 2 and 3.

Figure 2 shows the stress strain curves for Test Case 1. This is related to the behaviour of a  $[0^\circ]$  unidirectional lamina under in-plane shear loading with the presence of a transverse tensile stress component. The lamina is made of carbon/epoxy material. From the results shown in Figure 1, it is clear that, while the shape of the stress strain curves is similar for all the models, the difference in the predicted strains to failure is quite large; with a factor of 2.5 between smallest and largest predicted values. Owing to the nonlinear response, the difference between the predictions of the failure stress is less - only a factor of 2 between the highest and lowest values.

Figure 3 shows selected results for Test Case 4. The laminate is  $[0^\circ/90^\circ/0^\circ]$  glass/epoxy under a uniaxial tension. The challenging task here is to predict the stress strain curves and various damage modes, including matrix crack density. The results in Figure 3 show the following features:

-All the models presented here predicted the laminate to suffer from damage.

-The strain (or stress) at which damage (cracking) initiates varies from one model to another. There was a factor of 4.7 between the largest and the lowest predicted strains, at which damage was initiated.

-One model predicted a sudden change in damage state in the composite.

-Three models predicted a linear increase of damage with strain, although the rate of increase varied drastically between one model and another.

It should be noted here that the results shown above are only examples of the results of the WWFE-III and readers are urged to wait until the full compilation of the predictions of all the models and their applications to providing solutions to all of the Test Cases.

## 5. Concluding remarks

-The exercise has taken considerable time and effort on the part of the participants to whom the authors are extremely grateful. This is no doubt a consequence of the very challenging set of Test Cases.

-The paper has provided an update of the activities and the results obtained so far as well as some of the lessons learnt.

-It is clear from the results already that the area of damage prediction remains very challenging. A lack of consensus exists in terms of how damage is developed in various laminates and how changes in geometry and lay-up sequence affect the development of cracks, delamination and ultimate failure.

## 6. Acknowledgements

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## 7. References

- [1] Hinton M J, Kaddour A S, Li S and Smith P A, 'The Background To Part A of The Third World-Wide Failure Exercise (WWFE-III)'.
- [2] Kaddour A S and Hinton M J, 'Input data for Test Cases used in WWFE-III'.
- [3] Varna J, 'Modeling Mechanical Performance of Damaged Laminates'.
- [4] Singh C V and Talreja R, 'A Synergistic Damage Mechanics Approach to Mechanical Response of Composite Laminates with Ply Cracks'.
- [5] Soutis C, 'Compressive strength of composite laminates with an open hole: Effect of ply blocking'.
- [6] Kashtalyan M and Soutis C, 'Predicting residual stiffness of cracked composite laminates subjected to multi-axial inplane loading'.
- [7] Sapozhnikov S B and Cheremnykh S I, 'The strength of FRP under a complex loading'.
- [8] Forghani A, Zobeiry N, Poursartip A and Vaziri R, 'A Structural Modelling Framework for Prediction of Damage Development and Failure of Composite Laminates'.
- [9] Th. Flatscher, C. Schuecker, H.E. Pettermann, 'A constitutive ply model predicting stiffness degradation as well as inelastic strain accumulation and its application to WWFE-III (Part A)'.
- [10] McCartney L N, 'Energy methods for modelling damage in laminates'.
- [11] McCartney L N, 'Ply cracking in general symmetric laminates'.
- [12] Daghia F and Ladev`eze P, 'Identification and validation of an enhanced mesomodel for laminated composites within the WWFE-III'.
- [13] Chamis C C, Abdi F, Garg M, Talagani F and Huan D, 'World Wide Failure Exercise (WWFE-III): PART(A) Micro-mechanics Based Progressive Failure Analysis Prediction of WWFE-III Composite Coupon Test Cases'.
- [14] Pinho S T, Vyas G M and Robinson P, 'Response and damage propagation of polymer-matrix fibre-reinforced composites: Predictions for WWFE-III Part A'.
- [15] Laurin F, Carrere N, Huchette C and Maire J-F, 'A multiscale hybrid damage and failure approach for strength predictions of composite structures'.
- [16] Kaddour A S, Hinton M J, Smith P A and Li S, 'A comparison between various damage models employed in the WWFE-3'.

Name	Organisation
Chamis et al	NASA (USA)
Ladeveze and Daghia	lmt.ens-cachan (France)
Carrere et al	ONERA (France)
McCartney	NPL (UK)
Pettermann et al	Vienna University (Austria)
Pinho et al	Imperial College (UK)
Poursartip and Vaziri et al	UBC (Canada)
Sapozhnikov and Cheremnykh	South Ural State University (Russia)
Soutis	Sheffield Uni (UK)
Kashtalyan and Soutis	Aberdeen Uni /Sheffield Uni/ (UK)
Talreja and Singh	Texas University (USA)
Varna	Lulea University (Sweden)

Table 1 A List of participants taking part in the WWFE-III

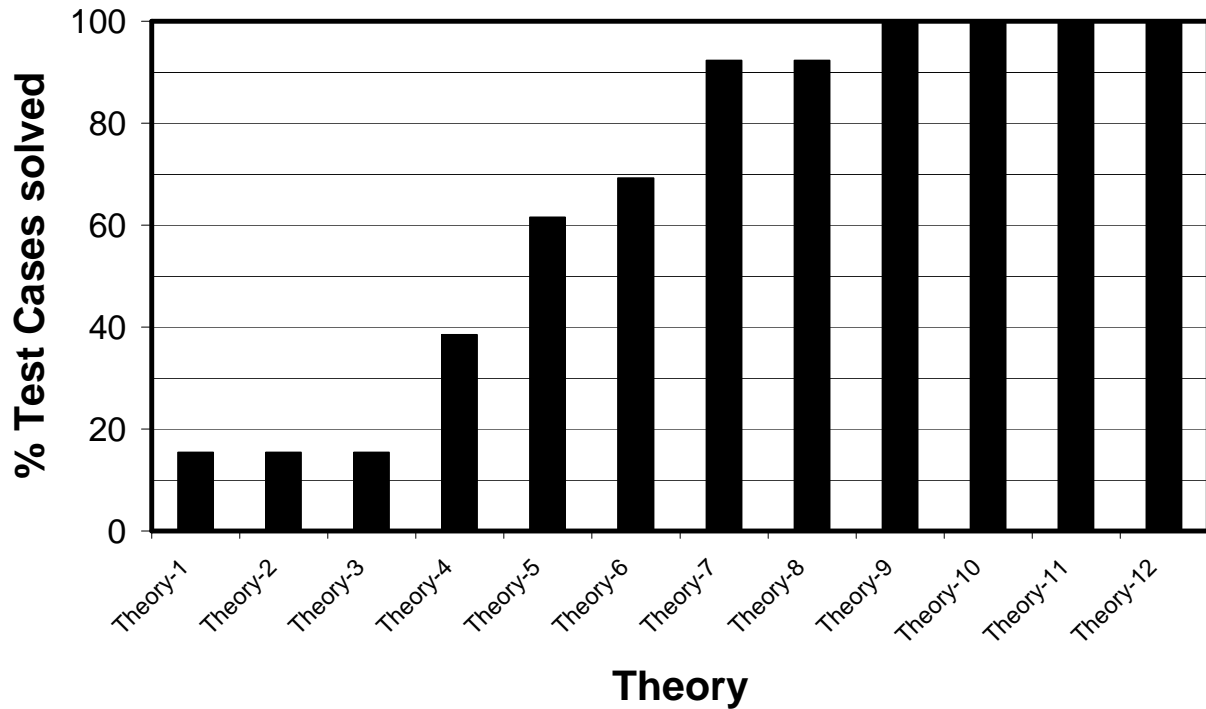


Figure 1 showing the number of Test Cases attempted by the participants.

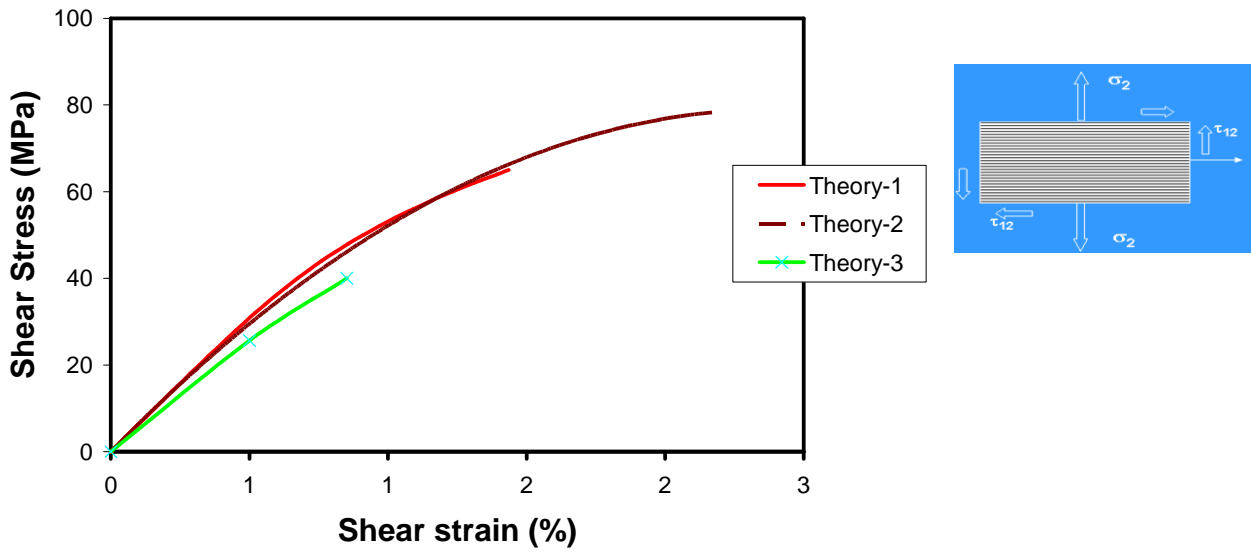


Figure 2: (Right) A schematic showing loading for Test Case 1 and (Left) selected predictions, made by WWFE-III participants, for the shear stress strain curves for Test Case 1.

### Test Case 4

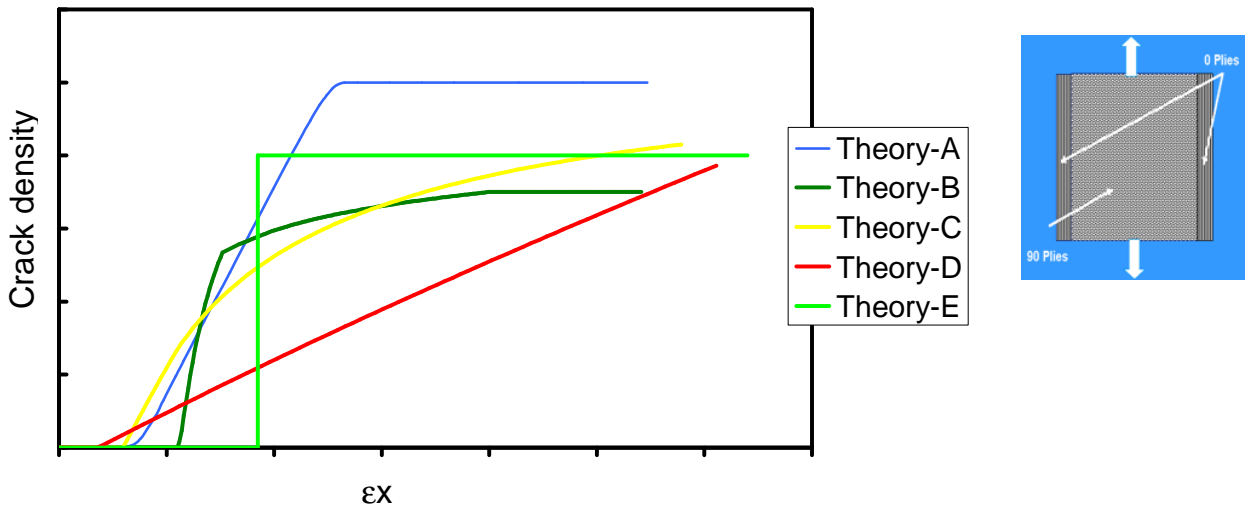


Figure 3: (Right) A schematic showing loading for Test Case 4 and (Left) selected predictions, made by WWFE-III participants, for the matrix crack density development as a function of laminate strain.