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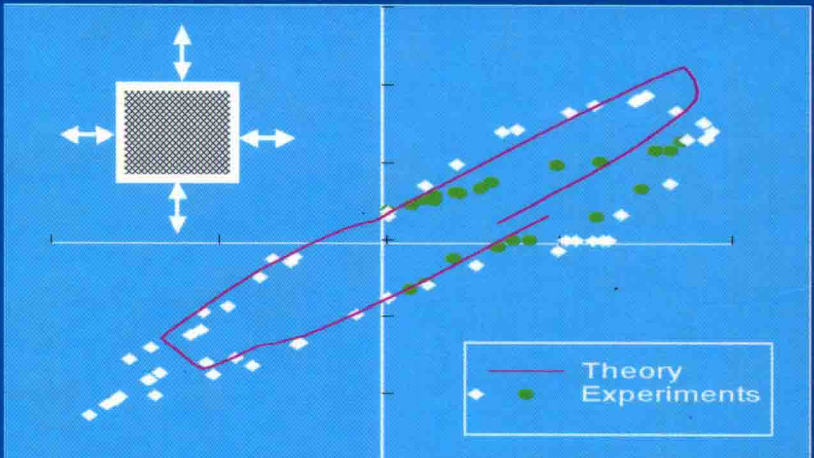
The World-Wide Failure Exercise

A Composites Science and Technology Compendium



Editors:
M.J. Hinton, A.S. Kaddour, P.D. Soden

Failure Criteria in Fibre Reinforced Polymer Composites:

The World-Wide Failure Exercise

This volume contains 34 previously published papers from the journal Special Issue Composites Science and Technology and four new papers

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Preface

Fibre Reinforced Polymer composite materials (FRP's) are now widely utilised in many applications including aircraft, yachts, motor vehicles, chemical and process plant, sporting goods and a wide range of military equipment. They are an extremely broad and versatile class of material, encompassing a wide range of fibre and matrix combinations that provide a multiplicity of component design and manufacturing options. Their high strength coupled with light weight leads to their use wherever structural efficiency is at a premium.

FRP's are inherently more complex than metals. By their nature, they are heterogeneous in construction (asymmetric arrays of many thousands of fibres, each with diameter of the order 10 microns, in a polymeric matrix) and they are anisotropic (the strength parallel to the fibres being typically two orders of magnitude greater than that in the transverse directions). Thus, it is perhaps not unsurprising to find that the challenge in predicting the strength of an FRP laminate with accuracy is significantly larger than that in predicting the strength of a conventional metal.

In moving from the metals world to the FRP world, a structural designer is faced with many more variables and the need for an additional set of design methods. It is, perhaps, self evident that such methods must be accurate and valid in order to extract the maximum structural performance in terms of strength, deformation and stiffness. The consequences of using methods that have not been benchmarked against satisfactory data are potentially unsafe designs or over design, resulting in unnecessary cost and weight. In most of the early applications of FRP's (typically military, in the 1960s) this challenge was circumvented by a 'make and test' approach which was entirely justified at the time, given the relative novelty of the materials, the absence of proven analytical tools and the relatively poor computation capabilities. Whilst much development work has been conducted since then (and continues to this day) the degree of maturity of the current tools for predicting the strength and deformation of an FRP material, in the general case, has been a somewhat open question.

Over the last 12 years the editors of the book have organized and coordinated an international activity, known as the World Wide Failure Exercise, to improve the foundation on which design theories are based, namely the prediction of deformation and failure strength of laminated composite structures. Within the Exercise the leading failure theories for composite laminates have been compared with one another and with experimental data. As the Exercise progressed, the results were published in three special issues, of the international journal, '*Composites Science and Technology*'. The contributors of theoretical papers included many internationally renowned scientists, designers and engineers from six countries and experimental work was gathered from different groups in UK, USA and Germany.

This book captures the totality of the Exercise, by bringing together all of the results, encompassing 19 failure theories, and assessing them together in a single volume. The overall strategy and procedures are outlined where each contributor describes their own theory and employs it to solve 14 challenging problems (test cases) set by the organisers. Full details are provided of the test cases, whereby the prediction of failure envelopes and stress strain curves for a range of practical laminates made of unidirectional carbon or glass fibre reinforced epoxy layers were required. The theoretical predictions are compared with one another and with experimental results for each test case. The accuracy of the predictions and the performance of the theories are assessed and recommendations are made on the uses of the theories in engineering design.

The unique study reported in this book is intended to serve as a fundamental reference work for university students, research institutions, software houses and design engineers working in the field of prediction of failure strength and deformation in composite structures. All of the necessary information is provided for the methodology to be readily employed for validating and benchmarking new theories, as they emerge.

The editors are indebted to all who contributed experimental work to this Exercise (including S.R. Swanson (USA), R.M. Aoki and A.F. Johnson (Germany)) and particularly to the following who contributed the theories which form the critical mass of this book:

S. W. Tsai with K. S. Liu and A. Kuraishi (USA)
A. Puck with H. Schürmann (Germany)
P. Zinoviev with S. V. Grigoriev, O. V. Labedeva and L. R. Tairova (Russia)
T. A. Bogetti with C. P. R. Hoppel, V. M. Harik, J. F. Newill and B. P. Burns (USA)
G. C. Eckold (UK)
N. L. McCartney (UK)
C. T. Sun with J. X. Tao (USA)
C. C.Chamis with P. K.Gotsis and L. Minnetyan (USA)
A. Rotem (Israel)
E. C. Edge (UK)
L. J. Hart-Smith (USA)
W. E. Wolfe with T. S. Butalia (USA)
S. J. Mayes with A. C. Hansen (USA)
Z. M. Huang (China)
R. G. Cuntze and A. Freund (Germany).

This has been a truly collaborative effort, being totally reliant on the great perseverance, intellect and patience of the participants in committing their ideas to paper over a prolonged period of time.

The editors would also like to acknowledge the support received from the UK MoD Corporate Research Programme and through the sustained programme of collaborative work at UMIST and at QinetiQ.

Finally, we wish to acknowledge the encouragement by Bryan Harris, the Editor-in-Chief of the journal, '*Composite Science and Technology*', at the time this study commenced and by his successor, Karl Schulte, both of whom have been instrumental in the publication process. It was a phone call from Bryan (plus a good lunch in London) that persuaded the editors to take on this Exercise in the first instance. Some 12 years later, we are pleased to announce the completion of the task!

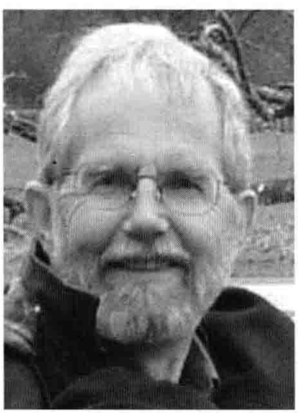
Editors: M. J. Hinton P. D. Soden A. S. Kaddour

About the editors

Professor Mike Hinton
Mike Hinton is a QinetiQ Senior Fellow with more than 30 years of experience in programmes aimed at gaining a fundamental understanding of composite materials and translation into practical hardware. His work includes theoretical and experimental investigations into the response of polymer composite structures when subjected to a wide variety of loading conditions encompassing multi-axial, impact, high strain rate and thermal events. He has developed a number of components for volume production where composites have been utilised to give innovative solutions.

He has collaborated extensively with UMIST on many projects and he is a visiting professor in the Department of Mechanical Aerospace and Manufacturing Engineering.

Dr A S Kaddour
Dr Kaddour is a senior scientist and a structural engineer with broad academic and industrial experience in design of lightweight structures, spanning more than 17 years. He possesses an in-depth understanding of the mechanics of composite materials and composite structures. His work includes modelling failure and improvement of validated computer codes for composites together with developing multi-axial rigs for testing composites tubes under a wide spectrum of loading. He obtained his Ph.D. in 1992 from the University of Manchester Institute of Science and Technology (UMIST) and joined QinetiQ in 1999. He worked in a number of projects sponsored by the UK MoD, DTI and aircraft, space and offshore industries. He has published and co-authored a number of articles in scientific journals.



Mr P D Soden
Peter Soden was a senior lecturer in the Department of Mechanical Engineering, at the University of Manchester Institute of Science and Technology (UMIST) until he retired in 1999. He is currently a visiting senior research fellow and part-time consultant at the same institution, which is about to be combined with another leading university to become The University of Manchester. For the last 30 years his research has been mainly into the behaviour of load bearing fibre reinforced polymer composite structures, including pressure vessels for use in the chemical and process industry, pipes and sandwich panels for use in the offshore oil industry and filament wound cylinders for a variety of applications. He has been joint supervisor of 30 research contracts and author of 90 papers and has acted as a consultant in the analysis of failure and design of a wide variety of components and structures.

Contents

Section 1

The World-Wide Failure Exercise: Its Origin, Concept And Content

Failure Criteria in Fibre Reinforced Polymer Composites

CHAPTER 1.1

The world-wide failure exercise: Its origin, concept and content

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Abstract

This paper sets the scene for an investigation into the status of polymer composite failure theories. It provides a historical context for the origin of the study and it contains a detailed account of the methodology employed by the organisers in striving to attain an impartial, independent and broad ranging assessment of the leading failure theories that forms the subject of this book. The study has become known within the composites community as the 'World-Wide Failure Exercise' (WWFE) and in some circles, the 'Failure Olympics'.

The paper includes a comprehensive description of the process by which the theories were selected, a brief description of the theories themselves, the data and instructions supplied to the contributors and the chronology of the key milestones.

1. Background to the WWFE – origin and rationale

The origin of the WWFE can be traced to an 'experts meeting' held at St Albans (UK) in 1991, on the subject of 'Failure of Polymeric Composites and Structures: Mechanisms and Criteria for the Prediction of Performance', Ref. [1]. The meeting was organised by the UK Science and Engineering Research Council (now the Engineering and Physical Sciences Research Council) together with the UK Institution of Mechanical Engineers (I Mech E), with the specific aim of establishing the level of confidence within the research and design communities in the current methods for failure prediction of fibre reinforced polymer composites (FRP's). Experts from many countries attended and the meeting took the form of a series of formal presentations interspersed with informal discussion groups.

Two key findings emerged:

(a) **There is a lack of faith in the failure criteria in current use** – Attendees concluded that, even at the lamina or laminate level, there was a lack of evidence to show whether any of the criteria could provide accurate and meaningful predictions of failure, over anything other than a very limited range of circumstances.

(b) **There is no universal definition of what constitutes 'failure' of a composite** – In the broadest sense, a designer would define 'failure' as the point at which the structure or component ceases to fulfil its function. The definition of 'failure' must, therefore, be application specific – a pipe designer might consider weeping of fluid through the pipe wall as constituting failure, whereas a bridge designer might consider (say) a 10% loss of stiffness as failure. Attendees concluded that the connection between events at the lamina level and the many definitions of structural failure required by designers, remains to be established.

To many people, these conclusions might be unexpected. After all, there is a large body of research into composite materials to draw upon, spanning at least 50 years, and there are numerous examples (aircraft, boat hulls etc) where composite materials are being used widely, and successfully, in primary load bearing structures. One might logically conclude that design procedures (including strength prediction) for FRP structures are fully mature.

Closer examination reveals the fact that current commercial design practices place little or no reliance on the ability to predict the ultimate strength of the structure with any great accuracy. Failure theories are often used in the initial calculations to 'size' a component (i.e. to establish the approximate dimensions, such as panel thickness, width etc). Beyond that point, experimental tests on coupons or structural elements (such as the notched hot/wet compressive strength tests in aerospace) are used to determine the global design allowables. These are typically set at levels which are less than 30% of the ultimate load carrying capability, thereby providing a wide safety margin to accommodate loss in performance due to fatigue, operating environments, impact and any other unaccounted features. The coupon/structural element testing approach is widespread in the aerospace industry, where large databases have been established at great expense. Small to medium sized companies tend to follow a broadly similar path, though on a much reduced scale. A 'make and test' approach combined with generous safety factors is commonplace, though in niche markets (such as sporting goods) confidence built up over several years is leading to reduced margins (as evidenced by the progression of lighter tennis rackets and skis over the last 10 years).

From an industrial perspective, therefore, there has been little pressure in the recent past to investigate or promote the need for improved failure theories, the view being that they are more of an academic curiosity than a practical design aid. This view is beginning to change, in light of the need to reduce the time and cost of bringing new components to the market place, and the desire to exploit the performance of FRP's in ever more complex applications. There is a growing realisation that 'make and test' is simply too slow and too costly. Improved design methods are now being called for which depend upon analytical modelling techniques. Central to this, is the need to establish the level of confidence which is applicable to current failure theories.

The 1991 St Albans meeting was memorable for the amount of heat and excitement that was generated over the question of the validity of established failure criteria. During informal intervals when people gathered to continue the disputes, it began to seem to one or two of the attendees that were involved in publishing – Paul Hogg, (then) Editor of the Elsevier ***Advanced Composites Bulletin***, and Bryan Harris, (then) Editor of the Elsevier ***Composites Science and Technology*** – abetted and encouraged by Clive Phillips and John Hart-Smith, that here was an excellent subject for a Special Issue of ***Composites Science and Technology*** with a possibility of some lively correspondence.

Encouraged by Peter Lanagan, then responsible for Elsevier's Composites journals, Bryan set about trying to find a Guest Editor. He solved the problem by approaching Mike Hinton and Peter Soden (i.e. two of the authors of this paper) who were both active in the field of failure prediction, and had a long history of working together in their research. They agreed to produce a publication that would provide an authoritative source for designers and researchers by making it possible, for the first time, to obtain unbiased comparisons of the merits and short-comings of current failure criteria. Later, in 1994, they were joined in this endeavour by a colleague, Sam Kaddour. It has to be said that Hinton, Soden and Kaddour (hereafter referred to as the 'organisers') did not envisage the shear scale and volume of the challenge that was ahead and that would occupy a significant portion of their efforts over the next twelve years!

2. Clarifying the aims of the WWFE

A critical first step was to define the objectives of the study. After some discussion the organisers targeted three broad aims:

(a) Establishing the current level of maturity of theories for predicting the failure response of fibre reinforced plastic (FRP) laminates.
(b) Closing the knowledge gap between theoreticians and design practitioners in this field.
(c) Stimulating the composites community into providing design engineers with more robust and accurate failure prediction methods and the confidence to use them.

Whilst (a) was the central focus of the study, the organisers felt that (b) and (c) were equally important issues that needed to be addressed. The 1991 St Albans meeting had highlighted a clear division between the arguably academic pursuit of polymer composite failure theories by many theoreticians and the practical needs of designers of composite structures. The organisers' intent was therefore to exploit the WWFE as a catalyst for healthy debate between theoreticians and designers, with the expectation that this would lead to progress in the field.

3. Constructing a definitive test of a failure theory – key principles

At an early stage in the planning process, the organisers decided to capture the key requirements for what would constitute a definitive test of a polymer composites failure theory and for a rigorous comparison of the best failure theories available. Not surprisingly, most of the principles are derived from standard scientific practice for testing any new hypothesis. They are:

(a) **The organisers of the exercise must maintain true independence** from those participants making the predictions. (i.e. there must be no insider dealing).
(b) Where predictions based on a given failure theory are required, the best approach is to request that **the originator of the theory carries out the calculations**. The room for misinterpretation by an intermediary is then removed.
(c) A true comparison of theories should **use a common set of test cases** that are clearly and unambiguously defined. Equally, the parameters to be predicted should be clearly defined, so that direct comparison is facilitated.

(d) In order to determine the bounds on the validity of a given theory, it is important to **test it over a wide range of conditions and to choose test problems that highlight the differences and similarities between the theories**. Careful thought is needed, therefore, to identify the laminate and loading conditions that will test a theory to the full and thereby identify any discriminating features.
(e) The **test cases should be chosen by the organisers** and not by those participants making the predictions. In this way, the test cases are unlikely to favour any one theory.
(f) There should be **matching, high quality, experimental data available for each of the test cases** to be analysed theoretically. Each theory can then be benchmarked directly against experimental observations. The debate can then be moved from whether theories (a) and (b) agree with each other, to which theory matches reality most closely and over what range.
(g) The **theoretical predictions should be made 'blind'** in the first instance (i.e. with no knowledge of the equivalent experimental results). The participants should not be given sight of the experimental results for the test cases until all of the papers containing their predictions are complete and in the hands of the organisers. This avoids any suspicion of 'tuning' the predictions.
(h) Whilst it is accepted that certain models can be 'tuned' to improve their accuracy, **it is important to be able to discriminate between a 'blind' and a 'tuned' prediction**. Clearly, in most design situations, the reliance will be placed on 'blind' predictions.

Principles (a) to (h) were adopted for the study, the remaining task being to develop a suitable framework for implementation. In a later section of this chapter, we will return to this key requirements list to check the level of compliance achieved within the framework that was finally adopted.

4. Lessons from previous studies in the literature

Given the magnitude of papers in the literature on failure theories for polymer composites, the organisers sought to pick up useful ideas or even a complete methodology for carrying out the WWFE, to meet the principles outlined in section 3. The literature contains a steady stream of work on failure of composite materials, starting in earnest in the 1950's. Papers containing a major theoretical content far outweigh those with a major experimental emphasis and the literature is particularly sparse in experimental data on the response of FRP materials when subjected to biaxial and triaxial stresses. This is especially surprising, given that most structural components are subjected to multi-axial loads (and hence multi-axial states of stress), and one would expect there to be sufficient, good quality, experimental data available to validate the many failure theories that purport to model such conditions.

The literature contains numerous attempts to conduct comparisons between competing theories and between theory and experiment (see for instance Refs [3–6]), and they generally take one of two forms:

(a) An author produces a computer programme containing a personal interpretation of a range of failure theories, devised by others and gleaned from the literature. In certain cases, the author has introduced a genuinely new theory of his/her own or a modification to someone else's theory. The programme is then used to generate failure predictions,