QinetiQ

Design and Failure of Materials Systems under Multi-Axial Loads

J Cook, AS Kaddour and C Williamson
Future Systems and Technology, QinetiQ, Fort Halstead, Sevenoaks, Kent, TN14 7BP

Introduction

Polymer composites are being increasingly used in a wide variety of industrial applications, but there are difficulties in applying these materials in ways that exploit their full potential. The main reason for this is that these materials are more complex than other engineering materials such as metals. The directional material properties of composites confer a number of design freedoms but at the same time lead to greater difficulties in applying these materials efficiently. One important aspect of this complexity is the behaviour of composites under multi-axial loading. For metals, the rules covering multi-axial behaviour are reasonably well established, but for composites the situation is far more complex, partly as a result of their anisotropy and partly due to the multiplicity of their failure modes. Nevertheless, the understanding of the behaviour of composites under multi-axial loading is of great practical significance, since bi- or even tri-axial loading regimes are the norm in real engineering structures.

The Word-Wide-Failure-Exercise

In recent years the question of failure criteria for composites has been the subject of an international collaborative exercise known as the World-Wide-Failure-Exercise (WWFE), which was completed in 2004. One of the main objectives of the WWFE was to compare existing failure criteria. The figure below shows the predictions by a number of theories for the bi-axial failure envelope for a quasi-isotropic CFRP laminate. It is evident that even for this simple problem, which is one of many test problems used in the exercise, there is considerable disagreement between the predictions from the various models.

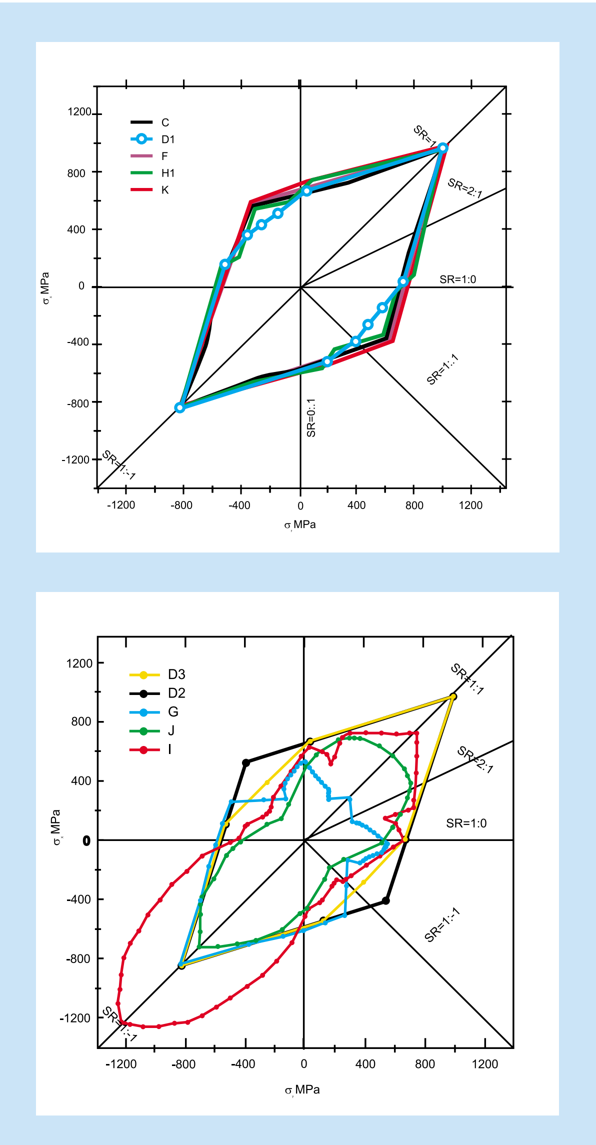

Figure 1 - The predictions by a number of theories of the bi-axial failure envelope for a quasi-isotropic CFRP laminate.

As a result of the WWFE, many such inconsistencies between the theories have been resolved.

Design and Failure of Materials Systems under Multi-Axial Loads (MMS5)

However, most of the materials on which the WWFE was based consisted of laboratory sized coupons or sub-components. There is virtually no data on the failure of bulk usage composites used by industry. In the automotive sector, for example, commodity materials are generally used such as glass fibre (both continuous and chopped) within a polyester or polypropylene matrix. Although components are generally designed to achieve a specified stiffness, accurate failure data is essential. This is particularly so for structures designed for crashworthiness, where the onset of damage must be determined within structural analyses. Similar considerations apply within the marine sector, but at present the appropriate materials data is simply not available.

In order to rectify this situation, a programme has been set up under the DTI's Measurements for Materials Systems (MMS) initiative. The specific programme addressing failure under multi-axial loading, termed MMS5, commenced in September 2002 and will run for three years. It is being run by a team consisting of QinetiQ, AEA Technology, Nottingham University, UMIST (ARP), NPL and Netcomposites, and the objective is to address the widest possible range of UK industry needs in this important area of technology. It is anticipated that large benefits will accrue to both industrial suppliers and to users of composites.

The purpose of MMS5 is to apply the existing multi-axial knowledge and testing techniques to a range of non-aerospace materials of wider commercial interest, and to extend the existing theoretical framework (which is substantial) to cover such materials. Individual multi-axial tests tend to be somewhat expensive, and so the theoretical understanding is important in determining which tests to carry out and in extracting the maximum value from them.

Industry involvement is vital in the selection of materials of greatest interest and in defining the applications. An Industrial Advisory Group (IAG) has been set up to guide this process. This IAG is open to the companies participating in MMS5, as well as to organisations wishing to gain insight into this important topic.

QinetiQ Test Facilities

The figure below shows the largest of QinetiQ's facilities for testing flat composite panels.

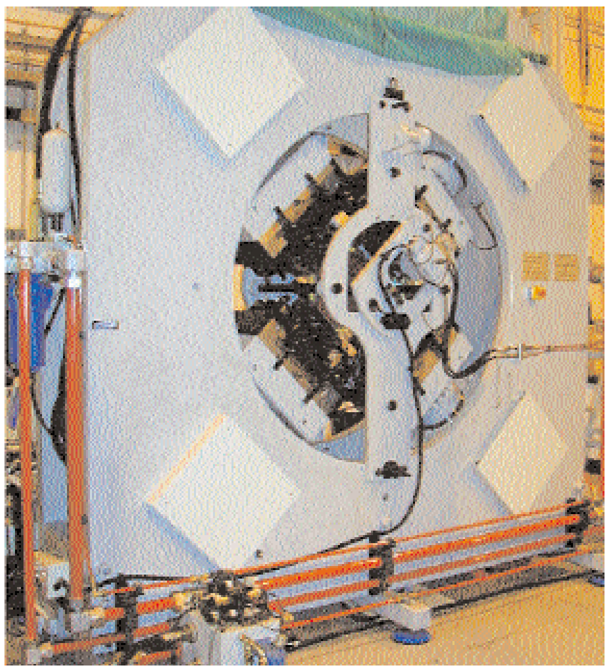

Figure 2 - The 1500kN bi-axial testing machine at QinetiQ Farnborough.

The machine shown has a capacity of 1500kN on each axis and has the additional capability of being able to apply a load to a fastener (in single or double shear) at the centre of a bi-axially loaded panel. A smaller, 500kN machine is being used for the MMS5 programme.

QinetiQ also has complementary facilities for the bi-axial testing of composites in the form of tubes. The figure below shows the way in which the basic test rig can be configured to explore different parts of the bi-axial failure envelope.

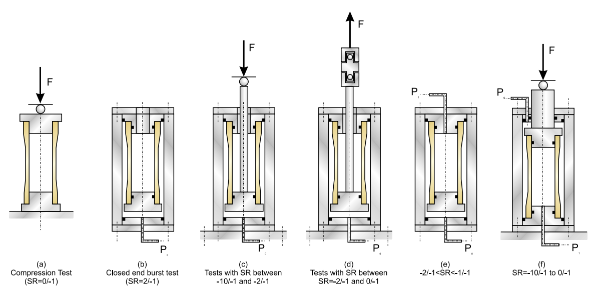

Figure 3 Various configurations of the composite tube testing rig.

The figure below shows a set of tubular test specimens after failure.

Figure 4 - A family of tubes, all manufactured in an identical manner, but tested to failure under different loading ratios.

Many of the results generated by QinetiQ from various aircraft and defence-based programmes have now been published, and more are due to be released in 2005.

Behaviour of Composites Under Tri-Axial Loading

A particular study that was carried out within MMS5 was a survey of the tri-axial behaviour of polymer composites. Such an in-depth study appears not to have been attempted previously. Tri-axial stress states arise in the cure of thermoset components or the cooling after moulding of thermoplastics. In the well-known problem of the cure of thick walled tubes, residual stresses arise that are time dependent. If in-service loads are then superimposed, as for example on the tubular vessel shown below, the stresses that arise superimpose on the residual stresses can be largely additive or subtractive depending on circumstances.

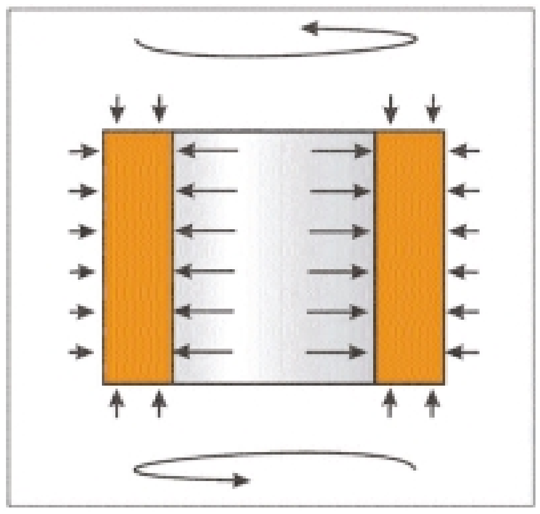

Figure 5 - Schematic of a thick walled composite tube under combined loading, as might be typical of a submersible.

Examples of where a stress on the third axis can be beneficial are shown in figures 6 and 7. Most composite mechanical properties are increased by the presence of super-imposed hydrostatic compression (although the extent depends on the exact loading combination). The second example is that of bolted joints, where the application of a through-thickness compressive stress, by compressing between two washers, is highly effective in suppressing delamination.

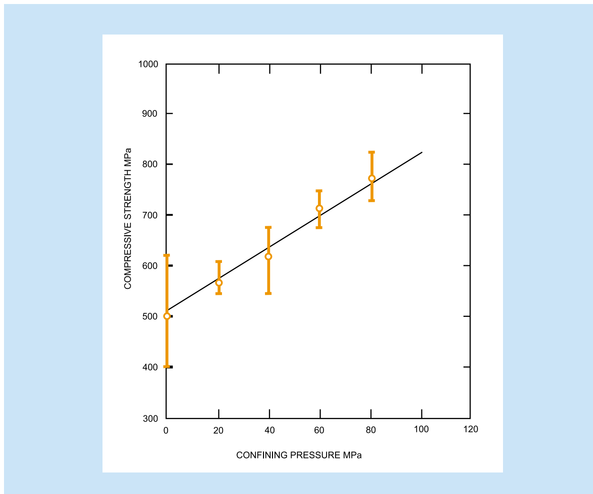

Figure 6 - Increase in longitudinal compressive strength of a unidirectional composite with superimposed hydrostatic pressure

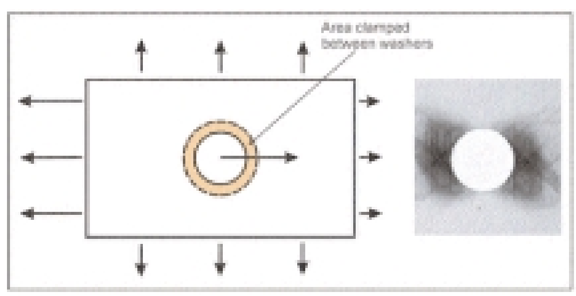

Figure 7 - Schematic of a bolted joint with washers imposing through-thickness compressive stress in the composite around the bolt.

Summary

An improved understanding of the behaviour of industrial composites under multi-axial loading conditions will lead to greater efficiency in the use of these materials. The MMS5 programme is making significant progress towards achieving this understanding.

For more information please contact:

Customer Contact Team
QinetiQ
Cody Technology Park
Ively Road, Farnborough
Hampshire, GU14 0LX
United Kingdom

Tel +44 (0) 8700 100942
www.QinetiQ.com

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