Composites Science and Technology 72 (2012) 397–411

Contents lists available at SciVerse ScienceDirect

Composites Science and Technology

journal homepage: www.elsevier.com/locate/compscitech

In-plane and through-thickness properties, failure modes, damage and delamination in 3D woven carbon fibre composites subjected to impact loading

Robert Gerlach *, Clive R. Siviour, Jens Wiegand, Nik Petrinic

University of Oxford, Department of Engineering Science, Parks Road, Oxford OX1 3PJ, United Kingdom

ARTICLE INFO

Article history:
Received 30 August 2011
Received in revised form 23 November 2011
Accepted 27 November 2011
Available online 3 December 2011

Keywords:
A. Textile composites
B. Fracture
C. Multiscale modelling
B. Matrix cracking
Strain rate

ABSTRACT

Two noncrimp 3D woven carbon fibre composites (through thickness angle interlock) of binder volume fractions 3% and 6% were characterised for their response to applied deformation. Experiments were performed at quasi static, medium and high strain rates under a large variety of load cases (tension in warp/weft direction, interlaminar/intralaminar shear, through thickness tension/compression, 3-point bending and plate bending). During the study, novel experimental methods were developed in order to address several challenges specific to 3D composite materials. The results show that, while the different binder volume fractions of 3% and 6% have only a small effect on the in-plane stiffness (warp and weft direction), its effect on the delamination resistance in plate bending experiments is considerable. This is a very important result for the use of these materials in the future. The availability, in previous publications, of complementary data for the matrix and the interface between matrix pockets and fibre bundles makes the comprehensive data set a generically useful reference for hierarchical numerical modelling strategies.

1. Introduction

3D fibre reinforced polymers (3DFRP), such as 3D weaves, offer several significant advantages over traditional in-plane fibre reinforced composites. Most importantly, their 3D reinforcement results in excellent delamination resistance and thus very good response to impact loading [1–5]. Furthermore, 3D weavings exhibit much higher permeability than stacked 2D preforms, resulting in increased matrix infusion rates, which allows a reduction of infusion time during manufacture or use of higher viscosity (e.g. toughened) matrix materials [6]. In addition, 3D weavings exhibit near net shape capabilities: complex preforms close to the shape of the final part can be produced [7–9]. These characteristics allow 3D weavings to be used in applications for which traditional laminates and 2D composites are not suited, whilst at the same time offering additional economic benefits.

Despite these advantages, 3D weavings have so far failed to achieve widespread application, which is mainly related to the difficulty of analytically or numerically predicting their complex mechanical behaviour. This, in turn, is a consequence of their structural complexity, the large number of different available weave architectures [10], and the numerous possibilities for combining different fibre and matrix systems. The resulting theoretically indefinite number of essentially different 3D weaving materials is generally concluded to require a hierarchical modelling approach, relating the material response of the constituents to the global response of the composite [6,11–25]. Therefore, experimental data for both the 3D composite, its constituents (matrix, fibre, interfaces) as well as information about the architecture of the weave are required in order to advance the development of generic numerical modelling capabilities for 3D weaves, and consequently, allow for a wider application of these promising materials.

Unfortunately, available experimental data for 3D composites are very rare; particularly in the case of carbon fibre reinforced polymer (CFRP) 3D weaves. It is especially challenging to develop data sets that are of sufficient comprehensiveness to serve as reference for constitutive model development. This is due to (i) the full anisotropy of 3D weaves, requiring characterisation in all six normal and shear directions, (ii) their complex failure and damage behaviour, (iii) the difficulty in experimentally characterising the out of plane properties and (iv) the requirement for complementary experimental data of the 3D weave constituents matrix and fibre.

The majority of experimental data addressing intrinsic material properties of 3D CFRP weaves deals with tension [1,3,5,26–28] and/or compression [23,29–31] for in-plane loading (warp and weft directions) only. This is because of the previously mentioned difficulty to address the out of plane material properties experimentally, especially as no generally accepted methods are available. However, a data set addressing only in plane properties is of questionable use in case of 3D weaves, as these composites were designed to improve the out of plane properties of 2D composite materials. Therefore, the experimental characterisation of the out of plane properties of 3D weaves is of particular importance.

* Corresponding author. Tel.: +44 1865 283475; fax: +44 1865 273906.
E-mail address: robert.gerlach@eng.ox.ac.uk (R. Gerlach).

0266-3538/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.compscitech.2011.11.032

So far, very few experimental data addressing interlaminar shear are available [32,33]. The methods currently used often rely on a sharp cutting edge to 'punch' through the 3D composite. It is questionable whether this method produces local stress states representative for a pure interlaminar shear load. No literature data for through thickness tension were found.

Furthermore, the data available in the literature are limited to the quasi static regime, and no publications investigating the high strain rate behaviour of 3D CFRP weaves could be found. However, as 3D weaves are designed to improve impact resistance, their high-strain rate properties are of particular importance. The strain rate dependent failure and damage behaviour 3D CFRP weaves is still not well understood, especially regarding the effect of the 3D reinforcement (called binder in 3D weaves) on both strength and damage propagation.

While data for material characterisation are scarce, even fewer data from validation experiments, such as short beam [4,27,30,34] and plate bending experiments [34–36] are available.

Finally, most of the published data concentrates on orthogonal and layer to layer angle interlock weave architectures only. The CFRP 3D weaves that have been investigated usually have high crimp induced by the through thickness reinforcement, and are therefore unsuitable for applications requiring high in-plane strength and stiffness. 3D weaves with less binder volume content, and therefore reduced crimp, are more interesting for many aerospace applications, where high in plane strength and stiffness are equally as important as impact resistance.

This paper addresses the important challenges and needs outlined so far by experimentally characterising two 'noncrimp' through-thickness angle-interlock architecture (TTAIL) 3D weaves, with 3D reinforcement specifically designed to maintain high in-plane properties. Experiments have been performed at quasi-static ($\sim 10^{-3}\ s^{-1}$), high ($\sim 10^{3}\ s^{-1}$) and in specific cases medium rates ($\sim 10^{1}\ s^{-1}$) of strain. In order to obtain a large set of material data, a number of different load cases were investigated. Tensile loading was applied in x (warp) and y (weft) direction, comparing the effect of the binder volume fraction on in-plane properties. Shear loading was applied in plane as well as in both interlaminar shear directions (xz and yz), addressing the effect of binder volume content on damage initiation and evolution. In addition, compression experiments in the through thickness direction were performed, and a novel experimental method to investigate the tensile out of plane properties was developed. These experiments provide intrinsic material properties and generate information about local failure and damage mechanisms as well as material nonlinearity and strain rate dependency. In order to further quantify the influence of the binder on delamination resistance, to characterise the delamination behaviour and to provide validation experiments for constitutive modelling approaches, beam- and plate-bending experiments were performed at quasi-static and impact speeds. Finally, conclusions and recommendations for numerical modelling strategies are presented.

It is important to note that the work reported here is related to previous experimental characterisations of the matrix material [37] and the interface between matrix pockets and fibre bundles [38] of the same constituent materials used for the TTAIL reported here. In conjunction with detailed information about the weave architecture (see Section 1.1) of the characterised TTAIL and available manufacturing data for the fibres, the data set reported here represents a comprehensive experimental database of generic usefulness for a variety of hierarchical modelling strategies.

1.1. Parent material

The selected TTAIL weaves were especially designed to minimise crimp and increase in-plane strength and stiffness. The two different TTAIL versions investigated here exhibit a comparably low binder volume fraction (3% and 6% respectively), and are otherwise identical. Idealised (regular) dimensions needed for modelling purposes are shown in Fig. 1 (6% binder version), and were obtained as an average of micrographs taken from slices extracted from different positions of the TTAIL (Figs. 2–4).

All warp and weft stuffers consist of Tenax HTS carbon rovings while the binder consists of Tenax HTA carbon fibre rovings. The warp stuffers are made up of two combined 12 k rovings (24 k in total), yielding an average warp fibre volume fraction (fvf) of 64.4% (using the dimensions listed in Fig. 1). The weft stuffers consist of a single 12 k roving, with an average fvf of 63.6%. For the 3% binder version of the weave, the binder consists of a single 6 k roving, while the 6% binder version uses two 6 k rovings. The overall fvf of the 3D weave is 51% for the 6% version and 49% for the 3% version.

The TTAIL weaves were obtained as unconsolidated fabrics, and infiltrated with RTM-6 resin using VARTM technology. The pressure used was one bar, the resin temperature at infiltration 80 °C and the tool temperature 120 °C. The cure cycle used was 2 °C min^{-1} heating to 130 °C, 1 h dwell at 130 °C, 1 °C min^{-1} heating to 180 °C and finally 2 h cure at 180 °C. Ultrasound scans were performed for each panel in order to check for cavities. Due to the good permeability of the fabric and the excellent flow characteristics of RTM-6, the achieved infiltration was very good.

Generally, the crimp of the stuffers is low, while the weft stuffers show higher distortion than the warp stuffers, as shown in Fig. 3. This results from the fact that the warp stuffers are kept in tension during the weaving process. The matrix pockets are of considerable size, while the yarns depict a sharp transition from areas of high fvf to pure matrix pocket (Fig. 2C). The stuffer cross sections are of ellipsoidal shape (Figs. 3 and 2B), except at the top and bottom surface of the TTAIL panel, where the binder deforms the surface weft yarns (Figs. 3 and 2A). The binder path is relatively irregular, in contrast to the idealised path shown in Fig. 1. The differences between the weave types are shown in Fig. 4. It can be seen that the binder is less curved for the 3% version of the weave and that the binder for the 6% weave completely fills the pocket. This implies that the 6% material represents the maximum amount of binder that could be used without introducing significant distortion in the stuffers.

Utilising the yarn dimensions extracted from the micrographs (Fig. 1), the average fibre volume fractions (fvf) in the respective yarn systems can be estimated utilising the yarn cross section area

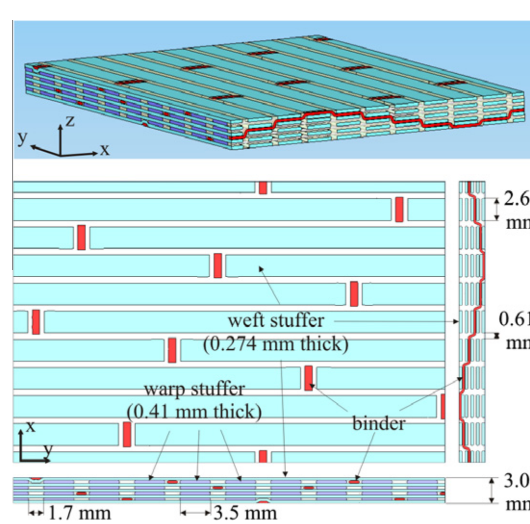

Fig. 1. Idealised geometry showing terminology and geometry of the TTAIL.