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Dynamic fracture in carbon-fibre composites: Air-blast loading

Laurence A. Coles\textsuperscript{a}, Craig Tilton\textsuperscript{b}, Anish Roy\textsuperscript{a}, Arun Shukla\textsuperscript{b}, Vadim V. Silberschmidt\textsuperscript{a}

\textsuperscript{a}Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, Leicestershire, LE11 3TU, UK
\textsuperscript{b}Dept. of Mechanical, Industrial and Systems Engineering, University of Rhode Island, Kingston, RI, 02881, USA

Abstract

In this study a response of a 2x2 twill weave T300 carbon fibre/epoxy composite flat plate specimen resultant air blast dynamic response observed is examined, using a combination of non-invasive analysis techniques. The study investigates deformation and damage following air blasts with incident pressures of 0.4 MPa, 0.6 MPa and 0.8 MPa, and wave speeds between 650m/s and 950m/s. Digital image correlation was employed to obtain displacement data from the rear surfaces of the specimens during each experiment. 3D x-ray tomography was used to visualize the resultant internal damage within the samples. It was shown that the global deformation and transitions in curvature of each specimen appear to be similar with varying out-of-plane displacements. Damage was observed to propagate from the rear surface of the specimens through to the front surface as the air blast magnitude increased.

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Keywords: carbon-fibre composites; air blast; damage; computed tomography

1. Introduction

A use of fibre-reinforced composites (FRCs) has increased across many areas of application including automotive, aerospace, naval, defence, energy and sport; dynamic loading regimes in all these areas are extremely likely (Silberschmidt, 2016). Therefore, understanding deformation, damage and fracture processes in FRCs under conditions of dynamic loading becomes important. Our study is limited to analysis of air-blast loading conditions, which may occur at close-proximity to explosions or sudden pressure increases.

There was a significant amount of prior research focused at understanding behaviour of fibre-reinforced composites (Langdon et al., 2014) under air-blast loading conditions (LeBlanc et al., 2007; Tekalur et al., 2008). Typically, the analysis of the resultant damage is limited to visual inspection of external surfaces, or use of invasive techniques to study internal damage that could introduce additional damage making the investigation difficult and inconclusive.

This paper describes the experimental case studies, in which carbon fibre/epoxy specimens were subjected to air-
blast/shockwave loading in order to compare and contrast the resultant deformation and damage processes observed using noninvasive techniques such as digital image correlation and high-precision X-ray micro computed tomography (CT).

2. Experimental Setup

2.1. Materials and Specimens

The carbon-fibre-reinforced epoxy specimens, measuring approximately 195 mm × 195 mm with a thickness of 5.6 mm were fabricated from 10 plies of carbon-fibre fabric, pre-impregnated with a toughened epoxy matrix (IMP530R). The 10 plies were formed to a laminate consisting of 2 surface (external) plies (T300 3K) and 8 central bulking plies (T300 12K), with a 0°/90° layup configuration; the specimens have a theoretical density of 1600 kg/m³. All specimens were manufacture using the autoclave process, cured at 120°C with a 1.5°C/min ramp rate and a soak time of 160 minutes at a pressure of 90 psi under vacuum.

2.2. Shock Tube Setup

In the undertaken experimental programme, the composite specimens were positioned vertically on a three-point bend-style fixture that consisted of two (slightly rounded) knife edges located 152.4 mm apart (as shown in Figure 1). A rubber band was used to keep the specimen firmly against the knife edges, positioned vertically on the fixture. The shock-tube apparatus (8 m in length) consisted of a driver, a diaphragm and a driven section, which produced the air-blast shockwave by pressurising the driver section up to a critical pressure, at which the diaphragm ruptures creating a dynamic pressure-wave profile. The muzzle of the shock tube, with an inner diameter of 76.2 mm, was moved towards the specimen until there was only a paper-thin (approximately 0.1-0.2 mm) gap between the specimen and the muzzle. Pressure sensors located towards the end of the muzzle recorded the shockwave profile that was acquired in the process of loading.

![Fig. 1. Air-blast regime and three-point-bending style fixture](image)

The deformation process of the composite plate was captured using three cameras (Photron SA1, Photron USA, Inc., CA, USA), with two cameras recording at 28,800 fps viewing the rear surface of the specimen for implementation of Digital Image Correlation (DIC) using the VIC-3D (Correlated Solutions) system. A third camera, also recording...
at 28,800 fps, was placed perpendicular to the edge of the composite specimen to acquire side-view images and observe realization of the deformation process for each specimen.

2.3. Profiles of Air-blast Pressure and Shock Waves

The air blast incident pressure magnitudes were chosen to produce three levels of damage within the specimens, namely, minor, medium and major (with the specimens still intact); these magnitudes were determined during preliminary calibration experiments. For this experimental study incident pressures of 0.4 MPa, 0.6 MPa and 0.8 MPa with respective reflected pressures of 1.35, 2.50 and 3.4 MPa. These parameters correspond to wave speeds of between 650 m/s and 950 m/s.

2.4. Configuration of X-Ray Tomography Scans

All the dynamically loaded specimens were inspected using a Metris 160 H-XT X-ray CT system to investigate the extent of the internal damage and its spatial distribution. Each computed-tomography scan was conducted at 140 kV and 130 µA using a tungsten target, with 2650 radiography projections taken over the 360° rotation for each specimen at an exposure of 500 ms. In order to reduce granular noise, 8 images were taken and averaged per projection. The total volume scanned for each composite specimen was 180 mm × 140 mm × 20 mm at a resolution of 97 µm.

3. Experimental results and discussion

Following the experiment case studies, a typical response of damage caused by the major air blast condition can be seen in Figure 2, with the specimen undergoing global flexural bending between the fixture supports. This resulted in typical tensile damage with fracture initiating at the centre of the rear surface, followed by propagation of tensile fracture through the plies leading to inter-ply delamination.

Fig. 2. Typical major damage case: dynamic response to the air blast at 0.13 ms

3.1. Deformation Analysis

Plots of the centre-point displacement for each specimen show an initial oscillation leading to maximum displacement, followed by a subsequent gradual decay of oscillations due to dissipation and resultant backpressure. For each used air-blast pressure magnitude, the onset of delamination was found to initiate after a different number of oscillations. The amplitude and frequency of the oscillations were seen to change after delamination due to the reduction in local stiffness of damaged composite specimens.

The experimentally obtained cross-sectional plots of vertical and horizontal out-of-plane displacements clearly demonstrated that the deformation and transitions in curvature of each specimen, resulting from the different air blast magnitudes, were similar: there were no obvious differences apart from the excepted increasing out-of-plane displacement. No signs of localization can be naturally explained by the widely distributed loading area, resulting in an almost instant transitioning of each specimen to global flexural bending. Still, observations of the out-of-plane
displacement of the specimens allowed the onset of damage and fracture to be registered, with specimens demonstrating greater deformation at the centre of the rear surface’s free edges as the air-blast magnitude increased. This growth in local displacement was due to the increasing amount of tensile fracture and delamination of the rear-surface plies as seen in Figure 2, caused by rising bending tensile stresses. Although this is more apparent for the major damage case, this progression of damage and increased displacement at the free edges can be observed at each air-blast loading magnitude (from the employed range) before resulting in a clear failure of the specimen in the major damage case.

3.2. Damage Analysis

The visual inspection of each specimen post-experiment demonstrated the absence of observable damage for the minor loading case, whereas the medium and major cases clearly resulted in increased damage levels at the rear surface. The damage observed across all the loading cases can be compared to that of standard quasi-static three-point bending, where, for this type of composite, the first signs of damage appeared along a central line between the supports where the bending stresses were highest. This central line of symmetry between the supporting locations clearly showed tensile fracture of the individual plies of the composite, followed by delamination between them. There appeared to be no sign of damage on the front surfaces of specimens up until complete failure, suggesting that the tensile fracture of the plies and resultant delamination propagated from the rear surface through the thickness to the front surface during dynamic deformation.

The results from the X-ray computed tomography confirmed the preliminary observations. The circular loading area was observed to transform into a central symmetrical horizontal band of damage; an example of the major damage case is shown in Figure 3. The transparent (i.e. with the digitally removed material) 3D rendered view shows the damage cloud (represented via change in greyscale intensity). The greater the intensity of the greyscale, the higher is the damage accumulated through the thickness of the specimen. Analysis of the CT scans together with their additional 2D digital cross-sections and partial 3D images demonstrated that the main damage modes under conditions of air blast were delamination or tensile ply and fibre fracture.

The main features of the obtained damage pattern are a defined central damage zone where the air blast load was applied as well as damage areas at the free edges of the tested composite specimens (see Fig. 3), each being a result of a localised maximum of out-of-plane displacement between the lateral oscillations (along the direction of the band of damage).

While studying the 2D horizontal and vertical cross sections of each specimen it was possible to approximately measure this spread of damage down to the features observable at 97 µm; Figure 4 shows the final averaged distribution of damage against the averaged maximum out-of-plane displacement for different damage cases (pressure amplitudes). An increasing trend in maximum out-of-plane displacement is apparent for the increasing loading magnitude, as expected, leading to complete failure of some specimens. Observations and assessments of the change in damage.
clouds size with pressure vividly demonstrated that the averaged damage area increased with the magnitude of air blast.

4. Conclusions

Analysis of the centre-point displacement of composite specimens exposed to air blasts of different amplitudes showed changes in the oscillation period after the appearance of tensile fracture and delamination damage caused by a reduction of stiffness. The global deformation and transitions in curvature of each specimen were similar as the air blast magnitude grew, with the only difference being the increase in out-of-plane displacement. It demonstrates that the magnitude has no effect on the curvature and modes of oscillation during deformation for the range of air blast magnitudes investigated. The mechanical behaviour followed the typical deformation pattern expected in a three-point-bending setup, showing that the distributed loading led to instant global flexural bending, thus avoiding any obvious significant localised indentation events and associated damage. For the major and failure damage cases, higher deformation of the rear-surface plies was observed at the free edges of the composite specimens, resulting from the initiation of the tensile fracture and delamination of the first few plies along the central band of damage.

The X-ray computed tomography demonstrated that damage is seen was initiated and propagated from the rear surface of the specimens through their thickness to the front surface as the air blast magnitude increased. For the minor damage case, no significant damage was observed, but for the major damage case the specimens experienced significant damage in the form of tensile fracture and widespread delamination propagating from the central line of the specimen’s symmetry. Given the similar global flexural bending behavior for all specimen across all damage cases, damage consistently was initiated at the centre and free edge of the specimens, where the local bending stresses appear to be highest.

5. References