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ScienceDirect

Procedia Structural Integrity 2 (2016) 366–372

Structural Integrity Procedia

www.elsevier.com/locate/procedia

21st European Conference on Fracture, ECF21, 20-24 June 2016, Catania, Italy

Dynamic Fracture in Carbon-fibre Composites: Effect of Steel and Ice Projectiles

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Abstract

In this study the resultant ballistic dynamic response observed in a 2x2 twill weave T300 carbon fibre/epoxy composite flat-plate specimen is examined, using a combination of non-invasive analysis techniques. The study investigates deformation, damage and fracture following the impacts with both solid (steel) and fragmenting (ice) projectiles travelling with velocities of 70-90 m/s and 300-500 m/s, respectively. Digital image correlation was employed to obtain displacement data for the rear surfaces of the specimens in each experiment, and used to assess the effect of impact velocity and projectile material on the specimen's response. 3D X-ray computed tomography was used to image and visualize the resultant internal cloud of damage and fracture, initiated by dynamic loading in each specimen. It was shown that solid projectiles led to greater localized deformation and, in some cases, penetration, whereas fragmenting projectiles destroyed on impact resulted in more distributed loading leading to major front-surface damage depending on the depth on indentation before fragmentation.

Peer-review under responsibility of the Scientific Committee of ECF21.

Keywords: Ballistic Impact; CFRP; X-ray Tomography; Deformation; Damage

1. Introduction

The use of fibre-reinforced composites (FRCs) has increased considerably over the last few decades across many areas of application including automotive, aerospace, naval, defence, energy and sport. In many of these applications dynamic loading is a part of in-service conditions and can result in a wide range of damage. Some examples of dynamic loading may include low- and high-velocity impacts (in the range between 1 and 1000 m/s), ranging from flight at Mach 1-2 (300-600 m/s) of fighter jets or intercontinental ballistic missiles through clouds of debris or

Peer-review under responsibility of the Scientific Committee of ECF21.
10.1016/j.prostr.2016.06.047

hailstones, to lower-velocity impacts caused by debris on runways, railway lines, auto race tracks etc. As a result, developing a full understanding of these types of dynamic loading conditions and their effect on responses of FRCs is very important, in terms of both local and global distributions of deformation as well as initiation and evolution of the visible and hidden damage.

Over many years there have been a vast amount of research efforts towards characterising the response of FRCs under various dynamic loading conditions, but drawing comparisons between these studies is challenging – and often impossible – due to their major differences such as the type of specimens and, more importantly, employed experimental and analytical methodologies. In the past, some papers tried to surmise an overview of impact behavior such as the work conducted by Abrate (1991 & 1994), but analysis of considerable amounts of experimental data drew mostly qualitative conclusions on differences in methodology and used specimens together with broad statements on the effect of projectile mass and velocity on delamination behaviour.

In dynamic studies, it is important to understanding the type of loading conditions and character of temporal interaction with the specimen. For instance, a high volume of both experimental and numerical studies was focused on the resulting deformation, damage and fracture caused by solid projectiles (typically steel), but in recent years some efforts have been made towards understanding the impact process of ice projectiles (Pernas-Sánchez et al., 2015) and the effect on composite specimens of fragmentation on impact and resultant distribution of loading and dispersion of kinetic energy (Kim et al., 2003; Appleby-Thomas et al., 2011). But, typically, the analysis of the resultant damage is limited to a visual inspection of external surfaces, or a use of invasive techniques to study internal damage that could introduce additional damage complicating interpretation of results (Nunes et al., 2004; Sevkat, 2012; Shaktivesh et al., 2013; Yahaya et al., 2014). Some studies became investigating damage using X-ray tomography (Karthikeyan et al., 2013).

This paper presents the experimental case studies, in which carbon fibre/epoxy composite specimens were subjected to ballistic loading with steel and ice projectiles, in order to investigate and compare the resultant deformation, damage and fracture observed using digital image correlation and X-ray computed tomography (CT).

2. Experimental Setup

2.1. Materials and Specimens

The used in the test carbon-fibre-reinforced epoxy specimens, measuring approximately 195 mm x 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 plies were formed to a laminate consisting of 2 surface plies (T300 3K) and 8 central bulking plies (T300 12K), with a 0/90° layup configuration. All specimens were manufactured using the autoclave process, cured at 120°C with a ramp rate of 1.5°C/min and a soak time of 160 minutes at a pressure of 90 Psi under full vacuum. A theoretical density of the produced specimens was 1600 kg/m^3.

2.2. Pneumatic Gun and Specimen Setup

The investigation was performed on specially developed ballistic experimental apparatus utilising a pneumatic gun. The CFRP specimens were installed into a 4-axis positioning system, and aligned with the barrel resulting in a cantilever clamping regime with all specimens being subjected to a perpendicular impact (as shown in Figure 1). The projectile was accelerated to the required speed in the barrel using compressed air, and muzzle velocity measurements were collected using a light gate device installed between the specimen and the end of barrel. Projectile velocities were then determined based on the time difference between the signal peaks from the light gates; the experiment was controlled by a PC via a PXI system (National Instruments). The impact process was captured using two high-speed cameras (Photron Fastcam SA5) configured in two arrangements, the first to capture the front and top views at 25,000 - 50,000 frames per second while the second captured the rear surface for digital image correlation (DIC) using the VIC-3D (Correlated Solutions) system at 60,000 frames per second.