Composite Structures 119 (2015) 90–98

Contents lists available at ScienceDirect

Composite Structures

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

On the ballistic response of an aerospace-grade composite panel to non-spheroidised fragment simulants

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ARTICLE INFO

Article history:
Available online 23 August 2014

Keywords:
CFRP
Ballistic impact
Fragment geometry

ABSTRACT

The low mass and high specific strength of composite systems has led to their widespread adoption in aerospace applications. Consequently their performance under impact from off-normal events, or even deliberate insult, for example from a munition such as an anti-aircraft missile, is of paramount importance. Experimental and computational work to-date has typically focused on the response of composite systems to impact from projectiles with simple spherical or cylindrical geometries. However, such geometries are not representative of the full range of likely threats. In addition, even within this simple set of constraints the effects of projectile geometry on composite response under impact have been highlighted. Here an attempt has been made to investigate the effect of more complex geometric structures – comprising two-dimensional flat and peaked-nosed structures – on composite systems. A series of ballistic tests were carried out accelerating various geometric 'fragment simulants' into an aerospace-grade composite material. Damage was monitored in real time using high-speed cameras. Resultant calculations of projectile energy loss in the target, combined with analysis of recovered material via ultrasonic c-scan, have shown a clear relationship between projectile geometry and CFRP failure mode.

1. Introduction

Both cost savings and performance improvements can result from weight reduction, providing a constant drive to minimise the mass of aerospace structures. Consequently, composite materials which combine low mass with high specific strengths are becoming ever more prevalent in the aerospace industry [1,2]. In-service, aerospace systems are vulnerable to impact events of either natural or artificial origin (e.g. hail or MANPAD anti-aircraft systems, respectively). Such impact events may occur in the ballistic or hypervelocity (>2 km/s) regime [3,4]. Here, lower velocity 'ballistic impact' events such as collision with hail stones or shrapnel from anti-aircraft munitions, are considered.

These threats necessitate an understanding of the impact response of aerospace materials. This requirement has been recognised in recent years by a number of reviews. Cantwell and Morton [5] provided an overview of the impact response of numerous continuous fibre-reinforced composites. Consideration was given to several factors affecting composite response, namely: fibre properties; matrix properties; interphase properties; the nature of fibre stacking and the geometry of the composite. In particular, the importance of the interphase (the bonding region between the matrix and fibres) was highlighted. For example, if only a single projectile needs to be stopped then a weaker bond would be desirable, as this would allow for fibre/matrix delamination and subsequent energy dissipation. However, if post-impact properties were to be maximised, then a stronger bond would be required; consequently a trade-off in properties would likely be required for real-world applications. In a similar way, high strain-to-failure (smaller diameter) fibres were shown to provide increased ballistic resistance. However, the fact that reducing fibre diameter also reduced compressive strength was highlighted.

In addition, Cantwell and Morton [5] found the effects of geometry to be important, as energy absorbing capability did not always scale with target volume; with factors such as the curvature of a target shown to influence damage evolution. Further, rate-dependant behaviour was noted, with areal geometry becoming less important at higher rates-of-strain. For example, specimens of 50 mm and 150 mm length were impacted and analysed via c-scan, showing negligible differences in the levels of damage present in each [6].

More recently, Hazell and Appleby-Thomas [7] conducted a review of the literature focussing on the impact response of structural composite materials. This review detailed the key factors influencing both carbon and glass fibre-based composite systems. The authors highlighted that the vast majority of research to-date

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http://dx.doi.org/10.1016/j.compstruct.2014.08.016
0263-8223/

has suggested that, for two-dimensional composites, fibre lay-up and sequence are only influential at relatively low impact velocities (shown previously, for example, by [8,9]). An example of this behaviour was published in a study by David-West et al. [10], in which two differently composite lay-ups were subjected to impacts by hemispherically-nosed projectiles via a drop-tower. The resultant data showed that, in this relatively low velocity regime, the 0/45/90 layup was less resilient to this form of assault, when compared to tests on a 0/90 layup employing the same impact conditions. Conversely, at higher impact velocities, penetration has been found to be relatively independent of the nature of the composite lay-up. Advantageously, Hazell and Appleby-Thomas [7] also presented information from the literature, which concerned the ballistic response of composites at low temperatures. In particular, they highlighted the fact that beyond the ballistic limit, energy absorbing capabilities of CFRPs are comparable to those at room temperature. This is a significant factor for aerospace systems, where low temperatures would be expected during normal in-service life.

The majority of the aforementioned experimental studies into the ballistic response of composites have centred on the effects of relatively simple projectile types [7,11–13]. For example, Cantwell and Morton [11] considered the effects of 6-mm diameter, 680 g hemispherically-nosed (driven at low velocity by a drop tower) and spherical, 6-mm diameter, 1 g projectiles (saboted projectiles driven to a high velocity by a light gas-gun) on different CFRP laminate geometries. They found that the loading strain-rate had a significant effect on composite response, with geometric factors key at lower velocities where elastic effects were important. Whereas at higher velocities, localised damage independent of factors such as target extent, were more prominent. This result was consistent with the general conclusions reached by Hazell and Appleby-Thomas [7], with regards to the influences of composite lay-up.

As already discussed, many researchers have employed spherical or hemispherically-fronted projectile arrangements in a similar manner to Cantwell and Morton [11]. These include Hazell et al. [12] who studied the effects of thickness and obliquity on woven CFRP performance when impacted with 11.97-mm diameter, 7.2 g annealed steel spheres. In this study, targets were impacted at velocities in the range 170 to 374 m/s and high-speed video was employed to monitor the impact events. A transition in failure mode from petalling at lower impact velocities to plug formation (shear) at higher velocities was observed, consistent with the strain-rate effects observed previously by Cantwell and Morton [11]. This correlated to a ballistic advantage in terms of kinetic energy absorbed per unit of composite thickness for thicker CFRP systems at lower impact velocities. This behaviour was attributed to the fact that the incident projectile required more energy to push the petals formed in thicker composites out of the way during penetration, as opposed to situations where thinner composites were impacted. However, at elevated impact velocities where petalling was no longer the dominant failure mode this advantage rapidly diminished. Further, while Hazell et al. [12] found evidence of enhanced performance for inclined CFRP targets, when penetration was normalised for the resolved thickness of the inclined targets the increased ballistic resistance was found to be entirely attributable to this geometric effect.

López-Puente et al. [14] also studied the effects of obliquity on the resilience of carbon/epoxy woven laminates. Targets angled at both 0° and 45° were impacted by 1.73 g steel spheres at velocities between 70 and 531 m/s via the employment of a gas gun. In line with other studies published in the literature, a high-speed camera was used to measure residual velocities. Below the ballistic limit, López-Puente et al. observed that the damage caused to targets at both angles increased with impact velocity, however above this limit, the opposite behaviour was noted. Results also showed that the ballistic limit increases with the obliquity of the target. Below the ballistic limit, greater levels of damage were seen in the 0° targets; however, at higher velocities, damage observed in 45° targets was shown to be greater than in the 0° arrangements. The authors attributed this behaviour to a change in the governing damage mechanism at the ballistic limit; below, delamination was the key mechanism whereas above, it was projectile piercing.

In a similar study to Hazell et al. [12], Caprino et al. [13] investigated the ballistic response of various thicknesses of stitched CFRP materials, designed to be more resistant to delamination than un-stitched systems. Targets were impacted with 12.7 and 20-mm diameter projectiles at nominal impact velocities of 129 and 65 m/s, respectively. In concord with the results from Hazell et al. [12], employing low impact velocities (comparable to those tested here), the perforation energy was found to increase non-linearly with panel thickness. This suggested a ballistic advantage for thicker panels in this velocity regime, presumably resulting from the failure mode in operation. Ultrasonic c-scan analysis of the impacted composites showed a number of interesting features: (1) stitching was found to inhibit subsurface delamination in places, with the failure contours following the stitching itself, and; (2) delamination was found to have a circular form with thicker plates and an elliptical nature (oriented along the fibre-direction) with thinner panels, suggestive of a thickness-dependant change in failure mode. In addition, experimental data was found to be in good agreement with two models from the literature [15,16].

Robinson and Davies [17] conducted a series of tests in which woven fibre reinforced composite laminates were impact with projectiles of a variety of masses. One of the main aims of this study was to observe the effects, if any, varying mass alone had on the stress distributions close to the impact point and the damage mechanisms present. The results of these tests showed that at the low velocities employed here both the damage seen and the peak force was purely a function of the impact energy, i.e. the combined effect of both mass and velocity, rather than either being solely responsible.

Other researchers have looked at the effects of cylindrical projectiles on composite systems [18,19,22]; these tests have often been carried out to aid in the validation of numerical models, as such projectiles ensure uniform contact area on the target composite. There have been numerous attempts to produce numerical models which enable simulation of the impact response of composite systems [18,20–23]. However, these have been complicated by the structural complexity inherent in such arrangements. Wen [18] derived a series of equations which allowed prediction of changes in penetration and ballistic limit of fibre reinforced polymers under impact from both flat, hemispherical, ogive and conically-shaped projectiles. However, only limited comparison to disparate literature data was made, with the assumption of localised damage on impact. Consequently, while a useful predictive tool, only limited insight into the physical nature of CFRP failure could be drawn. In a recent paper building on previous studies [20,21], Shaktivesh et al. [22] developed a numerical model based around an energy balance approach, in which a projectiles kinetic energy was equated to the various potential damage and energy absorbing mechanisms. The mechanisms studied were primarily shear plugging, compression of the composite yarns and tensile failure of elements of the composite. Penetration was considered to occur in three phases: (1) initial compression on impact – with compressive longitudinal and shear waves propagating through the composite, leading to local failure where material strength is overcome; (2) wave arrival at the rear face of the composite – potentially leading to conical deformation and consequent tensile loading of un-failed fibres, and; (3) frictional interaction between the projectile and failed composite material. Simulations from the numerical model were compared to a series of ballistic tests