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Review

Ballistic impact behaviour of stitched graphite/epoxy laminates

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Abstract

Four stitched graphite/epoxy laminates of different thicknesses were subjected to high-velocity impact tests. Two steel spheres, 12.7 and 20 mm in diameter, were used as bullets during the tests, carried out at two different speeds (65 and 129 m/s). Perforation occurred only under some of the experimental conditions adopted, whereas rebound was verified in other cases. As expected, the perforation energy increased with increasing the panel thickness and projectile diameter.

In order to predict the perforation energy as a function of target thickness and bullet diameter, the Reid and Wen model and the Cantwell and Morton model were used. The Cantwell and Morton model was suitably modified: a new hypothesis was made, and an easier formulation, needing a single constant to be experimentally determined, was obtained.

The dependence of perforation energy on laminate thickness was well described by the models considered, which provided very similar predictions. The same happened for the rebound conditions. However, only the modified Cantwell and Morton formula was effective in modelling the influence of the impactor diameter, while the Reid and Wen model provided a theoretical value about 50% higher than the measured one.

The delaminated area was measured by ultrasonic C-scan in pulse-echo mode. It was found that a linear relationship links the delamination extent and the maximum energy absorbed by the panel, whichever the specimen thickness and projectile diameter. This correlation becomes ineffective for thick laminates, probably because of a change in failure modes occurring at sufficiently high thicknesses.

Keywords: A. Polymer-matrix composites; B. Impact behaviour; C. Delamination; Stitching

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Contents

1. Introduction 326
2. Background. 326
3. Materials and experimental methods 328
4. Results and discussion 329
5. Conclusions. 334
6. Acknowledgements 334
References. 334

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1. Introduction

The concorde tragedy occurred in Paris in 2000, probably caused by a tire fragment moving at high speed and impinging the jet's fuel tanks, highlighted the importance of the impact behaviour of aeronautical materials. Among these, carbon fibre reinforced plastics (CFRPs) are well-known to be particularly vulnerable to damage from foreign objects, especially because of the brittleness of the polymeric phase, giving rise to a multiplicity of failure modes. For this reason, many studies have been undertaken to individuate the failure mechanisms induced in composites by impact [1–4], to model the impactor-material contact history [2,3,5–7], and to predict the post-impact material properties [3,8–11].

When a laminate is struck at low or moderate impact energy levels, fibre failures are seldom observed. More often, matrix-dependent damage, consisting of delamination and intralaminar cracks, is found. Amongst all the possible failure modes, delamination has received major attention. In fact, its occurrence is detrimental to the residual compression strength, which can be lowered to 40–60% of that of an undamaged component [12,13], even in absence of fibre failures. Delamination extent is usually measured by ultrasonic C-scan, which provides an in plane view of the damaged zone. By this technique, some information is lost on the actual damage state, which is typically made of several interlaminar cracks located at different heights along the material thickness [1–4,14,15]. Nevertheless, a C-scan procedure is easy to perform and relatively inexpensive, and experimental evidence is given that the in-plane dimensions of delamination can be correlated with the material residual strength [3,16]. Further, the delamination area as revealed by ultrasonic C-scan is frequently used to rank different laminates on the basis of their impact resistance [3,17].

In the last years, various strategies have been proposed to hinder intraply delamination, thus increasing the impact resistance of CFRPs [18]. They encompass toughened thermosetting and thermoplastic matrices, interleaving, *Z*-pinning and stitching. The latter method has been found to be particularly effective in improving damage tolerance [19,20], and it is generally agreed that stitching technology will play an important role in primary structures of next generation commercial airplanes. However, it has been also shown that the use of stitches can be detrimental to some mechanical properties, such as quasi-static in-plane stiffness and strength [20]. Recent results seem to indicate that the same holds for the perforation energy, when both low- [21] and high-velocity [22] impact conditions are concerned, although not much data are available on this particular topic. Lopresto et al. [21] found that the perforation energy of stitched CFRP laminates at low-velocity was about 30% lower than their unstitched counterparts. Hosur et al. [22] carried out high-velocity impact tests up to perforation on stitched and unstitched panels. The damage size was lower in the stitched samples as compared to the unstitched samples. However, the presence of stitches lowered the ballistic limit. It was concluded that the choice of stitched or unstitched laminates should be based on whether the design requirement is improved damage tolerance or improved perforation energy.

The phenomena occurring during the sample-bullet contact are quite complicated, involving dynamic aspects which can affect the target response and failure modes substantially [7,23]. Therefore, quite complex numerical analyses, relying on the observation of the failure modes actually occurring or on micromechanical approaches [2,6,24], have been performed by many authors to predict the entire contact history. In order to quickly evaluate the perforation energy, closed-form relationships deriving from the phenomena taking place at the macroscopic level have been also proposed [2,14,15,25]. One of the drawbacks of closed-form formulae is in their applicability, which is limited to a specific impact regime (high-velocity/low-mass or low-velocity/high-mass). However, these tools do not require a detailed modelling of the damage development during impact. Further, their simplicity makes them useful in the first stages of design, allowing a rapid comparison of the candidate materials available and a quick evaluation of the structural weights involved.

In this work, dynamic tests were performed on stitched CFRP panels of different thicknesses, which were struck by two spherical projectiles of different diameter. The experimental results generated were used to verify two closed-form models previously proposed [14,25] for the prediction of the perforation energy, one of which was suitably modified. The damage area of the impacted samples was recorded by ultrasonic C-scan, in order to study the correlation between delamination extent and the maximum energy absorbed by the target during impact.

2. Background

In this work, two different models available in the literature, aiming to predict the perforation energy of a composite laminate as a function of target thickness and projectile diameter, are considered. Their main features are recalled here.

Cantwell and Morton [14] used 6 mm diameter steel impactors to perform low- and high-velocity impact tests on CFRP panels of different laminations and thicknesses. For a given laminate, the perforation energy was higher at low-velocity than at high-velocity, although the failure modes were apparently the same. To explain the phenomenon, the authors shared the energy dissipated in perforation, U_p, in two parts:

$$U_p = U_e + U_f \tag{1}$$

where U_e is associated with the elastic flexural response of the panel, and U_f with the failures in the material. Cantwell and Morton speculated that, under low-velocity impact conditions, the contact time is relatively long, so that the whole panel has time to respond, storing elastic energy in