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Characterization of indentation damage resistance of hybrid composite laminates using acoustic emission monitoring

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ABSTRACT

This paper focuses on the experimental investigation of impact damage resistance in hybrid composite laminates. In this case, the low velocity impact behaviour of quasi-isotropic glass/epoxy, glass/basalt/epoxy (G/B/G, B/G/B) and glass/carbon/epoxy (G/C/G, C/G/C) composite laminates was simulated by carrying out quasi-static indentation (QSI) tests with online acoustic emission (AE) monitoring. The dent depth, back surface crack size and load-deflection behaviors were examined and there is no distinct differences could be seen between low velocity impact tests and quasi-static indentation tests. The QSI tests were performed on specimens with rectangular section, of size 150 mm x 100 mm, which were loaded at the centre by a hemispherical steel indenter with 12.7 mm diameter. The indentation response was evaluated by measuring peak force, absorbed energy and linear stiffness. The residual strength of the laminates following indentation was measured by testing them under compression load in a 100 kN universal testing machine, once again with AE monitoring. AE parameters, such as amplitude, rise time, cumulative counts and cumulative energy were considered for monitoring damage progression during quasi-static indentation loading. Also other parameters linked to AE monitoring, such as the rise angle (RA) and Felicity ratio (FR) were measured for evaluating the damage resistance in each cycle of indentation. In addition, sentry function was also computed based on the combination of mechanical strain energy accumulated in the materials and of the acoustic energy propagates by fracture events made it possible to evaluate the amount of induced damage. These results showed that the combination of glass and carbon fibres in glass/carbon/epoxy (C/G/C) laminates improved their interlaminar shear strength at a level well above the other configurations tested.

1. Introduction

Composite materials are widely utilized in modern vehicles, aircraft and other light-weight structures. These materials have high strength, high elastic modulus and easy fabrication process, compared to more traditional structural materials. On the other hand, laminated composite structures are susceptible to impact induced damage, a fact which may result in their catastrophic failure [1,2]. In the past few decades, the effect of fibre, matrix and interfacial properties of composite laminates on impact and post-impact residual strength behaviour was studied by different researchers [3–5]. Low energy impact is most dangerous for polymer matrix composites, because internal damage may not be detected by routine visual inspection of the impact surface, though possibly causing noticeable strength reduction. It was experimentally proven that damage occurring in polymer matrix composites due to quasi-static indentation (QSI) is similar to that produced by low-velocity impact (LVI) loading [6,7]. The non-transient out-of-plane transverse load can be represented using quasi-static indentation (QSI) tests [8].

Caprino and Lopresto [9] studied the external indication of damage by impact in the form of indentation, which is usually defined under the name of *barely visible impact damage* (BVID). In this case, a simple power law was used to correlate the dent depth with impact energy. The ratio between impact energy and penetration energy is adopted as an independent parameter, in that the relationship contemplates negligibly affected by fiber type and orientation or matrix type. The experimental results showed that the penetration energy is appreciably unaffected by the loading speed so that the formula suggested by these authors for the

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evaluation of the penetration energy is also effective in static tests [10,11]. A comparison between dynamic and static tests was offered by Abdallah and Bouver [12]. They concluded that the maximum force attained during the impact tests was quite greater than in the case of quasi-static tests. However, the absorbed energy and damage morphology are equivalent for both tests. Several studies [13–15] indicated a similarity between results obtained during quasi-static indentation and falling weight impact tests. In other words, the impact event can be simulated using a quasi-static indentation test, so that damage initiation and propagation can be studied thoroughly, and deformation can be directly measured with great accuracy and improved control over maximum contact force.

Many researchers have used different parameters to quantify local damage in composite laminates during quasi-static indentation tests [16–19]. The parameters that are commonly used to quantify local damage behaviour are peak load or ultimate load, incident energy, absorbed energy, elastic energy and dent depth or residual deformation. These measures of indentation response can be related to the damage developed during each cycle of indentation test. This analysis was successfully applied to sandwich structures [17] and composite laminates [16,18,19]. Quasi-static tests were performed by Kwon et al. [20] and Nettles et al. [21] as a replacement for dynamic tests, because much more data can be obtained from quasi-static indentation testing than from low-velocity impact testing. Low-velocity impact test of composite laminates complies with ASTM D7136-15 standard [22], while quasi-static test of composite laminates follows ASTM D6264-12 standard [23].

Non-destructive testing methods were also widely utilized to improve understanding of damage evolution in laminated composite materials [24]. Acoustic emission (AE) is a non-destructive testing method and showed potential for monitoring damage evolution of composite materials [25–27]. AE signal is the result of transient elastic strain waves generated inside materials as they undergo fracture or deformation. Therefore, this technique is capable to offer *in situ* information about damage mechanisms occurring during loading of composite materials. Andreikiv et al. [28] simulated low-velocity impact test results using quasi-static indentation test with AE monitoring for analysing damage initiation and progression. Using AE, a comprehensive damage characterization can be carried out by combining mechanical and acoustical parameters. In particular, sentry function [1,27,29], which combines mechanical and acoustic energy information, was demonstrated to be a useful tool. This function enabled measuring fracture energy release rate and following damage progression of composite laminates. This technique was also used to study damage propagation and to estimate the residual strength of composite materials subjected to indentation processes and lateral impact [1].

Hybridization of different fibres is an approach frequently used to increase the resistance of composite materials against impact damage by introducing two or more different types of fibres as matrix reinforcement. The effect of the various configurations of hybrid laminates has been investigated during recent years [30–33] and impressive results were reported. However, more research studies are still needed for sounder investigation of impact damage progression in hybrid composite laminates obtained with different layup configurations and using various materials. The purpose of using layers of different laminates in the same composites, hence obtaining a hybrid, would in particular allow having behaviour as much as possible tailored for the service needs, which is particularly important in the case of laminates likely to be subjected to highly inelastic damage, such as in the case of falling weight impact. For example, adding glass fibres was demonstrated to increase the dissipation of nonlinear deformations in carbon fibre composites without leading to intraply cracking [34]. In terms of impact, glass/basalt hybrids with intercalated stacking sequence exhibited higher impact energy absorption capacity than glass laminates, and enhanced damage tolerance capability [33]. These considerations suggest that hybridisation is able to offer a much more flexible behaviour and a large number of configurations are likely to be investigated in the future for the purpose to offer a distinctive sequence of performance tailored on the requirement of the specific application and context of use selected: generally speaking, a typical field where impact is a major concern is transportation.

In this study, the effect of hybridization on impact and post-impact performance of composite laminates is investigated. The behaviour after multiple impact loading of quasi-isotropic glass/epoxy, glass/basalt/epoxy (G/B/G, B/G/B) and glass/carbon/epoxy (G/C/G, C/G/C) laminates was simulated by cyclic quasi-static indentation (QSI) tests with online AE monitoring. The indentation response was evaluated using peak force, absorbed energy and linear stiffness. After indentation and impact, the laminates were subjected to compression after impact/indentation (CAI) tests with online AE monitoring for estimating the residual compressive strength. A number of parameters concerning AE analysis were examined, namely cumulative counts, normalized cumulative energy, rise angle (RA) and Felicity ratio (FR) to evaluate the damage resistance in each cycle of indentation. Mechanical and AE data were combined to serve to improve understanding of the damage evolution during indentation test.

2. Experimental procedures

2.1. Materials

A stitch-bonded unidirectional E-glass fibre of 220 g/m^2, unidirectional basalt fibre of 200 g/m^2, and unidirectional carbon fibre of 270 g/m^2 areal weight were used as reinforcements for composite laminates preparation. Epoxy resin (LY556) i.e., diglycidyl ether of bisphenol-A (DGEBA) with hardener (HY 951) in the ratio of 10:1 was used as the matrix materials.

2.2. Composite preparations

The composite laminates were prepared using a compression moulding machine. A total of five different lay-up configurations were produced, which are reported in Fig. 1. Care was taken to ensure that the thickness of the five different laminates was the same. The fibres were placed in the mould and the resin hardener mix was then applied to the fibres by hand layup process and cured using a 30 kN compression moulding machine at a hydraulic pressure of 50 kg/cm^2 and a room temperature for 24 h. The quasi-isotropic sequence of 16 layers composite laminates is yielding a nominal thickness of 4.5 ($\pm$0.25) mm. ASTM D6264-98 (04) standard indentation test, ASTM D7136M-05 standard low-velocity impact test and ASTM D7137M-12 standard compression after impact or indentation (CAI) test specimens 150 mm long and 100 mm wide were cut from the fabricated laminates using water jet cutting machine.

2.3. Falling weight impact (LVI) tests

Fractovis falling weight impact tester was used for inducing impact damage in 20 specimens (for each laminate configuration, four specimens were impacted) with a constant impact velocity of 3 m/s and a nominal impact energy of 9.45 J. The impacting plunger has a cross-head mass of 1.92 kg and the diameter of the hemispherical indenter was 12.7 mm with a clamping force of 1000 N.