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Investigation of the response to low velocity impact and quasi-static indentation loading of particle-toughened carbon-fibre composite materials

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ABSTRACT

This work investigates damage caused by low velocity impact and quasi-static indentation loading in four different particle-toughened composite systems, and one untoughened system. For impact tests, a range of energies were used between 25 and 50 J. For QSI, coupons were interrupted at increasing loading point displacement levels from 2 to 5 mm to allow for monitoring of damage initiation and propagation. In both loading cases, non-destructive inspection techniques were used, consisting of ultrasonic C-scan and X-ray micro-focus computed tomography. These techniques are complemented with instrumentation to capture force–displacement data, whereby load-drops are associated with observed damage modes. Key results from this work highlight particular issues regarding strain-rate sensitivity of delamination development and an earlier onset of fibre fracture associated with particle-toughened systems. These issues, in addition to observations on the role of micro-scale events on damage morphology, are discussed with a focus on material development and material testing practices.

1. Introduction

In addition to low velocity impact, composite structures may be susceptible to damage from non-transient out-of-plane point loads which can be represented using quasi-static indentation (QSI) experiments. It is reported in studies that the two loading conditions yield similar damage characteristics in both experimental and analytical cases due to the analogous loading and boundary conditions that arise [1,2]. Controlled QSI loading may therefore present a valuable experimental strategy to imitate the chronology of processes occurring during impact, but without incurring the complexities of real-time observation during an impact test. The non-destructive inspection capabilities of micro-focus computed tomography (μCT) [3] may then offer a powerful approach to monitor the evolution of damage, with the initiation and development of damage being measured as a function of the increasing applied displacements, and resultant loads [4]. Despite the similarities between QSI and impact, it is of course clear that QSI does not introduce the same dynamic and time-dependent components of impact events. It has previously been debated within the literature as to the limits of utilising QSI to represent low velocity impact events, *e.g.* [1,5].

In studies that compare QSI to impact loads, similarities have been reported in C-scan damage area and load displacement curves [6–12]. Whilst this provides an understanding of the general damage resistance response of such systems to loading, it neglects to identify if there are similarities in the interaction of different damage modes and if there are underpinning mechanistic similarities or indeed differences. Whilst previous studies have attempted to capture the micromechanisms of damage under increasing QSI loading, *e.g.* by using cross-sectional microscopy, no time-resolved 3D analysis has been reported. Such information may play a significant role in validating finite element models and guiding future toughening strategies, in which toughness may for example be targeted to certain ply interfaces [13].

This paper aims to highlight the importance of understanding damage mechanisms in order to guide material development and material testing practices under low velocity impact and QSI loading conditions. The vast majority of the work that has been done to date on impact and QSI loading has looked at characterisation of damage and definition of damage resistance and damage tolerance via relatively coarse measurements of overall damage areas, generally without definition of damage location and often without definition of damage type. In the present work, in order to characterise the

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response of composite systems more precisely, μCT is used to provide novel, detailed comparisons of damage under low velocity impact and interrupted QSI conditions, complementing ultrasonic C-scan and force–displacement data.

This work extends the understanding of the failure mechanisms operating in particle-toughened systems and builds upon previous work on the same material systems, including assessment of the role of particle-toughening micromechanisms in impact damage resistance [14], and observations of damage propagation in compression-after-impact tests [15].

2. Materials and test procedure

2.1. Materials

One untoughened (UT) and four particle-toughened (T1–T4) carbon-fibre prepreg systems were manufactured. The materials used are proprietary next generation prototype systems using an intermediate modulus carbon fibre. A quasi-isotropic layup $[45/0/-45/90]_{3S}$ was used to create test coupons measuring 150×100 mm with a thickness of approximately 4.6 mm. The toughened systems were labelled in order of impact damage resistance, as measured by the size of the projected delamination area obtained via ultrasonic C-scan (T1 being the largest projected damage area for a given impact energy and T4 the least).

For the particle-toughened systems, the matrix consisted of thermoplastic particles introduced to the base thermoset epoxy resin with varying sizes and chemistry used for each system. The particle–resin mixture was present at the interlaminar regions of the composite. Particle sizes were in the order of 4–30 μm in diameter. A particle-resin mixture was introduced to the surface of the prepreg during manufacture following a wetting process of the fibres with epoxy resin. The process of adding particles to the prepreg occurred sequentially on the same prepreg manufacturing line. The same particle to resin ratio (by weight) was used to form the matrix in the toughened systems. Regarding all the systems, the same fibre to matrix (resin plus particles) ratio by weight was used. The same intermediate modulus carbon fibre type and base epoxy resin system was used in all five material cases. The particle toughened systems shared the same lamina elastic modulus properties.

The interlaminar mode II fracture toughness of each composite system was supplied by the manufacturer and has been normalised by dividing individual fracture toughnesses by the largest measured toughness value. These values were measured from end notch flexure tests following ASTM D7905M standards. Corresponding normalised mode II fracture toughness values for UT, T1, T2, T3 and T4 systems are 0.4, 0.8, 0.3, 0.6 and 1.0 respectively.

2.2. Test procedure

Instrumented impact tests were conducted at 25, 30, 40 and 50 J and repeated three times for each material system. The exact impact energy was measured and in all cases was found to be within 3 J of the target energy. These tests were conducted in accordance with the ASTM D7136M standard using a 4.9 kg, 16 mm hemispherical tup and a base plate containing a 75×125 mm rectangular window. QSI experiments utilised the same tup geometry and base plate in order to achieve comparable boundary conditions as the impact experiment. QSI loading was applied at a cross-head displacement rate of 2 mm per minute; force–displacement data was recorded for the loading stage. Incremental displacement steps of 2, 2.5, 3, 4, and 5 mm were applied sequentially from the position where the tup contacted the coupon's surface. The range of incremental displacements was selected to capture damage initiation and damage growth. The first displacement step of 2 mm was chosen based on the force–displacement load drop observed in the UT system. The final displacement step of 5 mm was chosen to match the peak displacement reached in the majority of 40 J impact tests. The formation of a dent after the initial loading condition resulted in a total out-of-plane displacement slightly greater than 2.5, 3, 4 and 5 mm. QSI tests were conducted on three specimens for each material system.

After impact or application of QSI load increments to the coupons, ultrasonic C-scans and μCT scans were carried out. It should be noted that these were achieved non-destructively, with no cutting of the samples. The ultrasonic C-scans were performed at a 1 mm resolution. Due to time restrictions on the μCT equipment, the T2 system was omitted for detailed μCT analysis. Coupons of the other four materials were scanned in pairs; an XTEK™ Benchtop μCT scanner was used to scan the contact region of the QSI samples subjected to 2–4 mm displacements. A larger Nikon™ HMX system was used to scan the QSI samples subjected to 5 mm displacement and impacted coupons subjected to 25 J and 30 J for UT and particle-toughened systems respectively. A lower impact energy was chosen for the UT system to restrict the extent of damage to fit within the field-of-view. Samples were scanned using the following settings: 115 kV peak, 100 μA, 1301 projections, 2 frames per projection and 1 s exposures. This led to a voxel resolution of 12.6 and 14.2 μm for Benchtop and HMX scans respectively.

3. Results

3.1. Projected C-scan damage area

To assess damage resistance under quasi-static and impact loading conditions, C-scan damage areas have been plotted against the applied energies in Fig. 1 for both loading conditions. The applied energies for QSI data were calculated by integrating the area under the force–deflection plots for the loading increments *e.g.* see Fig. 2. The energies corresponding to each additional loading step were calculated by integrating the force–deflection beyond the deflection of the previous load step and adding this to the energy calculated from the previous loading stage to give the total energy applied. Applied energies for impact tests were based on the velocity at impact and the mass of the tup.

The plots in Fig. 1 shows a strong linear relationship between damage area and the applied energy for both impact and QSI loading conditions, with the exception of the T3 system where scatter in the order of a factor of two was observed at impact energies of 40 and 50 J. The gradients of the impact trend lines are reasonably consistent for UT, T1, and T2 systems with T4 showing a distinctly lower gradient trend line. Similarly, the gradients of the QSI trend lines are reasonably consistent between the UT and T2 system, and the T1, T3 and T4 systems with the former pair of systems exhibiting a steeper gradient of approximately a factor of two.

It is interesting to note the correlation between the QSI and impact loading conditions for each of the material systems. The UT, T2 and T4 systems show a good correlation between the QSI data and impact. However, two of the systems, T1 and T3, show distinctly different correlations between the two loading conditions with a significantly lower damage area response under QSI conditions above 30 J, on the order of two to three times respectively, as circled in Fig. 1. Furthermore, it should be noted that for the T3 system, the lower bound of the impact data which is particularly scattered above 30 J, does correlate closely with the QSI data.

3.2. Force–displacement comparisons

Force–displacement plots for quasi-static and impact loading conditions are shown in Fig. 2. 40 J impact curves were plotted as a representative comparison with QSI due to similar resulting