THE EFFECT OF DAMAGE ON THE IMPACT RESISTANCE OF COMPOSITE MATERIALS

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Abstract

Armour which is manufactured and distributed for personnel, vehicle and structural protection, primarily for military or policing applications, undergoes stringent testing to ensure that it can meet the demands of a range of impact scenarios. However, the effects of repetitive low-level damage are not fully understood and, in order to maintain a given level of protection, armour is recalled and replaced periodically, which is costly, and may be unnecessary. This paper reports preliminary studies on the relationship between minor damage and the resulting impact resistance of a woven fabric reinforced composite laminate (E-glass with epoxy resin). Specimens were subjected to displacement-controlled fatigue tests to introduce dispersed damage before being subjected to quasi-static indentation testing. The results showed that during penetration of the specimens, the peak load was reduced by approximately 10% for the pre-fatigued specimens, compared to the non-fatigued specimens, and there was some indication the energy absorption also reduced. It is proposed that the development of fibre fractures during the pre-fatigue of the specimens is the origin of these changes.

1. Introduction

Other than ballistic impact and blast debris where the damage to armour is clear, personnel, vehicle and structural protective systems can also be subjected to minor, everyday damage. This can range from misuse of armour for applications aside from protection, such as careless stowage, or repeated low-level damage during use (knocks/abrasions). The subsequent impact performance of composite armour that has received minor damage in service has received little attention and the overall aim of the work is to assess the effect of such minor damage on impact performance.

In the current work, cyclic (i.e. fatigue) loading has been used as a method of introducing the damage. Extensive research has been carried out on impact damage and its effect on residual mechanical properties (e.g. tensile and compressive strengths, residual stiffness, residual fatigue life [1–4]). In addition, there is a considerable body of work available on fatigue and the development of fatigue damage (e.g. [5,6]). Currently, little literature exists relating to the residual impact resistance of composites which have been damaged prior to impact [7].

Armour can be of two general types: “resin-starved” and “structural” composite armour. “Resin-starved” refers to composites manufactured using pre-preg containing 10-20% by volume resin content. “Structural” composites refers to fully-consolidated composites manufactured typically containing 40-50% resin content [8]. This paper presents preliminary results on the effects of low-level damage on the impact resistance of “structural” composite materials where the damage has been introduced using displacement-controlled fatigue. A quasi-static indentation test has been used to measure changes in the energy absorption and hence, penetration resistance as a consequence of the damage.

2. Materials and Methods

For this work, an eight-layer quasi-isotropic $[(0/90)_2(+45/-45)_2]_s$ woven glass fabric reinforced composite laminate was manufactured using a wet-layup approach [9], with resin introduced between each layer. The fabric reinforcement was a Y0094/205 E-glass plain weave fabric (obtained from Fothergill Engineering Ltd.), that has a thickness of 0.15 mm. The composite specimens were manufactured using a resin of Epoxide 300 (epoxy resin matrix), Methyl Nadic Anhydride (curing agent), and Ancamine (K61B catalyst), in the proportions of 100:60:4 by weight. This resin has a similar refractive index to that of E-glass fibres, and was chosen to ensure the resulting laminate would be transparent. Prior to laminating, the resin was degassed in a vacuum oven at 60 °C with a pressure of 0.1 MPa, for approximately one hour.

Laminate panels (300 mm x 300 mm x 1.25 mm), were produced with a fibre volume fraction of 0.45. The fabric was cut to size and laminates were laid-up between two flat glass plates (one approximately 400 mm x 400 mm, the other approximately 300 mm x 300 mm). Downland industrial mould wax (K&C Mouldings Ltd.) was applied to the plates, which were lined with polyester silicone release film sheets (Croylek® Melinex). Before curing, the laminate was left in a sealed vacuum chamber for one hour to promote complete wetting of the fabric and to assist the removal of air from the composite. Laminates were then cured at 100 °C for three hours. After curing, the laminate was removed to a flat surface and left to air-cool to room temperature. Circular test-specimens with a diameter of 140 mm were laser-cut from the resulting panels.

Quasi-static indentation tests were carried out using a quasi-static indentation rig fixed to a servo-hydraulic Instron 1341 machine; the rig is shown in Fig. 1a [10]. The circular specimens were clamped in the lower part of the rig, leaving an area 100 mm in diameter visible (Fig. 1b). The impactor, a glass sphere 16 mm in diameter (Fig. 1b), was driven through the specimens at a constant rate of 0.004 $m \cdot s^{-1}$, until it had fully penetrated the specimen.

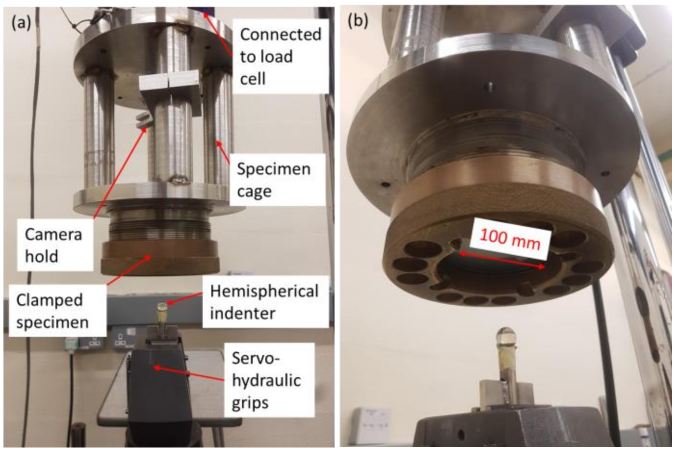

Figure 1. (a) Quasi-static impact testing rig, and (b) close-up of hemispherical impactor.

Load and displacement data were recorded during the test; the work done by the impactor to penetrate the specimens is the area under the curve. Fig. 2 shows a typical load-displacement graph obtained using the quasi-static indentation test, showing an increase in load as the impactor is driven into the specimen; a peak load at a corresponding displacement of ~ 8 mm; a sudden drop in load because of initial fibre breakage and macroscopic cracks [11]; and, finally, a drop in load as the impactor is driven through the specimen, up to complete penetration of the specimen.

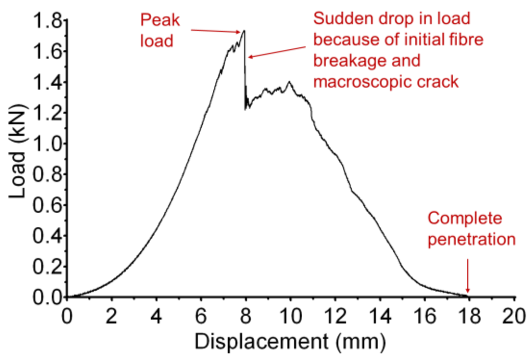

Figure 2. Typical load-displacement graph obtained from the quasi-static impact test, with the area of the graph corresponding to the energy absorbed over the course of the test.

Low-level damage was introduced by fatigue-loading the specimens under displacement control. It was found that using the impactor to displace the specimen (using a displacement amplitude of 1 mm, and a frequency of 3 Hz for 25,000 cycles) produced significant damage at the point where the impactor contacted the specimen. Consequently, in order to produce uniform and dispersed damage, a custom-made annulus shaped impactor was used in place of the spherical impactor. The annulus indenter (Fig. 3), made from 316 stainless steel, rested on a ball bearing secured to the bottom of the uniaxial testing machine; this enabled the annulus to distribute a uniform load when in contact with the specimen. The annulus contacted the specimen over a circle with a diameter L = 50 mm (Fig. 4). The annulus produced, in effect, a form of two-dimensional four-point loading of the specimen, causing the composite specimen within the circle contacted by the annulus to bulge out with the geometry of a spherical cap. Hence, under load, the quasi-isotropic laminate experienced equal strains in all directions within the annulus, introducing an area of axisymmetric damage into the specimen.

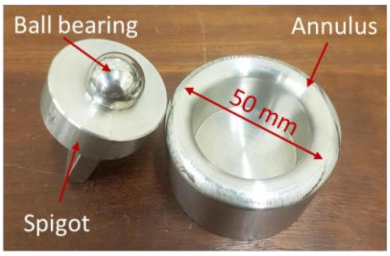

Figure 3. Dimension and shape of the annulus insert, with ball bearing to ensure uniform load can be distributed by the annulus when in contact with the specimen.

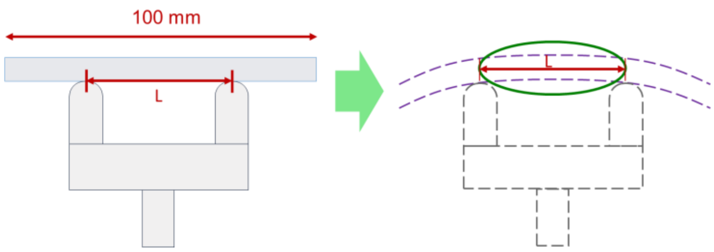

Figure 4. Schematic diagram showing how the annulus loaded the specimens, hence inducing damage into the central area of the specimen, with diameter L.

In order to estimate the strain applied to the composite during the displacement-controlled fatigue loading using the annulus, calibration was performed. A triaxial rosette strain gauge was bonded, using CN cynaoacrylate adhesive (Techni Measure Ltd.), to the specimen (Fig. 5a) to measure local strains due to loading using the annulus, and a fourth strain gauge was bonded outside the region loaded by the annulus. As expected, the three triaxial gauges (located at angles 0º, 45º and 90º) all showed approximately the same strain with displacement (Fig. 5b), which differed considerably from the behaviour of the gauge outside the annulus.

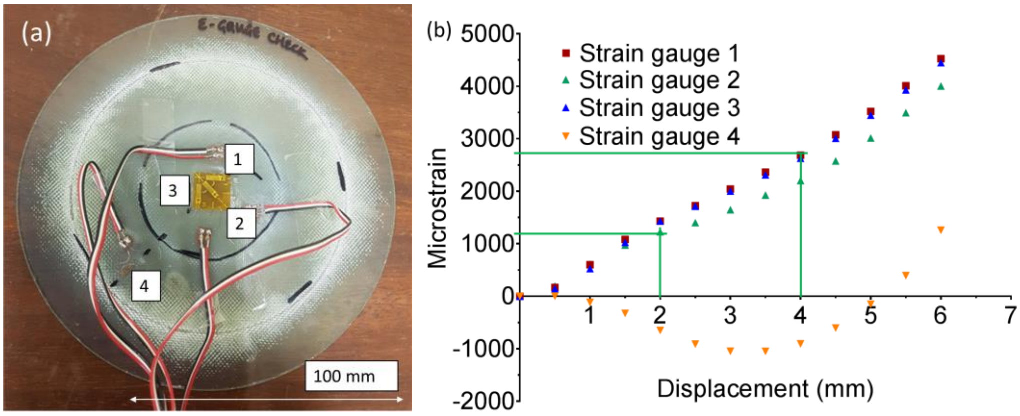

Figure 5. (a) Photograph showing location of strain gauges on specimen; (b) graph of strain versus displacement, and example range of relating displacements to microstrains highlighted in green.

To introduce the uniformly dispersed damage, the composite specimens were cycled under displacement control, driving the annulus to a mean displacement beyond initial contact with a sine-wave, displacement-controlled fatigue cycle superimposed on the mean displacement. In these tests, two mean displacements and two displacement amplitudes were used: 2 ± 2 mm and 3 ± 1 mm. Cycling was carried out, in each case, for 25,000 cycles, at a frequency of 3 Hz and three repetitions were completed for each series; a summary of the test conditions is shown in Table 1. The calibration of the deformation of the inner circle of material caused by the annulus (Fig. 5b) enabled the strain applied to the composite during the displacement fatigue to be estimated. For example, a fatigue displacement of 3 ± 1 mm (microstrain range highlighted in green in Fig. 5b) corresponds to a fatigue strain varying from a minimum of about 0.12% to a maximum of about approximately 0.27%.

Table 1. Summary of test conditions.

Specimen Series	Specimen name	Fatigue cycles	Displacement-controlled fatigue cycle (mm)
1	1-1 1-2 1-3	None	None
2	2-1 2-2 2-3	25,000	2 ± 2
3	3-1 3-2 3-3	25,000	3 ± 1

3. Results and Discussion

During fatigue loading, the composite panels were observed to have reduced in stiffness (estimated using the machine displacement and the reduction in the peak load) by about 8%. The observed stiffness reduction is an indirect measure of the fatigue damage developed in the composite [12–14]. An image of the damage in a fatigued specimen is shown in Fig. 6a where matrix cracking damage, induced by the fatigue loading, can be seen. The cracks run parallel to the fibre directions of the $[(0/90)_2(+45/-45)_2]_s$ laminates. Fig. 6b shows the typical exit face of the specimens after complete penetration.

Fig. 7 shows the load-displacement behaviour for all specimens during the quasi-static indentation tests. All nine specimens showed essentially the same behaviour, as described in Fig. 2. Table 2 shows the peak load and energy absorption obtained from the results. There is little difference in the results for the two sets of specimens fatigued with the different mean displacements and amplitudes (Specimen Series 2 and 3), although it is possible that the specimens with higher fatigue displacement amplitudes (Specimen Series 2) show larger changes for both peak load and energy absorption (typical curves of each Series are compared in Fig. 8). Overall, when compared with the specimens which were not fatigued (Specimen Series 1), it is clear that the peak load in the quasi-static indentation test has fallen by approximately 10% for Series 2 and 3 specimens as a consequence of pre-damaging the specimens by fatigue loading. There does not appear to be any clear difference in the energy absorbed between the pre-fatigued Series 3 specimens (lower fatigue displacements) and Series 1 specimens, however the Series 2 specimens show a 10% reduction in energy absorbed compared to the Series 1 specimens.

It is possible to speculate about the causes of the differences between the pre-fatigued and non-fatigued specimens. In the pre-fatigued specimens, the development of matrix cracking may have also led to associated fibre fracture in adjacent tows; this is a well-known phenomenon in both unidirectionally reinforced and woven composites as a consequence of fatigue [12, 15]. While the development of matrix cracking in itself is unlikely to lead to differences in penetration behaviour, significant fibre fracture developed during the pre-fatigue stages could lead to the fibre fracture required for initiation of penetration of the specimens to be reduced. Consequently, the peak load at which fibre fracture begins in the quasi-static indentation test might be expected to reduce in the pre-fatigued specimens, compared to the non-fatigue specimens, as has been found experimentally. Energy absorbtion during the through-thickness penetration of the specimens is perhaps less likely to be substantially affected by an initial dispersion of fibre fractures since macroscopic fracture of *all* tows through the thickness of the composite is required for penetration of the laminate. Further work is on-going to try to identify and quantify the relevant mechanisms.

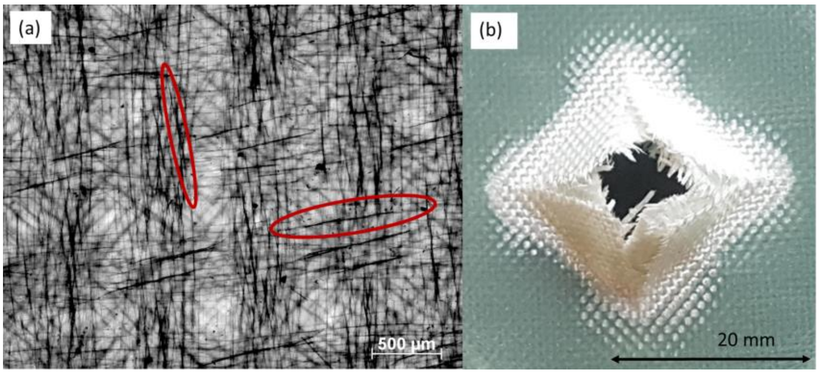

Figure 6. (a) Matrix cracking damage (examples highlighted in red) in a pre-fatigued specimen. (b) “Petals” formed as a consequence of the quasi-static indentation penetration of a specimen.

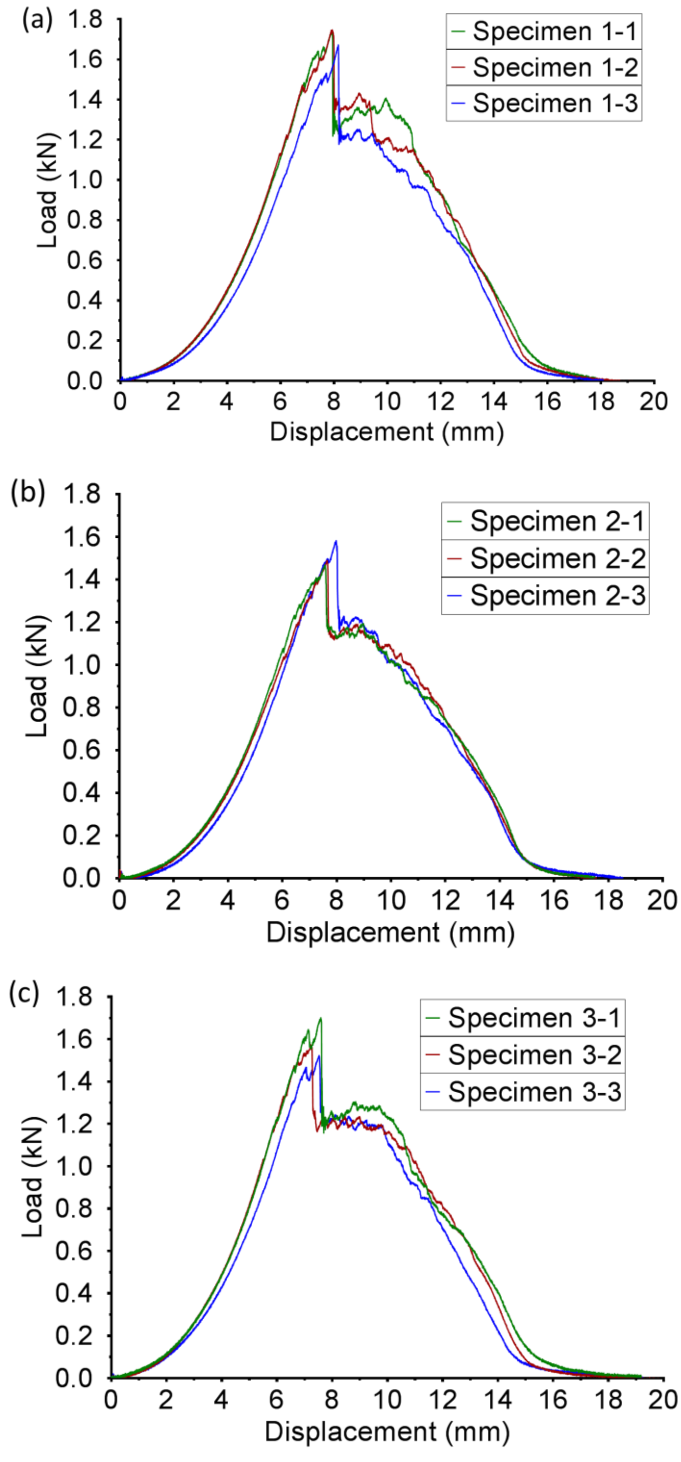

Figure 7. Load-displacement graphs for the quasi-static indentation of specimens that were (a) subjected to no pre-damage, (b) subjected to displacement fatigue of 2 ± 2 mm for 25,000 cycles, and (c) subjected to fatigue of 3 ± 1 mm for 25,000 cycles.

Table 2. Average peak load and energy absorption values of all specimens, with one standard deviation.

Specimen series	Specimen	Average peak load, F_{max} (kN)	Average energy absorption (J)
1	1-1 1-2 1-3	1.71 ± 0.05	11.3 ± 0.7
2 (displ. 2 ± 2 mm)	2-1 2-2 2-3	1.51 ± 0.05	9.8 ± 0.1
3 (displ. 3 ± 1 mm)	3-1 3-2 3-3	1.59 ± 0.08	10.7 ± 0.6

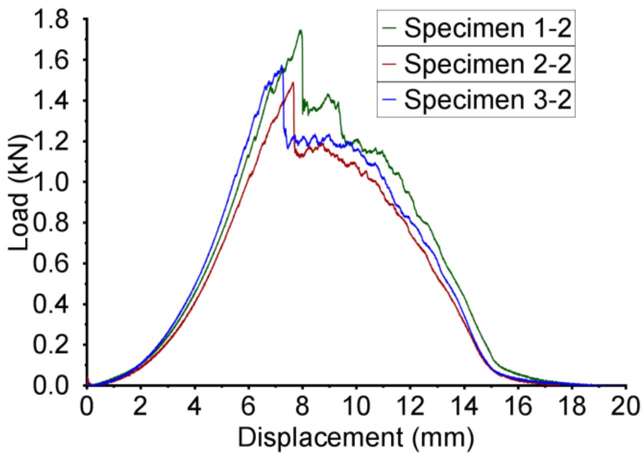

Figure 8. Comparison of representative curves from specimens of each test series.

4. Concluding remarks

GFRP composite specimens, based on plain woven glass fabric with an epoxy resin matrix, have been subjected to displacement-controlled fatigue to introduce dispersed damage, prior to a quasi-static indentation test. The damage produced a stiffness reduction of approximately 8% into the specimens, probably mostly due to a combination of matrix cracking and fibre fracture. The quasi-static indentation tests showed a substantial reduction, about 10%, in the peak load during penetration of pre-fatigued specimens, with little or no change in the energy absorption. It is suggested that an accumulation of fibre fractures during the pre-fatigue of specimens may be the reason for the reduction in the peak load, but further work is required to clarify the mechanisms involved.

Acknowledgments

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