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A SEM-Based Study of Structural Impact Damage

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Abstract
The ultimate objective of the current programme of work is to detect and quantify low-velocity impact damage in structures made from composite materials. There are many situations in the use of composites where an impact does not result in perforation of the material but causes damage that may not be visible, yet still causes a substantial reduction in structural properties. Impacts that do not cause perforation are usually termed *low-velocity*. When a composite structure undergoes such impacts, it is important to know the type and level of damage and assess the residual strength. In this study, following a systematic series of experiments on the induction of impact damage in composite specimens, Scanning Electron Microscopy (SEM) was used to inspect the topographies of the specimens at high magnification. Matrix cracking, fibre fracture, fibre pullout and delamination were the types of damage observed in the composite laminates after the low-velocity impacts. The study also conducted a (very) preliminary correlation between the damage modes and the impact energy.

Introduction
Many of the present technologies, especially among the materials used in the aerospace industry, require an unusual combination of properties that cannot be met by conventional metal alloys, ceramic and polymeric materials. For example, aerospace engineers are progressively searching for structural materials that have low densities and are strong, stiff and do not corrode over their lifetime. Therefore, since the early 1950's, composites have been used by the aerospace industry [1-3]. When composites were introduced into aircraft components, unexpected damage from in-service conditions occurred. These may have been due to impacts during flight operations [4-6] such as runway debris on composite airframes, bird-strike during flight operations or dropping of hand tools during maintenance work [5, 7]. For low-velocity impacts in composite structures, damages can not often be seen by the naked eye and are barely discernible. Such concealed damage is known as Barely Visible Impact Damage (BVID) [8] and is potentially undetectable without Non-Destructive Evaluation (NDE) techniques. Experimental investigations for identifying damages in composite laminates are habitually costly and time consuming. It is desirable to have automated systems for damage monitoring which can identify and classify damage from simply-measured response data. In order to build machine learning classifiers for such systems, one needs to acquire training data which associates measured data with given damage types and extents. This work addresses the overall aim by attempting to classify damage observed on CFRP laminates using a Scanning Electron Microscope (SEM) to inspect the topographies of impacted specimens at high magnification. The study also discusses a (very) preliminary correlation between the damage modes and the impact energy.

Fabrication of composite laminates

The composite material chosen for this work is a CFRP prepreg with a MTM57 epoxy resin system with CF2900 fabric, based on 120°C curing epoxy matrix resin. This material was fabricated to produce four large panels of 650 mm × 650 mm of which three were panels of 12 layers, and one had 11 layers on 50% area and 13 layers on the remainder. The processing used a standard vacuum-bagging procedure with the application of elevated temperature and pressure in an autoclave (cured for 30 minutes at 120°C at 5.8 bar). Each panel was cut into 8 test specimens of dimensions 250 mm × 150 mm with a diamond saw. PZT sensors of type Sonox P5 were placed on three different point of each test specimen to record the damage responses along different directions of the ply; the layout is illustrated in Figure 1.

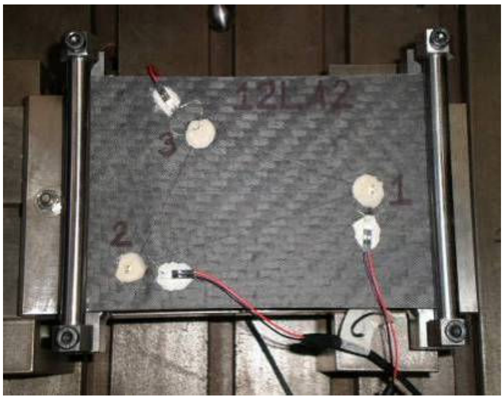


Figure 1. CFRP panel with PZT sensors as studied in this work.

Low velocity testing

An instrumented drop test rig was used to perform the tests. The rig consisted of a drop tower equipped with an impactor and a 0.0562 mV/N sensitivity force ring transducer. The impactor had a 13 mm diameter hemispherical tup nose. The height and mass of the impactor was varied in order to obtain various impact energies. For this work, the impactor was released from a chosen height and dropped freely along a guided rail. Together with the force ring transducer, the weight of the impactor was approximately 2.25 kg. The impact energy was set to range from 2.61 J to 41.72 J and the testing specimens were of 250 mm × 150 mm × 3.8 mm average thickness depending on the number of layers.

Non destructive Evaluation Techniques

X-radiography is a well-recognized non destructive evaluation technique used to assess damaged areas through images produced on film. The technique is based on differential absorption of penetrant radiation by the impacted or damaged surface; the presence of cracks and delaminations can be determined. However, difficulty may be expected in acquiring satisfactory X-ray images of adequate contrast, as there are some limitations. This is because the penetrant used only absorbs well in areas where damages are clearly visible. For damages that are not severe or only occur at the upper surface of a specimen, it is hard to produce an X-Ray image since the penetrant is not absorbed. As a result, the X-Ray radiation would not be able to image through the material. From another point of view, damage that is completely enclosed by non-damaged material will not be detected since the non-damaged material will act like a seal. Because of this constraint, X-ray is not considered the most suitable technique; although it is used here where sufficient damage occurred for penetrant absorption. X-ray analysis will generally give information about the overall area of damage, but will not allow resolution of different damage types. For this, SEM can be used with more accuracy.

SEM uses an electron beam of high intensity rather than light to produce an image. For this research work, JEOL JSM 6400 was used to determine the type of failure mechanisms observed from the composite laminates after the low-velocity impacts. Each specimen was observed at different magnification to distinguish the type of failure mechanisms. A high magnification SEM mode coupled with larger depth of focus and simplicity of sample observation makes the SEM one of the most suitable techniques for investigation of barely visible impact damage. The magnifications used for this current work were 35, 100, 500, 1000, 2500 and 5000. At 50-100 magnification, the fractographic analysis illustrates the overall view of the damage area, while at 500-750 magnification it allows one to look at the failure mechanism. Finally, at 1000-2500 magnification it gives one a chance to look at the failure mechanism in more detail. All the specimens were later used to make preliminary correlations between damage modes with the impact energy.

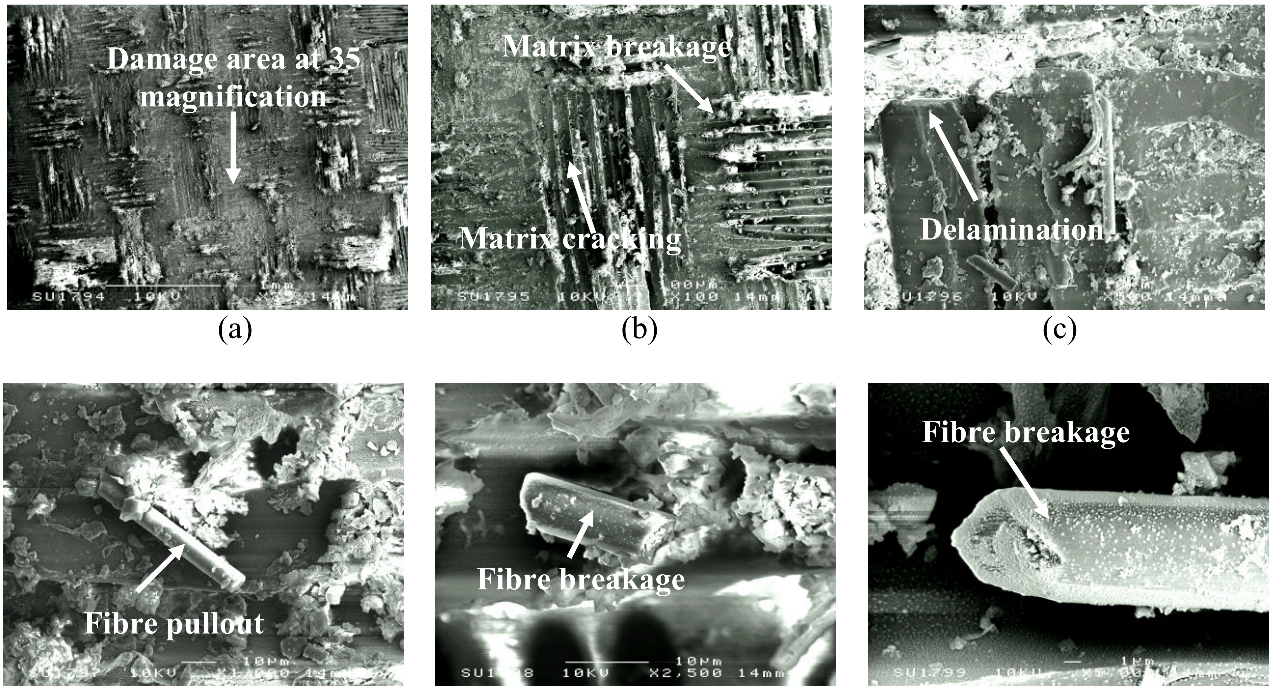
Results and discussion

A total of 24 specimens were used for the impact test of which 16 specimens possessed 12 layers and 4 each had 11 and 13 layers. The impact energies tested for the 12-layer specimens were set to range from 2.61 J to 41.72 J, while for the 11 and 13-layer samples, the specimens were tested at selected energy levels (10.43 J, 20.86 J, 31.29 J and 41.72 J). Due to the limited space here, only the results from the 12-layer specimens will be discussed. Two different methods were used to estimate the overall damage area; the first used the naked eye by measuring the damage size using a vernier caliper directly on the test specimen, while the second method used X-ray radiography. It was discovered from visual observation that the external damage area was circular in shape, however from the X-ray, the damage area was found to be rectangular. Table 1 summarises the different types of damage assessment for specimens with 12 layers. Note that for the damage estimation method that used X-ray, the notation ND given in the table means 'Not Detected'. This is because for damage that was not severe or that only occurred at the upper surface of a specimen, it was hard to produce an X-Ray image since the penetrant could not be sufficiently absorbed. Most of the damages are categorised as internal defects and generally consist of matrix cracking which usually cannot be detected by simply examining the surface of the specimen. The damages are only visually captured on the X-ray film for all impacts above 20.86 J. SEM was needed to determine the failure modes more precisely.

TABLE 1. ESTIMATED VALUES FOR IMPACT DAMAGE AREAS.

CFRP specimen identifier	Impact Energy (J)	Peak Force (N)	Damage Area (mm^2) from Visual Inspection	Damage Area (mm^2) from X-Ray
12LA1	41.72	3589.7	15.90	195
12LA5	39.11	3562.2	15.21	180
12LA6	36.50	3555.0	13.86	144
12LA7	33.89	3235.0	13.20	100
12LA2	31.29	3059.9	12.57	70
12LA8	28.68	3022.9	11.95	60
12LB1	26.07	2848.4	11.34	54
12LB2	23.47	2656.3	10.18	40
12LA3	20.86	2470.2	9.62	30
12LB3	18.25	2205.9	8.55	ND
12LB4	15.64	2069.0	8.04	ND
12LB5	13.04	1958.2	7.55	ND
12LA4	10.43	1927.2	7.07	ND
12LB6	7.82	1187.2	6.16	ND
12LB7	5.21	1064.2	4.52	ND
12LB8	2.60	810.0175	3.80	ND

Most of the specimens show the failure modes only at the contact area of the impactor. For low velocity impact, damage starts to propagate with the formation of a matrix crack [7,9]. The presence of the matrix crack does not affect the stiffness and toughness of the material. Delaminations, which form the critical failure mode after impact damage, propagate due to high transverse shear stresses in the location of the impacted surface [10-11]. The initiation and growth of delamination will results in progressive stiffness degradation and eventual failure of the composite structure. The damage will later propagate into other failure modes with the introduction of significant fibre damage, starting with fibre cracking, and further developing into fibre fracture and fibre pullout [12-13]. Figure 2(a-f) shows the micrograph images produced at the highest impact energy level. At this level, the highest impact energy and peak force recorded were 41.72 J and 3589.7 N respectively. Figure 2(a) illustrates the overall view of the SEM image captured at 35 magnification. At this point of enlargement, it can be seen that there is a significant damage in the test specimens. At the magnification of 100, matrix cracking and matrix breakage were observed, as shown in Figure 2(b). As the magnification increased to 500, delamination was discovered as seen in Figure 2(c), and at the magnification of 1000, there was a clear evidence of fibre pullout. Lastly, at magnifications of 2500 and 5000, there was a clear evidence of fibre breakage captured by the SEM. The threshold for damages observed at the internal sub-surface (cross sectional fractography) is still in progress and requires further study.



(a) (b) (c)

(d) (e) (f)

Figure 2. SEM images captured at different magnifications for 12LA1 (highest-energy impact).

Figure 3(a-f) presents micrograph images for the lowest impact energy level. As the impact energy decreases, the failure modes become different. At this level, the impact energy and peak force recorded were 2.61 J and 810.1 N, respectively. Referring to Figure 3(a), there was a clear damage detected on the surface of the plate. As the magnification increased, the damage mode became more evident; and, it could be seen that there was matrix cracking as the result of the impact. Figure 3(f) reveals that matrix cracking and matrix breakage were the only damage mechanisms discovered at this point, because the resin was still encapsulating the fibre, and this was the main difference with respect to the highest impact energy damage as shown in Figure 2.

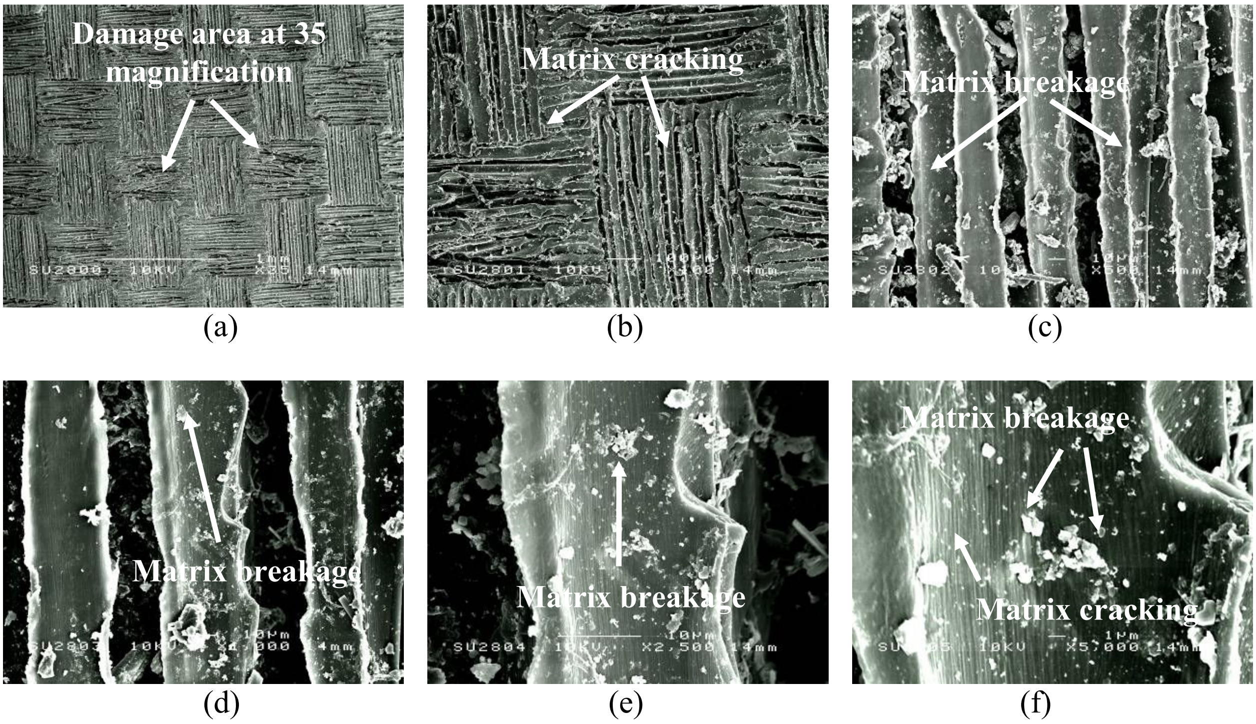


Figure 3. SEM images captured at different magnifications for 12LB8 (lowest-energy impact).

Only selected micrograph images are presented here due to the limited space; the overall failure modes observed from all the 12-layer specimens are collected and presented in Table 2. It can be seen that as the impact energy increases, the types of failure modes observed from the micrograph images proliferate. As the impact energy reaches 20.86 J, the progression of damage can be clearly observed. This is supported by the previous evidence showing that only from this energy level are damages visible on the X-ray films. From this point onwards (20.86 J), as the impact energy increases, the failure modes observed from the micrograph images progress. Damages that were observed below 20.86 J can be classified as not severe since they are in the form of matrix cracking and matrix breakage.

TABLE 2. PROGRESSION OF FAILURE MODES ON 12-LAYER SPECIMENS.

CFRP specimen identifier	Impact Energy (J)	Matrix cracking	Matrix breakage	Fibre cracking	Fibre breakage
12LA1	41.72	Yes	Yes	Yes	Yes
12LA5	39.11	Yes	Yes	Yes	Yes
12LA6	36.50	Yes	Yes	Yes	Yes
12LA7	33.89	Yes	Yes	Yes	Yes
12LA2	31.29	Yes	Yes	Yes	No
12LA8	28.68	Yes	Yes	Yes	No
12LB1	26.07	Yes	Yes	Yes	No
12LB2	23.47	Yes	Yes	Yes	No
12LA3	20.86	Yes	Yes	Yes	No
12LB3	18.25	Yes	Yes	No	No
12LB4	15.64	Yes	Yes	No	No
12LB5	13.04	Yes	Yes	No	No
12LA4	10.43	Yes	Yes	No	No
12LB6	7.82	Yes	Yes	No	No
12LB7	5.21	Yes	Yes	No	No
12LB8	2.60	Yes	Yes	No	No

Conclusions

The main objective of this study was to perform a series of low energy impacts in carbon fiber reinforced polymer composites, and then to carry out a sequence of SEM investigations to evaluate the failure modes. The objective is not to make any new observations on the nature of composite damage here, however to systematically build training data for machine learning analysis; in this respect, the SEM methods appear to have delivered a corpus of high-quality results which can form a valuable basis for further research [14]. From the work conducted, it can be concluded that (in agreement with previous fundamental research), as both impact energy and peak force detected increase, the number of distinct failure modes also increases. The experimental results allowed the identification of three critical impact energy thresholds. The threshold for matrix cracking and matrix breakage was identified as below the impact energy of 20.86 J whilst for fiber cracking it was identified between 31.29 J and 20.86 J. It is worth stating that the threshold energy for major damage was identified when the specimens were subjected to impact energy of more than 33.89 J. These thresholds will prove critical in later work when machine learning methods will be developed in order to infer damage extent and morphology from the structural dynamic response to impact.

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