HIGH SPEED DIGITAL IMAGE CORRELATION FOR IMPACT PERFORMANCE OF THERMOPLASTIC AND THERMOSET COMPOSITES

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Abstract

The impact performance of thermoplastic and thermoset composites has been investigated by conducting gas gun tests, initial velocities up to 110 m s^{-1}, employing with 3D Digital Image Correlation (DIC) technology. Woven fabric Carbon Fibre Reinforced Polyether-ether-ketone (CF/PEEK) and Carbon Fibre Reinforced Epoxy (CF/Epoxy) laminates, and the impactors with various hardness have been used, to simulate foreign body strike to airplanes during air travel. The extension of the damage induced in the tested samples, has been measured by C-scanning. It has been found that the tested samples have absorbed higher kinetic energy when subjected to soft impact. Further, based on DIC and C-scan results, the CF/PEEK laminates have showed superior impact resistance compared with the CF/Epoxy laminates.

1. Introduction

Lightweight materials are of great importance in the transportation and energy industries, e.g. automotive, wind turbine, and especially aerospace, where the weight of a structure has a direct influence on operating cost and performance. Among these materials, Carbon Fibre Reinforced Polymers (CFRPs) have been given the most attention, and extensively applied on modern civil aircrafts, due to their excellent specific mechanical properties, e.g. high strength-to-weight ratio. In the latest generation passenger aircrafts, such as Dreamliner Boeing B787 and Airbus A350, composite materials account for 50 wt% [1] and 53 wt%[2], respectively. The fuselage and wings of aircrafts are major structures which are mainly made of CFRPs, however, more vulnerable to high-velocity impact by foreign bodies, e.g. birds, hailstones and runway debris [3]. According to the report of American Federal Aviation Administration (FAA) published in 2016, there are 13,795 bird strikes reported to the FAA from 1990 to 2015 [4]. Further, more than 262 people have been killed, and over 247 aircrafts have been destroyed by wildlife strikes since 1988 [4]. And 272 hailstone impact incidents were reported by the United States Air Force from 1951 through to 1959 [5]. As a result of the increasing number of these incidents, more attention has been paid toward the performance of CFRPs subjected to high-velocity impact. For this purpose, carbon fibre composites reinforced with various types of matrices, both thermoplastics and thermosets, have been studied by many scientific researchers. Although thermoset composites have extensive use on aircrafts, the interest in thermoplastic composites is of great growth rate thanks to their excellent inherent properties, e.g. higher strength-to-weight ratio, eco-friendly manufacture consumption and recyclability [6-8]. As far as thermoplastic and thermoset polymers for composite materials are concerned, Polyether-ether-ketone (PEEK) and epoxy have dominated the scientific literature, which are representatives of high performance semi-crystalline thermoplastics and cross-linked thermosets respectively. For this study, Carbon Fibre Reinforced PEEK (CF/PEEK) and Carbon Fibre Reinforced Epoxy (CF/Epoxy) have been chosen.

Experimental investigations have been employed to understand the CFRPs subjected to quasi-static loading [9-11], low-velocity impact [12-16] and high-velocity impact [17-19] in many recent studies. For instance, the compression tests conducted by Lee [10] using CF/PEEK and CF/Epoxy laminates, indicated that CF/PEEK laminates show similar compression strengths but lower matrix shear modulus to CF/Epoxy laminates. Henaff-Gardin et al. [9] compared fatigue behaviour of cross-ply CF/PEEK and CF/Epoxy laminates. They conducted that CF/PEEK composites showed slightly superior on monotonic tensile loading, but far shorter fatigue lives during tension-tension fatigue tests. Dan-Jumbo et al. [11] also conducted the tension-compression tests to investigate the effect of load frequency on fatigue life. The fatigue life of CF/PEEK decreased as the load frequency increased, whereas the behaviour of CF/Epoxy showed an opposite phenomenon. The impact behavior of CFRPs subjected to low-velocity impacts have been paid considerable attention. Morton [13] have conducted drop-weight tests on CF/PEEK and CF/Epoxy laminates. Tests on two different stacking sequences showed that CF/PEEK laminates are superior to that of CF/Epoxy laminates on impact damage tolerance and residual compressive strength. Also, Ishikawa et al. [16] have investigated the compression strength after impact (CAI) of CF/PEEK and CF/Epoxy panels after subjected to drop-weight impact, and they found that the CAI strain of CF/PEEK panel is two times greater than that of CF/Epoxy panel. By Contrast, the number of studies on CFRPs subjected to high-velocity impacts is relatively low. Limited research was performed to investigate the effects of stack consequence of CFRPs [17], the environmental temperature [17], the incident velocity [19] and the incident angle [18]. However, no research articles were found employing 3D Digital Image Correlation (DIC) to assess the impact performance of the CFRPs based on their full-field deflection and strain value.

Noting the very limited amount of work on CFRPs subjected to high-velocity impact, the main aim of the present study is to compare the impact performance of thermoplastic and thermoset composites. Woven fabric CF/PEEK and CF/Epoxy laminates will be conducted to investigate the effect of resin matrix on impact performance, whereas the effect of impactor material will be studied by applying different harness of impactors. These effects will be studied firstly under gas gun tests employing with 3D DIC, where the impact resistance and the effect of impactor material will be determined, and secondly under C-scan testing, where the impact performance will be further assessed.

2. Materials

Carbon fibre reinforced PEEK and carbon fibre reinforced epoxy have been used for gas gun ballistic test conducting with DIC technology. Both types of samples, were made from woven prepregs and manufactured at Haufler Ltd., Germany, using standard press molding up to 400 °C for CF/PEEK and standard autoclave procedures for CF/Epoxy. The CF/PEEK panels are made of 7 plies of prepreg with nominally 50 % volume fraction of Torayca T300 carbon fibre, whereas the CF/Epoxy panels are made of 8 plies of prepreg with a nominal 55 % of fibre volume fraction. All types of test specimens are nominally 2 mm thick with a dimension of 140 x 140 mm. The essential information of each material is summarised in Table 1.

Table 1. The essential information of CF/PEEK and CF/Epoxy samples.

Specimen	Resin System	Weaving mode of prepreg	Number of prepreg plies	Thickness (mm)	Density (g cm^{-3})	Volume Fraction (%)
A	PEEK	Woven	7	2	1.54	50
B	Epoxy	Woven	8	2	1.57	55

For the 3D DIC measurements, the non-impacted side (i.e. the back face of the sample) of the CFRP sample was prepared according to the GOM instructions [20] for the target samples, which was painted with a matt white acrylic paint. The matt paint was used to reduce the amount of the reflection from the CFRP panel. This was necessary to achieve good DIC results, especially where large deflection of the sample occurred. A random speckle pattern was hand-painted on the white surface using a matt black marker to achieve the maximum contrast. The size of the black speckles was measured to be approximately 1.5–2.0 mm.

3. Experimental Procedure

3.1. Projectile

In order to simulate the foreign body impact on aircraft structures and investigate the effects of the projectile materials on the impact performance of CFRPs, four types of the projectiles including aluminium, HDPE (high-density polyethylene), PLA (Polylactic acid) and gelatin, were used in the tests. All the projectiles were manufactured as cylinder objects with flat-fronted noses. A nominal diameter of 24.85 ± 0.05 mm, which is slightly smaller than the diameter of the barrel of the gas gun, was used for the projectiles to achieve the reproducible maximum velocity. For the consistency of the experiment, these projectiles have a similar weight of 25 ± 0.15 g. The aluminium projectiles were machined from 7075-T6 aluminium and represented as the rigid projectile. The 70% filled 3D printed PLA and HDPE projectiles were considered as semi-rigid projectiles because of their medium hardness compare to aluminium and gelatin. A gelatin projectile was designed based on the substitutive bird model developed by Wilbeck et al. [21]. A 0.1 mm thick polyester cylinder mould was employed to form the soft gelatine into a cylindrical shape and decrease the friction between the projectile and the barrel. In detailed, 10% gelatine solution was poured into the mould and cured in fridge for over 8 hours. These projectiles were taken out from the fridge 10 minutes before the tests.

3.2. Gas Gun Set-up

As noted earlier, high-velocity impact tests were conducted using a gas gun apparatus shown in Fig. 1, which is similar to that described by Kaboglu et al. [22]. Helium gas was used to feed a four-litre pressure vessel, connected to a three-metre-long barrel by a fast-acting pneumatic value. The velocity of the projectile was controlled by changing the pressure of the vessel and measured by two pairs of infrared radiation sensors located at the end of the barrel. High-speed 3D DIC technique was employed to track the deformation history of the back face of the tested CFRP sample. Two synchronized high-speed cameras (i.e. ‘Phantom Miro M/R/LC310’ cameras), which have a distance of 925 mm from the centre point of the target, were located at the rear of the target chamber. The distance and angle between two cameras is 410 mm and 25˚, respectively. which is recommended by GOM Ltd [20]. A pair of the 50-mm fixed focal length ‘Nikon’ lenses, was employed for both cameras. These two cameras were triggered simultaneously by the signal generated from infrared radiation sensors and recorded the testing process at their maximum rate of 39000 frames per second. Two halogen lamps were employed to illuminate the back face of the CFRPs sample, which were only turned on a few seconds before the experiment was initiated. For DIC data processing, it should be noted that for images captured by the high-speed cameras, speckles occupied 3-5 pixels, with a facet size of approximately 17-19 pixels for each displacement point, following the recommendations for the optimum speckle size [20]. In order to monitor the full-filed deformation of the samples, the image size for this specimen dimension was selected as 256 x 256 pixels.

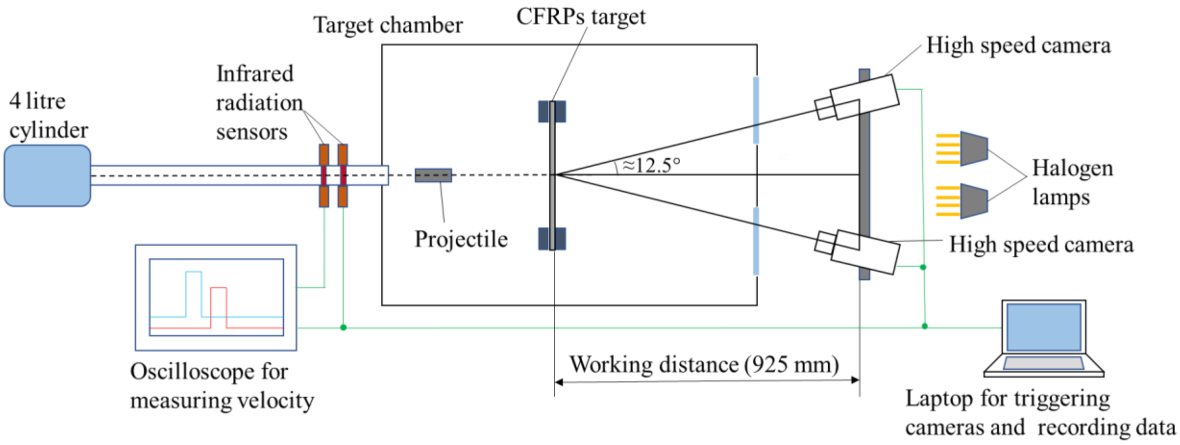

Figure 1. Gas gun set-up for conducting high-velocity impact test employing DIC technique.

3.3. Ultrasonic C-scan

Ultrasonic camera system (i.e. DolphiCam CF08 ultrasonic C-scan camera) was employed for NDT inspection of CFRP samples. This camera has an array of transducers with 124 x 124 elements over a 31 x 31 mm^2 silicone-based transducer pad. Contact gel was used to improve coupling on the surfaces of the specimens. These transducers are designed based on the pulse-echo method, which can create high-resolution 2D and 3D images of suspected damage areas to assess the structural condition of the CFRP samples. Due to the size limit on transducer pad, to obtain the C-scan images for the entire specimen, manually stitching mode is needed. Each scanned region has 5 mm width overlap area with adjacent regions. For this study, a region of 130 x 130 mm was C-scanned in sequence. In order to eliminate the negative effect of potential damage caused from transportation or manufacturing, each sample was C-scanned before the impact test.

4. Results

4.1. Results of 3D DIC impact tests

In this section, the out-of-plane displacement and major strain of the CFRP samples subjected to high-velocity impact are reported from using 3D DIC technique. The impact performance of CF/PEEK and CF/Epoxy laminates was compared, and the effects of using different materials of the projectiles were discussed. Various types of the projectiles were employed to conduct the impact tests at a velocity range of 30-110 m s^{-1}. However, only the tests on CFRPs subjected to soft gelatin impact were carried out successfully with the 3D DIC technique, as damage occurred on the back surface of the samples subjected the rigid and semi-rigid impactor even at the lowest velocity the gas gun can achieve, which led to artificial strain or failure traction in the DIC results. As a detailed example, Fig. 2 shows the out-of-plane displacement maps obtained from the CF/PEEK laminate under soft impact loading, where both the loading and the unloading phases were included. The deformation profile across the middle section of the panel is shown in Fig. 2b, where the behavior of the tested samples in both phases can be found. This CF/PEEK sample was tested at an initial impact velocity of 75 m s^{-1}, and had a maximum out-of-plane displacement about 4 mm. It is important to note that there were no signs of any damage e.g. fibre breakage and matrix cracking on both front and rear faces of the sample. Fig. 3 gives the experimental results obtained from the CF/Epoxy laminate tested at an initial impact velocity of 71 m s^{-1}. The response of the sample was very similar to the CF/PEEK sample, but it delivered a higher maximum out-of-plane displacement of approximate 4.5-4.7 mm. It is of interest to point out that there was a little amount of fractures observed at the back face of the sample.

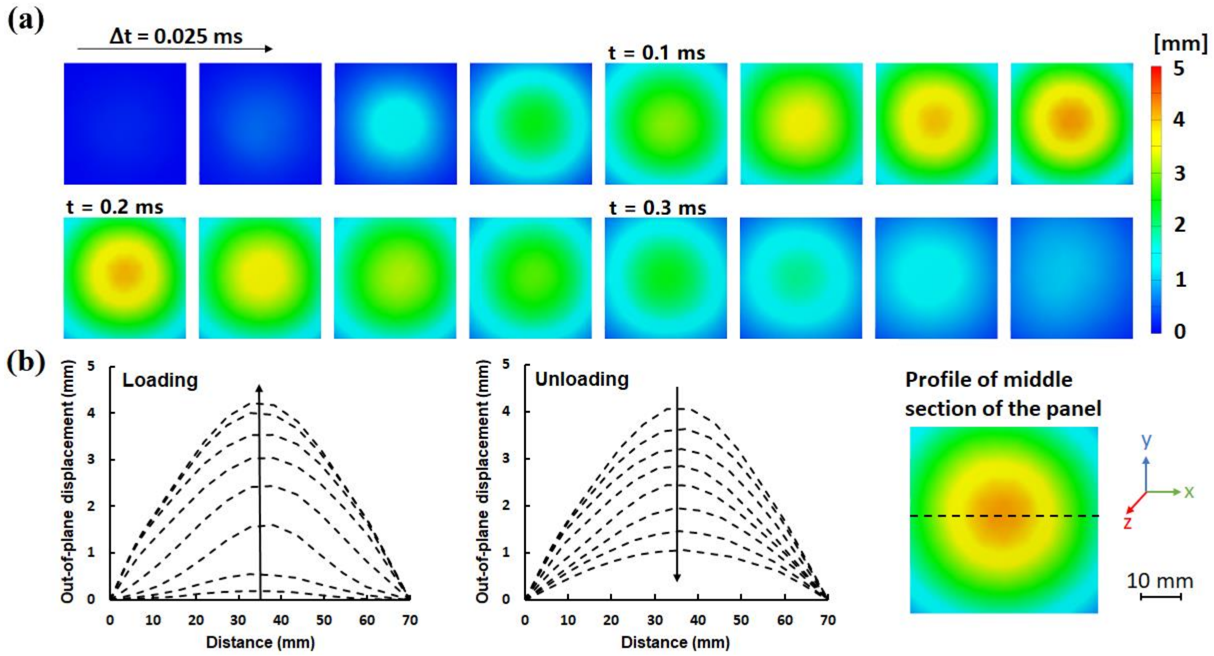

Figure 2. Experimental results of the CF/PEEK panel impacted at a velocity of 75 m s^{-1} for the: (a) out-of-plane displacement maps; (b) out-of-plane displacement profile during loading and unloading phases.

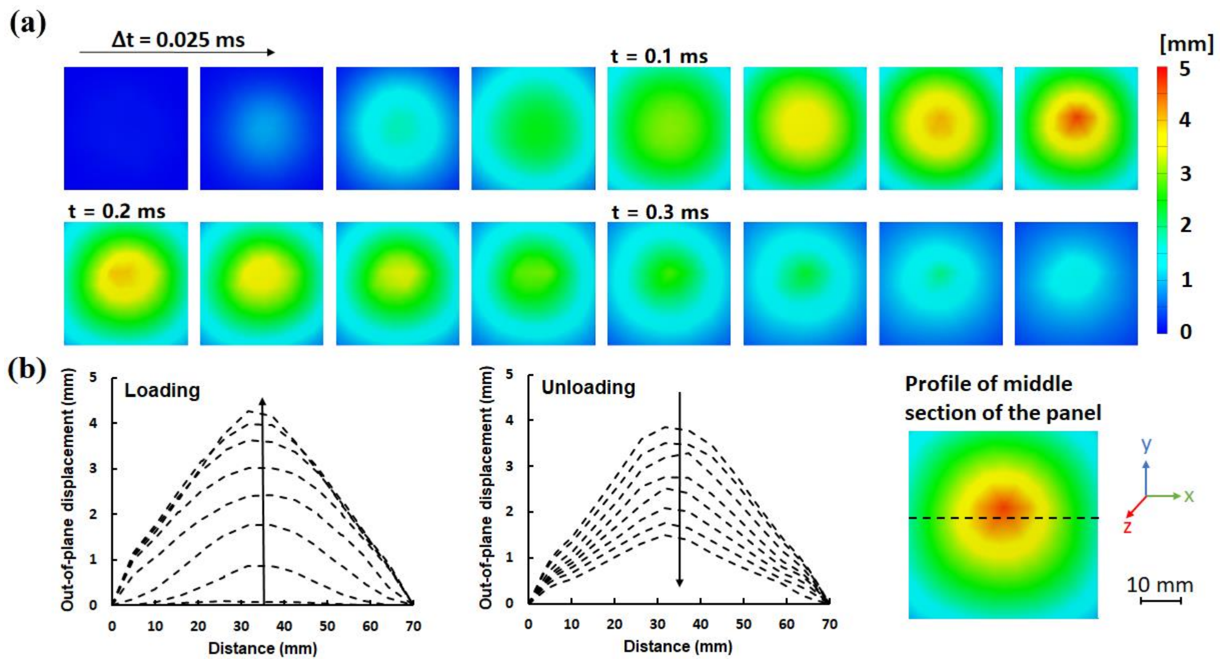

Figure 3. Experimental results of the CF/Epoxy panel impacted at a velocity of 71 m s^{-1} for the: (a) out-of-plane displacement maps; (b) out-of-plane displacement profile during loading and unloading phases.

As stated above, the major strain of the back face of both samples was captured using 3D DIC technique. The strain maps and strain profile across the middle section the sample for the CF/PEEK and CF/Epoxy laminates were demonstrated in Fig. 4 and Fig. 5, respectively. The maximum major strain of the CF/Epoxy sample was approximately 4.2%, which is three times larger than that of the CF/PEEK sample. Based on the observation of the tested sample, it was deemed that the fracture on the back surface led to the dramatical increase on the value of the major strain obtained from the CF/Epoxy sample.

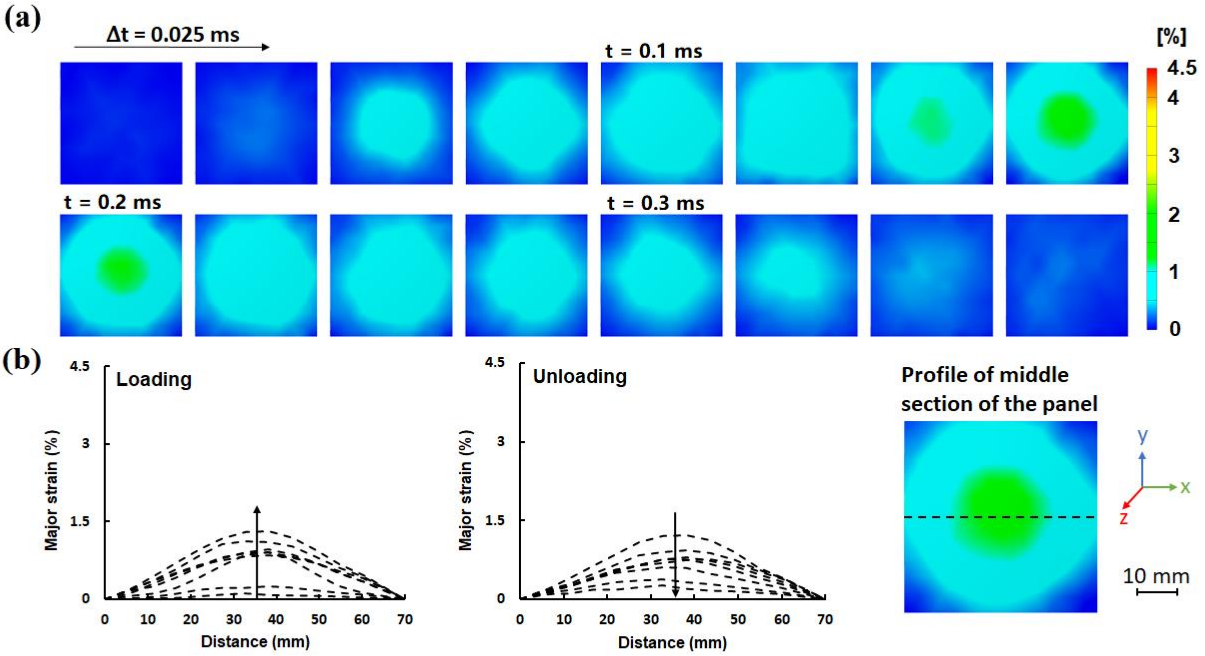

Figure 4. Experimental results of the CF/PEEK panel impacted at a velocity of 75 m s^{-1} for the: (a) major strain maps; (b) major strain profile during loading and unloading phases.

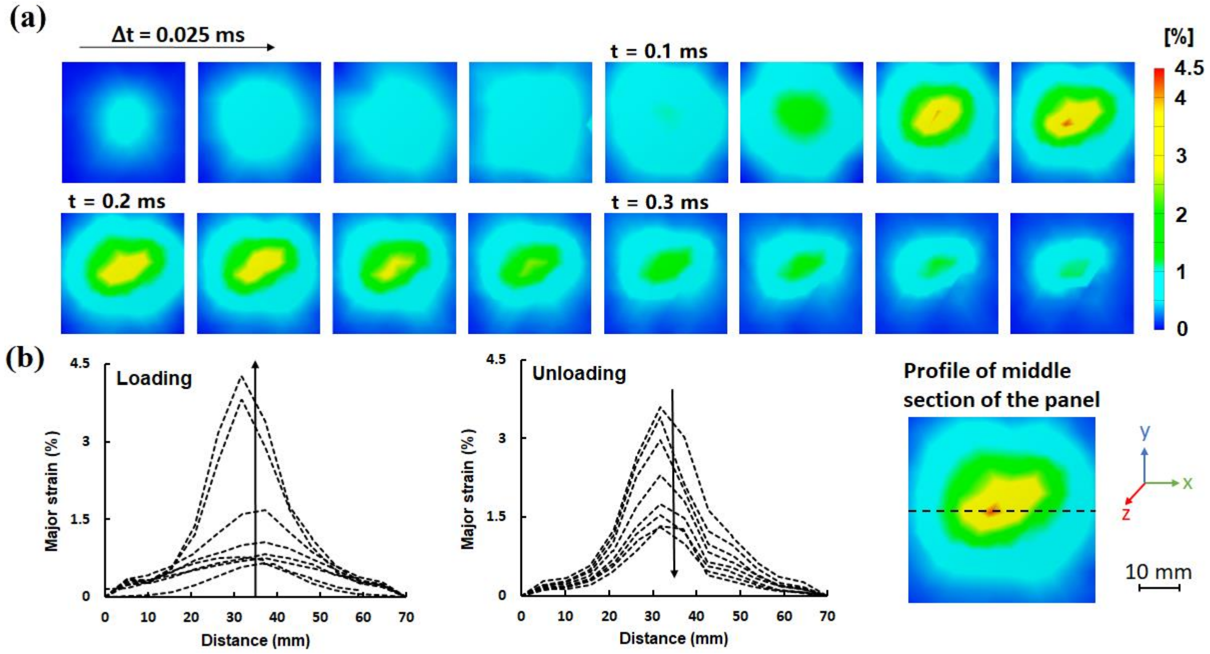

Figure 5. Experimental results of the CF/Epoxy panel impacted at a velocity of 71 m s^{-1} for the: (a) major strain maps; (b) major strain profile during loading and unloading phases.

Some typical values measured from the physical tests are summarized in Table 2. The total kinetic energies, for the CF/Epoxy sample and the CF/PEEK sample, are very similar. The maximum values of deflection and major strain obtained from both CF/Epoxy sample and CF/PEEK samples were extracted from the post-process results. As a conclusion to this section, it appears that CF/PEEK shows impact resistance than CF/Epoxy subjected to high-velocity soft impact.

Table 2. Results of high-velocity soft impact tests.

	Specimen A	Specimen B
Incident Impact Velocity (m s^{-1})	75	71
Incident Impact Energy (J)	53.4	52.2
Maximum Displacement (mm)	4.22	4.69
Maximum Major Strain (%)	1.36	4.27

4.2. Results of Ultrasonic C-scan

The C-scan maps of the tested samples provide further information on the impact performance, and usually used as the indication for the damage area. Fig. 6 shows the C-scan results obtained from the CF/PEEK and the CF/Epoxy laminates subjected to high-velocity soft impact. The joint lines in the C-scan maps were generated through the stitching mode in the C-scan system. This function allows the completion of the scanning operation on the tested sample, which has a larger dimension than the probe of the C-scanning system. In the C-scan maps, it can be found that the CF/PEEK laminate shows smaller damage area than the CF/Epoxy laminate. Considerable damage was found in the CF/Epoxy laminate, and the largest damage area was presented at the depth of 0.4-1.5 mm. Due the usage of the woven fabric architecture, two separated damage regions can be observed in the tested CF/PEEK laminate, which is not a typical phenomenon in the impact test. It was speculated that this might be caused by the polyester film of the gelatin projectile at the initial stage of the impact, likewise, the horizontal ends of the damage areas within the CF/Epoxy laminate may also be relevent to the polyester film. Hence, a further study with a substitute for the polyester film will be carried out in the future. No typical 'peanut' or 'diamond' damage shape, which are usually found in the unidirectional carbon fibre reinforced laminates [23], was observed in both tested CF/PEEK and the CF/Epoxy laminates.

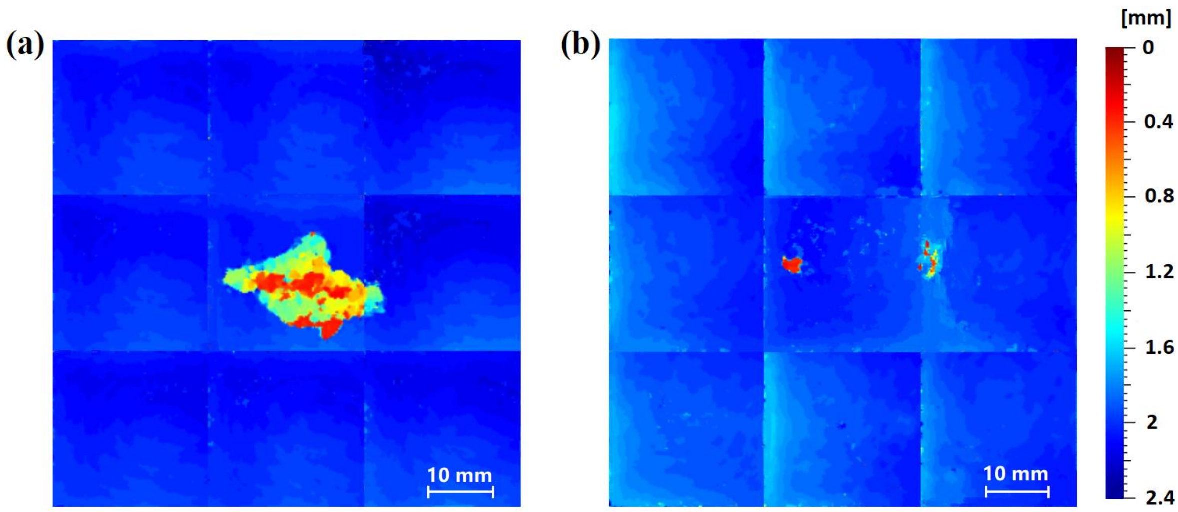

Figure 6. Ultrasonic C-scan maps for (a) CF/Epoxy; (b) CF/PEEK.

5. Conclusions

In the present study, the impact performance of the CF/PEEK and CF/Epoxy laminates subjected to high-velocity impact has been compared based on the DIC technique. Further, the effects of the projectile materials on damage of the CFRPs have been investigated. The C-scan system was employed to provide further assessment on the impact performance of tested samples.

- The CFRPs are more vulnerable subjected to the high-velocity rigid and semi-rigid impact because of the brittleness property. As the hydrodynamic characteristics of the soft impact, it causes global deformation of samples, so that the CFRPs could absorb higher kinetic energy.
- Small amount of fractures can be observed on the back face of CF/epoxy sample, which contributed relatively high value on maximum major strain.
- Based on DIC and C-scan results, CF/PEEK composites showed superior impact resistance than CF/epoxy composites under high velocity soft impact (73± 2 m/s).

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