Structural Response and Damage Characterisation of Non-Crimp Fabric CFRP Panels under Impact Loading

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ABSTRACT

Impact damage formation and resistance is of great importance to all designers of structural components whether mobile or stationary. This is particularly true in the case of composite materials where the lack of a local plastic deformation mechanism means that even small impacts can result in complete fracture of constituent members, accompanied with a substantial or complete loss of the load carrying capabilities in the region of damage.

This paper presents the experimental approach used to examine the structural response and resulting damage in non-crimp fabric carbon fibre reinforced epoxy composite samples at varying strain rates. The strain rates considered are those associated with quasistatic, low-velocity impact, and high-velocity impact loading rates. The differentiating characteristics of these regimes is discussed, and their effect on the samples is shown through experimental damage characterisation including physical measurements and ultrasonic C-scans.

It is found that there is a clear difference in the form of damage that occurs with a change in strain rate regime. Quasistatic and low-velocity impact loading produces similar damage levels to each-other at similar energies, and results in more extensive fibre fracture and permanent deformation. However, high-velocity impact favours interlaminar matrix failure (delamination), and also absorbs more energy at equivalent lower impact energy levels, producing more damage. The resulting conclusion being that damage from high velocity impact is harder to identify, and damage resistance for lower energy impacts decreases as impact velocity increases – even though the total impact energy may be equivalent.

KEYWORDS: Damage, Non-Crimp Fabric, Impact, Strain Rate Dependency, Ultrasonic

1 INTRODUCTION

A key concern for aerospace, automotive, marine and other industries with regards to the use of composite materials is their ability to withstand impact loads with a minimum of damage (damage resistance) and continue to withstand their usual structural loads (damage tolerance). Impact is particularly challenging as it can generally involve a wide range of strain rates that may greatly affect the damage resistance of a composite structure due to an increase in peak load at higher impact velocities and other effects (Olsson, 2000). Additionally, the reduction of labour required for manufacturing composite parts is a substantial concern for all industries as the current cost of a composite structure is often greater than its equivalent metallic counterpart (Rao et al., 2018). To this end, many manufacturers are interested in liquid composite moulding technology that allows the use of preforms that are relatively thick in their through-thickness direction compared to traditional unidirectional composite tapes. Utilization of these thick pre-forms allows for rapid deposition of the reinforcement material onto the tool surface, thereby reducing production cycle time. One such fibre architecture commonly used in liquid composite moulding is non-crimp fabric (NCF). In this work, the damage resistance of NCF samples is examined at strain rates including quasistatic (QS), low-velocity/high mass impact (LVI/HM), low-velocity/intermediate mass impact (LVI/IM), and high-velocity/low mass impact (HVI/LM) loading.

While impact conditions are frequently referenced by their velocity, this is often just a matter of convenience and convention as the impact regime is not strictly governed by the velocity of impact. Rather, it is based on the duration of the impact event relative to the time required for stress waves to propagate to the boundaries of the sample (Delfosse & Poursartip, 1997). These boundaries may be either the back-face of a sample on which longitudinal through-thickness waves will reflect, or the supports of the sample on which transverse flexural and shear waves are constrained. Should the impact occur in a shorter time than required for the through-thickness waves to reach the back face, the impact would be considered ballistic. Conversely if the impact duration is longer than required for the flexural and shear stress waves to reach the boundary, then the global bending response of the plate will develop, and the sample should act in a similar fashion to a quasistatic (non-impact) loading. In between these two limits where the impact duration is shorter than the time for the flexural and shear waves to reach the boundary, but longer than the time for the through thickness waves to reach the back face; it is considered a high-velocity impact (Olsson, 1993). Thus, it is clear that the determination of an impact regime for a given impact event is not only dependent on the impact velocity, but also the impactor characteristics, the size of the part, the locations of its boundary conditions or supporting structure, as well as the speed of the waves through the structure.

By utilizing loadings corresponding to the quasistatic, low-velocity and high-velocity impact regimes, this study identifies the strain rate dependencies that exist as the impact regime transfers from one to another. By comparing and contrasting strain rate dependent data, designers will have a better understanding of what types of failure modes to expect under varying conditions.

2 EXPERIMENTAL DETAILS

2.1 Materials

The NCF material has a layup sequence of $[0/60/-60]_{2S}$ with a total average thickness of 2.56mm. X-ray computed tomography (CT) inspection shows that the average thickness of the 0-degree plies is 0.3mm while the average thickness of the 60 and -60 degree plies are each 0.17mm. These materials are cut into 100mm x 100mm square coupons for impact testing. This non-standard coupon size – compared with 100 mm x 150 mm in ASTM D7136 (2015) – was chosen based on the size of the manufactured panels available.

2.2 Loading Apparatus and Instrumentation

The experimental procedure utilized for this work is focused on four different impact velocity ranges – and, by extension, masses – that are achieved with separate experimental apparatus. These experiments were carried out at both The University of British Columbia (UBC) facilities in Vancouver, and the facilities at the German Aerospace Center (DLR) Institute of Structures and Design in Stuttgart, Germany as part of the DLR@UBC collaboration. Quasistatic and intermediate mass gas gun tests were carried out at UBC with an Instron load frame and instrumented gas gun respectively; while high mass drop tower and low mass gas gun tests were carried out at DLR. The equipment that was used, along with the impact mass and velocity ranges are summarized in Table 1 and shown in Figure 1 below.

Table 1 Parameters of test apparatus used for impact experiments

Designation	Impact Regime	Equipment	Facility	Impactor Mass (g)	Velocity Range (m/s)	Data Recorded
Quasistatic	QS	Load Frame	UBC	N/A	2.1E-5	Load & Displacement
High Mass	LVI	Drop Tower	DLR	2818	1.3-3.0	Load & Displacement
Intermediate Mass	LVI	Gas Gun	UBC	438	4.0-9.5	Load & Displacement
Low Mass	HVI	Gas Gun	DLR	4.75	39.7-85.3	Displacement

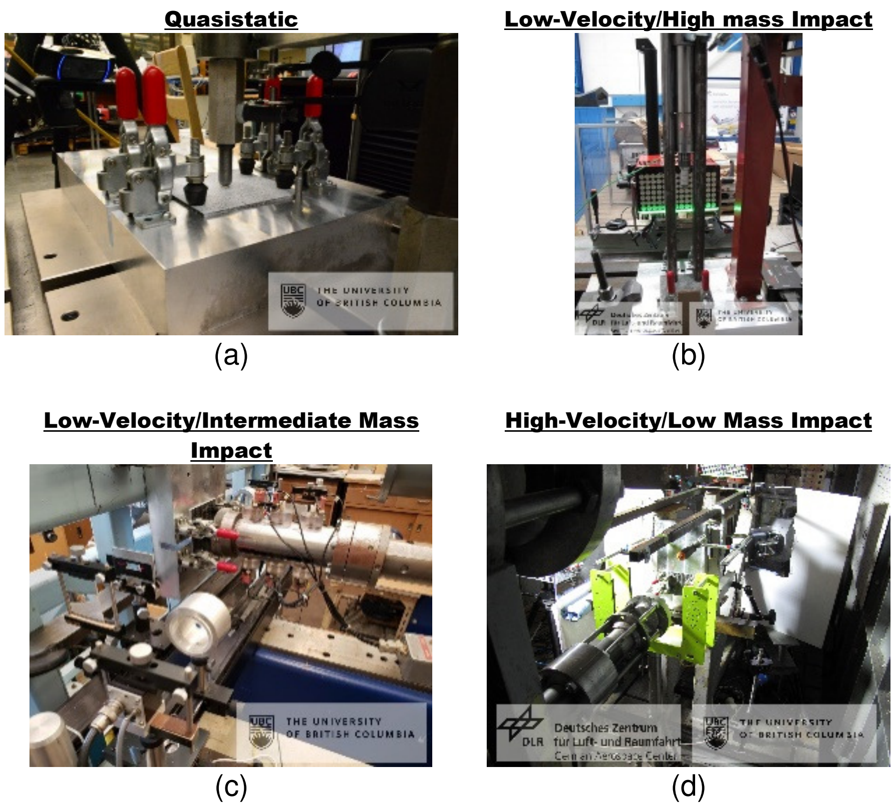

Figure 1 Test apparatus used for experiments; (a) Instron load frame, (b) Drop tower (2818g), (c) Gas gun (438g), (d) Gas gun – free flying sphere (4.75g)

The apparatus and instrumentation utilized for recording both force and displacement for the intermediate mass tests has been described previously in other publications (Delfosse et al., 1993; Starratt et al., 2000). In the case of the high mass and low mass experiments, a high-speed camera was utilized to monitor displacement of the projectile; and for the high mass experiment a load cell was used to monitor force during impact. Due to the free-flying nature of the low mass projectile, there was no recording of force during the impact.

The samples are situated on a 47.5mm thick aluminium fixture with a 75mm x 75mm square cut out centred beneath the samples. This cut-out is resized from the ASTM D7136 standard (2015) based on the non-standard sample size as discussed earlier. The samples are held in place with four toggle clamps having rubber tips to providing light fixturing pressure.

2.3 Impact Velocities and Energy Calculations

To achieve high-velocity impact for this study, the experiments were designed to create the conditions necessary to satisfy the limits as described above. Namely that the impact duration is shorter than the time for the flexural and shear stress waves to reach the boundary. This complex problem has been shown with an analytical method to have a single criterion for the case of an impactor striking at the centre of a simply supported square plate. The mass of the impactor must be less than one-quarter of mass of the square plate that is not supported by the boundary (Olsson, 1993). Thus, the high-velocity impact criterion is not a "velocity" criterion at all, and by utilizing a small mass impactor the wave propagation criteria has been met.

The impactor in all cases is of hemispherical shape with a diameter of ½" (12.7mm). In the case of the quasistatic, high mass and intermediate mass tests, the same steel tupp was used either in the test machine (quasistatic) or with different masses behind the tupp (high and intermediate mass impact). For the low mass tests, a ½" diameter titanium sphere was utilized to minimize the mass of the impactor. The 4.75g mass of this sphere is just less than one-quarter of the unsupported plate mass of 20g, thus meeting the criteria for high-velocity impact, but not allowing for instrumentation to record force.

The range of impact energies examined has been kept constant between all experimental apparatus at levels between 3.4J and 18.1J. In the case of quasistatic tests the equivalent impact energy is calculated after the test by integrating the area under the force-displacement curve during loading (until maximum displacement); additionally, the total energy absorbed by the sample (damage energy) is calculated by subtracting the area under the unloading curve from the area under the loading curve. For all the impact tests, the impact energy is calculated as the kinetic energy of the projectile just prior to impact; and the absorbed damage energy is the residual of the kinetic energy of the impactor (kinetic energy after impact minus kinetic energy before impact).

2.4 Damage Characterisation

Damage characterisation has been focused on two primary independent metrics: permanent dent depth immediately after the impact and ultrasonic pulse-echo C-scans for damage area quantification. X-ray computed tomography for through-thickness damage inspection has also been made, and future publication is planned in an impact discipline journal.

Permanent dent depths were collected with a combination of digital dial gauge and Faro-arm measurements. The ultrasonic C-scans are collected with an Olympus Omniscan MX2 system and a glider-encoder system.

3 RESULTS

3.1 Permanent Dent Depth

Where possible, the procedures within this experimental work were aligned with the ASTM standard for Damage Resistance of Fibre-Reinforced Polymer Matrix Composite to a Drop-Weight Impact Event (D7136-15, 2015). This standard specifies that the depth of the dent created by the impactor is measured immediately after the impact event. These results are plotted against the impact energy in Figure 2 below. It can be seen in general that the dent depth does increase with increasing impact energy for the cases that involve lower velocities and higher masses; but as the impact velocity increases into the high-velocity/low mass regime it is seen that the permanent dent depth does not increase substantially with increasing impact energy.

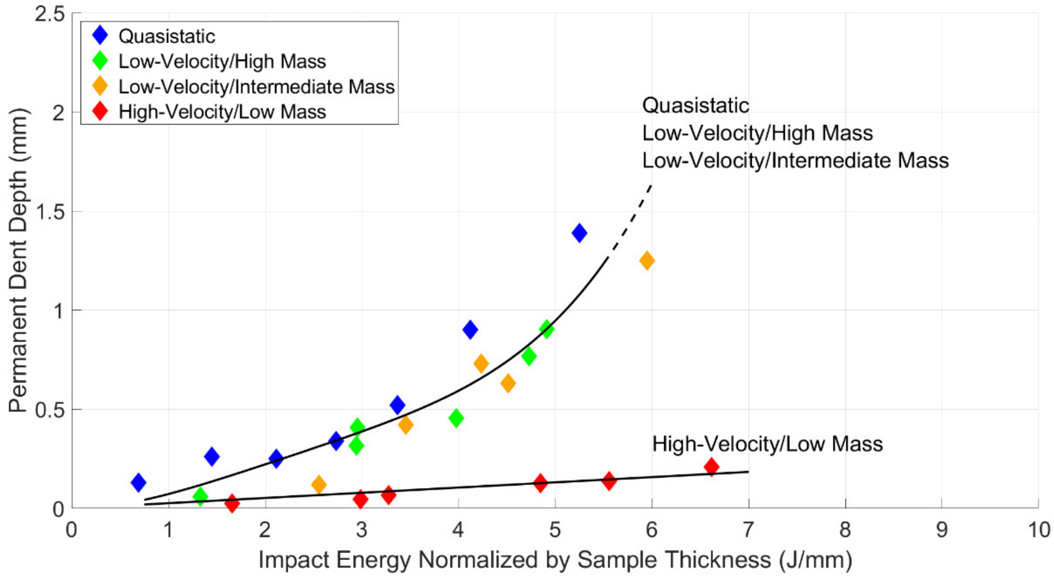

Figure 2 Permanent dent depth cross-plotted with normalized impact energy; it is clear under quasistatic and low-velocity impact conditions there is a tendency to generate substantially larger permanent dents as energy increases, however, only minor dent depth increase is observed with high-velocity/low mass impacts

3.2 Ultrasonic Damage Characterisation

After testing the coupons, ultrasonic pulse-echo C-scans were made to quantify the size of the damage zone in the plane of the sample. The C-scan results for the materials are shown in Figure 3 below. The energy level selected for this figure is in the ~5-6J/mm range (normalized by sample thickness) and they are presented from left to right in order of increasing impact velocity. From this figure it is seen that in all cases there exists a local region of damage centred around the impact site, however, the high-velocity impact case shows a much different form of damage area compared to those in the low-velocity regime that is larger and indicative of a substantial delamination zone.

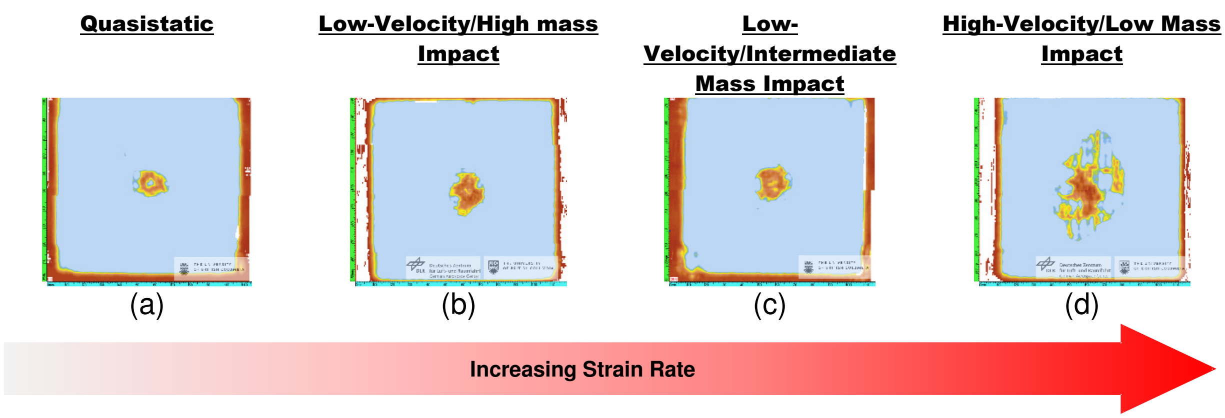

Figure 3 Ultrasonic C-scans of NCF material with ~13-14J of energy (5-6 J/mm of thickness) showing a substantially larger delamination zone in the case of high-velocity/low mass impact

After quantifying the planform damage areas from all tests and plotting the areas against the permanent dent depth, there are distinct trends that become visible relative to the rate of loading. These are identified in Figure 4 below.

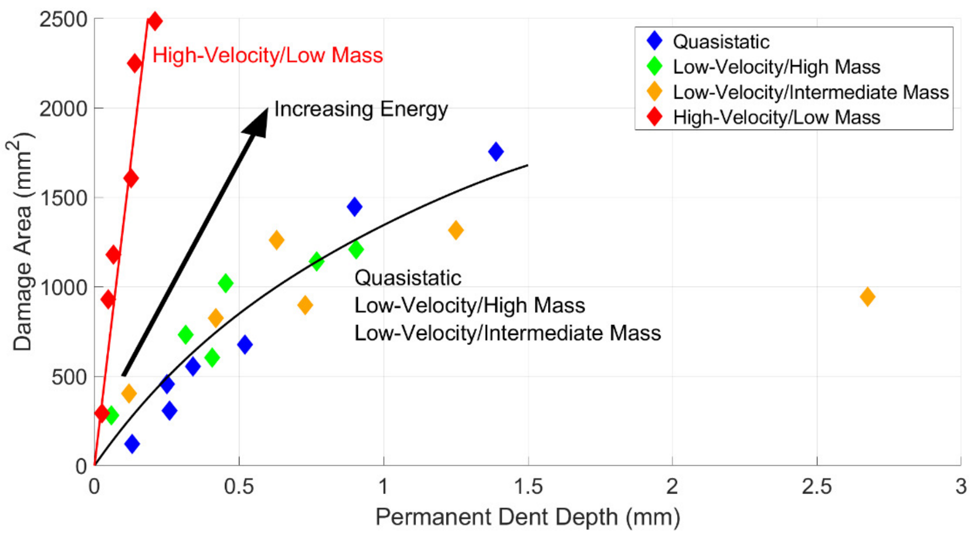

Figure 4 Damage area from C-scans cross-plotted against permanent dent depth as impact energy is increased; there is a clear distinction between large delaminations with small dents (high-velocity) and smaller delaminations with larger dents (quasistatic/low-velocity)

4 DISCUSSION

From Figure 4 it is apparent that under all conditions the NCF material is prone to developing large delamination zones given sufficient energy, but there appears to be a trade-off between delamination zone size and permanent dent depth. At low velocities there is a tendency to develop substantial permanent deformations; providing an indication that much of the energy may be dissipated through the processes involved in creating the dent, such as large-scale fibre fracture. Conversely at high velocities the tendency is instead to develop larger delamination areas with minimal permanent dent depth. This bifurcation of damage modes and the different mechanisms through which impact energy is dissipated for different impact regimes has been shown previously (Delfosse & Poursartip, 1997).

Visual inspection techniques have a greater efficacy for detecting damage when substantial surface indications are present. The lack of substantial permanent dents at higher impact velocities as seen in Figure 4 is of great concern for those in the field of non-destructive testing, and is known as “barely visible impact damage”. Even though there is substantial interlaminar delamination, this damage is not easily detectable without methods such as tap testing and ultrasonic scanning.

To determine which damage mode results in a greater proportion of damage for a given impact energy, it is important to examine the amount of energy being absorbed relative to the total energy of the impact. This proportion of absorbed energy can be interpreted as an indicator of damage resistance and give an indication as to how well the composite material can return impact energy back to the impactor elastically instead of sustaining permanent damage. Figure 5 below shows the percentage of the total impact energy that has been absorbed by the sample.

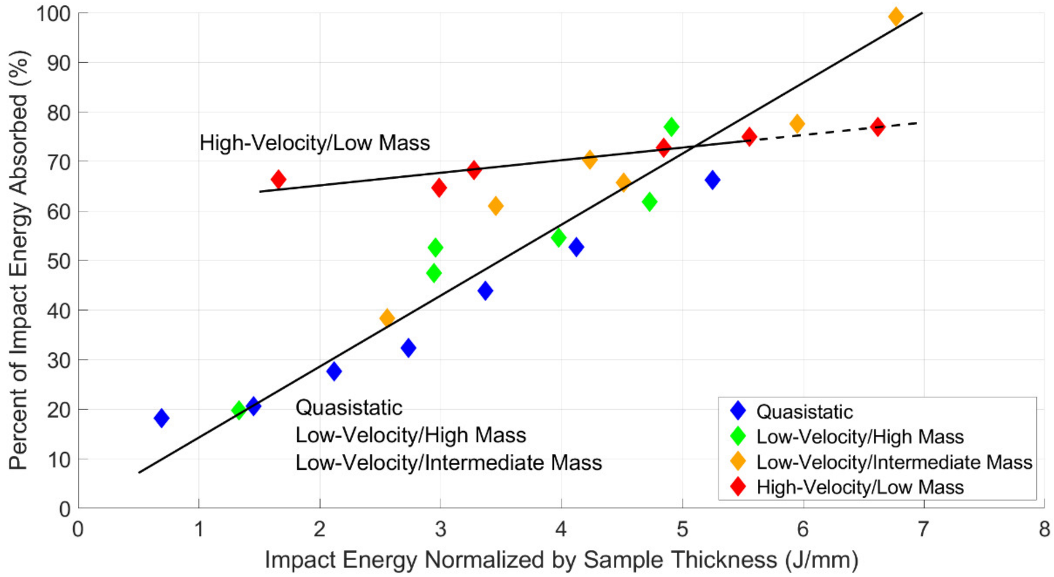

Figure 5 Percent of impact energy converted to damage cross-plotted with normalized impact energy; low mass, high-velocity impacts appear to be less damage resistant at lower energy levels when compared with low-velocity impact

In this figure it is evident that there are two trends occurring that are differentiated by membership in the high-velocity impact regime or the lower velocity regimes. With lower velocities it is seen that the amount of impact energy converted to damage increases linearly with respect to impact energy and appears to approach zero as the impact energy approaches zero. This is expected as the damage at lower energy levels should be minimal or non-existent if all the impact energy is stored as elastic strain energy and returned to the projectile on unloading. However, in the case of high-velocity impact there is no sign of the absorbed energy approaching zero as the impact energy decreases. Of course, it is necessary that at some lower energy level the absorbed energy reaches zero, however it is evident that this transition must occur in a very non-linear fashion at a lower energy level than tested. Based on this data it is proposed that under high-velocity impact conditions – where there is insufficient time for strain energy to be stored elastically in the larger structure of the sample – the local loads in the vicinity of the impact site increase rapidly to the point that substantial damage may occur even with relatively minimal impact energy as this energy must be handled by a smaller volume of material (before the shear and flexural stress waves have time to spread through the sample). Thus, damage resistance is diminished under high-velocity impact loading and the resulting damage primarily takes the form of interlaminar delamination that is not as easily detected.

5 CONCLUSIONS

Through this work it has been shown that non-crimp fabric carbon fibre reinforced epoxy composite materials have a significant strain rate sensitivity between the high-velocity and lower velocity impact regimes. At higher impact velocities their damage resistance at lower energy levels is diminished as evidenced by the substantially higher percentage of energy absorption that occurs at low energies. Furthermore, it has been shown that under high-velocity impact conditions there is no substantial formation of a permanent dent in the sample for the energies tested, and thus the energy that is absorbed must be dissipated through damage mechanisms that do not result in a substantial dent. It has been shown that this reduction in permanent deformation at the impact site is correlated with larger delamination as the ultrasonic C-scans show extensive delamination beyond the initial impact site. It is proposed that the creation of a large equiaxed delamination zone is formed instead of the permanent dent because of the reduced volume of material available for elastic energy absorption and return under high-velocity impact conditions; although further work involving numerical models may be needed to better understand the exact cause of this tendency towards delamination. This tendency for damage to be localized to the interlaminar regions at higher velocities, without substantial surface indications is of concern to users and maintenance personnel working with structures composed of this material. The increased attentiveness and rigour necessary to identify damaged regions with this type of damage increases the likelihood that damage may go undetected and potentially result in issues with structural integrity.

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