Effect of High Velocity Ballistic Impact on Pretensioned Carbon Fibre Reinforced Plastic (CFRP) Plates

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Abstract. This work describes an experimental investigation of the pretensioned thin plates made of Carbon Fibre Reinforced Plastic (CFRP) struck by hemispherical and blunt projectiles at various impact velocities. The experiments were done using a gas gun with combination of pretension equipment positioned at the end of gun barrel near the nozzle. Measurements of the initial and residual velocities were taken, and the ballistic limit velocity were calculated for each procedures. The pretension target results in reduction of ballistic limit compared to non-pretension target for both flat and hemispherical projectiles. Target impacted by hemispherical projectile experience split at earlier impact velocity compared to target by flat projectile. C-Scan images analysis technique was used to show target impact damaged by hemispherical and flat projectiles. The damage area was shown biggest at ballistic limit velocity and target splitting occurred most for pretension plate.

1. Introduction

For decades, large number of studies had been conducted to investigate the impact behavior of composites at low and high velocities using different projectile nose shapes\textsuperscript{[1][2]}. At low velocity impact, the damage is not visible by naked eye but may affect the internal mechanical properties strength. However, at high velocity impact, the damage is relatively much severe and contributes to instant catastrophic.

Ulven et al.\textsuperscript{[3]} performed a series of ballistic impact tests on eight-harness satin weave carbon/epoxy laminates with four different projectile geometries. The perforation mechanism, ballistic limit and damage evolution of each laminate has been analyzed. At high velocity impact conical projectile resulted in the greatest amount of energy absorbed followed by flat, hemispherical, and fragment simulating projectile impact. During impact, flat projectile creates shear zone, which results in plugging while conical and hemispherical result in fibres stretching.

A review on the literatures conclude that the data of impact on pretension targets is limited and therefore it is difficult to make comparisons between experimental results\textsuperscript{[4][5]}\textsuperscript{[5]}. Hence the effect of pretension on plates during impact is not conclusive and require further works. Several authors have studied the effects of pretension on the dynamic response of composite structures/panels at low velocity impact\textsuperscript{[6][7][8]}. Whittingham et al.\textsuperscript{[9]} presented experimental data of pre-strained composite materials under drop weight low velocity impact. Three different strain conditions, 500, 1000 and 1500 \textmu{e}, were applied to the samples. The results showed that the pre-strain did not affect the peak force, impact energy, depth, penetration, or perforation of the specimens. The relationship indicated that the strains value is small when a pretension of less than 15\% of the ultimate strength is applied. Low strain value is seen contribute to reduce effects on the results.

Different findings were produced by Chiu et al.\textsuperscript{[10]}, who reported a much more convincing experimental results for pretension test. A higher pretension of 20\% of the ultimate tensile strength was used with a drop weight impact tester on a composite laminate. The pretension contribution shows a decrease in impact resistance and ballistic limit value while increasing its damage area.

This argument was supported by Bhavani and Sun \textsuperscript{[11]}, who investigated the low velocity impact on composite laminates with an existing preload. An approximation of 22 KN load (about one-third of
the ultimate strength of the sample) preload was applied to study its impact behaviour. The results showed that the pretension did reduce the tensile strength of the material. However, results from the low velocity impact cannot be extrapolated to a high velocity impact.

To date, little works have been published on the impact of structures subjected to pretensions under high velocity impact[12][13]. Few studies are available with regard to metal structures under pretensions. Garcia-Castillo et al.[12] performed an experiment using glass/polyester woven plates under pretensions of 31% of ultimate tensile strength. Its ballistic limit shows difference of only 10% with non-pretension samples.

Later in 2011, Garcia-Castillo et al.[14] conducted an experiment on the aluminium alloys under pretension and non-pretension conditions. A tensile pretension of 243 MPa and at about 38% of the ultimate strength of the aluminium alloy was applied axially to the plate. Impacted by hemispherical projectile, it revealed that there is only a small difference of less than 5% on the measured ballistic limit.

An almost related study were conducted by Garcia-Castello et al.[15] which investigate pretension damage at high velocity impact with existence of pretension using hemispherical type projectile. Studies shows that higher damage occurred at higher impact velocity near ballistic limit however damage reduction occurred when velocity above than ballistic limit.

It is clear that ballistic impact focussing on the effect of pretension has been studied widely. However, less attempts have been made on damages caused by hemispherical and flat projectiles. The purpose of this research is to observe the ballistic limit and damage influence of uniaxial pretension on the CFRP plate under impact using two different projectile shapes.

2. Experimental Methods

The Carbon Fibre Reinforced Plastic(CFRP) material with the commercial name HEXCEL AS4 (12K) was supplied by a company dealing with fabrication of aircraft components. The individual layers of the unidirectional CFRP prepreg, known as ply, have a thickness of 0.125 mm, and the overall density of the material is approximately 1600 kg/m$^3$. The elastic and strength properties are shown in Table 1. The CFRP rectangular panel was manufactured using a hand layup technique, consisting of 24 plies of layup forming a bidirectional composite. The test panels were cut into required sizes using a diamond disc cutter with coolant to avoid any heating and stress concentration, which might have caused delamination and damage. The target dimension was 145x45x3 mm for length, width, and thickness respectively.

| Description and (unit) | Symbol | Value |
|-------------------------|--------|-------|
| Young’s modulus in fibre direction 1 (GPa) | $E_{11}$ | 145 |
| Young’s modulus in fibre direction 2 (GPa) | $E_{22}$ | 11 |
| Poisson’s ratio | $\nu_{12}$ | 0.3 |
| Shear modulus, 1-2 plane (GPa) | $G_{12}$ | 4.5 |
| Tensile failure stress in fibre direction 1 (MPa) | $X_{1T}$ | 1620 |
| Compression failure stress in fibre direction 1 (MPa) | $X_{1C}$ | 1200 |
| Shear strength, 1-2 plane (MPa) | $S_{12}$ | 120 |

Figure 1 shows the flat and hemispherical nose geometry of projectile with a mass of approximately 3 grams. The silver steel projectiles were machined using a lathe, then subjected to a hardening process to increase their strength. Both projectiles were 5 mm in diameter, with the hemispherical nose a little longer in order to have the same weight with the flat projectile.
Light sensors and high speed camera were used to measure the impact and residual velocity respectively. A tensile rig has been designed specifically to run the pretension job. It is attached near the gas gun testing machine as shown in Figure 2. A couple of hydraulic cylinders were used to pull the upper and lower frame in the opposite direction to create tensile force to the specimen. To measure the strain, a simple ‘load cell’ is attached on the tensile rig position in-line with the tensile direction. The load cell is attached with reading indicator and when the strain reached the required value, the hydraulic cylinders are locked to maintain a constant pretension before the impact test take place on the required velocity.

Tests for CFRP specimens were performed under two axial loading conditions; without pretension (0%), and with a pretension of 30% of the maximum tensile strength. The ultimate tensile strength of the bidirectional CFRP was approximately 705 MPa, therefore 30% of pretension is 211.5 MPa. After the impact test, the specimens were inspected by a non-destructive inspection with C-Scan technique using Olympus Phase Array C-Scan MX2. Here an ultrasonic sound will inspect any defect in the specimens.
3. Results and Discussion

3.1 Ballistic Limit Prediction

Figure 3 presents the ballistic test result under impact of flat and hemispherical projectiles with target pretension of 0% and 30% from material ultimate strength. Using the modified-Navy ballistic limit, four tests consisting of two complete and two partial penetrations, were used to predict the ballistic limit \( V_{50} \) [16]. For a target with 0% pretension, an average ballistic limit from flat projectile was approximately 102 m/s. While for a hemispherical-nose projectile, the average ballistic limit was approximately 118 m/s. The ballistic limit for a flat-nose projectile is 15% lower than that for a hemispherical-nose projectile. Figure 3 shows detail of impact tests with plate under 30% pretension. Similarly, using the modified-Navy definition, the ballistic limit for a flat-nose projectile was approximately 90 m/s, whereas the ballistic limit for a hemispherical-nose projectile was approximately 99 m/s. At 30% pretension, the ballistic limit for a flat-nose projectile was found to be 10% lower than a hemispherical-nose projectile. For a flat-nose projectile, plate splitting only occurred after a complete penetration has occurred. However, for a hemispherical-nose projectile, plate splitting occurred for both partial and complete penetrations.

Existence of pretension led to a reduction in the ballistic limit for both projectile types. Under 0% and 30% target pretension, flat projectile results in 12% reduction. On the other hand, at impact velocity of 85 m/s with 30% target pretension, the results show that the flat projectile perforated through the sample while the hemispherical only dented the sample. This indicates that hemispherical projectile require a higher velocity to reach ballistic limit. This also proved that shear and plugging behaviour by flat projectile are easily to perforate compared to hemispherical projectile.

![Figure 3: Variations of the residual velocity with impact velocity for CFRP panels with and without pretension.](image)

3.2 Damage Assessment of impacted CFRP plate

Figure 4 shows damage images of all plates inspected by the C-Scan at three different speed categories: (i) below than ballistic limit, (ii) ballistic limit \( V_{50} \) and (iii) above the ballistic limit. Most images show that the damage areas are localized in the centre. The C-Scan inspection reveals only the projection image of the area. However, the lamination between plies is not been observed. It can be seen that the damage area was smaller at velocity lower than ballistic limit, as shown in Figure 4a, b, c and d. The
damage area becomes larger when approaching ballistic limit velocity (Figure 4e, f, g and h). As the impact velocity increases higher than ballistic limit, the perforation threshold shows the reduction. For pretension target which was impacted at higher velocity than ballistic limit, it shows split on target (Figure 4j and l). In overall, although the size and shape are differed, the results are having some similarities to the works of Garcia-Castillo et al.[15]. In addition, with existence of pretension, hemispherical projectile tends to split the target at early impact velocity of 95 m/s compared to flat projectile at 105 m/s.

![Figure 4: C-Scan images of CFRP target at impact velocity below, average and higher than ballistic limit.](image)

4. **Conclusions**
Two projectiles types, flat and hemispherical shapes have been used to evaluate the ballistic performance of CFRP plate subjected to high velocity impact with the effect of axial pretension. The impact velocity, residual velocity, the ballistic limit and the damages were obtained. The damage for pretensioned target behaves differently due to sample splitting. In high velocity impact, the damaged area increases until the ballistic limit is reached and experience reduction at velocity higher than ballistic limit. It is also observed that hemispherical projectile split target plate at lower impact velocity compared to flat projectile. It was due to tensile damage by hemispherical projectile compared to shear failure by flat projectile. Using the C-Scan, it shows clear images of internal damage due to the pretension target being impacted by flat and hemispherical projectiles.

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