BALLISTIC RESPONSE OF ALUMINIUM ALLOY AND CFRP PANELS WITH PRETENSION

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ABSTRACT

Name of the University: The University of Manchester

Candidate’s full name: Kamarul-Azhar Kamarudin

Degree Title: Doctor of Philosophy

Thesis Title: Ballistic Response of Aluminium Alloy and Carbon Fibre Reinforced Plastic Panels with Pretension

Aircraft disasters during take-off and landing by the impact of foreign object debris (FOD) have always been an important issue. When the wing is lifted, its upper and bottom surfaces are subjected to compressive and tensile stresses, respectively. The bottom surface of the aircraft wing is vulnerable due to the threat of runway debris, which may travel at high speed, leading to the catastrophic failure of structures under tension. This thesis studies the ballistic performance of a structural panel subjected to projectile impact when the influence of in-plane pretension is considered.

An experimental program was proposed to obtain the laboratory testing results where a special rig was designed to apply pretension to the panel as it is being hit by a projectile launched from a gas gun at velocities between 60 to 160 m/s. Instrumentation was used to record impact and residual velocities at different stages of the impact process. The panel was supported on opposing sides in one direction with two free sides in the other direction. Two target materials related to aircraft structure were considered, i.e., aluminium alloy, 2014-T6 and carbon fiber reinforced plastic (CFRP). Two projectile nose shapes - including flat and hemisphere - were used to account for the influence of debris on the ballistic performance of the target. Target materials were fully characterized in the experimental program.

Finite element (FE) models were established and validated, and were used to simulate the response and damage of the panels in the experiments when the influence of pretension is considered. The damage of aluminium alloy, 2014-T6 was modeled using shear failure criterion with damage evolution. For CFRP, the in-plane damage initiation was modeled using Hashin’s damage criterion with damage evolution in terms of fracture energy. Parametric studies were done for both aluminium alloy 2014-T6 and CFRP panels with various pretensions of up to 50% of the material ultimate strength. It has been shown that the pretension has more profound effect on the ballistic behavior of the CFRP panel in comparison with its influence on the ballistic behavior of aluminium alloy panel. The simplified analyses and the numerical modeling reflect the physical nature of the impact response and damage of aluminium alloy and CFRP target panels. Hashin’s damage model for CFRP needs to be extended from in-plane to out-of-plane in order to include shear failure, which may happen for the flat nose projectile impact.
DECLARATION

No portion of the work referred to in this thesis has been submitted in support of an application for another degree of qualification of this or any other university, or other institution of learning.
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## NOMENCLATURE

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<thead>
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<tr>
<td>$A$</td>
<td>Cross section area</td>
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<tr>
<td>$C_{dr}$</td>
<td>Elasticity matrix</td>
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<td>Individual damage variable</td>
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<td>$\bar{\sigma}$</td>
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CHAPTER 1. INTRODUCTION

Aluminium alloy was first discovered in the early 18\textsuperscript{th} century, and its development started circa 1911. During the First World War - leading to continuous increase of its strength - aluminium alloy started to be used for aircraft manufacturing (Fridlyander, 2008). Aluminium alloy is known for its low density, light weight, corrosion resistance and recyclability (Aalco, 2013). Structural components made from aluminium and its alloys are vital to the aerospace industry, and are important for other industries such as transportation. To date, aluminium alloys are classified according to categories (“Automotive Aluminium Alloys and Applications”, 2008). Aluminium alloys have an elastic modulus which is lesser than steel but having similar ultimate strength. Therefore, this has made them to be more advantageous compared to steel.

Other than aluminium alloys, polymer composites have also become another important material in aircraft manufacturing. Composites are materials that combine two or more organic or inorganic components. One material serves as the ‘matrix’, which is the material that holds everything together, while the other material serves as the ‘reinforcement’. The matrix in the composite structure is very important in protecting the fibre and transferring stresses to other areas. Polymer composites based on carbon fibre and glass fibre reinforced (GRP) are anisotropic and heterogeneous materials. Compared to other material types, composites offer the advantage of allowing the designers to tailor their mechanical and thermal properties, by adjusting their orientation, loading and resin type. Other advantages of composite materials are high strength/stiffness to weight ratio, ease of handling and many other attractive mechanical performances for structural applications.

The use of carbon fibre reinforced plastic (CFRP) composites in aircraft structures has been consistently increasing in the past decades. Continuous development of CFRP composites has been due to the large demand for higher strength and lighter materials for both commercial and military aircrafts. Aircraft model Airbus 350 itself has 53\% composite in terms of weight, which greatly reduces the non-pay-load weight and saves fuel. (Airbus 350, 2014).
Reduction in structure performance due to impact can be expected during manufacturing, in-service and even maintenance. The impact can be categorised into two velocity ranges i.e., low velocity and high velocity impact. Impact damage tolerance of the structure is dependent on the impact speed of the impactor and mechanical properties of the target. Damage from impact by a large mass with a low initial velocity may be different from the one that is caused by a small mass with high initial velocity. During manufacturing process, low impact velocity usually occurs when the structure is accidently struck by a large-mass tool that may cause indentation and internal damage. The internal damage such as cracking and delamination for a composite sample as shown in Figure 1.1 contribute to the reduction in structural strength.

![Figure 1.1: Low velocity impact damage. (López et al., 2008).](image)

In aviation, Foreign Object Debris (FOD) is a term used to describe debris, ice from wings, hail storm, volcanic ash, striking birds and tools left on the runway (Figure 1.2a), which may potentially cause severe damage to the aircraft, as shown in Figure 1.2b (“FOD”, 2014; “Aviation safety investigations and reports”, 2013; “The science of bird and aircraft collisions”, 2009; “United Plane Suffers Bird Strike near Denver”, 2012). For wings with internal truss, undercarriage with landing gear and fuselage with internal pressure, damage by FOD impact may be different.

Impact threats from FOD increase the cost of maintenance and training that are carried out to provide awareness and consequently reduce the damage caused by FOD. The safety measurements include housekeeping, tools handling record, debris collector inventory and reporting of missing items. Even though awareness and training activities could reduce impact damage accidents, records have shown that damage from FOD impact still causes
damages. From 1958 to 2008, it was recorded that most aircraft accidents and fatalities happened during take-off and landing. These are the times when the aircraft positions are most likely to be impacted by FOD. It was shown that at speeds of 160 to 180 knots (81.5 – 91.7 m/s) during take-off and landing, tendency of casualties from FOD impact should be considered seriously.

In the year 2000, a Concord was involved in a crash and was caught on fire. The incident was caused by a FOD in which, a piece of titanium debris dropped accidentally on the runway by another aircraft that took off only four minutes earlier (CNN wire staff, 2012). Another potential threat to aircraft comes from hailstorm. In 1999, a hailstorm had caused damages on 20,000 properties including 25 aircrafts near Sydney airport (Hailstorm, 2014). In August 2006, another aircraft, a Boeing 727-200 was forced to make an emergency landing after being struck by hailstorm during climbing.

Aircraft structure is subjected to various stresses during its service due to the existence of internal pressure, self-weight, drag and lift forces. During take-off, the lower surface of the aircraft wings experience continuous change of stress states from compression to tension, with a continuous increase of airlift. This area is exposed to the impact of runway debris. Furthermore, pressure differences around the tip, vortex and turbulence from wind pressures around the wings may also carry high speed debris that threatens the integrity of aircraft structures.
Some structures are designed to withstand high velocity impact. Unfortunately, few materials like fibre reinforced plastics (FRP) are vulnerable to impact and are prone to interlaminar fracture due to its low strength in the transverse and thickness directions (Mouritz, 2011). Compression-after-impact (CAI) tests have shown that the compressive strength of CFRP composite may be reduced of up to 30% due to impact damage. Extended research has been done for CFRP composites to understand their buckling, delamination, indentation and compression behaviours (Fan et al., 2011b; Kinsey et al., 1995; Zhang et al., 1999; Heimbs et al., 2009).

Although there have been some studies on impact behaviour of panels, they are mostly limited to non-pretension impact. Meanwhile, research on impact with pretension had been done for decades but most studies focus on low velocity impact and only few researches had been performed on high velocity impact with pretension (Mikkor et al., 2006; Garcia et al., 2006; Garcia et al., 2013). Therefore, it is necessary to study the impact of FOD on aircraft structures with pre-stress at high impact velocities to fill the knowledge gap.

The research will begin from the determination of the mechanical properties of the material using tensile and shear experimental results. The mechanical properties obtained from the experimental tests will be used in the simulation for impact test. Ballistic tests will be conducted experimentally on side using both aluminium alloy 2014-T6 and CFRP panels with and without pretension effects. A finite element simulation using Abaqus/Explicit was used to model the impact test. Two types of projectiles with different nose shapes i.e., flat and hemispherical projectiles will be used in the study, to consider the different effects of projectile sharpness.
1.1 Problem Statement

The ballistic behaviours of thin-walled aluminium alloy and CFRP panels subjected to hard projectile impact will be studied, with the consideration of different nose shapes and pretension effects. Respective analytical, experimental and numerical methods will be applied to understand the above-mentioned phenomena, which cover the basic mechanisms observed for aircraft structures when subjected to FOD impact.

1.2 Aim, Scopes and Objectives

The aim of this study is to investigate the structural behaviour of metal and composite panels under projectile impact and analyse their respective structural performances in terms of ballistic limit when the influence of the in-plane pretension is considered.

The scopes of this study are to:

a) Prepare samples for UD-CFRP and conduct mechanical properties test.

b) Design a tensile rig and load cell for the impact apparatus.

c) Conduct impact tests to investigate the pretension effects on ballistic behaviours.

d) Simulate the impact test using ABAQUS FEM model to understand the experimental results.

The objectives of this research are to:

a) Develop techniques to predict the ballistic limit of aluminium alloys and CFRP panels subjected to high velocity impact.

b) Develop modelling capabilities to simulate the responses of aluminium alloy and CFRP panels under impact using finite element method.

c) Understand the effects of projectile nose shapes and the existence of pretension on the ballistic behaviour of the target panels.

d) Understand the failure mechanisms of aluminium alloy and CFRP panels under various pretensions that are subjected to projectile impact.
1.3 Thesis Outline

This thesis is comprised of seven chapters,

In Chapter 1: Introduction of the thesis, including the description of the aim, scope, objective and overview of the study.

In Chapter 2: A literature review is presented on relevant experimental and numerical studies on the response and failure of isotropic and composite panels subjected to the impact of a hard projectile.

In Chapter 3: Mechanical properties tests were conducted on CFRP to characterize its mechanical behaviours. Standard procedures were followed for the fabrication and material testing. Experimental results were used to determine the mechanical parameters, which will be applied into the material model in Chapter 6.

In Chapter 4: Impact tests on aluminium alloy 2014-T6 and CFRP target are presented. A tensile rig was developed for the application of pretension onto the target when it is impacted by the projectile launched by a gas gun. The ballistic limits were determined and compared for targets with and without pretensions.

In Chapter 5: Finite element model using Abaqus/Explicit was developed to simulate the high speed impact on aluminium-alloy 2014-T6. Metal plasticity shear failure criterion was used in the simulation to determine the deformation and failure behaviours. Finite element models were validated against the experimental results presented in Chapter 4. The models were also used to simulate impact behaviour of the target with the existence of pretension.

In Chapter 6: Abaqus/Explicit finite element models were developed to simulate the high speed impact on CFRP panel. Hashin’s failure model was used in the simulation to determine the material failure. The finite element models were validated against the experimental results as presented in Chapter 4 which were then used to study the pretension effects on the ballistic performance of CFRP panels.

In Chapter 7: Conclusions with findings and recommendations for future work were presented.
CHAPTER 2. LITERATURE REVIEW

2.1 Introduction
This chapter presents a review of past and current works on impact engineering on panels subjected to low and high velocity impact. A brief overview of the types of equipment employed during an impact event is also presented. Other important aspects included in this review are the finite element analyses together with mesh sensitivity technique used to predict ballistic limit. In addition, relevant studies on pretension target materials under low and high velocity impact are discussed.

2.2 Low Velocity Impact
Two most common methods used in low velocity impact tests are the Charpy and drop tests; whereby the apparatuses are as shown in Figure 2.1. The Charpy test has been used to measure material toughness; its relatively low cost and ease of operation for both metals and composites testing have made it a reliable testing method for many years. The free fall drop weight impact test is another low velocity testing apparatus which makes use of a mass with a guided rail and often applied for structural panel behaviour studies. The dynamic behaviour of fibre laminates is more complex as compared to isotropic materials because these structures adapt different mechanisms of failure such as laminate failure, delamination, matrix cracking, plastic deformation and displacement (López et al., 2008).

Fan et al., (2011a) investigated the impact damage behaviour of glass fibre composite under low velocity impact. They used two different projectile nose shapes - flat and hemispherical - for impact on 40 ply glass fibre laminates. Based on experimental and finite element (FE) results, it has been shown that the increased projectile bluntness is related to an increase in the energy required to perforate the sample (Figure 2.2).
Figure 2.1: Low velocity impact apparatus (a) Charpy tester. (Altenaiji et al., 2011), (b) Drop test (Yang and Cantwell, 2010)

Figure 2.2: (a) Graph of load vs. displacement. (b) Schematic diagram of glass fibre impacted by drop weight apparatus (Fan et al., 2011a).

Lee et al., (1997) studied the impact response of hybrid laminate plates using finite element method. They showed that different lay-ups of a hybrid plates result in different
impact energy absorption. A Kevlar-carbon-Kevlar arrangement was proven to have much higher energy absorption than a carbon-Kevlar-carbon laminate. This indicates that a material having a good impact resistance should be used as the outer layer of a laminate structure.

Shyr and Pan (2003) had tested glass fibre reinforced plastic panels(Fibredux 924C-T300(6k)) using a low velocity drop test. A destructive method was used to identify the damage. The impact was performed on two layer types (7-layer and 13-layer) with multi-axial warp and both woven and non-woven arrangements. It was shown that the impact had caused fibre fracture and delamination in both thick and thin laminated non-crimped fabric composite respectively, which results in excellent impact resistance.

![Figure 2.3: Damage by hemispherical indenter (Shyr and Pan, 2003)](image)

Impact velocity is related to low velocity such that it does not involve ballistic limit prediction but more on damage and energy absorption. Fibre reinforced plastic targets impacted by hemispherical projectile show damages in the form of delamination and fracture, while for metallic targets; damage is manifested in the form of petalling. Experiments involving low velocity impact can easily be presented by a load vs. displacement graph and compared to that of high velocity impact. In this chapter, the material is not influenced by pretension; however, pretension will be considered and studied in the following chapter with regards to its damage and structural behaviour.

### 2.2.1 Low Velocity Impact on Pretension Targets

Low velocity impact has been intensively studied for nearly two decades (Abrate, 1998; Reid and Zhou, 2000). Nonetheless, only a few studies focused on the influence of pretension on the structural impact (Chiu et al., 1997; Whittingham et al., 2004; Mitrevski et al., 2006).
Mines et al., (2000) carried out a static experiment with pretension for a 32-layers unidirectional CFRP laminate as it was transversely loaded by an indenter. An in-plane load of up to 30kN was applied to the sample using a hydraulic cylinder. The energy absorbed was determined in order to estimate the structure behaviour under pretension. It was shown that, the existence of the in-plane load, has little effects on the energy absorbed.

Further experiments had been carried out by Mitrevski et al., (2006), in a series of impact tests on GRP specimens under pretension using 4 different projectile nose shapes. Two different pretensions (500 and 1000µε) were applied to the specimens with dimensions of 215 x 215 mm and an impact window of 140 x 140 mm. A drop weight rig was used as the low velocity impact medium. The results showed that there was little difference in the damage area, contact duration and maximum deflection for samples with and without pretension. However, the researchers had found that, at certain pretension levels, the impact energy absorption and the indentation depth start to increase.

In an early study of the same subject matter, Whittingham et al., (2004) presented an experimental data for pre-stressed carbon fibre composites using the drop weight low velocity impact. The specimens, all having the same dimensions of 215 x 215 mm and impact window of 140 x 140 mm, were loaded in either the uniaxial or biaxial direction. Three different strain conditions; 500, 1000 and 1500µε, were applied to the sample. The results had showed that pre-strain existence does affect the penetration depth but not much difference was measured in the levels of absorbed energy.

There are few findings showing that the existence of pretension affects the target stiffness and resistance. Mines et al., (2000) showed that the existence of in-plane load slightly increases the transverse deflection.

Earlier in 1997, Chiu et al., reported the experimental results of impacts in a pre-stressed sample. A pre-stress at 20% of ultimate tensile strength was applied in the drop weight impact test. The tested samples were made of graphite epoxy laminate with length and width of 152.4 x 10.16 mm respectively. However, for samples with pretension, the length was extended to 203 mm in order to accommodate the space for clamping. When the applied pre-stress was increased, the samples had showed a decrease in impact resistance, indicated by the decrease of the ballistic limit and the increase of the damage area. This also supports
the earlier observations by Sankar and Sun (1985), who investigated low velocity impacts onto graphite epoxy laminate; whereby, a pretension with an approximate load of 22kN - about one third of the sample’s ultimate strength - was applied in the study. The presence of pre-stress had reduced the impact velocity required for damage initiation and development, and also generated delamination for higher impact velocities.

In other findings, Robb et al., (1995) compared the results of pre-loaded targets under uniaxial and biaxial tension. Generally, the pre-stress loadings are more detrimental to the target in terms of impact damage. Samples under uniaxial stress had showed a larger damage area, higher peak indentation and more absorbed energy compared to those under bi-axial stresses. Similar biaxial pretension experiment was done by Mitrevski et al., (2006) who compared the displacement obtained from four impactors with different nose shapes. A conical shape gave the largest displacement in comparison to ogival, spherical and flat shaped noses. The flat shaped nose gave the smallest deflection due to the early initiation of plugging (instead of stretching).

Findings have also shown that the existence of pretension affects the target stiffness. However, pretension value does play an important role. There are few studies by Whittingham et al., (2004) and Mitrevski et al., (2006) which reported the use of a pretension value that is too small onto the target such that it does not affect the structural behaviour.

2.2.2 Low Velocity Impact Devices with Pretension

One of the requirements in a pretension test is the development of the pretension device, which should be rigid and able to absorb vibrations from the impact. A purposely-built pretension device for the target panels is shown in Figure 2.4. In general, the device comprises of two stiff frames that are placed at the top and bottom of the composite panel. For low impact velocity drop test, the rig is placed horizontally, facing upwards below the drop test. The device is usually attached to a hydraulic or screw-type puller to perform the pretension. A load cell is attached to the device to measure the loadings applied on the target sample.
Figure 2.4: Various pretension devices used with the drop test apparatus. (a) Mines et al., (2000); (b) Top view of compression/tension devices positions (Mitrevski et al., 2006); and (c) Bracket steel holder (Pickett et al., 2009).

2.3 High Velocity Impact on Target

The equipment used for a high velocity impact testing is different from that used for low velocity impact testing. A gas gun is used to accelerate the projectile at high velocity. The velocity can be measured by several techniques such as a light sensor, thin film sensor or a high speed camera. Figure 2.5 shows the basic set-up of a ballistic gas gun and velocity meter.
Chapter 2: Literature Review

The perforation of the targets by projectiles at high velocity impact covers a wide range of structures. The penetration problem can be categorized by angle of impact, material properties, initial velocity and projectile nose shape (Abrate, 1998; Sabet et al., 2011). In order to understand structural perforation performance, it is important to know the minimum impact velocity which will result in complete penetration i.e., the ballistic limit.

![Gas gun set up for high speed impact test](image.png)

Figure 2.5: Gas gun set up for high speed impact test (Jenq et al., 1994).

2.3.1 Ballistic Limit Predictions

‘Ballistic limit’ is defined as the lowest initial impact velocity which is just sufficient to result in a complete penetration of the specimens. Corbett and Reid (1993) defined ballistic limit as the highest impact velocity in which the target could withstand without causing a complete perforation. Ballistic limits (BL) are practically described by \( V_{50} \), which is the average of a series of impact velocities; at which 50% of impacts will result in a complete penetration of the material.

Various ballistic limit predictions are widely used by researchers; either using energy conservation or experimental techniques (Backman and Goldsmith, 1978; Recht and Ipson, 1963; Bovrik et al., 2002; Kasano, 2001). Backman and Goldsmith (1978) defined ballistic
limit as the average of two striking velocities, one of which is the highest velocity giving a partial penetration and the other is the lowest velocity giving a complete penetration. They also address several measures used in rating the resistance of armour or other materials to penetration, whereby the three most widely used ballistic limit definitions are; the Army Limit, Protection Limit and Navy Limit. The essential difference between these tests is the criteria employed to define a perforation, as illustrated in Figure 2.6.

![Figure 2.6: Different definitions of ballistic limit (Backman and Goldsmith, 1978).](image)

Prediction of ballistic limits for the certification of armour using experimental techniques is considered to be very costly since a series of tests is needed to meet the testing requirements. Consideration of the conservation of energy principle during a perforation process may reduce the testing numbers (Sabet et al., 2011; Kasano, 2001). The energy conservation is given as,

\[
\frac{1}{2} m v_i^2 = E_p + \frac{1}{2} m v_r^2
\]  

(2.1)

where \( E_p \) is the perforation energy and \( v_i \) and \( v_r \) are the incident and residual velocities respectively. This equation assumes that the perforation energy is independent of the projectile velocity. This means that, for a complete penetration, the residual kinetic energy is proportional to the initial kinetic energy.
At the ballistic limit, \( v_r = 0 \), and Eq. (2.1) becomes:

\[
E_p = \frac{1}{2} M v_b^2
\]  

(2.2)

where \( v_b \) is the ballistic limit.

Reid and Zhou (2000) had produced the experimental results of foam core sandwich panels struck by a 10.5 mm diameter hemispherical nosed projectile (17.9 g) at a velocity of up to 305 m/s. Figure 2.7 shows the residual impact velocity and the prediction of ballistic limit determined using a simplified version of Eq. (2.1) and (2.2) as:

\[
v_r = \frac{1}{2} m(v_i^2 - v_b^2)
\]  

(2.3)

Figure 2.7 shows that the predictions using Eq. (2.3) are in good agreement with the experimental results.

The ballistic limit velocity is also affected by the oblique angle of the impact. Zhou and Stronge (2008) had pointed out that smaller oblique angle will lower the ballistic limit. Similarly, Hazell et al., (2009) also investigated the impact response of a projectile on a composite target at normal and oblique angles of incidence. The ballistic limit for the normal incidence showed a lower impact velocity which means that the ballistic limit for normal impact is smaller than that for oblique impacts. In addition, to provide an accurate measurement of the ballistic limit, a projectile needs to be aligned perpendicularly to the target plane.
Figure 2.7: Residual velocity versus impact velocity of square sandwich panel (Reid and Zhou, 2000).

Wambua et al., (2007) reported the effects of the striking velocity on the amount of energy absorbed, $E_a$ by the composite material. The absorbed kinetic energy, the impact and the residual kinetic energies were linked in equation (2.1). The experimental results in Figure 2.8 has showed that the absorbed kinetic energy increases with increasing impact velocity until approximately the ballistic limit (where residual velocity, $v_r = 0$) of the material. As long as the target is not perforated by the projectile, all the kinetic energy is absorbed by the material (Cunniff, 1992). Above the ballistic limit - immediately after perforation has occurred - the amount of absorbed energy becomes level but then begins to increase again as the velocity increased. The ‘energy level’ that happened at the ballistic limit was due to the material ejected by the projectile during perforation. Similar results were also found by Wu and Chang in 1995. The ballistic tests conducted on a composite panel showed that after the ballistic limit is reached, the energy absorption will be briefly constant before inclining again as the impact velocity continues to increase.
Figure 2.8: Kinetic energy effect of impact velocity (Wambua et al., 2007).

Chan et al., (2007) performed the experimental work on composite structure for high velocity impacts which were then compared with numerical simulation data. In contrast to previous researchers, they had measured the experimental ballistic limit based on the $V_{50}$ concept of the average initial velocity of perforating and non-perforating projectiles.

Kasano (2001) had investigated high velocity impact tests using a steel sphere on CFRP, both experimentally and analytically. The sphere was 5mm diameter, 0.51g in weight and impacted the target at a normal angle. Two analytical models of ‘conservation law of energy’ and ‘conservation laws of momentum and energy’ had been used to process the experimental test results. The thicker sample plate of the same material had showed a significant increase in the ballistic limit. The relationships between the impact and residual velocities also showed a similar pattern in the parabolic region near the ballistic limit, with an observable linear increase as the impact velocity is further increased.

Mamivand and Liaghat (2010) had presented a simple analytical model to predict the ballistic limit of a Kevlar fabric. The analysis has been based on a layer-by-layer examination of the configuration of the transverse wave and the strain failure criterion of the yarn. The results have been compared with another finding which used semi-analytical equations, specific to projectile fragment simulation. However, this technique has been limited to specific configurations and selected projectiles.
Sevkat et al., (2009) investigated the experimental prediction of ballistic limit for hemispherical shaped copper bullet using a gas gun. Two different glass fibre lay-up (24 layers each) configurations were investigated. The targets were instrumented with strain gauges to measure the dynamic strain. The validations were performed using dynamic strain and damage pattern analysis. The experimental data was also compared with the FE simulation results. To validate the ballistic limit, two experimental tests were conducted at 120 m/s and 298 m/s, which resulted in partial penetration of the target plate. It was found that the ballistic limit was between 298 m/s and 342 m/s.

Both empirical and semi-empirical (energy conservation) methods were used by many researchers to predict the ballistic limit. All these techniques provide convincing predictions of ballistic limit at high velocities impact.

2.3.2 Projectile Geometry

A number of works have been published to study the effects of projectile geometry on impact behaviour of the target. Most results are focused on the absorbed energy related to projectile nose shape. (Chen and Medina, 1998; Hazell et al., 2009; Hou et al., 2010; Ulven et al., 2003).

Leppin and Woodward (1986) illustrated the local impact effects for a cone nosed projectile on a metal plate with different thicknesses, as shown in Figure 2.9. As the plate thickness is increased, the plug form also changed. For a thin plate, tearing and plate bending can be clearly seen. As the thickness is increased, the damage formation becomes enlarged to form a single hole or plugging.
Ulven et al., (2003) idealised the projectile impact for four nose shapes; conical, flat, hemispherical and fragment simulation, as shown in Figure 2.10 on carbon fibre reinforced plastic target. From their findings, it has been shown that conical shapes transmit the most energy, followed by flat, hemispherical and fragment simulation projectiles. Flat and fragment projectile shapes tended to result in plugging and shearing. But, due to the existence of an edged angle, the fragment projectiles created a smaller shear zone. Failure of the panel for conical and hemispherical nose shapes was due to spreading and stretching of the fibres during penetration.
Hou et al., (2010) had performed an experiment on quasi-static and dynamic impact loadings using three different projectiles with flat, conical and hemispherical noses on metallic sandwich panels as shown in Figure 2.11. They claimed that the increase in penetration energy for the flat tip projectile has been caused by the greater inward compression due to the blunter projectile tip thus leading to more energy consumption. The hemispherical and conical tips tended to push the material sideways, causing less energy dissipation during compression. It is noticeable that the flat projectile produced the highest energy absorption compared to the others. The edge of the flat nose sheared the fabric across its thickness instead of stretching it towards failure. These findings have shown similarities with the results of Ulven et al., (2003) for flat nosed projectiles, which have high energy absorption compared to the other projectile shapes. They also claimed that bigger impact face does contribute to higher energy absorbed due to shearing and plugging instead of spreading and stretching. Upon that, Ulven et al., (2003) and Hou et al., (2010) have proved that the ballistic limit for a flat projectile is higher than that of hemispherical and conical projectiles.

![Comparison of quasi-static and dynamic energy dissipation by different shapes of projectile. (Hou et al., 2010)](image-url)
Figure 2.12: Energy absorption for a single and double ply fabric. (Lim et al., 2002).

In contrast, Lim et al., (2002) had published a paper comparing energy absorption from different projectile shapes. Figure 2.12 shows the energy dissipated by the hemispherical and flat shaped projectiles impacted on Twaron®CT 716 fabric. Out of the two nose shapes, the target impacted by the hemispherical shaped projectile had produced the highest energy absorption which was almost three times as compared to the target impacted by the flat nosed projectile. Ballistic limits for hemispherical and flat nosed projectiles on a single ply has been measured as 163 and 103 m/s respectively, while a double ply showed an increase of the ballistic limit up to 246 and 125 m/s. It is noticeable that the flat projectile produced small differences as compared to the hemispherical projectile. It is due to the peripheral edge behaviour of flat head projectile during perforation. The edge seemed to shear the fabric along its thickness instead of stretching them towards failure.

This view has been supported by Iqbal et al. (2010), who discussed the ballistic limit results through various projectile nose shapes with high velocity impact on aluminium alloy target plates. Projectiles shapes had been design based on the ratio of the nose radius to the diameter of projectile (CRH). Projectiles of 0 CRH (flat nose) were found to have a higher residual velocity when compared to 0.5 CRH (hemispherical nose). This showed that the target had produced higher resistance to a hemispherical shaped nose projectile than a flat nosed projectile; therefore, the hemispherical projectile had a higher ballistic limit compared to the flat projectile.
2.3.3 Damage Behaviour in High Velocity Impacts

A number of studies had been conducted to evaluate the damage behaviour of target plates under high velocity impact. The damage characteristics were compared under the influence of different projectile nose geometries.

Borvik et al., (2002) simulated the target impacted by various projectile nose shapes - flat and hemispherical - without any pretension influence on the targets. The elements of the mesh were built with aspect ratio, AR=1. Besides having good results when compared with experimental data, the images in Figure 2.13 show a good view of the target behaviour. Flat projectile impact resulted in plugging and shearing with a little tensile deformation. However, for hemispherical projectiles, it has been found that due to round nose shape the material elements mainly experienced tensile deformation. Plug created from hemispherical projectile impact has been found to be smaller than that of the flat nosed projectile.

Figure 2.13: FE simulation of impact on target by flat and hemispherical projectiles. (Borvik et al., 2002)
Backman and Goldsmith (1978) identified several types of failure of target impact by different nose shape projectiles, as shown in Figure 2.14. Different damage behaviour was found in different scenarios based on projectile nose shape, target properties and target thickness. The damage categories are based on fracture stress waves, brittle cracks, scabbing, plugging, petalling, fragmenting and hole-enlargement. For thin plate impact by a relatively sharp projectile, petalling was observed in the rear side of the target (Figure 2.14(f)).

Goldsmith (1999) investigated the impacts in aluminium alloy-2024-T3 and mild steel-SAE1010 to determine their ballistic limit. Three different projectiles were used; flat, hemispherical and conical. The flat shaped projectile caused failure by plugging while the hemispherical projectile resulted in plate thinning and cracking towards the projectile’s spherical cap. However the conical projectile caused a combination of cracking and petalling on the target.

Cantwell and Morton (1989) investigated the effects of damage caused by high velocity impact in CFRP laminate from hemispherical projectiles. A range of fibre stacking sequences with various thicknesses was used in the experiment. Initial failure was found in the lower surface of the target due to the local high flexural stress fields. The delamination area increases with the increase of impact energy. However, the delamination happened more frequently than that seen in low velocity impacts of similar targets. The damage from high velocity impacts was found to be more local but larger, as compared to low velocity impacts where the damage was distributed across the target length.
Chen and Medina (1998) had compared the perforation holes and damage zones impacted by circular and flat projectiles on fibre metal laminate made from Boron fibre and aluminium. The damage diameter was measured by comparing it with the ratio of initial diameter projectile. It had been found that the flat projectile produced larger damage zones and larger perforation holes. The result was also supported by Hou et al., (2010) when a flat projectile pierced the target thus resulting in larger petal area.
Jenq et al., (1994) conducted an experiment whereby a high velocity and quasi static punch test were employed on glass/epoxy composite laminates using hemispherical shaped nose projectiles. For both tests, most damages detected were delamination and fibre breakage but greater damage pattern was mostly seen from the dynamic testing. Ballistic limit from the simulation was compared with the experimental test which was predicted using energy conservation principles. However, the results had showed large differences between the two limits when static parameters were used in the dynamic simulation.

Sevkat et al., (2009) presented the damage behaviour of FRP plates subjected to high velocity impact by comparing both the simulation and the experimental data. Aside from having good agreement on the post impact damage pattern between both results, the target impacted by the hemispherical shaped projectile had also resulted in the delamination of the FRP.

Iqbal et al., (2010) compared the deformation of the targets by different nose shape projectiles. Besides having signs of local displacement, the target impacted by flat nosed projectile resulted in minimal displacement compared to hemispherical projectiles. However, hemispherical projectile showed the highest displacement during global plastic deformation.

2.4 High Velocity Impact on Pretension Targets

Studies related to impacts on targets have mostly focused on impacts without pretension. The non-pretension and pretension structures subjected to high velocity impact may perform differently. There are very few studies on the impact behaviour of composite laminates under in-plane load, especially those related to high velocity impact. Ballistic limit prediction was mostly determined in high velocity impact studies. In 2006, together with non-pretension targets, Garcia et al. also investigated the ballistic limit of GRPs under the effect of uniaxial and biaxial pretension as shown in Figure 2.15. The pretension on the target was 114MPa, which is approximately 26% of the ultimate strength of the target. The ballistic limit was found to be up to 4% higher in comparison between non-pretension and uniaxial; and approximately 6% higher between uniaxial and biaxial pretension. The experimental ballistic limits were also compared with the analytical model. The results did not agree with the analytical findings, whereby the ballistic limit had been reduced as the pretension increased. They claimed that the difference in the ballistic limit between the experimental and the
analytical was due to the static parameter used in the equations instead of dynamic parameters. Besides that, the researchers did not mention the fibre volume fraction for the sample target which made it inconclusive and questionable (5 fibre layers result in 3.19mm which is too thick hence the sample would be rich in resin).

![Figure 2.15](image1.png)

Figure 2.15: (a) Non-pretension (b) Uniaxial (c) Biaxial. (Garcia et al., 2006).

In 2009, Garcia et al., performed an experiment using a similar glass/polyester woven plate under pretension at 31% of the ultimate tensile strength. The tests focused on biaxial pretension, and were compared with non-pretension tests. With the existence of pretension on the target, the ballistic limit was found to be higher than without pretension. At velocities below the ballistic limit, the kinetic energy of the projectile decreases due to the influence of secondary yarn deformation and plate delamination. However, at velocities higher than the ballistic limit, the formation of cones at the back side of the target plate has become the main contributor to the main energy absorption mechanism (Ulven et al., 2003).

Another experiment was done by Garcia et al., in 2011 for aluminium alloy 7075-T6 target; with and without pretensions. A spherical shaped nose of 8.33g in mass was used as an impactor. The target plates, having a dimension of 140 x 200mm, were used for a high velocity impact test with pretension of 243MPa - approximately 38% of the material ultimate strength. It was found that the existence of pretension did increase the ballistic limit by 4.6%.

The latest research paper on high velocity impact with target pretension was done by Garcia et al., (2013); focusing on impact damage in a wide interval of impact velocities between 90m/s and 360m/s. Material types of glass reinforced plastic (GRP) with different
fibre arrangement were used in the study. There were three pretension boundary conditions used in the experiment; non-pretension, uniaxial and bi-axial. The pretensions applied on the uniaxial and biaxial target were approximately 166MPa and 122MPa which is 38% and 27% of its ultimate strength respectively. The ballistic limit for the bi-axial pretension was the lowest compared to uniaxial (10% difference) and the non-pretension targets which has the highest limit (12% different between uniaxial to non-pretension). Figure 2. shows residual velocity compared to impact velocity with the existence of pretension. The ballistic limit on each plate showed reduction due to the existence of pretension. The pretension values for both uniaxial and biaxial are not similar after comparison (27% and 38%). However, the results produced using a similar technique by Garcia et al., (2006) had found the opposite such that they are similar.

![Graphs showing residual velocity compared to impact velocity with different pretension conditions.](image)

**Figure 2.16:** (a) Non-pretension (b) Uniaxial (c) Bi-axial. (Garcia et al., 2013).

Under low velocity impact, Kelkar et al., (1998) had found that, a higher pretension will result in a larger impact force, whereas the damage area will also be increased. This
statement had been approved by Chiu et al., (1997), who concluded that the peak force and damage area will increase together with pretension. However, under high velocity impact, different damage patterns had been reported. Garcia et al., (2006) observed that the damage grew linearly as the impact energy was increased, until it reached the ballistic limit. Figure 2. shows the C-Scan images of the target damage without pretention (images a, b, c), uniaxial (images d, e, f) and biaxial (image g, h, i). Images a, d and g represent the impact damage at lower ballistic limits for various pretensions applied. At velocities higher than the ballistic limit, the damage area was seen decreased as shown in images c, f and i. The damage area from the images was found to be related to the delamination of the impacted specimens.

<table>
<thead>
<tr>
<th>Non-Pretension</th>
<th>(a) 163 m/s</th>
<th>(b) 233 m/s</th>
<th>(c) 443 m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniaxial</td>
<td>(d) 176 m/s</td>
<td>(e) 236 m/s</td>
<td>(f) 513 m/s</td>
</tr>
<tr>
<td>Biaxial</td>
<td>(g) 171 m/s</td>
<td>(h) 261 m/s</td>
<td>(i) 521 m/s</td>
</tr>
</tbody>
</table>

Figure 2.17: C-Scan of the damages of non-pretension (a, b, c) uniaxial (d, e, f) and biaxial (g, h, i) (Garcia et al., 2006).

In another major study, Mikkor et al., (2006) investigated the impact damages at low, medium and high velocities on CFRP targets under pretension. The simulation results were compared with the experimental results of targets without pretension and with axial pretension. They found that the damage for low velocity impacts is internal and invisible, but caused the reduction in overall strength. It was also found that, at certain impact velocities, the model might experience catastrophic failure. Catastrophic failure is showed in the model.
by experiencing damage and in this case, it splits the part into two which is in the direction perpendicular to the axial loading. Similar to Garcia et al., (2006), the damage area was found to increase with increasing impact velocity. Most catastrophic damage occurs below the ballistic limit. With a minimum 50kN of applied pretension load, the stress was measured at approximately 294MPa, which is 42% of the material ultimate strength; this pretension was found to be too high to avoid any catastrophic failure. At certain loads, the pretension applied was above 50% of material ultimate strength; whereby the maximum pretension load applied ranged from 98kN to 544MPa (78% of ultimate strength).

Table 2.1 summarises the related studies of high velocity impact on pretension target. Literature on experiments involving pretension at high velocity impact is very limited while the pretension devices used in high velocity impact test were not presented and explained well by researchers (Garcia et al., 2006; Garcia et al., 2011; Mikkor et al., 2006). Therefore a new pretension device will be designed and explained in detail in this study.

Table 2.1: Previous related work of high velocity impact on pretension target.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Aluminium alloy</td>
<td>CFRP</td>
<td>GRP</td>
<td>GRP</td>
<td>Alum 7075-T6</td>
</tr>
<tr>
<td></td>
<td>UD-CFRP</td>
<td></td>
<td></td>
<td></td>
<td>GRP</td>
</tr>
<tr>
<td>Projectile</td>
<td>Simulation</td>
<td>Flat</td>
<td>Simulation</td>
<td>Experiment</td>
<td>Experiment</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Flat</td>
<td>Hemispherical</td>
<td>Spherical</td>
<td>Spherical</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Flat</td>
<td>Experiment</td>
<td>8.9, 300 and</td>
<td>12.5mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hemispherical</td>
<td>Simulation</td>
<td>650gm,</td>
<td>8.33 gm</td>
</tr>
<tr>
<td>Pretension (%)</td>
<td>Simulation</td>
<td>Experiment</td>
<td>42-77.7</td>
<td>26</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td>Experiment</td>
<td>Experiment</td>
<td></td>
<td></td>
<td>Uniaxial – 37.6%</td>
</tr>
<tr>
<td></td>
<td>Boundary Conditions</td>
<td>Uniaxial</td>
<td></td>
<td></td>
<td>Biaxial – 27.6%</td>
</tr>
<tr>
<td></td>
<td>Ballistic Limit</td>
<td>Uniaxial</td>
<td></td>
<td></td>
<td>Uniaxial – 37.6%</td>
</tr>
<tr>
<td></td>
<td>Prediction</td>
<td>Biaxial</td>
<td></td>
<td></td>
<td>Biaxial – 27.6%</td>
</tr>
<tr>
<td></td>
<td>Force – time</td>
<td>NA</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>prediction for HV</td>
<td>NA</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Damage</td>
<td>Petalling</td>
<td>Image</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Crack before</td>
<td>-</td>
<td>Delamination</td>
<td>-</td>
<td>Delamination</td>
</tr>
<tr>
<td></td>
<td>catastrophic</td>
<td>Yes</td>
<td>using C-Scan</td>
<td>NA</td>
<td>using C-Scan</td>
</tr>
<tr>
<td></td>
<td>Catastrophic</td>
<td>Only measured</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hemispherical</td>
<td>Critical Boundary</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Flat</td>
<td>towards</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>catastrophic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Catastrophic due to</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Pretension</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Damage model</td>
<td>PAM CRASH</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

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2.5 Pressurised Vessel under Impact

Pressurised vessels are another example of pretension structure but using gas or air as the pressure medium. Pressure creates structural expansion from inside the wall. Due to pretension, the impact by an external object could lead to catastrophic failure and the creation of debris could create more damage.

Earlier in 1989, Cour-Paiais and crew ran a simple experiment on cans to determine failure behaviour. They compared the impacts of the unpressurised and pressurised cans. Results had showed that pressurised cans undergo catastrophic failure while unpressurised cans have observable ruptures in several parts of the can with petalling occurring at the back of the can.

In 1997, Lambert and Schneider investigated gas pressured vessels using impact by hypervelocity projectile. The projectile and pressure vessel are made of aluminium, impacted at normal trajectory with constant velocity of 7000m/s. Due to the impact, its kinetic energy had increased and the pressure vessel experienced burst at the front and rear. A numbers of tests were performed; where front and rear bursts were separated by a boundary that depends on the stress level on the vessel wall.

Later in 2008, Kaneko et al. conducted an experiment on pressurized cylinder filled with water. At pressures lower than the failsafe pressure, the loadings required for penetration was found to be higher. However, as the pressure exceeds the safety limit, burst failure could happen and failure starts to progress in the axial direction of the fibre. Also following the increase in pressure, the work and load of the projectile for penetration was found to be smaller.

The studies had shown that there is a threshold between low and high pressures of compressed container which gives the configuration and plausible conditions for catastrophic failure. The energy stored in the container contributes to the failure. It is also the energy that creates pretension thus reducing the ultimate strength of the container.
2.6 Strain Rate Effect in Materials

The use of strain rate and its effectiveness have been considered, when conducting numerical simulations for material behaviour. This is due to the response of the material which will act differently when put under dynamic loading than that under quasi static loadings.

Heimbs et al., (2007) investigated the loading rate effects on the material behaviour of glass fibre reinforced and phenolic resin. This was done by increasing the tensile loading rates on the GRP from static to dynamic. A stress-strain diagram was determined from the test which also showed the value of the ultimate strength and also a prediction of Young’s modulus. As strain rate was increased, the ultimate strength of the material increased as well; as shown in Figure 2.18. The stress-strain line which formed the elastic value was almost similar; save the yield stress value, as it was found to be higher for higher dynamic strain rate as compared to lower strain rate. In the plasticity graph, besides having a similar pattern for both strain rates, that of the dynamic results in higher ultimate strength.

![Stress strain curve of GRP under various strain rates](image)

Figure 2.18: Stress strain curve of GRP under various strain rates (Heimbs et al., 2007).

Similar results were obtained by Lindholm in 1964 who reported that rate sensitivity are present for many materials (with plasticity behaviour) under dynamic and lower strain rates. Split Hopkinson pressure bar was experimentally used on lead, aluminium and copper to look for its strain rate sensitivity. It is shown that the ultimate strength gradually increased as the strain rate is increased for all materials.

Dynamic strain rate is not only restricted to isotropic materials but also extended to orthotropic materials such as boron, graphite and glass reinforced plastic. The materials were tested of its strain rate; affected by compression, tension and shear technique (Hamouda and
Hashmi, 1998). They had found that the geometry of the specimen and the material properties are both important to measure its sensitivity.

Despite knowing various values of strain rate sensitivity of materials, several attempts by Iqbal et al., (2010; 2010a; 2010b) in their finite element simulations only relied on low strain rate value. The predicted results are almost similar to the experimental results. This had proven that for finite element simulations, the strain rate effect provides less sensitivity to the results. Interestingly, this argument has been discovered earlier by Johnson et al., (2009) when they claimed that strain rate are effectively limited to the material types, wherein the simulations became too complex with many uncertainties; thus they decided not consider strain rate in their studies (Chan et al., 2007).

2.7 Mesh Sensitivity Study

Many researchers have applied mesh size sensitivity study in order to model the impacts on a structure using finite element method. The reason for using a mesh sensitivity technique is to decide the best element size which might contribute to the most accurate prediction and utilize minimum processing time. Mesh sensitivity usually depends on the material model i.e., isotropic or orthotropic materials. Studies have shown that elements for isotropic material are made to be close to a cube (Iqbal et al., 2010) while elements for orthotropic material have a cuboid geometry shape (Mikkor et al., 2006; Sun et al., 2009). Table 2.2 summarizes the mesh sizes used by different researchers. The element shape was described by the aspect ratio (AR) of length to thickness. It was found that the aspect ratio (length over thickness) for composites is mostly larger than 1.

After running a mesh sensitivity analysis for fine and coarse meshes, Choi and Chang (1992) had showed that a fairly good result for force and delamination in the composite laminate can be best fit by using a relatively coarse mesh size of 6.33 x 6.25 x 0.54 mm. The parameters (force and delamination) were found converged as the element increased towards fine meshes. A similar investigation was performed by Chan et al., (2007) for various element sizes in comparison with the target stoppage time in the experiments which showed that an AR=13.3 was chosen based on the optimum simulation time.

Mikkor et al., (2006) studied the effect of mesh size on the damage prediction in plain weave carbon fibre composites due to impact. They found that in order to predict damage
behaviour which is similar to the experimental results, the impact velocity required for the simulation should be much lower than the experimental velocity.

Table 2.2: Element sizes used in the literature.

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Mesh Size (mm)</th>
<th>Aspect Ratio</th>
<th>Material Type</th>
<th>Validation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Choi and Chang(1992)</td>
<td>6.33 x 6.25 x 0.54</td>
<td>~11.72</td>
<td>Graphite/Epoxy</td>
<td>Impact force Displacement</td>
</tr>
<tr>
<td>Chan et al., (2007)</td>
<td>1.47 x 1.47 x 0.15 2 x 2 x 0.15 2.86 x 2.86 x 0.15</td>
<td>9.8 13.3 19</td>
<td>CFRP</td>
<td>Ballistic limit</td>
</tr>
<tr>
<td>Mikkor et al., (2006)</td>
<td>1.5 x 1.5 x 0.2</td>
<td>~7.5</td>
<td>Carbon/Epoxy</td>
<td>Crack pattern</td>
</tr>
<tr>
<td>Silva et al., (2005)</td>
<td>0.4 x 0.4 x 0.4</td>
<td>1</td>
<td>Kevlar 29</td>
<td>Ballistic limit</td>
</tr>
<tr>
<td>Sun et al., (2009)</td>
<td>4.6 x 4.1 x 1.6</td>
<td>2.88</td>
<td>Kevlar/Glass/Wool</td>
<td>Damage pattern</td>
</tr>
<tr>
<td>Abu and Kim (2009)</td>
<td>0.25 x 0.25 x 0.25 0.2 x 0.2 x 0.2 0.16 x 0.16 x 0.16 0.1 x 0.1 x 0.1</td>
<td>1</td>
<td>Steel</td>
<td>Ballistic limit</td>
</tr>
</tbody>
</table>

Abu and Kim (2009) had employed cubic shaped elements to simulate the ballistic limit for steel plate. Their mesh sensitivity study had showed that a very fine element mesh was needed to give a promising ballistic limit result and that the damage pattern results compared well with the experimental data.

From all the mesh sensitivity studies reviewed so far, different mesh sizes have been employed by many researchers for various simulations. It is important to perform this study in modelling the impact problem. A proper mesh sensitivity study will help to select an optimum element size and provide a fair prediction for most parameters related to the impact.

2.8 Ballistic Limit Prediction using Finite Element Software

Experimentation is often costly due to the required equipment, time consumed, the material and labour expenses. To avoid this problem, finite elements analysis can be used to simulate the experiment and obtain predicted results. To date, a number of material models have been developed for simulations ran using commercial finite element software such as Abaqus, Ansys and Autodyne.
A few researchers (Tita et al., (2008); Fan et al., (2010)) used Abaqus software to simulate damage caused by low velocity impact. They had showed that the commercial damage model in Abaqus is capable of simulating damage behaviour effectively.

Other than Abaqus software, Silva et al., (2005) used Autodyne software in their simulation for high velocity impact on Kevlar 29/Vyniliester laminates. They developed a material model with variable coefficients which were determined by fitting their predictions to the experimental results. They then simulated the ballistic limit and damage pattern in the laminates. Residual velocity and crack deformation showed good agreement between the simulation and experimental results.

Mikkor et al., (2006) developed an impact model and implemented the model into Pam Crash to simulate the impact damage and ballistic limit. The Explicit FE code is suitable for dynamic modelling on damage for matrix and unidirectional fibre phases. Damage for the matrix was using shear or volumetric damage, while orthotropic materials were based on strain parameters. It is shown that similar behaviour was observed for impact in the comparison with experimental results but there was also an over-estimate in damage size and catastrophic failure which occurred at lower velocities. Another disadvantage of Pam Crash software is that it was unable to model delamination which is one of criteria for damage modes in the composite laminates.

Chan et al., (2007) simulated high velocity impact using LS-DYNA software, where Hashin’s failure material model is used to simulate the progressive damage. The numerical result accurately predicted most of the models in comparison with the experimental results to determine its ballistic limit. The contact algorithm in the software between the target and projectile was properly addressed to avoid any problems involved in element distortion due to high stresses. Strain rate effect on the material was avoided in the simulation by only using static properties value. However, this action affected the energy absorbing ability of the material due to the drastic delamination failure but had been avoided by adjusting the scale factor on the damage equation.

2.9 Analytical Formulation for Ballistic Limit Prediction
An investigation was done by Aly and Li (2008) on the studies related to empirical formula used for critical perforation energy of metallic plates impacted by rigid projectiles. They
claimed that there is very limited studies on the empirical formula of critical perforation energy and does not provide an adequate data range for the comparison with experimental results. However, there are several studies on analytical prediction which had gained interest.

Jenq et al., (1994) investigated analytically the quasi-static impact of woven glass/epoxy composite laminates by hemispherical shaped projectile. The event was compared using two different material properties i.e., static and dynamic properties test which involved the principle conservation of energy equation. By using static material properties, the results had shown a large difference to the experimental results in comparison to that of dynamic material properties.

Fatt and Lin (2004) carried out an analytical study of the static indentation of fully clamped E-glass/polyester panel. The analytical solutions for the deformation and interlaminar shear stresses were compared with finite element predictions using Abaqus. It was shown that the computational results were in good agreement with the analytical data. The failure was also predicted using ply by ply supported by the Tsai-Wu failure criterion.

A study on analytical prediction was also done by Wen (2000) who analytically derived a simple ballistic limit model which comprised of two categories i.e., the quasi-static resistive pressure of linear elastic limit and the dynamic resistive pressure with assumption of localized deformation on the target. The equation as shown in equation (2.4) is based from the cross section of the projectile shapes and initial kinetic energy. The projectiles were made of rigid body with various shapes (truncated, conical, flat, ogival and hemispherical) penetrating normally into the FRP target. It is shown that the analytical equation gives good agreement compared with the available experiment results. Since then, similar analytical equation was used extensively on few studies. For instance, it was successfully used by He et al., (2007) to measure the depth of penetration on a thick plate and also the ballistic limit. A number of studies (Wen, 2001; Wu et al., 2012) had also shown that the related equations give good correlation with other studies using experimental results.

\[ v_b = \frac{\pi \sqrt{\rho_l \sigma_e \theta^2 t}}{2m} \left[ 1 + \sqrt{1 + \frac{2m}{\pi \rho_l \theta^2 t}} \right] \]  (2.4)
In another study, Ulven et al., (2003) tried to compare their experimental results with the analytical equations by Wen (2000). Using carbon/epoxy composite panel as the target and four projectile types ran at high velocity impact, Ulven et al., (2003) addressed the ballistic limit with two different panel thicknesses and claimed that the model is overestimating the ballistic limit with an average of 30%. However, the argument was then explained by Wu et al., 2012 who suggested Ulven et al., (2003) to modify the value of linear elastic limit in through thickness using a different value obtained from Soden et al., (1998).

2.10 Conclusions
This chapter presents a literature review of past and present research works on targets under low and high velocity impact. The damage behaviour by low velocity impact is different than high velocity impact. In addition, impact behaviour due to material pretension and projectile shapes were also studied. It is shown that pretension does affect the characteristics of the target. To date, limited literature is available for pretension targets under impact by high velocity projectile. There are also very few finite element studies on pretension effects. Therefore, this research considers the ballistic limit of the targets with pretension when impacted at high velocity. Two projectile nose shapes will be used, and the investigation will start with panels made of isotropic material followed by orthotropic material.
CHAPTER 3. MECHANICAL PROPERTIES OF CFRP

3.1 Introduction

This chapter explains the experimental static test procedures used in this research. A range of tests were conducted on the UD-CFRP composite under different stress states including tensile tests in the 0\(^{\circ}\) fibre direction and 90\(^{\circ}\) fibre direction and shear test in the 45\(^{\circ}\) fibre direction. These tests were performed at room temperature. The tests were carried out using the universal testing machine (Instron 200kN), with strain measurements from a Solartron 3530 Orion digital strain meter and data-logging system. All samples were manufactured from prepreg materials and then cured in an autoclave with the required temperature-time profile. Up to five samples were prepared for each type of test. The speed of the cross-head was 2mm/min, which is in-line with the ASTM standard loading rate for quasi-static tests. Strain gauges were attached to the samples in appropriate directions in order to determine strains in the relevant directions. The load, displacement and strain measurements were monitored for all tested specimens, and saved in MS Excel format for graph plotting. The average and standard deviation from the test results were then determined.

3.2 Mechanical Properties of CFRP Composite

3.2.1 Tensile Test

The tensile properties of UD-CFRP were determined experimentally according to ASTM D3039/D3039M-00, using a sample with the dimensions of 250 x 15 x 1.2mm for length, width and thickness, and a gauge length of 138mm. The lay-up of the sample was [0\(^{\circ}\)]\(_6\), and five samples were tested. Tabs were attached to each coupon to provide extra grip for the wedged jaw clamp of the Instron machine. Strain gauges were attached to the surface of the sample in the fibre and transverse directions, as shown in Figure 3.1. The strain gauges used have a gauge length of 6mm and a resistance of 120\(\Omega\). Outputs from the test were strains in 0\(^{\circ}\)(\(\epsilon_x\)) and 90\(^{\circ}\)(\(\epsilon_y\)) directions from the axial load. Figure 3.2 illustrates the stress-strain curve for the quasi-static test. The results show that the carbon fibre composite experienced a brittle failure which showed almost no plastic deformation. The main failure characteristic shown in
Figure 3.2 is fibre cracking, which can be seen clearly before the complete failure of the sample. The fibre cracking may have been caused by a bonding defect during the fabrication process. The portion of the stress-strain curve for the determination of elastic modulus was taken between 1000 and 3000 με. The details of the mechanical properties results are shown in Table 3.1.

Figure 3.1: Strain gauge orientations on the sample used for ASTM D3039 tensile test.

Figure 3.2: Stress-strain diagram for 0° UD-CFRP composites under tension.
It was also found that several samples failed near to the gripping area. This may have been caused by stress concentration during clamping in the vice. An improper clamping technique may have caused excessive inter-laminar stresses near the clamping area, and may contribute to tab failure, as shown in Figure 3.3. To avoid stress concentration, the tab should be clamped approximately 10-15mm within the grip jaw. Figure 3.4(a) shows the correct position of a tab being fully clamped for tensile test. Figure 3.4(b) shows an improper positioning of the tab outside the vice clamp, which might damage the tab due to stress concentration. Due to the damage on few samples, only three were successfully run with the average failure load taken of approximately 16.89kN. Figure 3.5 shows an example of sample failure in a unidirectional tensile test. On average, the elastic modulus obtained from tensile tests in the $0^\circ$ fibre direction is 144.89GPa.

Figure 3.3: An example for the failure of a sample at the tab (a) inter-laminar de-bonding; (b) fibre slip.
Figure 3.4: Gripping position (a) tab inside grip area; (b) tab outside grip area.

Figure 3.5: Failed sample of 0° UD-CFRP composite under tension.
Table 3.1: Mechanical properties of unidirectional composite in longitudinal tensile test.

<table>
<thead>
<tr>
<th>Test Sample A</th>
<th>Tensile Modulus (0^0) (GPa)</th>
<th>v_{12}</th>
<th>Ultimate Strength(GPa)</th>
<th>Ultimate Strain(\varepsilon_{Ult})</th>
<th>Failure Load(kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>143.92</td>
<td>0.30</td>
<td>1.63</td>
<td>1.12</td>
<td>17.85</td>
</tr>
<tr>
<td>2</td>
<td>146.23</td>
<td>0.31</td>
<td>0.78</td>
<td>0.57</td>
<td>8.07</td>
</tr>
<tr>
<td>3</td>
<td>134.31</td>
<td>0.31</td>
<td>0.81</td>
<td>0.76</td>
<td>8.00</td>
</tr>
<tr>
<td>4</td>
<td>144.07</td>
<td>0.31</td>
<td>1.47</td>
<td>1.05</td>
<td>15.21</td>
</tr>
<tr>
<td>5</td>
<td>146.69</td>
<td>0.29</td>
<td>1.75</td>
<td>1.22</td>
<td>17.62</td>
</tr>
<tr>
<td>Average(mean)</td>
<td>144.89</td>
<td>0.30</td>
<td>1.62</td>
<td>1.13</td>
<td>16.89</td>
</tr>
<tr>
<td>Std dev</td>
<td>1.56</td>
<td>0.01</td>
<td>0.14</td>
<td>0.09</td>
<td>1.46</td>
</tr>
</tbody>
</table>

The UD-CFRP specimen for the transverse loading has 12 layers of fibre laid up in the 90^0 (transverse) direction, i.e., \([90^0]_{12}\). The cross-head speed of the loading machine was 2mm/min, and the dimensions of the specimen were 175 x 25 x 2.4(mm) for length, width and thickness, with gauge length of 125mm. Tabs were attached to each coupon to provide extra grip to prevent them from slipping from the wedged jaw clamp of the Instron machine. Strain gauges were attached to the surface of the sample in the fibre and transverse directions, as shown in Figure 3.1. The tensile properties were determined experimentally according to the ASTM D3039/D3039M-00 (the same standard that was used for the longitudinal tensile test), and the results are shown in Figure 3.6. The section that was used in the graph for the determination of elastic modulus is between 1000 and 3000\mu e.

It was also observed that brittle failure of the material occurs at the end of the elastic region without plastic deformation. Figure 3.7 shows an example of sample failure for the transverse test. Transverse tests were performed successfully, with failures mostly within the gauge length. Due to the strength of the material being mainly dependent on the matrix properties, the failure occurred with an elongation in the transverse of fibre direction.
Figure 3.6: Stress-strain diagram for transverse (90°) UD-CFRP composite under tension.

Figure 3.7: Failure of sample for 90° UD-CFRP composite.
Table 3.2: Mechanical properties of unidirectional composite under transverse tensile test

<table>
<thead>
<tr>
<th>Test</th>
<th>Tensile Modulus (90°) (GPa)</th>
<th>$\nu_{12}$</th>
<th>Ultimate Strength (MPa)</th>
<th>Ultimate Strain ($\varepsilon_{\text{Ult}}$)</th>
<th>Failure Load (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11.78</td>
<td>0.031</td>
<td>55.88</td>
<td>0.50</td>
<td>2.07</td>
</tr>
<tr>
<td>2</td>
<td>9.96</td>
<td>0.024</td>
<td>52.82</td>
<td>0.54</td>
<td>1.95</td>
</tr>
<tr>
<td>3</td>
<td>10.71</td>
<td>0.040</td>
<td>50.60</td>
<td>0.48</td>
<td>1.72</td>
</tr>
<tr>
<td>4</td>
<td>11.51</td>
<td>0.026</td>
<td>57.20</td>
<td>0.49</td>
<td>2.06</td>
</tr>
<tr>
<td>Average(mean)</td>
<td>10.99</td>
<td>0.03</td>
<td>54.13</td>
<td>0.50</td>
<td>1.95</td>
</tr>
<tr>
<td>Std dev</td>
<td>0.82</td>
<td>0.007</td>
<td>2.98</td>
<td>0.03</td>
<td>0.16</td>
</tr>
</tbody>
</table>

### 3.2.2 Shear Test

The stacking sequence for the shear test specimen is $[45/-45]_{4s}$, which consists of 16 layers of fibre. The dimensions of the specimen were 200×25×3.2(mm) for length, width and thickness, with a gauge length of 88mm. The sample was fabricated and tested according to ASTM D3518 and ASTM D3039/D3039M-00, respectively. The testing cross-head speed was 2mm/min. Strain gauges were arranged in the fibre direction ($45^\circ$), or using a $45^\circ$ rosette, as shown in Figure 3.8(a) and (b) respectively.

Equations (3.1) to (3.4) were used to calculate the shear stress and strain from the measurements of the rosette strains (Figure 3.9). Typical shear stress-strain curves are presented in Figure 3.10, based on which, the average shear modulus is 5.76GPa. The calculation of the shear modulus is based on the shear stress and strain points, taken from 15.15 to 37.24MPa and 1964 to 5643$\mu$e, respectively.
Figure 3.8: (a) Two strain gauge and (b) 45-degree Rosette strain gauge arrangements.

Figure 3.9: Strain gauge rosette arrangement

The shear stress and strain are calculated using following equations:

\[
\tau_{12} = \frac{F}{2A}
\]

where \( F \) is the load acting on the cross section area, \( A \) of the laminate.
\[ \gamma'_{x'y'} \text{ can be determined by:} \]

\[ \gamma'_{x'y'} = \varepsilon'_{x} - \varepsilon'_{y} \]  

(3.2)

Where:

\[ \varepsilon'_{a} = \varepsilon_{x}' \cos^{2}\theta_{a} + \varepsilon_{y}' \sin^{2}\theta_{a} + \gamma'_{x'y'} \sin \theta_{a} \cos \theta_{a} \]

\[ \varepsilon'_{b} = \varepsilon_{x}' \cos^{2}\theta_{b} + \varepsilon_{y}' \sin^{2}\theta_{b} + \gamma'_{x'y'} \sin \theta_{b} \cos \theta_{b} \]

\[ \varepsilon'_{c} = \varepsilon_{x}' \cos^{2}\theta_{c} + \varepsilon_{y}' \sin^{2}\theta_{c} + \gamma'_{x'y'} \sin \theta_{c} \cos \theta_{c} \]

(3.3)

To determine the shear strain, \( \gamma'_{x'y'} \), values of \( \theta_{a} \), \( \theta_{b} \), and \( \theta_{c} \) are replaced by \(-45^\circ\), \(0^\circ\) and \(+45^\circ\), respectively, and therefore, Eq. (3.4) becomes:

\[ \varepsilon'_{c} - \varepsilon'_{a} = \gamma'_{x'y'} \]  

(3.4)

Figure 3.10: Stress-strain curve under shear for UD-CFRP composite.

Table 3.3 presents the shear results of UD-CFRP composites for three tested samples. For shear tests, there is good correlation for all the results. The ultimate shear strength has a relatively small standard deviation of 0.09MPa, with an average of 85.09MPa. From the present study, it was found that failure occurs mostly around the stress concentration point near to the gripping area. Fibre delamination may occur at this point, due to the stress concentration, which might weaken the sample. These discrepancies may have contributed to
the slippage on the tab during the test for the third sample (E3), which has an above-average ultimate shear strength value. For this reason, only two tests for the ultimate shear strength results were considered in the calculation.

The offset strength is generally determined in situations when the value of yield strength has not been clearly defined from the stress-strain graph. A typical offset strain of 0.2% is usually used, and the strength is determined by the intersecting point between the stress-strain curve and the parallel line to the elastic line, as shown in Figure 3.10. The offset shear strength occurs at 66.77MPa with an offset strain of approximately 1.4%. Another finding to take into consideration is that, due to shear behaviour, the strain gauge on the sample can easily detach during the test, which may disqualify the result.

Table 3.3: Mechanical properties of UD-CFRP under shear test.

<table>
<thead>
<tr>
<th>Test</th>
<th>Shear Modulus $G_{12}$ (GPa)</th>
<th>Offset Strength (MPa)</th>
<th>Ultimate Shear Stress (MPa)</th>
<th>Ultimate Shear Strain, $\gamma_{12}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample E</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>5.78</td>
<td>60.72</td>
<td>85.02</td>
<td>3.40</td>
</tr>
<tr>
<td>2</td>
<td>5.50</td>
<td>68.00</td>
<td>85.15</td>
<td>4.50</td>
</tr>
<tr>
<td>3</td>
<td>6.00</td>
<td>71.60</td>
<td>-</td>
<td>4.97</td>
</tr>
<tr>
<td>Average(mean)</td>
<td>5.76</td>
<td>66.77</td>
<td>85.09</td>
<td>4.29</td>
</tr>
<tr>
<td>Std dev</td>
<td>0.25</td>
<td>5.54</td>
<td>0.09</td>
<td>0.81</td>
</tr>
</tbody>
</table>

Table 3.4 shows the resulting parameters obtained from material property tests. It was found that the UD-CFRP results agree well with the results of other researchers. The elastic modulus obtained from tensile tests in the $0^\circ$ fibre direction is 144.9GPa which is around 5% different from the results obtained by other researchers.
Table 3.4: Comparison of experimental results for unidirectional CFRP composites.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s Modulus (0°)</td>
<td>(GPa)</td>
<td>144.9</td>
<td>135.0</td>
<td>135.0</td>
<td>139.0</td>
</tr>
<tr>
<td>Young’s Modulus (90°)</td>
<td>(GPa)</td>
<td>10.99</td>
<td>10.00</td>
<td>8.00</td>
<td>9.85</td>
</tr>
<tr>
<td>In-plane Shear Modulus</td>
<td>(GPa)</td>
<td>5.76</td>
<td>5.00</td>
<td>-</td>
<td>5.25</td>
</tr>
<tr>
<td>Major Poisson’s Ratio</td>
<td></td>
<td>0.3</td>
<td>0.3</td>
<td>-</td>
<td>0.3</td>
</tr>
<tr>
<td>Ult. Tensile Strength (0°)</td>
<td>(GPa)</td>
<td>1.62</td>
<td>1.50</td>
<td>1.85</td>
<td>-</td>
</tr>
<tr>
<td>Ult. Tensile Strength (90°)</td>
<td>(MPa)</td>
<td>54.1</td>
<td>50.0</td>
<td>50.0</td>
<td>-</td>
</tr>
<tr>
<td>Max In-Plane Shear Strength</td>
<td>(MPa)</td>
<td>85.09</td>
<td>70.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Ult. Tensile Strain (0°)</td>
<td>(%)</td>
<td>1.13</td>
<td>1.05</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Ult. Tensile Strain (90°)</td>
<td>(%)</td>
<td>0.5</td>
<td>0.5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Max In-Plane Shear Strain</td>
<td>(%)</td>
<td>4.3</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

3.3 Conclusions

This chapter investigates the mechanical properties of the UD-CFRP composite in the longitudinal, transverse and shear directions. Sample geometry and experiments were performed in accordance with ASTM standards. Even though the testing results showed good consistency, few tests show sample failure near the tab area. It could be due to high clamping stress from the clamp, which caused excessive delamination and weakening of the area near to the tab. The occurrence of the delamination could also loosen the clamp grip, allowing slippage to occur easily.
CHAPTER 4. HIGH VELOCITY IMPACT TEST

4.1 Introduction
This chapter will investigate experimentally the target phenomena under high velocity impact on two different target plates - aluminium alloy 2014-T6 and CFRP - using hemispherical and flat shaped nose projectile. Pretension was applied to some specimens, and the testing results with pretension were compared with those without pretension. The applied pretension stress was taken as a percentage of the ultimate tensile strength of the target material. To perform the pretension process, a special tensile rig was manufactured, using two clamping jaws from the Instron tensile machine, and two hydraulic cylinders for loading purposes. The rectangular shaped targets were free at two ends and fixed at the other two ends by using clamping jaws. The residual velocities were measured, and the ballistic limits were obtained for all the tests using a high speed camera. Then, the experimental results will be compared with the results of the simulation studies in Chapters 5 and 6.

4.2 Gas Gun Setup
The impact testing was carried out using a gas gun as shown in the schematic diagram in Figure 4.1, with an internal hardened steel barrel of 23 mm diameter, which is able to withstand a maximum operating pressure of up to 11MPa. Before operating, the projectile is inserted into a single-use Teflon sabot, which holds and centralizes the projectile in the barrel. The sabot is not reusable because it will be damaged in each projectile launch. The projectile and the sabot should fit in the barrel and slide outwards easily. During launch, the sabot will carry the projectile towards the end of the barrel. When the sabot reaches the end of the barrel, a stopper will prevent it from travelling further, and the projectile will leave the sabot as a free-flying projectile moving towards the plate.
Figure 4.1: Schematic illustration of the high velocity impact test arrangement.

### 4.2.1 Pretension Rig

In this study, a special tensile rig was designed to apply the pretension. As shown in Figure 4.1 the tensile rig is attached at the end of the gas gun near the barrel. It was built using a rigid frame which was attached with two clamping jaws (borrowed from the Instron tensile machine that is capable of holding a maximum load of 200kN) and a couple of hydraulic cylinders. A hand lever was used to actuate the hydraulic pack that was used to activate the ENERPAC cylinders. One advantage of using a mechanical hand lever is that it gives the user the ability to control the pretension stress applied to the specimen during tensioning. When the hydraulic cylinders were extended, they will push the top beam upward and at the same time subject pretension to the sample. A simple ‘load cell’ design of strain measurement (will be discussed further in Chapter 4.2.3) was attached axially in-line with the target, between the sample and the upper beam.

### 4.2.2 Impact and Residual Velocity Sensors

In this study, three techniques were used to measure the impact and residual velocities of the projectile, i.e. a light sensor, a thin-film sensor, and a high-speed camera. To form the light sensor, two laser velocimeters (Figure 4.2: sensors A and B) were attached to the nozzle barrel. The projectile passing through sensors A and B, with a known distance between the
two, will generate two signals on the time base of the transient recorder, and therefore the average impact velocity between A and B can be determined.

A thin-film velocity sensor is considered as a low cost velocity measurement device. It operates in a similar way to a light sensor, but the sensor is activated by breaking a circuit rather than interrupting a light beam. The film should be very soft and easy to break when the projectile strikes it. The thin-film can be made from thin wire, aluminium foil or copper tape. The circuit diagram is powered by a 1.5 volt AA battery and attached with a 250 ohm resistance. In a closed circuit, the output voltage of the grid is designed to be 0 Volts. Upon impact of the projectile, the circuit is broken, and a voltage pulse will be produced due to the break of the circuit. The display monitor will show the amplitude difference on a time base and the average velocity between the given distances of the two film screens can be determined. The thin-film technique was used for the residual velocity measurement, while the light sensor technique was used for the impact velocity measurement.

Alternatively, the impact and residual velocities can be measured using a high-speed video camera. The camera used was a Vision Research Phantom V7.1 (monochrome), with a Nikon 24-85mm F2.8 macro zoom lens and Pentium 4 PC. Various resolution selections are available depending on the requirement and as the pixel increased frame rate becomes reduced and vice versa. For this work a resolution of 640x480 pixels with approximately 7300 frame per second (fps) was used. The equipment was loaned by the Engineering and

Figure 4.2: Impact velocity measurement using light sensors.
Physical Sciences Research Council (EPSRC). The high speed cameras were placed at the rear to record the residual velocity of the projectile as well as to observe the phenomena during impact.

4.2.3 Load Cell Based on Strain Measurement

Figure 4.8a shows the device used to measure the axial strain in order to obtain the axial stress applied during pretension. The devices were fabricated in-house as a load cell. A pair of strain gauges oriented at 0° and 90°, were glued onto the surface of the cylinder, which was connected to a strain reader. The device was positioned on the Instron machine (Figure 4.3b) and calibrated quasi-statically using an axial load cell. A strain reader (Figure 4.3c) was attached to the device during calibration to measure the axial strain. Therefore, the relationship between force and strain can be established as shown in Figure 4.9d. In order to estimate the order of the strain, the Young’s Modulus of the steel material was taken as 200GPa. The diameter of the steel rod, on which the strain gauge is fixed, was determined based on the estimated strain, i.e., \( \varepsilon = \frac{F}{AE} \). If the selected cross-sectional area of the rod is too large, the strain value will be too small to maintain the necessary accuracy of the measurement. A 25 mm diameter steel rod was selected after several trials.
Figure 4.3: (a) Load cell, (b) Calibration of the load cell using Instron testing machine, (c) Strain indicator reader (d) Strain vs load calibration measurement.
4.2.4 The Projectile Profile

Figure 4.4 shows the nose geometry of each projectile with mass of approximately 3 grams. The projectiles were made of silver steel which is commonly known as tool steel. Due to the properties of being high in carbon, its application is widely used in punches, engravers and screwdrivers fabrication (“Silver Steel”, 2014). The silver steel projectiles were machined using a lathe, and then subjected to a hardening process to increase their strength with having approximately 65 Rockwell C. The silver steel was machined into two different nose shapes; flat and hemispherical. Both projectiles are 5mm in diameter, with the hemispherical nose a little longer in order to have the same weight as that of the flat projectile.

Figure 4.4: (left) Flat projectile and (right) Hemispherical shaped nose projectile (dimensions in mm).
4.3 Definitions of Ballistic Limit

This research is concerned with the prediction of the ballistic limit for aluminium alloy 2014-T6 and CFRP. Several methods to predict the ballistic limit have been used for experimental purposes.

(a) Energy conservation equation

The ballistic limit can be estimated from the initial and residual velocity. The following equation, based on energy conservation, is used:

\[
\frac{1}{2} mv_i^2 = \frac{1}{2} m v_b^2 + \frac{1}{2} m v_r^2
\]  

(4.1)

where \( m, v_b, v_i \) and \( v_r \) are the projectile mass, ballistic limit, impact velocity and residual velocity, respectively.

(b) Ballistic Limit \( V_{50}(\text{MIL-STD-662F, 1997}) \)

Ballistic limit \( V_{50}(\text{MIL-STD-662F, 1997}) \) is defined from the average of an equal number of partial penetrations and complete penetrations. Generally the average of two partial and two complete penetrations is used, but this could be increased to three or even five. The velocity span that is considered for partial/complete penetration should be between 18 to 38 m/s. A Navy definition (Backman and Goldsmith, 1978) of partial and complete penetrations was used. However, in some cases, the projectile may be found to have stopped at the middle of the target where the decision to attribute a partial or complete penetration is uncertain. The Navy definition does not define this situation; therefore a modified-Navy definition was introduced.

In Figure 4.5, three final positions of the projectile are introduced. The nature of the partial and complete perforations will depend on the final stop of the projectile penetrating into the target. When the after-length, \( (b_i) \), of the projectile outside the target is greater than the fore-length, \( (b_f) \), it is referred to as a ‘partial penetration’. However, if the fore-length is greater than, or equal to, the after-length, the penetration is referred to as a ‘complete penetration’.
In this study, the aluminium alloy 2014-T6 test target did not experience the situation such that the projectile stopped in the target, and thus, the normal Navy ballistic definition was followed. However, for the CFRP target, a number of projectiles were stuck in the target, implying the need to use the modified-Navy criterion to determine the ballistic limit for the CFRP panel.

Another phenomenon, known as ‘split’ or ‘catastrophic failure’ was discovered in the ballistic tests. ‘Split’ behaviour was found to be during indentation or perforation cases when the target was separated into two due to the impact. Targets that experience catastrophic failures were mostly found on CFRP targets impacted by projectiles which will be explained further in Chapter 4.6.1. Figure 4.6 shows further refined definitions for more cases observed in partial and complete penetration, i.e., ‘indentation’, ‘limit’, ‘through’ and ‘split’.

Figure 4.5: Modified-Navy criterion of ballistic limit.
4.4 Test Procedure on Aluminium Alloy 2014-T6 Plate
The material used was aluminium alloy 2014-T6, with mechanical properties adopted from Hao et al. (2009) as shown in Table 4.1. The 2mm-thick sample plates were cut into a rectangular shape of 45 x 145mm using a press cutter. The target was positioned vertically by a couple of vice holding on the top and bottom as shown in Figure 4.7. A total of seventeen samples were tested, with and without pretension, using two different projectile nose shapes. During clamping and the application of pretension on the specimen, the alignment of the specimen with the axial axis was checked carefully.

Table 4.1: Mechanical properties of aluminium alloy 2014-T6 (Hao et al., 2009).

<table>
<thead>
<tr>
<th>Properties</th>
<th>Aluminium alloy 2014-T6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s Modulus</td>
<td>73 GPa</td>
</tr>
<tr>
<td>Density</td>
<td>2800 kg/m³</td>
</tr>
<tr>
<td>Poisson ratio, v</td>
<td>0.3</td>
</tr>
<tr>
<td>Yield Strength</td>
<td>414 MPa</td>
</tr>
<tr>
<td>Ultimate Strength</td>
<td>483 MPa</td>
</tr>
<tr>
<td>Elongation at Failure</td>
<td>23%</td>
</tr>
</tbody>
</table>
A load cell based on a strain gauge transducer was used to measure the applied pretension load. The cross-sectional area of the plate was measured to be 90.34 mm$^2$. The applied pretension load from the load cell was set to 10kN, which corresponds to 23% of the ultimate strength of the aluminium alloy 2014-T6 properties (483MPa). Referring to a load-strain calibration table in Figure 4.3(d), the strain required for 10kN is approximately 244$\mu$ε. Therefore, the pretension on each aluminium alloy 2014-T6 target was ‘locked’ at 244$\mu$ε using the hydraulic cylinder, to maintain a constant pretension load.

### 4.4.1 Ballistic Limit Test on Aluminium Alloy 2014-T6 Plate without Pretension

Table 4.2 presents the ballistic test results for a non-pretension aluminium alloy 2014-T6 target impacted by flat nased and hemispherical projectiles. Due to the limited number of test specimens, only four tests were performed with the flat nased projectile, and three tests with the hemispherical projectile. The ballistic limits were measured from an average of equal number of the highest velocity in partial perforation with the lowest velocity in complete perforation. The ballistic limits for the flat and hemispherical projectiles without pretension

Figure 4.7: Experimental target set-up.
on the targets were approximately 134 m/s and 145 m/s, respectively. While using Eq. (4.1) the ballistic limits were 128 m/s and 145 m/s.

Table 4.2: Ballistic tests of aluminium alloy 2014-T6 plate without pretension.

<table>
<thead>
<tr>
<th>Target</th>
<th>Impact Velocity (m/s)</th>
<th>Residual Velocity (m/s)</th>
<th>Ballistic Limit (m/s)</th>
<th>Displacement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat 1</td>
<td>174</td>
<td>Not measured</td>
<td>134</td>
<td>0.18</td>
</tr>
<tr>
<td>Flat 2</td>
<td>151</td>
<td>80</td>
<td></td>
<td>0.34</td>
</tr>
<tr>
<td>Flat 3</td>
<td>143</td>
<td>62</td>
<td></td>
<td>0.76</td>
</tr>
<tr>
<td>Flat 4</td>
<td>125</td>
<td>0</td>
<td></td>
<td>1.00</td>
</tr>
<tr>
<td>Hemis 1</td>
<td>174</td>
<td>88</td>
<td>145</td>
<td>2.6</td>
</tr>
<tr>
<td>Hemis 2</td>
<td>154</td>
<td>68</td>
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<td>3.87</td>
</tr>
<tr>
<td>Hemis 3</td>
<td>138</td>
<td>0</td>
<td></td>
<td>4.00</td>
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</tbody>
</table>

Table 4.3: Ballistic limit of aluminium alloy 2014-T6 plate without pretension.

<table>
<thead>
<tr>
<th>Target</th>
<th>Impact Velocity (m/s)</th>
<th>Residual Velocity (m/s)</th>
<th>Ballistic Limit (m/s)</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat 1</td>
<td>151</td>
<td>80</td>
<td>128</td>
<td>-</td>
</tr>
<tr>
<td>Flat 2</td>
<td>143</td>
<td>62</td>
<td>129</td>
<td>0.707</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td>128</td>
<td></td>
</tr>
<tr>
<td>Hemis 1</td>
<td>174</td>
<td>88</td>
<td>150</td>
<td>-</td>
</tr>
<tr>
<td>Hemis 2</td>
<td>154</td>
<td>68</td>
<td>138</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td>145</td>
<td>8.49</td>
</tr>
</tbody>
</table>

4.4.2 Ballistic Limit Test on Aluminium Alloy 2014-T6 Plate with 23% Pretension

Table 4.4 shows ten ballistic tests, five using projectiles with a flat nose and five with a hemispherical nose. The flat nosed projectiles were tested within the velocity range of 73 to 140 m/s. The average ballistic limit for flat nosed projectiles was approximately 124 m/s, which was taken from the average result of two completely-perforated tests. The results are shown in Table 4.5. For hemispherical nosed projectiles with pretension targets, the tests were run within a velocity range of 148 to 167 m/s. The average ballistic limit for the hemispherical nosed projectile was approximately 150 m/s, which was taken from three
completely-perforated tests. The average ballistic limit for the hemispherical nosed projectile is approximately 21% higher than that for the flat nosed projectile.

Table 4.4: Ballistic tests of aluminium alloy 2014-T6 plate with 23% pretension

<table>
<thead>
<tr>
<th>Target</th>
<th>Impact Velocity (m/s)</th>
<th>Residual Velocity (m/s)</th>
<th>Ballistic Limit (m/s)</th>
<th>Displacement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat 1</td>
<td>140</td>
<td>62</td>
<td></td>
<td>0.53</td>
</tr>
<tr>
<td>Flat 2</td>
<td>125</td>
<td>24</td>
<td>124</td>
<td>0.6</td>
</tr>
<tr>
<td>Flat 3</td>
<td>121</td>
<td>0</td>
<td></td>
<td>1.11</td>
</tr>
<tr>
<td>Flat 4</td>
<td>108</td>
<td>0</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td>Flat 5</td>
<td>73</td>
<td>0</td>
<td></td>
<td>0.2</td>
</tr>
<tr>
<td>Hemis 1</td>
<td>167</td>
<td>73</td>
<td></td>
<td>1.17</td>
</tr>
<tr>
<td>Hemis 2</td>
<td>154</td>
<td>32</td>
<td>150</td>
<td>1.5</td>
</tr>
<tr>
<td>Hemis 3</td>
<td>151</td>
<td>12</td>
<td></td>
<td>2.23</td>
</tr>
<tr>
<td>Hemis 4</td>
<td>149</td>
<td>0</td>
<td></td>
<td>1.42</td>
</tr>
<tr>
<td>Hemis 5</td>
<td>148</td>
<td>0</td>
<td></td>
<td>1.38</td>
</tr>
</tbody>
</table>

Table 4.5: Ballistic limit of aluminium alloy 2014-T6 plate with 23% pretension.

<table>
<thead>
<tr>
<th>Target</th>
<th>Impact Velocity (m/s)</th>
<th>Residual Velocity (m/s)</th>
<th>Ballistic Limit (m/s)</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat 1</td>
<td>140</td>
<td>62</td>
<td>125.5</td>
<td>-</td>
</tr>
<tr>
<td>Flat 2</td>
<td>125</td>
<td>24</td>
<td>122.7</td>
<td>1.97</td>
</tr>
<tr>
<td>Average</td>
<td>124</td>
<td>24</td>
<td>124</td>
<td></td>
</tr>
<tr>
<td>Hemis 1</td>
<td>167</td>
<td>73</td>
<td>150.2</td>
<td>-</td>
</tr>
<tr>
<td>Hemis 2</td>
<td>154</td>
<td>32</td>
<td>150.6</td>
<td></td>
</tr>
<tr>
<td>Hemis 3</td>
<td>151</td>
<td>12</td>
<td>150.5</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>150</td>
<td></td>
<td>150</td>
<td>0.28</td>
</tr>
</tbody>
</table>

Figure 4.8 compares the experimental results of the residual velocities for two different projectile nose shapes with and without pretension, from which the ballistic limits can be determined. In general, the projectile nose shape has a considerable effect on the target resistance i.e., the ballistic limit is reduced by the reduction in the sharpness of the projectile nose. The pretension target impacted by flat projectile reduced only 8% of the ballistic limit.
compared to that without pretension, while for hemispherical projectile the ballistic limit shows an increase of approximately 3%.

Figure 4.8: Residual velocity versus impact velocity for aluminium alloy 2014-T6 plate.

4.5 Impact Damage of the Aluminium Alloy 2014-T6 Panel

In the following set of impact tests, the effects of pretension on displacement, plug and petal impacts are examined.

4.5.1 Displacement, Plug and Petal of the Aluminium Alloy 2014-T6 Panel

Figure 4.9 shows the variation of the maximum plastic displacement of aluminium alloy 2014-T6 plate, compared to the impact velocity. It shows that, as the perforation velocity was increased toward the ballistic limit, the displacement also gradually increased to a maximum; with a further increase in impact velocity beyond the ballistic limit, the displacement of the target gradually reduced. This phenomenon was observed for both nose shapes, and for both supporting conditions (i.e. with and without pretension). The measurement of target displacement was taken from an average distance near the perforation area.

It can also be observed in Figure 4.9 that the local deformation of the target for the hemispherical shaped nose is larger than that for the flat shaped nose, which implies that the hemispherical shaped nose projectile is faced with higher resistance from the target. In
addition, the hemispherical shaped nose leads to greater stretching of the target, thus producing more plastic deformation compared to the plugging caused by the flat shaped nose.

In Figure 4.9, the pretension does have influence on the target displacement. For both hemispherical and flat nosed projectiles, the maximum plastic displacement was reduced due to the existence of pretension. For a hemispherical projectile target, a reduction of more than 50% in the plastic displacement was observed, due to the existence of pretension. For a flat nosed projectile, the reduction in the plastic displacement was approximately 20%, due to the existence of pretension.

Figure 4.9: Plastic displacement measured from centre of the target plate with different projectile nose shapes.

Figure 4.10 and Figure 4.11 show the effect of the flat nosed projectile compared to the effect of the hemispherical nosed projectile on perforation failure. The flat projectile caused shear plugging in the target plate, while the hemispherical projectile formed petalling (see Figure 4.11). Interestingly, it was also observed that the hemispherical projectile produced shear behaviour at the nose tip; a small shear plug was found during the impact of the hemispherical projectile, followed by petalling in the subsequent penetration process, as shown in Figure 4.12. Figure 4.12 also compares the plugs formed by a flat nosed projectile
and a hemispherical nosed projectile where the plug produced by a flat nosed projectile was found to be larger than that produced by a hemispherical nosed projectile.

Table 4.6 and Table 4.7 identify the number of petal formation impacts by the hemispherical projectile, without and with pretension target. It can be seen that the number of petals increased as the projectile velocity became higher. In 2008, Johnson et al. performed an experiment on aluminium alloy 2014-T6 target which also resulted in a higher number of petal deformation as the impact velocity increased. After each perforation, by average, the diameter of the hole was found to be smaller than that of the projectile. This may be caused by the ‘elastic recovery’ of the deformation of the plate material. Due to pretension, even though the perforate diameter is smaller than the size of the projectile, it is still bigger than the perforate diameter of non-pretension targets. This is due to pretension effects on the target itself. Meanwhile, the perforation for the flat nosed projectile shows a very similar diameter for both pretension and non-pretension targets which is approximately 5mm.

![Image](image1.jpg)

Figure 4.10: Target damage by (a) hemispherical-nose projectile and (b) flat-nose projectile.

![Image](image2.jpg)

Figure 4.11: Petalling formation from the hemispherical nosed projectile impact at 154 m/s.
Figure 4.12: Plugs formed by impact from (left) hemispherical-nose projectile and (right) flat nosed projectile.

Table 4.6: Non-pretension target perforate by hemispherical projectile.

<table>
<thead>
<tr>
<th>Impact Velocity (m/s)</th>
<th>Perforate Diameter (mm)</th>
<th>Number of Petals</th>
</tr>
</thead>
<tbody>
<tr>
<td>154</td>
<td>4.60</td>
<td>8</td>
</tr>
<tr>
<td>174</td>
<td>4.88</td>
<td>9</td>
</tr>
</tbody>
</table>

Table 4.7: Pretension target perforate by hemispherical projectile.

<table>
<thead>
<tr>
<th>Impact Velocity (m/s)</th>
<th>Perforate Diameter (mm)</th>
<th>Number of Petals</th>
</tr>
</thead>
<tbody>
<tr>
<td>151</td>
<td>3.57</td>
<td>6</td>
</tr>
<tr>
<td>154</td>
<td>4.62</td>
<td>8</td>
</tr>
<tr>
<td>167</td>
<td>4.97</td>
<td>9</td>
</tr>
</tbody>
</table>
4.5.2 Stress Concentration Effect on Aluminium Alloy 2014-T6 Panel

After perforation of the target plate by the projectile, with regards to continuous in-plane pretension, a maximum stress $\sigma_{\text{max}}$ will lead to stress concentration along the area as shown in Figure 4.13. Taking average stress, $\sigma_{\text{ave}} = P/A$ where $P$ is the loading and $A$ is the net cross sectional area with the perforation diameter (Beer et al., 2006; Hibbler RC, 2008), the concentrated stress $\sigma_{\text{max}}$ can be estimated by (Craigh, 1999):

$$\sigma_{\text{max}} = K_c \cdot \sigma_{\text{ave}}$$ (4.2)

where $K_c$ is the stress concentration factor (Craigh, 1999).

![Figure 4.13: Stress distribution under pretension load.](image)

The stress concentration around the perforated boundary of the aluminium alloy 2014-T6 plate under 23% of pretension is calculated as:

$$\sigma_{\text{ave}} = \frac{P}{A} = \frac{9936}{7 \times 10^{-5}} = 142\text{MPa}$$

$$\sigma_{\text{max}} = K_c \cdot \sigma_{\text{ave}} = 2.75 \times 142 \times 10^6 = 390\text{MPa}$$

where $A$ is the cross-sectional area of the panel after perforation, and $P$ is the pretension load applied. The concentrated stress around the penetration area was 2.75 times higher than the average stress of 142MPa. The maximum stress value was measured as 390MPa, which is
still lower than 483 MPa, the ultimate strength of the aluminium alloy 2014-T6, and therefore catastrophic failure was avoided.

4.5.3 Damage Assessment on Aluminium Alloy 2014-T6 Panel
The failure modes of the aluminium alloy 2014-T6 target plates are discussed in this section. Figure 4.14 shows images for both non-pretension and pretension plates impacted by flat and hemispherical projectiles. Figures also show the damage difference at below and above the ballistic limit velocity. Images a, c, e and g show a failure mode at a velocity lower than the ballistic limit, whereas images b, d, f and h show a failure mode at velocities higher than the ballistic limit. The impact damage in images a-d shows a well-defined shear failure by a flat projectile at non-pretension and pretension plates. The target failure mode at velocities higher than the ballistic limit also result in more local damage failures due to edge formation as shown in Image d.

Images e, f, g and h show damaged target plates impacted by the hemispherical projectile. The damage resulting from hemispherical projectile impact was found to be different than that from flat projectile impact, where petalling is normally formed. The petals formed due to the hemispherical shaped projectile pushing the target sideways along its penetration axis and at the same time create plasticity near the perforation area. Due to the phenomena, hemispherical projectile needs longer time to perforate through the target which explains why the ballistic limit for the hemispherical projectiles is higher than the flat projectiles. Besides having higher ballistic limit, hemispherical projectile also formed larger target displacement on the target compared to flat projectile. The results can be seen in Figure 4.9 where the targets experienced larger displacement by the hemispherical projectiles compared to the flat projectiles. These scenarios were observed for targets both with and without pretension.
### Chapter 4: High Velocity Impact Test

#### Below Ballistic Limit

<table>
<thead>
<tr>
<th>Front surface</th>
<th>Rear surface</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
<tr>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
</tr>
<tr>
<td><img src="image9.png" alt="Image" /></td>
<td><img src="image10.png" alt="Image" /></td>
</tr>
</tbody>
</table>

#### Above Ballistic Limit

<table>
<thead>
<tr>
<th>Front surface</th>
<th>Rear surface</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image11.png" alt="Image" /></td>
<td><img src="image12.png" alt="Image" /></td>
</tr>
<tr>
<td><img src="image13.png" alt="Image" /></td>
<td><img src="image14.png" alt="Image" /></td>
</tr>
<tr>
<td><img src="image15.png" alt="Image" /></td>
<td><img src="image16.png" alt="Image" /></td>
</tr>
<tr>
<td><img src="image17.png" alt="Image" /></td>
<td><img src="image18.png" alt="Image" /></td>
</tr>
<tr>
<td><img src="image19.png" alt="Image" /></td>
<td><img src="image20.png" alt="Image" /></td>
</tr>
</tbody>
</table>

Figure 4.14: Front and rear images of aluminium alloy 2014-T6 impact-damage on pretension and non-pretension target by flat and hemispherical nosed projectiles at below and higher than ballistic limit. Images (a,c,e,g) show the impact at below the ballistic limit which formed indentation on the target and images (b,d,f,h) show the impact at above the ballistic limit which formed shear for flat projectile or tensile failure for hemispherical projectile.
4.6 Test Procedure for Bidirectional Cross-ply CFRP Panel

Unidirectional Carbon Fibre Reinforced Plastic (CFRP) prepreg has been widely used in aircraft components due to its high strength, light weight, good fracture and corrosion resistance, and excellent impact damage tolerance. In this study, CFRP material with the commercial name HEXCEL AS4 (12K) was supplied by Composite Technology Research Malaysia (CTRM), a company dealing with the fabrication of aircraft components. The individual layers of the unidirectional CFRP prepreg, known as ply, have a thickness of 0.125mm, and the overall density of the material is approximately 1600 kg/m³. The CFRP rectangular panel consists of 24 plies of layup forming a bidirectional composite, as indicated in Table 4.8. The elastic and strength properties of the unidirectional CFRP laminate panel were taken from experimental tests as shown in Table 3.4. The test plates were cut from the panel into 145 x 45 x 3mm of length, width and thickness using a diamond disc cutter with coolant to avoid any excessive heating and stress concentration, which may cause delamination and damage.

Table 4.8: Dimensions of the unidirectional CFRP specimen.

<table>
<thead>
<tr>
<th>Fibre Type</th>
<th>Dimension</th>
<th>Orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unidirectional</td>
<td>145mm(l) x 45mm(w) x 3mm(t)</td>
<td>[0,90]₁²</td>
</tr>
<tr>
<td></td>
<td>(yarn thickness 0.125mm/ply)</td>
<td></td>
</tr>
</tbody>
</table>

The tests for CFRP specimens were performed under two axial loading conditions, without pretension, and with pretension of 30% of the maximum tensile strength. The ultimate tensile strength of the bidirectional CFRP is approximately 705 MPa, therefore 30% pretension is about 211.5 MPa. The sample was clamped at its two ends, while the other two sides were left free. For a plate with a cross-sectional area of approximately 135x10⁻⁶m², the estimated tensile load at 30% pretension is approximately 28kN. Referring to the load-strain calibration table in Figure 4.3(d), the strain required for 28kN is approximately 700µε, which can be measured using the strain gauge attached to the sample during the operation of the hydraulic cylinder. The pretension load was chosen with consideration of the maximum allowable frame load of 12 metric tons, given by the manufacturer. When the strain reached
the required value, the hydraulic cylinder was locked to maintain a constant pretension, and the impact test was performed at the required velocity.

Trial tests were performed to estimate the range of impact velocity for the ballistic tests. The projectile was aligned perpendicular to the specimen by using L-square ruler measured between gas gun barrel and target plate to avoid any oblique impact.

### 4.6.1 Ballistic Limit Test on CFRP Plate

Table 4.9 and Table 4.10 list the experimental results for flat and hemispherical nosed projectiles under 0% and 30% pretension. Definitions for partial and complete penetrations have been explained extensively in Chapter 4.3 for the determination of ballistic limit. The tables also denote the phenomena of indentation (D), Limit (L), Through (T) and split(S).

Table 4.9 presents the behaviour of the target without pretension, under the impact of flat and hemispherical projectiles. For flat nosed projectiles impacting CFRP plates without pretension, seven tests were performed at velocities from 76 to 134 m/s. Using the modified-Navy ballistic limit (see Chapter 4.3), four tests consisting of two complete and two partial penetrations were used to predict the ballistic limit. The average ballistic limit from these four tests, for a flat projectile, without pretension was approximately 102 m/s. For a hemispherical nosed projectile impact without pretension, the average ballistic limit for two partial and two complete penetrations was approximately 118 m/s. The ballistic limit for a flat nosed projectile is 15% lower than that of a hemispherical nosed projectile, for a target without pretension.
Table 4.9: Ballistic tests of cross-ply CFRP plate without pretension.

<table>
<thead>
<tr>
<th>Target</th>
<th>Impact Velocity (m/s)</th>
<th>Residual Velocity (m/s)</th>
<th>Remarks</th>
<th>Ballistic Limit (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat 1</td>
<td>76</td>
<td>0</td>
<td>Partial D</td>
<td>102</td>
</tr>
<tr>
<td>Flat 2</td>
<td>87</td>
<td>0</td>
<td>Partial D</td>
<td></td>
</tr>
<tr>
<td>Flat 3</td>
<td>98</td>
<td>0</td>
<td>Partial L</td>
<td></td>
</tr>
<tr>
<td>Flat 4</td>
<td>99</td>
<td>0</td>
<td>Partial L</td>
<td></td>
</tr>
<tr>
<td>Flat 5</td>
<td>105</td>
<td>0</td>
<td>Complete L</td>
<td></td>
</tr>
<tr>
<td>Flat 6</td>
<td>106</td>
<td>29</td>
<td>Complete T</td>
<td></td>
</tr>
<tr>
<td>Flat 7</td>
<td>134</td>
<td>87</td>
<td>Complete T</td>
<td></td>
</tr>
<tr>
<td>Hemis 1</td>
<td>98.7</td>
<td>0</td>
<td>Partial D</td>
<td>118</td>
</tr>
<tr>
<td>Hemis 2</td>
<td>98.8</td>
<td>0</td>
<td>Partial D</td>
<td></td>
</tr>
<tr>
<td>Hemis 3</td>
<td>106.1</td>
<td>0</td>
<td>Partial D</td>
<td></td>
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<tr>
<td>Hemis 4</td>
<td>114.3</td>
<td>0</td>
<td>Complete D</td>
<td></td>
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<tr>
<td>Hemis 5</td>
<td>121</td>
<td>51</td>
<td>Complete T</td>
<td></td>
</tr>
<tr>
<td>Hemis 6</td>
<td>129</td>
<td>53</td>
<td>Complete T</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.10 presents eleven impact tests for 30% sample pretension, including five tests for a flat nosed projectile and six tests for a hemispherical nosed projectile. Similarly, using the modified-Navy definition, the ballistic limit for a flat-nose projectile was determined as 90 m/s, from the average of four tests involving partial and complete penetrations, whereas the ballistic limit for a hemispherical nosed projectile was determined as 99 m/s. While under pretension of 30% of the tensile strength, the ballistic limit for a flat nosed projectile was found to be 10% lower than a hemispherical nosed projectile.

For impact tests with a 30% pretension, the CFRP panel may experience catastrophic failure or split during or after penetration. For a flat nosed projectile, plate splitting only occurred after complete penetration. However, for a hemispherical nosed projectile, plate splitting occurred for both partial and complete penetrations.
Table 4.10: Ballistic tests of cross-ply CFRP plate with 30% pretension.

<table>
<thead>
<tr>
<th>Target</th>
<th>Impact Velocity (m/s)</th>
<th>Residual Velocity (m/s)</th>
<th>Remarks</th>
<th>Ballistic Limit (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat 1</td>
<td>78.3</td>
<td>0</td>
<td>Partial</td>
<td>D</td>
</tr>
<tr>
<td>Flat 2</td>
<td>85</td>
<td>0</td>
<td>Partial</td>
<td>L</td>
</tr>
<tr>
<td>Flat 3</td>
<td>97.6</td>
<td>0</td>
<td>Complete</td>
<td>L</td>
</tr>
<tr>
<td>Flat 4</td>
<td>100</td>
<td>5</td>
<td>Complete</td>
<td>T</td>
</tr>
<tr>
<td>Flat 5</td>
<td>105</td>
<td>5</td>
<td>Complete</td>
<td>T,S</td>
</tr>
<tr>
<td>Hemis 1</td>
<td>85</td>
<td>0</td>
<td>Partial</td>
<td>D</td>
</tr>
<tr>
<td>Hemis 2</td>
<td>88.8</td>
<td>0</td>
<td>Partial</td>
<td>D</td>
</tr>
<tr>
<td>Hemis 3</td>
<td>95</td>
<td>0</td>
<td>Partial</td>
<td>D,S</td>
</tr>
<tr>
<td>Hemis 4</td>
<td>99</td>
<td>0</td>
<td>Partial</td>
<td>T,S</td>
</tr>
<tr>
<td>Hemis 5</td>
<td>101</td>
<td>0</td>
<td>Complete</td>
<td>T,S</td>
</tr>
<tr>
<td>Hemis 6</td>
<td>101</td>
<td>25</td>
<td>Complete</td>
<td>T,S</td>
</tr>
</tbody>
</table>

Figure 4.15 shows the residual velocity as a function of impact velocity for a CFRP target impacted by flat and hemispherical projectiles and subjected to 0% and 30% pretensions. Pretension led to a reduction in the ballistic limit for both projectile types; for a flat projectile, the ballistic limit was reduced from 102 to 90m/s (about a 12% reduction), and the ballistic limit for a hemispherical projectile decreased from 118m/s to 99m/s, which is approximately a 16% reduction.

Tests at 85m/s impact velocity for both flat nosed and hemispherical nosed projectiles with 30% target pretension showed that the flat projectile perforated the panel while the hemispherical projectile simply dented the sample. A higher velocity is required to perforate it. In addition, the shear plugging that happened for the flat projectile led to a lower ballistic limit, in comparison with the ballistic limit associated with the hemispherical nosed projectile.

It is shown in Figure 4.15 that the hemispherical shaped nose projectile is subjected to higher resistance upon impact, compared to that of the flat-nose projectile, regardless of the pretension. This increased resistance is due to the increased contact surface area. The hemispherical shaped nose allowed the target to stretch sideways to create more elastic deformation, while the sample fails by shear plugging for the flat nosed projectile.
4.6.2 Ballistic Limit Effect Due to Pretension

With the pretension applied to the target, the ballistic limit for a hemispherical projectile impacting on CFRP panel was found to be different when compared with that of aluminium alloy 2014-T6. In CFRP, the ballistic limit for a pretension target is lower than non-pretension target, which is different from the observations for aluminium alloy 2014-T6 target where the ballistic limit with pretension is higher than a non-pretension target. It is considered that this was due to the failure mechanism of the fibre and its construction arrangement in the composite. Axial pretension applied to bidirectional fibre staking gave the Poisson ratio effect as in Table 3.4 which resulted in fibre displacement within the matrix as shown in Figure 4.16(a). The displacement increased the difference between each fibre as in Figure 4.16(b) which allowed the hemispherical projectile to perforate easily. This proof could explain the similar observations from previous researchers (Robb et al, 1995; Mines et al, 2000; Whittingham et al, 2004; Duan et al, 2005) which resulted in higher penetration for projectile/indenter when compared to non-pretension target.

Figure 4.15: Residual velocity versus impact velocity for CFRP panels with and without pretension.
Figure 4.16: (a) Target under pretension (b) Fibre arrangements before and after pretension; whereby pretension results in fibre displacement.
### 4.7 Damage Behaviour of Carbon Fibre Reinforced Plastic

Figure 4.17 shows two different failure modes, impacted by two different projectiles, i.e., (a) flat and (b) hemispherical projectiles. It can be seen that the flat projectile resulted in plugging along the target thickness, while the hemispherical projectile tried to push the fibre sideways during penetration, and formed petalling.

![Figure 4.17: Target cross section due to impact by (a) flat projectile and (b) hemispherical projectiles.](image)

**4.7.1 Fast Fracture Criteria**

A structure may fail catastrophically through the mechanism of fast fracture. An example of fast fracture is a pressure vessel exploding under large internal pressure due to the existence of crack in an imperfect weld, which may suddenly become unstable and grow at high speeds, close to the shear wave speed. Consider the plate shown in Figure 4.18, with radius of hole R, an existing crack, \( a \) and fixed loads acting on both sides of the plate (Murakami, 1987).
The critical stress condition for the start of fracture is:

$$G_c = \frac{\pi a \sigma^2}{2E}$$

(4.3)

where $G_c$ is the fracture energy, kJ/m$^2$).

The critical stress condition becomes;

$$\sigma_c = \sqrt{\frac{2EG_c}{\pi a}}$$

(4.4)

and the critical fracture toughness (or stress intensity, MNm$^{3/2}$), $K_c$ is,

$$K_c = F. \sigma_c \sqrt{\pi a} = F. \sqrt{EG_c}$$

(4.5)

where $F$ is the geometrical correction factor. Simplifying equation (4.5) above, the critical stress equation becomes,

$$\sigma_c = \frac{K_c}{F. \sqrt{\pi a}}$$

(4.6)

Using equation (4.6), a calculation has been performed to estimate the critical stress for the CFRP target under pretension, impacted by projectile which created various radius of hole (R). Taking various size of crack length and radius of hole, stress intensity factor $K_c = 32$ MNm$^{3/2}$ (Ashby and Jones, 2005), the interpolation of geometrical F value from Murakami (1987), resulted in the calculated critical stress as shown in Table 4.11.
Table 4.11 is translated to the graph of the critical stress pattern vs crack length which is shown in Figure 4.19. In Region A, if the hole with radius $R$ becomes similar or larger than crack ‘a’ (meaning no crack exists on the target) thus the critical stress becomes higher. However if the hole radius $R$ is smaller than the crack length $a$, the critical stress reached its lowest level thus becoming extremely small as shown in Region B and contributed to the reduction of material strength. The estimation used in equation (4.6) shows that as the crack length becomes bigger than the hole, the critical stress for the plate becomes lower, which further reveals that the plate could experience catastrophic failure at minimum load applied.

Table 4.11: Critical stress of target impact with increase of crack length.

<table>
<thead>
<tr>
<th>Hole radius(m)</th>
<th>0.001</th>
<th>0.0025</th>
<th>0.004</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crack length, $a$ (m)</td>
<td>Critical Stress(MPa)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.0025</td>
<td>439</td>
<td>649</td>
<td>1236</td>
</tr>
<tr>
<td>0.003</td>
<td>398</td>
<td>588</td>
<td>1120</td>
</tr>
<tr>
<td>0.01</td>
<td>143</td>
<td>151</td>
<td>146</td>
</tr>
<tr>
<td>0.02</td>
<td>51</td>
<td>58</td>
<td>48</td>
</tr>
</tbody>
</table>

Figure 4.19: Graph of critical stress versus crack length of a plate with various perforated hole radius.
4.7.2 Stress Concentration Effect on CFRP Plate

Another method used to predict the catastrophic failure is by using a stress concentration equation. Consider a plate perforated by a projectile with the existence of in-plane pretension, similarly as shown in Figure 4.13 but with the thickness of 3mm will lead to a stress concentration near the circular hole. The concentrated stress $\sigma_{\text{max}}$ can be estimated by equation (4.2) (Craigh, 1999). The average and maximum stress around the perforated boundary of the CFRP plate under 30% pretension is then calculated as:

$$\sigma_{\text{ave}} = \frac{P}{A} = \frac{28500}{1.15 \times 10^{-4}} = 248\text{MPa}$$

Thus,

$$\sigma_{\text{max}} = k_f \sigma_{\text{ave}} = 2.75(248 \times 10^6) = 681.5\text{MPa}$$

where $k_f$ is the stress concentration factor value, $A$ is the cross-sectional area of the plate after perforation (Beer et al., 2006; Hibbler, 2008), and $P$ is the pretension load applied. The maximum stress around the perforated hole is 681.5MPa, which is near to the ultimate strength (705MPa) of the CFRP target. It should be noted that the maximum stress is calculated without considering the vibration of the plate, which may also contribute to cracking and catastrophic failure. Further explanation of cracking and failure will be given in Chapter 4.8.2.

4.8 Catastrophic Phenomena at Ballistic Limit Velocity

Material damage in the CFRP panel was observed to determine the correlation between damage and failure. The observations were performed at velocities close to the ballistic limits, which were divided into three categories, i.e. lower than ballistic limit, equal to ballistic limit, and higher than ballistic limit. Figure 4.20 to Figure 4.22 shows a series of high-speed video images depicting the penetration process of bidirectional CFRP plate impacted by a projectile of 5mm diameter and 20mm length. Pretension stress in the target was approximately 211.5 MPa, which is 30% of its 705 MPa ultimate strength. Table 4.10 shows that most catastrophic failure occurred when the pretension targets were impacted by the hemispherical nosed projectile.
4.8.1 Response and Failure of CFRP at impact Velocity Lower than Ballistic Limit

Figure 4.20 shows the image sequence of a panel at 30% pretension, impacted by hemispherical nosed projectile at 85m/s (below ballistic limit) which resulted in an indentation on the target. Due to the impact, the target area was influenced to displacement and started to vibrate forwards and backwards a few times. During the vibration process, the target experienced tension and compression, which led to crack in the impact area (Image 689μs). It can be seen that the existence of pretension does contribute to further crack growth in the target. However, at this level of impact velocity, the initial damage formed might be small, and the panel would still be able to withstand the pretension load. Somehow, for the impact velocity of 95m/s by a hemispherical nosed projectile (see Table 4.10), the increase in the impact velocity led to an increased target global displacement resulting in the catastrophic splitting of the target.

![Image sequence of impact](image)

Figure 4.20: Photographic sequence of impact below than ballistic limit.

4.8.2 Response and Failure of CFRP plate at Ballistic Limit

In this section, fast fracture phenomena were observed for the impacted plate under pretension. Figure 4.21 shows the sequence event of the projectile hitting the target and stopped at the middle of its passage. Similar to the scenario found in Section 4.8.1, the impact generated vibrations which caused the plate to move forward and backward several times. The panel experienced tension and compression due to the vibration. Full perforation of the target was found occurring at 997μs. Then, the crack was seen to grow around the perforation area perpendicular to the load direction. This could be clearly seen from the image at 2565μs
where a single crack line emerged. The combination of pretension, cross-section area reduction, plate vibration, and the formation of crack growth had led to catastrophic failure, which happened at 3990μs.

Figure 4.21: Photographic sequence at ballistic limit velocity which contributed to catastrophic failure due to fast fracture.
4.8.3 Response and Failure of CFRP at Velocity Higher than Ballistic Limit

Figure 4.22 shows the sequence events of penetration at an impact velocity of 101 m/s. At 130 μs, the perforation caused reduction of the cross section area. A small crack was seen to form from the impact, near to the perforation area. From 413 to 551 μs, the impact generated forward and backward vibration of the plate. Together with the pretension in the plate, the crack extended along the line, which led to the catastrophic failure of the target.

Figure 4.22: Photographic sequence of projectile at higher than ballistic limit.
4.9 Damage Assessment on CFRP plate

Figure 4.23 shows the failure modes of non-pretension targets, at front and rear sides, for partial and complete penetrations. Images (a) and (b) clearly show a perforated hole indicating shear failure for partial penetration. The hole at the rear side of the target (image b) is less obvious than the hole of the front side, due to the occurrence of delamination damage. Similar phenomena were observed for the failure modes associated with complete penetration, as shown in images (c) and (d), where the damage became more localised with the increase of impact velocity.

Images e, f, g and h, show damages resulting from a non-pretension target under hemispherical nosed projectile impact. It can be clearly seen that the damage resulting from a hemispherical nosed projectile is different from that produced by a flat-nose projectile. The hemispherical-nose projectile penetration round nose shape will push the target sideways during impact. After the completion of perforation, the damaged target material will try to return to its original position and form petalling. These phenomena were observed for impact velocities both higher and lower than the ballistic limit.

Figure 4.24 compares the failure modes of 30% pretension target at the front and rear sides, for partial and complete penetrations. The shear plugging failure mode is associated with the flat nosed projectile while fibre tension failure is related to the hemispherical nosed projectile. For both the partial and complete penetrations shown in Figure 4.24, pretension may have led to the splitting of the target where a single line (crack) fracture is formed at the rear, near the perforated area (image j). The crack line is related to target splitting, or catastrophic failure which occurred when pretension was applied. Comparison of Figure 4.23 and Figure 4.24 also show that crack formation is related to the pretension.
<table>
<thead>
<tr>
<th></th>
<th>Front View</th>
<th>Rear View</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Impacted by Flat Projectile</strong></td>
<td><img src="image" alt="Front View Partial" /></td>
<td><img src="image" alt="Rear View Partial" /></td>
</tr>
<tr>
<td><strong>Complete</strong></td>
<td><img src="image" alt="Front View Complete" /></td>
<td><img src="image" alt="Rear View Complete" /></td>
</tr>
<tr>
<td><strong>Impacted by Hemispherical Projectile</strong></td>
<td><img src="image" alt="Front View Partial" /></td>
<td><img src="image" alt="Rear View Partial" /></td>
</tr>
<tr>
<td><strong>Complete</strong></td>
<td><img src="image" alt="Front View Complete" /></td>
<td><img src="image" alt="Rear View Complete" /></td>
</tr>
</tbody>
</table>

Figure 4.23: Photographic of front and rear CFRP non-pretension target at partial and complete perforation impacted by flat (a-d) and hemispherical (e-h) projectiles.
<table>
<thead>
<tr>
<th></th>
<th>Front View</th>
<th>Rear View</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Impacted by Flat Projectile</strong></td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>Partial</td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td>Complete</td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
</tbody>
</table>

| **Impacted by Hemispherical Projectile** | ![Image](image7.png) | ![Image](image8.png) |
| Partial       | ![Image](image9.png) | ![Image](image10.png) |
| Complete      | ![Image](image11.png) | ![Image](image12.png) |

Figure 4.24: Photographic of front and rear CFRP at 30% pretension target on partial and complete perforation impacted by flat (i-l) and hemispherical (m-p) projectiles.
4.10 Conclusions

In this chapter, the impact resistance of aluminium alloy 2014-T6 and CFRP under impact by flat nosed and hemispherical nosed projectiles have been thoroughly investigated. For both material types, it was shown that the ballistic limit for the hemispherical shaped nose is higher than that for the flat shaped nose. It was also shown that the hemispherical shaped nose is associated with a petalling failure mode while the flat shaped nose is associated with a shear plugging failure mode. For aluminium alloy 2014-T6 plate target, the pretension had led to a reduction of the ballistic limit for flat nosed projectile. However, opposite results were observed for hemispherical nosed projectile. For CFRP target, pretension always gave a reduction in the ballistic limit on both projectile nose shapes. Pretension had allowed for the fibre to create gaps for the hemispherical nosed projectile to perforate through the plate. Material stretching affects the stiffness of the plates. These affected the ballistic limit such that it shows a very small difference.

Having pretension applied to the target will create crack as the main contributor that leads towards catastrophic failure. The hemispherical nosed projectile experienced catastrophic failure at almost all impact velocities near to the ballistic limit, whereas the flat nosed projectile resulted in catastrophic failures only at velocities higher than the ballistic limit.
CHAPTER 5. NUMERICAL SIMULATION OF ALUMINIUM ALLOY 2014-T6 PANEL UNDER IMPACT

5.1 Introduction
This chapter presents finite element model analysis and related procedures on the damage modelling in metallic materials, followed by the simulation results focusing on high velocity impacts on an aluminium alloy 2014-T6 target plate. A 3D numerical simulation using Abaqus/Explicit was performed to predict the ballistic limit of flat and hemispherical projectiles. For isotropic materials like aluminium alloy 2014-T6, the shear failure material model was used along with the Abaqus ductile damage evolution criterion. In order to validate the finite element models, the simulation results of the ballistic limit will then be compared with the experimental results.

5.2 Modelling Damage and Failure for Isotropic Materials
The aluminium alloy 2014-T6 target was modelled as a 3D solid using element type C3D8R in Abaqus package software together with flat and hemispherical projectile modelled as rigid bodies. The shear failure criterion function, one of the main models of the fracture characteristics for a ductile metal, was used to study the damage and failure of aluminium alloy 2014-T6 plate. The FE modelling uses a combination of damage evolution and element removal method.

5.2.1 Damage Initiation
The shear damage initiation criterion is a model for predicting the onset damage due to shear band localization. The model used in Abaqus (2010) assumes that shear stress ratio $\theta_s$ and strain rate $\dot{\varepsilon}^{\text{pl}}$ define the equivalent plastic strain $\bar{\varepsilon}_s^{\text{pl}}$ at the onset of damage:

$$
\bar{\varepsilon}_s^{\text{pl}}(\theta_s, \dot{\varepsilon}^{\text{pl}})
$$

where $\theta_s = (q + k_s p)/\tau_{\text{max}}$ is the shear stress ratio, with $q$ being the Mises equivalent stress, $p$ is the hydrostatic pressure stress, $\tau_{\text{max}}$ is the maximum shear stress, and $k_s$ is a material parameter. The value of $k_s$ used for aluminium alloy is 0.3 (Hooputra et al., 2004).
Shear damage will be initiated if the following condition is satisfied:

\[
\omega_s = \int \frac{\Delta \varepsilon^{pl}}{\varepsilon_s^{pl}(\theta_s, \varepsilon^{pl})} = 1
\]

(5.2)

where \(\omega_s\) is a state variable that increases monotonically with plastic deformation proportional to the incremental change in equivalent plastic strain in the element. At each increment during the analysis, the incremental increase in \(\omega_s\) is computed as (Abaqus, 2010):

\[
\Delta \omega_s = \frac{\Delta \varepsilon^{pl}}{\varepsilon_s^{pl}(\theta_s, \varepsilon^{pl})} \geq 0
\]

(5.3)

### 5.2.2 Damage Evolution

After reaching the damage initiation criterion, damage evolution is applied. Damage evolution was used to describe the post damage-initiation material behaviour and is assumed to be characterised by the progressive degradation of the material’s stiffness.

Considering the stress-strain behaviour of the material under test, as shown in Figure 5.1, the material response after damage initiation, as shown in the graph, is divided into two categories: softening of the yield stress, and degradation of the elasticity. The solid curve can be seen to represent the damaged stress-strain response, while the dashed line represents the undamaged response. The formulation is based on the scalar damage approach, given by (Abaqus, 2010):

\[
\sigma = (1 - D) \bar{\sigma}
\]

(5.4)

where \(\bar{\sigma}\) denotes the stress due to the undamaged response. \(D\) is defined as the overall damage variable of active damage mechanisms and is computed from individual damage variables for each mechanism, \(d\), which will be described latter in this section.

In the graph, \(\sigma_{y0}\) and \(\varepsilon^{pl}_0\) are the yield stress and equivalent plastic strain at damage commencement (damage variable, \(D=0\)), while \(\varepsilon^{pl}_f\) is the equivalent plastic strain at failure (damage variable, \(D=1\)).
The damage evolution is related to an equivalent plastic displacement, $\bar{\mathbf{u}}^{pl}$. After damage initiation, the effective plastic displacement $\bar{\mathbf{u}}^{pl}$ evolves according to the following equation (Abaqus, 2010):

$$\dot{\bar{\mathbf{u}}}^{pl} = L^e \dot{\mathbf{e}}^{pl}$$  \hspace{1cm} (5.5)

where $L^e$ is the characteristic length of the element. In the Abaqus/Explicit model, the relationship between the damage variable and the effective plastic displacement can be specified in tabular, linear or exponential form. In this study, linear evolution (Figure 5.2) is used to define the damage evolution.
The linear damage evolution law is defined by

\[
\dot{d} = \frac{L \dot{\varepsilon}_{pl}}{\bar{u}_{f}} = \frac{\dot{\varepsilon}_{pl}}{\bar{u}_{f}}
\]  

When damage variable reaches unity \((d=1)\), the material is fully degraded and the effective plastic displacement achieves failure value \((\bar{u}_{pl} = \bar{u}_{f}^{pl})\). This is when all of the material points in an element fail thus contributing towards the deletion of the element. However, if the material in an element is only partially damaged \((\text{when } d < 1)\) then the element will continue to function. As mentioned earlier, \(d\) is defined as the individual damage variable for each mechanism. If there are more than one damage mechanisms, the combined damage variable can be chosen as follows:

\[
d_{total} = 1 - \prod_{k \in N_{total}} (1 - d_k)
\]

where \(k\) is the number of damage variables used for damage evolution; as only one damage model was used in the current analysis, \(d\) is equal to \(D\) for overall damage variable \((\text{Abaqus, 2010})\).
5.3 Finite Element Modelling using 3D Solid Element

In this study, a three-dimensional finite element model of the target plate and projectile was developed to simulate the ballistic impact test. The simulation was designed to replicate target position from the experiment as shown in Figure 4.7. The target will experience two conditions: non-pretension and pretension, and being impacted by the projectile at high velocity.

5.3.1 Finite Element Model

The Abaqus/Explicit package was used to simulate the target as a deformable solid using elements C3D8R with 'reduce integration' function, while the projectile was modelled as an analytical rigid body using four nodes bilinear quadrilateral elements (R3D4). Figure 5.3 shows an example of the mesh used in the study. The size of the rectangular target is 100 x 45mm, with a thickness of 2mm. An adaptive mesh was applied to all models to reduce the computational time. The target area, which is located at the centre of the plate, consisted of the most refined mesh used in the simulations. Moving away from the centre of the impact area, the elements become less dense. In addition, as the elements become smaller, the number of elements through the plate thickness increases. Since the critical area is considered to be only at the middle of the target model, the element size outside of the target area was not critically analyzed. Using adaptive meshing will help to avoid error termination of the program due to excessive distortion occurred within the elements.

Figure 5.3: Finite element simulation model.
5.3.2 Interaction in Modelling
The algorithm used to define contact and interaction in this chapter is a contact-pair algorithm. To model the interaction between the aluminium alloy 2014-T6 plate and the projectile, the surface interaction was defined between the two surfaces. The surface of the projectile was selected as a master surface, and the surface formed by the nodes of the aluminium alloy 2014-T6 plate was selected as a slave surface. Interaction properties for the Abaqus/Explicit model were determined by two criteria: tangential behaviour and normal behaviour. In ‘tangential behaviour’ parameter, the friction coefficient for Aluminium alloy 2014-T6 was adopted from Hao et al., 2009 and is simplified to 0.3. While in ‘normal behaviour’ parameter, the hard-contact was chosen under pressure-over closure with the help of separation of the element after contact.

5.3.3 Boundary Conditions and Application of Pretension
There are two separate boundary conditions for non-pretension and pretension that were used in Abaqus/Explicit. The prescribed displacements were applied to two parallel sides of the target, and the other two are kept free. For non-pretension, fixed boundary conditions were applied to both ends, as shown in Figure 5.4. For pretension conditions, axial displacements were applied to the two ends of the plate by using the Amplitude function which is already built into the Abaqus software to create pre-tension stress in the target (Figure 5.5). The Amplitude function begins from 0 and increases to 1 linearly, and then remains constant, as shown in Figure 5.6. A time range is given for the force to pull both ends and create the required pretension stresses in the target. The pretension remains constant throughout the test from projectile impact until it stops. The average stress was calculated based on the pretension value. The ultimate strength for aluminium alloy 2014-T6 was taken as 483MPa, hence the pretension values calculated at the centre of the target for 10%, 23% and 50% pretension were 48MPa, 112MPa and 240MPa, respectively. The displacements required to generate these pretensions are calculated based on the extension stiffness of the plate and are shown in Table 5.1. The pretensions obtained by this simulation technique are shown in Figure 5.7. In addition, the boundary condition for the projectile was assigned at the nose tip, with the reference point (RP) moving only in the z-direction. The projectile was also assumed to have no rotation during impact. The initial position of the projectile was such that the projectile would only travel to impact the target after the pretension had been applied to the target and reached a steady-state.
Figure 5.4: Fixed boundary conditions.

Figure 5.5: Displacement boundary conditions.

Figure 5.6: Amplitude used for displacement in pretension.

Table 5.1: Displacement on both target-ends.

<table>
<thead>
<tr>
<th>Pretension</th>
<th>Stress(MPa)</th>
<th>Displacement(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10%</td>
<td>48</td>
<td>3.333e-5</td>
</tr>
<tr>
<td>23%</td>
<td>112</td>
<td>7.777e-5</td>
</tr>
<tr>
<td>50%</td>
<td>242</td>
<td>0.000168</td>
</tr>
</tbody>
</table>
Figure 5.7: Pretension using the amplitude function.
5.3.4 Material Properties
The target was made of aluminium alloy 2014-T6, which is commercially known as L157-T6. The material properties used for aluminium alloy 2014-T6 are given in Table 4.1, and the additional isotropic hardening data are shown below in Table 5.2. Due to un-deformable projectile structure during experimental testing, the mechanical properties of flat and hemispherical projectiles for finite element simulation were not determined and are considered as rigid body.

Table 5.2: Material constant of aluminium alloy 2014-T6.

<table>
<thead>
<tr>
<th>Flow stress (MPa)</th>
<th>Plastic Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>414</td>
<td>0</td>
</tr>
<tr>
<td>483</td>
<td>0.23</td>
</tr>
</tbody>
</table>

5.4 Mesh Sensitivity Analysis
A mesh sensitivity analysis was performed on a 2mm-thick aluminium alloy 2014-T6 plate. The study involved variable dimensions and aspect ratios of the elements. The size of the element was varied by increasing the number of elements in the plate thickness, starting from 2, 4, 6, 8, 10, 14 and 20 elements, which results in seven element sizes: 1x1x1mm, 0.5x0.5x0.5mm, 0.33x0.33x0.33mm, 0.25x0.25x0.25mm, 0.2x0.2x0.2mm, 0.14x0.14x0.14mm and 0.1x0.1x0.1mm, respectively. The number of elements for the entire model based on these mesh sizes are listed in Table 5.3.

The impact of a projectile (hemispherical or flat shaped nose) with a mass of 3 grams onto the target was then simulated using different mesh sizes. The initial impact velocity was chosen from the velocity value of which is closest to the experimental work. This is the reason why different initial velocities were used for different projectiles and different pretensions in the target panel.
Table 5.3: Element sizes and total element numbers.

<table>
<thead>
<tr>
<th>Element Size (mm)</th>
<th>Number of element over thickness</th>
<th>Element Total</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>1x1x1</td>
<td>2</td>
<td>1000</td>
<td>200</td>
</tr>
<tr>
<td>0.5x0.5x0.5</td>
<td>4</td>
<td>6080</td>
<td>1600</td>
</tr>
<tr>
<td>0.33x0.33x0.33</td>
<td>6</td>
<td>46080</td>
<td>5400</td>
</tr>
<tr>
<td>0.25x0.25x0.25</td>
<td>8</td>
<td>52160</td>
<td>12800</td>
</tr>
<tr>
<td>0.2x0.2x0.2</td>
<td>10</td>
<td>94000</td>
<td>25000</td>
</tr>
<tr>
<td>0.14x0.14x0.14</td>
<td>14</td>
<td>153216</td>
<td>72576</td>
</tr>
<tr>
<td>0.1x0.1x0.1</td>
<td>20</td>
<td>353963</td>
<td>200000</td>
</tr>
</tbody>
</table>

Table 5.4 and Table 5.5 show the initial impact velocity and the residual velocity of the projectile after impact, obtained from different mesh sizes. For this study, the initial impact velocity of the flat projectile was taken as 160m/s for non-pretension tests, and 140m/s for tests with 23% pretension; while for the hemispherical projectile, the initial impact velocity was taken as 160m/s for non-pretension, and 155m/s for 23% pretension tests.

Table 5.4: Mesh sensitivity study of aluminium alloy 2014-T6 impacted by flat projectile.

<table>
<thead>
<tr>
<th>Nose Type</th>
<th>0% Pretension ($v_i$=160m/s)</th>
<th>23% Pretension ($v_i$=140m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Elements</td>
<td>$v_f$ (m/s)</td>
<td>$v_R$ (m/s)</td>
</tr>
<tr>
<td>Flat</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>77</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>123</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>130</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>137</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>136</td>
</tr>
</tbody>
</table>
Table 5.5: Mesh sensitivity study of aluminium alloy 2014-T6 impacted by hemispherical projectile.

<table>
<thead>
<tr>
<th>Nose Type</th>
<th>0% Pretension ($v_i=160\text{m/s}$)</th>
<th>23% Pretension ($v_i=155\text{m/s}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of Elements</td>
<td>$v_r$ (m/s)</td>
</tr>
<tr>
<td>Hemispherical</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>76</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>86</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>77</td>
</tr>
</tbody>
</table>

The results for the mesh sensitivity study on a flat projectile impacting a target without pretension are shown in Figure 5.8. In the early stage, using higher element size (low number of element) shows no value of residual velocity but the residual velocity changes as the element size reduces (high number of element). As the number of elements increases the residual velocity increases; however, the residual velocity converges at an element size of 0.14x0.14x0.14mm. At this point, the number of elements is 14 over thickness and was selected for further validation analysis.

Figure 5.8: Variation of residual velocity of flat projectile over target thickness at 0% pretension.
Figure 5.9 shows the residual velocity against the number of elements in thickness for a pre-tension target impacted by a flat projectile. It can be seen that the residual velocity increases as the number of elements increases. However, at 14 elements over thickness with element size of 0.14x0.14x0.14mm, the residual velocity converged.

![Graph of residual velocity against number of elements.](image)

**Figure 5.9:** Variation of residual velocity of flat projectile over target thickness at 23% pretension.

Figure 5.10 depicts the trend between the residual velocity and the number of elements in the thickness of the non-pretension target impacted by a hemispherical projectile. It is shown that, as the element size decreases (and number of elements increases); the residual velocity also gradually increases. However, at one point, the residual velocity starts to converge; due to the scenario of convergence, the number of elements over thickness that is required for convergence was found to be ten, with an element size of 0.2x0.2x0.2 mm.
Figure 5.10: Variation of residual velocity of hemispherical projectile over target thickness at 0% pretension.

Figure 5.11: Variation of residual velocity of hemispherical projectile over target thickness at 23% pretension.

Figure 5.11 demonstrates the relationship between the residual velocity and the number of elements in the plate thickness when a pretension target was impacted by a hemispherical projectile. It was observed that the residual velocity increases as the number of elements increases. However, at ten elements over thickness, with an element size 0.2x0.2x0.2mm, the residual velocity converged, similar to the non-pretension case. Due to
the convergence, ten elements over thickness was selected for further analysis. The best element must be chosen as the optimum element for the analysis because a higher number of elements over thickness will result in closer approximation, but with longer time to process the data.

The mesh sensitivity study showed that pretension does not affect the mesh sensitivity when a similar element is selected for convergence. In addition, the study shows that the flat projectile requires more refined mesh than the hemispherical projectile to achieve convergence.

5.5 Ballistic Limit Prediction using FE Simulation

After running a mesh sensitivity study on every projectile type and various mesh sizes, as mentioned in chapter 5.4, a suitable mesh size was chosen for further analysis. For a flat projectile impacting a target with 0%, 10%, 23% and 50% pretension, a mesh size of 0.14x0.14x0.14mm was chosen to predict the ballistic limit. A series of impact at different impact velocity was simulated to determine the projectile’s residual velocity, as shown in Table 5.6. The ballistic limit of the targets with 0%, 10%, 23% and 50% pretension was then found to be 116m/s, 114m/s, 112m/s and 100m/s respectively.

For a hemispherical projectile impacting on a target with 0%, 10%, 23% and 50% pretension, from mesh sensitivity studies, a mesh size of 0.2x0.2x0.2mm was chosen to predict the ballistic limit. A series of simulations was run at different impact velocities to determine the projectile’s residual velocity. The results are shown in Table 5.7. The ballistic limits of the target for 0%, 10%, 23% and 50% pretension were found to be 139m/s, 138m/s, 138m/s and 137m/s respectively.
Table 5.6: Simulation results of aluminium alloy 2014-T6 impacted by flat projectile.

<table>
<thead>
<tr>
<th>Pretension</th>
<th>0%</th>
<th>10%</th>
<th>23%</th>
<th>50%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nose Type</td>
<td>( v_i ) (m/s)</td>
<td>( v_r ) (m/s)</td>
<td>( v_i ) (m/s)</td>
<td>( v_r ) (m/s)</td>
</tr>
<tr>
<td>Flat</td>
<td>300</td>
<td>280</td>
<td>300</td>
<td>280</td>
</tr>
<tr>
<td></td>
<td>145</td>
<td>117</td>
<td>155</td>
<td>131</td>
</tr>
<tr>
<td></td>
<td>135</td>
<td>101</td>
<td>137</td>
<td>104</td>
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<tr>
<td></td>
<td>120</td>
<td>55</td>
<td>135</td>
<td>101</td>
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<tr>
<td></td>
<td>117</td>
<td>27</td>
<td>120</td>
<td>58</td>
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<tr>
<td></td>
<td>116</td>
<td>0</td>
<td>117</td>
<td>36</td>
</tr>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>114</td>
<td>0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.7: Simulation results of aluminium alloy 2014-T6 impacted by hemispherical projectile.

<table>
<thead>
<tr>
<th>Pretension</th>
<th>0%</th>
<th>10%</th>
<th>23%</th>
<th>50%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nose Type</td>
<td>( v_i ) (m/s)</td>
<td>( v_r ) (m/s)</td>
<td>( v_i ) (m/s)</td>
<td>( v_r ) (m/s)</td>
</tr>
<tr>
<td>Hemispherical</td>
<td>300</td>
<td>262</td>
<td>300</td>
<td>262</td>
</tr>
<tr>
<td></td>
<td>160</td>
<td>86</td>
<td>155</td>
<td>74</td>
</tr>
<tr>
<td></td>
<td>145</td>
<td>27</td>
<td>145</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>140</td>
<td>5</td>
<td>140</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>139</td>
<td>0</td>
<td>138</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

The results in Table 5.6 and Table 5.7 are plotted in Figure 5.12, hence depicting the relationship between the impact velocity and residual velocity for an aluminium alloy 2014-T6 plate struck by two different projectiles, with and without pretension applied to the target. The overall response showed that the residual velocity increases in a parabolic manner near to the ballistic limit. As the impact velocity increases, the residual velocity increases linearly and becomes closer to the other velocities. It was observed that the trends for both projectiles are almost the same. The results from non-pretension and pretension tests for each projectile show a similar result, having only a small difference caused by the pretension effect. It was also observed that projectile nose shape has a significant effect on the resistance of the target. The target offered a higher resistance to the impact from hemispherical nosed projectiles.
There is a difference of only 14% in the ballistic limit between the targets with 50% pretension and without pretension, as it was hit by a flat projectile. Similarly, using a hemispherical projectile, a difference of less than 2% was observed in the ballistic limit between the targets with 50% pretension and without pretension.

As the pretension in the target increases, the ballistic limit is seen to decrease. The differences in the ballistic limit for 10%, 23% and 50% pretension are 1.7%, 3.5% and 13.8% lower than the value without pretension, respectively.

![Figure 5.12: Residual velocity versus impact velocity of flat projectile impacted on targets with different pretension values.](image)

Figure 5.13 shows the finite element simulation results of the residual velocity of the hemispherical projectile hitting the targets under various values of pretention. Similar to the result seen for the flat projectile, as the pretension in the target increases, the ballistic limit is seen to decrease. 10% and 23% pretension lowers the ballistic limit by less than 1%, and a 50% pretension lowers it by just 1.5% when compared to the ballistic limit for non-pretension target.
Figure 5.13: Residual velocity versus impact velocity of hemispherical projectile impacted on targets with different pretension values.

Figure 5.14 compares the predicted residual velocities of the flat and hemispherical projectiles striking the targets under various levels of pretension. The residual velocities of the hemispherical projectile are seen to be higher than the flat projectile. These phenomena prove that the panels have more impact resistance to a hemispherical projectile than a flat projectile. A large difference in ballistic limit between flat projectile impact and hemispherical projectile impact was found when the pretension in the target is 50%.

Figure 5.14: Comparison of flat and hemispherical projectile impacted on targets with different pretension values.
5.6 Ballistic Limit comparison using Finite Element and Experimental Result

Figure 5.15 shows the predicted residual velocity for the flat projectile impacting on a target with 0% and 23% pretension, in comparison with the experimental results. The comparison shows a fairly good agreement between the simulation and the experiment. For the target with 23% pretension, the predicted ballistic limit for a flat projectile is 9.7% lower than the experimental result. The target without pretension shows a ballistic limit difference of about 9.4% between the results of the finite element simulation and the experimental results.

Figure 5.16 shows the residual velocity of the hemispherical projectile as a function of impact velocity, when hitting an aluminium alloy 2014-T6 plate without pretension and with 23% pretension. The comparison shows a fairly good agreement between results of the simulation and the experiment. For targets with 0% pretension, the predicted ballistic limit is 4.1% lower than that obtained from the impact by the hemispherical projectile experiment. For a sample with 23% pretension, there is 8% difference in the ballistic limit between the result of the finite element simulation and the experimental result. Even though the results from the simulations and experiments showed good agreement in terms of the ballistic limit, it can be seen that experimental ballistic limit for pretension tests is higher than the result for non-pretension tests. However, the simulation shows that the pretension reduces the ballistic limit, although the reduction is very small (approx. 1m/s).
Figure 5.15: Comparison between the experiment (with ‘E’ and clear marker fill) and the simulation (with ‘S’ and dark marker fill) residual velocity of flat projectiles.

Figure 5.16: Comparison between the experiment (with ‘E’ and clear marker fill) and the simulation (with ‘S’ and dark marker fill) residual velocity of hemispherical projectiles.
5.7 Impact Response of Aluminium Alloy 2014-T6 Plate
The failure modes and damage characteristics were observed when the target is impacted by the flat and hemispherical projectiles at velocities above their ballistic limits.

5.7.1 Failure Modes of Aluminium Alloy 2014-T6 Target
Figure 5.17 shows the failure sequence event of a 2mm thick aluminium alloy 2014-T6 target under pretension of 0%, 10%, 23% and 50% ultimate stress, impacted by a flat shaped projectile at a velocity of 117m/s which is typically higher than the ballistic limit of flat shaped projectile. It was observed that, in all cases, the projectile caused panel thinning in the contact area, which is a characteristic of the failure mode of the panel. The flat shaped nose caused shear plugging when the material in front of the projectile was compressed. However, other than shear plugging, which is shown in Figure 5.17, it can also be seen that a small amount of the material is pushed sideways by the target, which created extra edges around the hole after perforation. This shows that, even for a flat projectile, a small amount of petalling can be seen in the target.

In addition, for every value of pretension tested, the thickness of the compressed plug was measured. There was no significant change in the plug thickness due to the existence of pretension. On average, less than a 3% difference in thickness was found under pretension. The increase of pretension does affect the projectile perforation and the ballistic limit. This occurred because, as the pretension was increased, the stress in the target became closer to the material’s ultimate strength. In other words, the pretension will reduce the impact strength of the target, which leads to easier perforation.

Figure 5.18 shows the progressive failure sequence of the target struck by a hemispherical projectile under various levels of pretension. The impact velocity was 145m/s which is just above the ballistic limit such that the projectile could perforate through the target. It was observed that, in all cases, the projectile caused a tensile failure as the material was pushed sideways upon perforation. The cause of this failure is clearly related to the hemispherical shaped nose of the projectile. The larger impact surface area of the hemispherical projectile - compared to that of the flat projectile - results in a longer time for the penetration of the target to complete. This was shown in the figures where the hemispherical projectile needs a higher velocity to perforate the target (or over a longer time).
Meanwhile the flat projectile can perforate at lower velocity (or over a shorter time). The increase in target pretension increased the projectile perforation as well as reduced the ballistic limit. The impact by a hemispherical projectile contributed to the formation of petalling near to the impact target area. Table 5.8 shows that the number of petals increased as the impact velocity increased. In addition, Table 5.9 shows that the number of petalling formations increased significantly as the pretension was increased. It can therefore be concluded that there is an apparent connection between petal formation, pretension and impact velocity.
Chapter 5: Numerical Simulation of Aluminium alloy 2014-T6 Panel under Impact

<table>
<thead>
<tr>
<th>Pretension</th>
<th>10µs</th>
<th>50µs</th>
<th>100µs</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
<tr>
<td>10%</td>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
<tr>
<td>23%</td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
<td><img src="image9.png" alt="Image" /></td>
</tr>
<tr>
<td>50%</td>
<td><img src="image10.png" alt="Image" /></td>
<td><img src="image11.png" alt="Image" /></td>
<td><img src="image12.png" alt="Image" /></td>
</tr>
</tbody>
</table>

Figure 5.17: Failure sequence of aluminium alloy 2014-T6 impacted by flat projectile at 117m/s.
Figure 5.18: Failure sequence of aluminium alloy 2014-T6 impacted by hemispherical projectile at 145m/s.
Table 5.8: Petal formation of 0% pretension target impacted by hemispherical projectile.

<table>
<thead>
<tr>
<th>Impact Velocity (m/s)</th>
<th>Number of Petals</th>
</tr>
</thead>
<tbody>
<tr>
<td>145</td>
<td>8</td>
</tr>
<tr>
<td>155</td>
<td>11</td>
</tr>
<tr>
<td>180</td>
<td>12</td>
</tr>
</tbody>
</table>

Table 5.9: Petal formation on various pretension targets impacted at velocity of 145 m/s.

<table>
<thead>
<tr>
<th>Pretension</th>
<th>0%</th>
<th>10%</th>
<th>23%</th>
<th>50%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Petals</td>
<td>8</td>
<td>10</td>
<td>10</td>
<td>11</td>
</tr>
</tbody>
</table>

5.7.2 Target Damage with Pretension Effect

Figure 5.19 and Figure 5.20 depict the finite element simulation of two different impact scenarios, i.e., impact velocity below and above the ballistic limit, for flat and hemispherical projectiles respectively. An impact velocity of 115m/s, which is below the ballistic limit, was used for 0%, 10% and 23% pretension, while 88m/s impact velocity for 50% pretension. A higher impact velocity of 135m/s, which is above the ballistic limit, was also used for 0%, 10%, 23% and 50% pretension. Surprisingly, in Figure 5.19, a special failure phenomenon was observed at 50% pretension when the target experienced a catastrophic failure due to impact by a flat projectile. A crack line was observed near the impact area which may contribute to catastrophic failure or splitting of the target. Similar splitting phenomena can be observed during the experimental work done in Chapter 4.6.1. As the impact velocity increased, a clean shear failure was seen in the target. With 50% initial stress in the target, the stress may have easily reached the material’s ultimate strength after the target is impacted and this might have contributed to the reduction in the ballistic limit.

Figure 5.20 shows partial perforation or ‘dent’ images on 0%, 10% and 23% pretension target while for 50% pretension, small penetration was imposed on the target. The targets were hit by the hemispherical projectile at 120m/s which is below the target ballistic limit. The images of the target when impacted by the hemispherical projectile at the velocity of 145m/s which is above the ballistic limit were also shown. Petalling formation was seen
due to perforation by hemispherical projectile. Overall, as the pretension increased, the stress became closer to the ultimate strength of the sample. When the projectiles impacted the target, the impact energy will reduce the residual stress and target strength and this contributed to the reduction in the ballistic limit.

<table>
<thead>
<tr>
<th>Pretension</th>
<th>Below Ballistic Limit</th>
<th>Above Ballistic Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>10%</td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td>23%</td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
<tr>
<td>50%</td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
</tr>
</tbody>
</table>

Figure 5.19: Various pretension aluminium alloy 2014-T6 targets impacted by flat projectile.
### 5.8 Impact Force and Deflection

Four typical impact force history curves obtained from FE for high velocity impacts are plotted in Figure 5.21. The results of this investigation had shown a force-time prediction for a flat projectile impacting on a pretension aluminium alloy 2014-T6 plate. The basic pattern of the curves shows the peak load occurring early during the perforation impact event.

A comparison on all impact events had shown that the highest force was at 0% pretension. The force curves for 0%, 10% and 23% pretension showed similar force values.
As pretension in the target was further increased, the graph shows a reduction in force peak value, with the greatest reduction experienced at 50% pretension, while the contact time changed from a maximum of 65μs to a lower duration of 45μs, a reduction of approximately 30%. Taking the force-time graph at 50% pretension in Figure 5.21 and relating it with Figure 5.22; at point I, the projectile starts to impact the target whereby an amount of kinetic energy from the projectile is transferred to the target. At point II the target experienced failure when its strain exceeded strain failure. At point III, impact energy from projectile was transferred to the target. Near point IV, a plug was observed from the perforation. Due to shearing, the taper shaped plug at the back plate creates resistance which forms rebounding on the target. A small rebounding creates enough force to jump at a small amount. A similar rebounding behaviour was also presented by Naik et al., (2005) based on the impact phenomena on glass reinforced plastic (GRP). As the projectile perforated through the target i.e., the velocity was beyond the ballistic limit then the force returned to zero.

![Figure 5.21: Graph force vs time by flat projectile impacted on various pretension aluminium alloy 2014-T6 targets at 117 m/s.](image)
The influence of pretension on the impact force of a hemispherical projectile striking an aluminium alloy 2014-T6 target is summarized in Figure 5.23. Points I to IV are marked on the graph in Figure 5.23 with sequence images shown in Figure 5.24. Similar to the results for the flat projectile, the highest peak force occurred for a target with 0% pretension, followed by 10%, 23% and 50%. However, in its early impact stage, the target experienced a step-change in load before reaching its peak value. This is different from that seen in the impact by the flat projectile (see Figure 5.21). The hemispherical shape of the projectile with
its tip resulted in a significant reduction in perforation energy. At point II, hemispherical tip form crushing but later results in reduction due to material tension. The material tension at point III can be seen to spread sideways which is shown in the high stresses images in Figure 5.24. At point IV, further penetration of projectile cross-section with crushing, results in the highest impact load. Point V shows an existence of tearing zone around the hemispherical projectile circumference which results in the small plug shown in point VI. Hemispherical projectiles require more time to perforate the target, which is longer compared with flat projectiles. It was also seen that the contact time was also increased, from 55μs using the flat projectile (Figure 5.21) to 75μs for the hemispherical (Figure 5.23) one; an increase of approximately 36%.

![Diagram of force versus time for hemispherical projectile impact](image)

**Figure 5.23:** Graph of force versus time by hemispherical projectile impacted on various pretension aluminium alloy 2014-T6 targets at 145 m/s.
Figure 5.24: Sequence images of hemispherical projectile on target. (I) Initial impact (II) Normal pressure and crushing from nose tip (III) Stress spread sideways from tension (IV) Normal pressure at larger nose surface area (V) Tearing zone (V) Perforate through performed plug with residual velocity.
Figure 5.25 shows the velocity versus displacement curves for a flat projectile impacting aluminium alloy 2014-T6 target with pretension. As the pretension was increased, the residual velocity was seen to reduce whereby the projectile displacement became smaller to perforate the target.

![Velocity vs displacement of flat projectile impacted on various pretension aluminium alloy 2014-T6 targets.](image)

Figure 5.26 shows the velocity versus displacement curves for a hemispherical projectile impacting aluminium alloy 2014-T6 target with pretension. Although each curve has similar shapes, there are still small differences. As pretension was increased, the velocity reduced and a smaller projectile displacement was needed to perforate the target.
Figure 5.26: Velocity vs displacement of hemispherical projectile impacted on various pretension aluminium alloy 2014-T6 targets.

5.9 Conclusions
Extensive finite element simulations were conducted to simulate the impact behaviour of an aluminium alloy 2014-T6 target struck by two different projectiles i.e., flat and hemispherical shaped nose. The amplitude technique used to present pretension and the available material model in the Abaqus software have shown a very convincing result in running ballistic limits on isotropic materials with the help of mesh sensitivity technique. Petalling and plug shapes have also shown significant results when compared with the experiments. Higher pretension results in ballistic limit reduction which can be seen through force reduction. As the pretension increased, the residual velocity was seen to reduce whereas a smaller projectile displacement was needed to perforate the target.
CHAPTER 6. NUMERICAL SIMULATION OF CARBON FIBRE COMPOSITE UNDER IMPACT

6.1 Introduction

This chapter presents a theory of damage and related simulations, focusing on high velocity impacts on CFRP target panel. Hashin’s failure criteria, commercially available in the Abaqus/Explicit software, was used to predict the ballistic limit using a hemispherical projectile (Abaqus, 2010). The transverse shear stress-dominated shear failure caused by a flat projectile was not considered in the finite element simulation; instead, an attempt was made to predict the ballistic limit by using a formula available in the literature. The ballistic limit and damage characteristics from the simulation will be compared with the experimental results given in Chapter 5.

6.2 Modelling Damage and Failure for Laminated Composites

The damage model has become an important element in the analysis of material damage and failure. The present analysis on CFRP panel employs Hashin’s damage and failure criteria (Hashin and Rotem, 1973; and Hashin, 1980) which is available in the Abaqus/Explicit FE package (Abaqus, 2010). The damage model involves damage initiation and evolution. After the material is fully damaged, the related element can be removed from the finite element model.

6.2.1 Progressive Damage Modelling

Damage initiation in the composite is based on Hashin’s failure criteria, using four different damage mechanisms: fibre tension, fibre compression, matrix tension and matrix compression. The failure criteria are adapted from Abaqus (2010) for damage initiations are expressed as below:

Fibre tension: \( \sigma_{11} \geq 0 \)

\[
F_{T} = \left( \frac{\sigma_{11}}{F_{T}} \right)^2 + \alpha \left( \frac{\tau_{12}}{F_{T}} \right)^2 = 1; \tag{6.1}
\]

cont.
Fibre compression: \((\sigma_{11} < 0)\)
\[
F_{fc} = \left(\frac{\sigma_{11}}{X_{1c}}\right)^2 = 1;
\]

Matrix tension: \((\sigma_{22} \geq 0)\)
\[
F_{mT} = \left(\frac{\sigma_{22}}{X_{2T}}\right)^2 + \left(\frac{\tau_{12}}{S_{12}}\right)^2 = 1;
\]

Matrix compression: \((\sigma_{22} < 0)\)
\[
F_{mc} = \left(\frac{\sigma_{22}}{2S_{13}}\right)^2 + \left[\left(\frac{X_{2c}}{2S_{13}}\right)^2 - 1\right] \left(\frac{\sigma_{22}}{X_{2c}}\right)^2 + \left(\frac{\tau_{12}}{S_{12}}\right)^2 = 1;
\]

where \(\sigma_{11}, \sigma_{22}, \tau_{12}\) are the longitudinal, transverse and shear stress in the lamina, while \(X_{1T}\) and \(X_{1c}\) denote tensile and compression strength in the fibre direction, \(X_{2T}\) and \(X_{2c}\) denote tensile and compression strength in the transverse direction, and \(S_{12}\) and \(S_{13}\) denote the longitudinal and transverse shear strength. The coefficient \(\alpha = 0\) is used as the contributor of shear stress to the fibre tensile damage initiation in the present work.

### 6.2.2 Damage Evolution

Based on the brittle behaviour of the CFRP material, the material is linearly elastic before damage initiation. Damage evolution will occur in post-damage initiation, which occurs just after damage initiation (Abaqus, 2010). The general form of constitutive laws for orthotropic elastic materials is computed as:

\[
\sigma = C_d \varepsilon
\]  

(6.2)

where \(C_d\) is the elasticity matrix given as:

\[
C_d = \frac{1}{D} \begin{bmatrix}
(1 - d_f)E_{11} & (1 - d_f)(1 - d_m)v_{12}E_{11} & 0 \\
(1 - d_f)(1 - d_m)v_{12}E_{22} & (1 - d_m)E_{22} & 0 \\
0 & 0 & (1 - d_s)G_{12}\end{bmatrix}
\]  

(6.3)

where \(D = 1 - (1 - d_f)(1 - d_m)v_{12}v_{21}\) and \(d_f, d_m, d_s\) reflects the current state of fibre damage, matrix damage and shear damage, respectively. \(E_{11}\) and \(E_{22}\) are the Young’s
modulus in the fibre and transverse directions respectively, while $G_{12}$ is the shear modulus and $v_{12}$ and $v_{21}$ are the Poisson’s ratios of the laminate.

The damage variables, $d_f$, $d_m$ and $d_s$, used in Equation (6.3), are derived from the damage variables $d_f^t$, $d_f^c$, $d_m^t$ and $d_f^c$, which are related to the four failure modes (fibre tensile, fibre compression, matrix tensile, matrix compression) (Abaqus, 2010) as follows:

$$d_f = \begin{cases} d_f^t & \text{if } \sigma_{11} \geq 0 \\ d_f^c & \text{if } \sigma_{11} < 0 \end{cases}$$

$$d_m = \begin{cases} d_m^t & \text{if } \sigma_{22} \geq 0 \\ d_m^c & \text{if } \sigma_{22} < 0 \end{cases}$$

$$d_s = 1 - (1 - d_f^t)(1 - d_f^c)(1 - d_m^t)(1 - d_m^c)$$

The damage variables are determined by considering a bilinear equivalent stress-displacement relationship shown in Figure 6.1, from the line with a negative slope after damage initiation has occurred.

![Figure 6.1: Damage initiation and damage variable behaviour (Abaqus, 2010).](image)

Element usage in simulation becomes an important factor, due to the fact that most results depend on element shape, size and dimensions. The constitutive law in Abaqus is expressed in terms of stress-displacement relations.
Chapter 6: Numerical Simulation of CFRP under Impact

The equivalent displacements and stresses for the four damage modes are defined as follows (Abaqus, 2010):

Fibre tension: \( (\sigma_{11} \geq 0) \)
\[
\delta^{FT}_{eq} = L^c \sqrt{(\varepsilon_{11})^2 + \alpha \varepsilon_{12}^2}
\]
\[
\sigma^{FT}_{eq} = \frac{\langle \sigma_{11} \rangle (\varepsilon_{11}) + \alpha \tau_{12} \varepsilon_{12}}{\delta^{FT}_{eq} / L^c}
\]

Fibre compression: \( (\sigma_{11} < 0) \)
\[
\delta^{FC}_{eq} = L^c (\varepsilon_{11})
\]
\[
\sigma^{FC}_{eq} = \frac{\langle -\sigma_{11} \rangle (\varepsilon_{11})}{\delta^{FC}_{eq} / L^c}
\]

Matrix tension: \( (\sigma_{22} \geq 0) \)
\[
\delta^{MT}_{eq} = L^c \sqrt{(\varepsilon_{22})^2 + \varepsilon_{12}^2}
\]
\[
\sigma^{MT}_{eq} = \frac{\langle \sigma_{22} \rangle (\varepsilon_{22}) + \tau_{12} \varepsilon_{12}}{\delta^{MT}_{eq} / L^c}
\]

Matrix compression: \( (\sigma_{22} < 0) \)
\[
\delta^{MC}_{eq} = L^c \sqrt{(-\varepsilon_{22})^2 + \varepsilon_{12}^2}
\]
\[
\sigma^{MC}_{eq} = \frac{\langle -\sigma_{22} \rangle (\varepsilon_{22}) + \tau_{12} \varepsilon_{12}}{\delta^{MC}_{eq} / L^c}
\]

where \( L^c \) is a characteristic length which is based on the element geometry. In the present analysis, a shell element is employed to model the composite laminate, \( L^c \) is calculated to be the square root of the surface area of the shell element. The Macaulay bracket operator \( \langle \ldots \rangle \) is defined as \( \langle \alpha \rangle = (\alpha + |\alpha|)/2 \). After damage initiation (i.e. \( \delta_{eq} \geq \delta_{eq}^0 \)) shown in Figure 6.1, the damage variable for a particular mode is given by the following expression(Abaqus, 2010).
where $\delta^0_{eq}$ is the equivalent displacement at which the initiation criterion for the mode is met, and $\delta^f_{eq}$ is the displacement at which the material is completely damaged in this failure mode. The value $\delta^0_{eq}$ for the various failure modes depends on the elastic stiffness, and the strength parameters specified. In Abaqus, it is necessary to assign each failure mode to the energy dissipated due to failure, $G^e$, which is equal to the area of the triangle OAC in Figure 6.2. Therefore, the values of $\delta^f_{eq}$ for the various modes depend on the respective $G^e$ values. Considering a partially damaged point as point B in Figure 6.2, by unloading the plot of equivalent stress vs. equivalent displacement will retract along a linear path towards the origin, O.

![Linear damage evolution](image)

Figure 6.2: Linear damage evolution. (Abaqus, 2010).
6.3 Finite Element Modelling using Continuum Shell Element

In Abaqus/Explicit, the element which is only able to use Hashin’s damage model is the continuum shell element. The target was modelled with a deformable shell element (SC8R), using the ‘reduce’ integration method, while the projectile was modelled as an analytical rigid body using a bilinear quadrilateral four nodes element (R3D4). Similar to the aluminium alloy model in Chapter 5, the target experienced two conditions of non-pretension and pretension with the projectile impacts the target at high velocity in the middle of the target.

6.3.1 Finite Element Model

Abaqus/Explicit was used to simulate the impact scenario shown in Figure 6.3 which also presents the mesh pattern used in the study. The size of the rectangular CFRP target is 100x45x3mm. An adaptive mesh was applied to the models when the impact area, which is located in the central area as shown in Figure 6.3, consists of the most refined mesh. Moving further from the centre of the impact area, the elements become less dense. The purpose is to reduce the computational time for the simulations. A fix of 12 elements through the plate thickness was used for the entire model. Since the critical area is considered to be only in the middle of the plate, element behaviour outside the impact area was not critically analysed.

Figure 6.3: Finite element model with 12 elements through thickness.
6.3.2 Material Properties of Carbon Fibre Reinforced Plastic

The composite plate is made of 24 layers or unidirectional carbon fibres in an epoxy resin of a \([0,90]_1\) layup. The mechanical properties as an input into the finite element simulations are taken from the experimental tests in Table 3.4 and previous studies using similar CFRP material (Simulia, 2009). The mechanical properties are summarized in Table 6.1. Failure energies for fibre tension and compression were taken as 12.5kJ/m\(^2\) while failure energies for matrix tension and compression were taken to be 1 kJ/m\(^2\) (Lapczyk and Hurtado, 2007).

<table>
<thead>
<tr>
<th>Description</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus in fibre direction 1 (GPa)</td>
<td>(E_{11})</td>
<td>145</td>
</tr>
<tr>
<td>Young’s modulus in fibre direction 2 (GPa)</td>
<td>(E_{22})</td>
<td>11</td>
</tr>
<tr>
<td>Young’s modulus in fibre direction 3 (GPa)</td>
<td>(E_{33})</td>
<td>11</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>(\nu_{12})</td>
<td>0.3</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>(\nu_{13})</td>
<td>0.3</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>(\nu_{23})</td>
<td>0.45</td>
</tr>
<tr>
<td>Shear modulus, 1-2 plane (GPa)</td>
<td>(G_{12})</td>
<td>4.5</td>
</tr>
<tr>
<td>Shear modulus, 1-3 plane (GPa)</td>
<td>(G_{13})</td>
<td>4.5</td>
</tr>
<tr>
<td>Shear modulus, 2-3 plane (GPa)</td>
<td>(G_{23})</td>
<td>2.5</td>
</tr>
<tr>
<td>Tensile failure stress in fibre direction 1 (MPa)</td>
<td>(X_{1T})</td>
<td>1620</td>
</tr>
<tr>
<td>Compression failure stress in fibre direction 1 (MPa)</td>
<td>(X_{1C})</td>
<td>1200</td>
</tr>
<tr>
<td>Tensile failure stress in transverse matrix direction 2 (MPa)</td>
<td>(X_{2T})</td>
<td>55</td>
</tr>
<tr>
<td>Compression failure stress in transverse matrix direction 2 (MPa)</td>
<td>(X_{2C})</td>
<td>250</td>
</tr>
<tr>
<td>Tensile failure stress in transverse matrix direction 3 (MPa)</td>
<td>(X_{3T})</td>
<td>55</td>
</tr>
<tr>
<td>Compression failure stress in transverse matrix direction 3 (MPa)</td>
<td>(X_{3C})</td>
<td>250</td>
</tr>
<tr>
<td>Shear strength, 1-2 plane (MPa)</td>
<td>(S_{12})</td>
<td>120</td>
</tr>
<tr>
<td>Shear strength, 1-3 plane (MPa)</td>
<td>(S_{13})</td>
<td>137</td>
</tr>
<tr>
<td>Shear strength, 2-3 plane (MPa)</td>
<td>(S_{23})</td>
<td>90</td>
</tr>
</tbody>
</table>
6.3.3 Boundary Conditions and Pretension Technique

Two different boundary conditions were used to model non-pretension and pretension in the Abaqus/Explicit. The methods that were used involved applying the required boundary conditions to both parallel sides of the plate, but keeping the other two sides free, as shown in Chapter 5.3.3. The ultimate strength for CFRP was taken as 705MPa; hence the pretension values calculated for 10%, 30% and 50% of the ultimate strength were 70.5MPa, 211.5MPa and 352.5MPa, respectively. The projectile nose tip was assigned with a reference point (RP) and a boundary condition was applied such that only translation movement in the z-direction is allowed and there is no rotation during impact.

6.3.4 Interaction in Modelling

The algorithm used for contact and interaction in this chapter was the contact pair algorithm. To model this interaction, surface interaction was selected between the CFRP plate and the projectile. In Abaqus, the surface of the projectile was selected as the master surface, while the surface made of nodes of the CFRP plate was selected as a slave surface. Interaction properties for Abaqus/Explicit were determined by two criteria - tangential behaviour and normal behaviour. The tangential behaviour used a friction coefficient of 0.3 which were used in other studies (Rebouillat, 1996; Chan et al., 2007; Feng and Aymerich, 2014), and a ‘penalty’ contact was defined using friction formulation. In normal behaviour, the hard contact was chosen under pressure-overclosure, with the help of separation of element after contact.

6.4 Mesh Sensitivity Analysis

A mesh sensitivity study was performed on a 3mm thick CFRP panel. The plate was modelled by 12 continuum shell elements in the plate thickness, which represents 24 layers of lamina in the structure. Due to limitations of the material damage model in predicting tensile failure (see Chapter 6.3), the analysis only focussed on a hemispherical-shaped projectile.

The mesh studies involved dimension variables and aspect ratios of the elements in the impacted area. The element has the same size in length and width and this size was varied, while the thickness of each element remains at 0.25mm. Six element sizes are shown in Table 6.2. The elements constructed by these unique 6-meshes were in a cuboid shape,
which differ from the isotropic cubic elements employed for the aluminium alloy panel in Chapter 5.

To analyse the sensitivity of the mesh, the impact of a projectile with a mass of 3g on the CFRP panel was simulated. Table 6.2 lists the predicted residual velocities obtained from using various mesh sizes when the initial impact velocity was taken at 135m/s. Pretensions of 0%, 10%, 30% and 50% were applied to the CFRP plate.

Figure 6.4(a-d) shows the effect of mesh size on the predicted residual velocity of the projectile after impacting the panel under various pretension levels. The results from an impact velocity of 200m/s were also included. The reason for having two impact velocities for the mesh sensitivity study is due to the unclear convergence behaviour at a specific velocity. It can be seen that, as the element gets smaller, the residual velocity tends to become constant. Due to this convergence, the element size 1x1x0.25mm was selected for further analysis.

Table 6.2: Mesh sensitivity result for CFRP impacted by hemispherical projectile.

<table>
<thead>
<tr>
<th>Element Size(mm$^3$)</th>
<th>0% Pretension ($v_i=135m/s$)</th>
<th>10% Pretension ($v_i=135m/s$)</th>
<th>30% Pretension ($v_i=135m/s$)</th>
<th>50% Pretension ($v_i=135m/s$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$v_r$ (m/s)</td>
<td>$v_r$ (m/s)</td>
<td>$v_r$ (m/s)</td>
<td>$v_r$ (m/s)</td>
</tr>
<tr>
<td>0.55x0.55x0.25</td>
<td>80</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0.625x0.625x0.25</td>
<td>85</td>
<td>100</td>
<td>92</td>
<td>115</td>
</tr>
<tr>
<td>0.714x0.714x0.25</td>
<td>85</td>
<td>100</td>
<td>92</td>
<td>115</td>
</tr>
<tr>
<td>1x1x0.25</td>
<td>82</td>
<td>105</td>
<td>100</td>
<td>115</td>
</tr>
<tr>
<td>1.67x1.67x0.25</td>
<td>91</td>
<td>105</td>
<td>107</td>
<td>118</td>
</tr>
<tr>
<td>2.5x2.5x0.25</td>
<td>107</td>
<td>-</td>
<td>100</td>
<td>-</td>
</tr>
</tbody>
</table>

Remark: (-) sign indicates no value taken.
Figure 6.4: Mesh sensitivity of (a) 0% pretension (b) 10% pretension (c) 30% pretension and (d) 50% pretension.

6.4.1 Mesh Sensitivity Study Impact of Flat Projectile

Mesh sensitivity studies was also run using flat nosed projectile on the target plate. Unfortunately, the results are not convincing due to unstable residual velocity values as shown in Figure 6.5. A fluctuation graph instead of convergence (as in Figure 6.4) shows that the element is not prone to flat shaped projectile damage of shear but preferably by tensile failure using hemispherical shaped nose projectile. As mentioned by Fan et al., (2011c), convergence during mesh sensitivity job is needed to provide good prediction for simulation. Due to this limitation, the prediction for ballistic limit using flat nosed projectile used the analytical method which will explained further in Chapter 6.9.
6.5 Ballistic Limit Prediction of Hemispherical Projectile using FE Simulation

From the mesh sensitivity results in Table 6.3, an element size of 1x1x0.25mm was chosen to model the CFRP plate and to run the impact simulation in order to determine the relevant ballistic limit. Four different pretensions, 0%, 10%, 30% and 50% of the overall material strength were applied to the panel which is then impacted by a hemispherical projectile. Simulations were performed at a series of impact velocities and the residual velocities were determined. The results are shown in Table 6.3.

Table 6.3: Simulation results for CFRP target under hemispherical projectile impact.

<table>
<thead>
<tr>
<th>Pretension (%)</th>
<th>Impact Velocity, $v_i$ (m/s)</th>
<th>Residual Velocity, $v_r$ (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>200</td>
<td>135</td>
</tr>
<tr>
<td>0</td>
<td>170</td>
<td>82</td>
</tr>
<tr>
<td>10</td>
<td>172</td>
<td>100</td>
</tr>
<tr>
<td>30</td>
<td>173</td>
<td>100</td>
</tr>
<tr>
<td>50</td>
<td>183</td>
<td>115</td>
</tr>
</tbody>
</table>
The results of the impact velocity simulation in Table 6.3 are plotted in Figure 6.6, showing the comparisons between results at 0%, 10%, 30% and 50% pretensions. The residual velocity increases parabolically near to the ballistic limit, and then linearly increases with the increase of impact velocity. The ballistic limits were estimated from the simulation results where the projectile failed to perforate the sample. Ballistic limit reductions for non-pretension to 10% pretension, 10% to 30% pretension, and 30% to 50% pretension were found to be 5%, 5.2% and 33% respectively; and the total reduction in the ballistic limit between a target with no pretension (0%) and 50% pretension is approximately 40%.

Figure 6.6: Parametric finite element simulation of CFRP impacted by hemispherical projectile.
6.6 Ballistic Limit Finite Element against Experimental Result

Figure 6.7 shows the predicted residual velocity of a hemispherical projectile impacting on plates under the influence of 0% and 30% pretension, in comparison with experimental results. The comparison shows a fairly good agreement between simulation and experiments, where both lines are seen to align to each other. For a target without pretension (0%), there is a difference of only 6.7% between the simulated and experimental ballistic limit, under impact from a hemispherical projectile. Similarly, in targets with 30% pretension, a small difference of 4% in the simulated ballistic limit was found in comparison with the experimental results. From the graphs, it is clear that the existence of pretension does contribute to a reduction in ballistic limit for a CFRP target. Due to limitations of the material model, this analysis only presents ballistic results for a hemispherical projectile.

![Figure 6.7: Experimental and simulation of residual velocity versus impact velocity for CFRP target impacted by hemispherical projectiles.](image-url)
6.6.1 Failure Modes of CFRP Target after Impact

Figure 6.8 shows the sequence of damage events in a 3mm-thick CFRP target impacted by a hemispherical shaped projectile at a velocity of 110m/s; a velocity just above the ballistic limit. This study showed the effect of pretension on failure modes in the target. It was observed that due to the hemispherical nosed geometry, the projectile caused a tensile failure scenario when the material is pushed sideways during perforation and caused thinning in the contact area. The increase of pretension helped the projectile to perforate more easily, which contributed to a reduction in the ballistic limit velocity. This can be seen at 100μs, where the projectile moved further as the pretension increased, which shows that it perforates more easily during penetration. Impact using a hemispherical projectile also contributed to the formation of petalling near to the impact target area.
<table>
<thead>
<tr>
<th>Pretension</th>
<th>25µs</th>
<th>50µs</th>
<th>100µs</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
<tr>
<td>10%</td>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
<tr>
<td>30%</td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
<td><img src="image9.png" alt="Image" /></td>
</tr>
<tr>
<td>50%</td>
<td><img src="image10.png" alt="Image" /></td>
<td><img src="image11.png" alt="Image" /></td>
<td><img src="image12.png" alt="Image" /></td>
</tr>
</tbody>
</table>

Figure 6.8: Failure sequence of hemispherical projectile impacted on various pretention CFRP target.
6.7 Damage Assessment from Simulation and Experiment

The images provide both front and rear target views of damage under various conditions of pretensions. It is interesting to note that the FE result shows important damage phenomena with ‘logarithmic strain’ images which are similar to the experimental results. With the target under pretension, there are more obvious strain variations that can be seen in the FE target simulation.

Figure 6.9 presents the damage of the non-pretension CFRP target at below and higher than ballistic limit. Experimental observation of front view image a corresponds to FE simulation image b. Due to impact velocities below the ballistic limit, an indentation occurs which shows similarities in comparison with the experimental result in image a. Strain images were seen concentrated at the impact and damage area. Images c and d show the rear view of targets a and b with vertical high strain formation pattern which shifted towards a crack pattern in the experiment target. When impact velocity is above the ballistic limit, as expected, the front view images e and f show perforation. Fibres were broken due to the tensile failure caused by the hemispherical projectile. However, image g shows broken fibres on the back, close to the perforation hole after the hemispherical projectile went through. Fibres are not shown in the simulation image f due to the technique elements deletion that was used by the FE software. Images g and h present a rear image of the target plates e and f. The fibre damage in g shows petalling from the impact, while image h simulates the vertical high strain formation, which is similar to the fibre damage pattern in g.

Figure 6.10 compares the damage by the hemispherical projectile when pretension in the plate was increased to 30%. The images show similar damage behaviour in the plates from the front and rear views of experimental and FE simulation. Comparison between images k and l shows a similarity in fibre cracking with high strain formation in the FE simulation. An experiment panel in images m and o did not fail catastrophically upon impact. From observation of the high speed camera during the experiment, the panel will first experience cracking together with few vibrations (bouncing forward and backward) before catastrophic failure occurs. However, in the FE simulation, higher strain formation can be seen from the rear view, in images n and p, which might have contributed to fibre cracking and catastrophic failure.
<table>
<thead>
<tr>
<th>Partial (0% Pretension)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Front View</strong></td>
</tr>
<tr>
<td><img src="image1.png" alt="Image" /></td>
</tr>
<tr>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td><strong>Rear View</strong></td>
</tr>
<tr>
<td><img src="image3.png" alt="Image" /></td>
</tr>
<tr>
<td><img src="image4.png" alt="Image" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Limit/Complete (0% Pretension)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Front View</strong></td>
</tr>
<tr>
<td><img src="image5.png" alt="Image" /></td>
</tr>
<tr>
<td><img src="image6.png" alt="Image" /></td>
</tr>
<tr>
<td><strong>Rear View</strong></td>
</tr>
<tr>
<td><img src="image7.png" alt="Image" /></td>
</tr>
<tr>
<td><img src="image8.png" alt="Image" /></td>
</tr>
</tbody>
</table>

Figure 6.9: Hemispherical projectile impact on 0% pretension CFRP targets.
Chapter 6: Numerical Simulation of CFRP under Impact

<table>
<thead>
<tr>
<th>Partial (0% Pretension)</th>
<th>Limit/Complete (30% Pretension)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Front View</strong></td>
<td><strong>Front View</strong></td>
</tr>
<tr>
<td><img src="image1" alt="Image" /></td>
<td><img src="image2" alt="Image" /></td>
</tr>
<tr>
<td><img src="image3" alt="Image" /></td>
<td><img src="image4" alt="Image" /></td>
</tr>
<tr>
<td><strong>Rear View</strong></td>
<td><strong>Rear View</strong></td>
</tr>
<tr>
<td><img src="image5" alt="Image" /></td>
<td><img src="image6" alt="Image" /></td>
</tr>
<tr>
<td><img src="image7" alt="Image" /></td>
<td><img src="image8" alt="Image" /></td>
</tr>
</tbody>
</table>

Figure 6.10: Hemispherical projectile impact on 30% pretension CFRP targets.
6.7.1 Damage Target Volume

An observation was done on the FE target to measure the number of elements eliminated after the impact. The key was to determine the amount of damage around the impact area. Figure 6.11 shows the target plate impact damage area by the hemispherical projectile. The damage pattern was found to be smaller at the front face and larger towards the rear. After perforation occurred at the surrounding projectile exit area, a number of elements were found undeleted (Figure 6.11b) which similar to petal in experimental Figure 6.9g. Table 6.4 shows the target volume under various pretensions. It is shown that with pretension, more areas are deleted and this could be the reason for ballistic limit reduction as pretension increased. The observation also found that catastrophic failure occurred more easily with pretension as more target space is deleted.

![Figure 6.11: Element deletion due to perforation by hemispherical projectile.](image)

<table>
<thead>
<tr>
<th>Pretension Level</th>
<th>Before Impact (mm³)</th>
<th>After Impact (mm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Partial 0% pretension</td>
<td>13500</td>
<td>13437</td>
</tr>
<tr>
<td>Complete 0% pretension</td>
<td>13500</td>
<td>13406</td>
</tr>
<tr>
<td>Partial 30% pretension</td>
<td>13500</td>
<td>13394</td>
</tr>
<tr>
<td>Complete 30% pretension</td>
<td>13500</td>
<td>13402</td>
</tr>
</tbody>
</table>
6.8 Impact Force

Four predicted impact force-time curves for hemispherical projectiles impacting on plates with various pretensions were plotted in Figure 6.12. The impact velocity for all four cases is taken at 135m/s. At 0% pretension, the force achieved the highest value compared to other pretension values. As pretension in the target is increased, the graph shows a reduction in the peak load. The highest reduction was experienced from 50% target pretension - the force reduction from 0% to 50% pretension was found to be approximately 25%. The graph indicates that pretension in the target reduced the time taken for the projectile to perforate. In the early impact stages, the graph shows an early step in load before reaching its peak. The phenomenon is stated as Region 1 in Figure 6.12. Similar phenomena were noted by Sun et al., (2009), who concluded that this is due to the target bounce caused by the impact from the projectile. As the pretension increases, the fibre becomes more stretched and this reduces its bounce.

Figure 6.12: Graph force versus time on various pretension CFRP targets.
The various pretensions applied to the CFRP target gave the characteristic shape to the velocity profile, as shown in Figure 6.13. An increase in projectile movement was seen for the projectile to perforate as the pretension of the target is increased. Although each curve has a very similar pattern, there is still a small difference. As pretension was increased from 0% to 10%, the velocity shows a reduction (higher resistance). However, as the pretension is increased to 30% and 50%, the target’s resistance shows a reduction which allows for easier perforation. Pretension makes the fibre more stretched and increases its resistance to the projectile. However, pretension also increases the stress in the fibre and makes its failure easier, thus this reduces the resistance of the plate to the projectile. It is believed that fibre stretch is dominant when pretension is low and high pretension in the plate contributes more to the fibre failure.

Figure 6.13: Velocity vs. displacement of hemispherical projectile impacted on various pretension CFRP targets
6.9 Analytical Ballistic Limit Prediction for Impact by Flat Nosed Projectile

Hashin’s damage model in Abaqus package can only deal with in-plane failure of composites. The element used in the model is the shell element and was not able to run using 3D solid element eg. C3D8R. The model creates tensile failure which is unable to form shear failure from flat nosed projectile impact. A mesh sensitivity study on the impact using flat projectile for the material model was determined as shown in Chapter 6.4.1, which produced an awkward results of convergence. Impact by flat nosed projectile produces high transverse shear stress in the composites plate and this stress causes the plate failure. An analytical model by Wen (2000) is adapted to predict the ballistic limit due to the failure to produce convincing results from impact on CFRP panel. The analytical model was derived from energy balance relationships. It assumes the events during penetration and a localised deformation. The ballistic limit is given by the following equation (Wen, 2000);

\[ v_b = \frac{\pi \sqrt{\rho_t \sigma_e \varnothing^2 t}}{2m} \left[ 1 + \frac{2m}{\pi \rho_t \varnothing^2 t} \right] \]  \hspace{1cm} (6.7)

where \( v_b, \rho_t, \sigma_e, t, \varnothing \) and \( m \) are the ballistic limit velocity, laminate density, elastic limit in through thickness compression, laminate thickness, projectile diameter and projectile mass, respectively.

For the composite plates in the present study, the following parameters were used:

\[ \rho_t = 1600 kg/m^3, \quad \sigma_e = 211 MPa, \quad t = 3 mm, \quad \varnothing = 5 mm \quad and \quad m = 3g. \]

Elastic limit value in through thickness compression, \( \sigma_e \) (Wen, 2000; Kim et al., 2010) was used without pretension effects. But with pretension, physical change of the structure by the mean of Poisson ratio and the material strength reached its limit. Due to the pretension \( \sigma_t \), the value of the linear elastic limit of laminates in through thickness compression, \( \sigma_e \) in Equation (6.7) will be reduced with each pretension increment. The value of \( \sigma_e \) is defined as:

\[ \sigma_e = \sigma_{eo} - \sigma_t \]  \hspace{1cm} (6.8)
where $\sigma_{eq}$ is an initial linear elastic limit of laminates in through thickness compression. The linear elastic limit of laminates in through thickness compression $\sigma_e$ at 0%, 10%, 30% and 50% pretension were calculated as 211MPa, 190MPa, 147.7MPa and 105.5MPa respectively. Using Equation (6.7), the ballistic limit was predicted and shown in Table 6.5 and plotted in Figure 6.14. It is evident from Figure 6.14 that the predicted ballistic limits are in good agreement with the experimental data. At 0% pretension there is a difference of only 9.4% between the prediction and the experiment, while at 30% target pretension the difference is only 1%. Relatively, the elastic limit in through thickness compression $\sigma_e$ in Equation (6.7) does have influence on the ballistic limit results. Elastic limit through thickness compression $\sigma_e$ at 0%, 10%, 30% and 50% (compared to reference line in Figure 6.14) results in reduction on ballistic limit of 2.5%, 7.5%, 18.3% and 30.8%.

Table 6.5: Ballistic limit prediction versus experimental result of flat projectile.

<table>
<thead>
<tr>
<th>Pretension</th>
<th>0%</th>
<th>10%</th>
<th>30%</th>
<th>50%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equation (Wen, 2000) (m/s)</td>
<td>117</td>
<td>111</td>
<td>98</td>
<td>83</td>
</tr>
<tr>
<td>Experimental (m/s)</td>
<td>106</td>
<td>-</td>
<td>97</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 6.14: Predicted and experimental ballistic limit for flat projectile.
6.10 Conclusions

In this chapter, an Abaqus/Explicit FE was used to simulate the impact behaviour of CFRP target from hemispherical shaped nose projectile. Pretension was applied to the composite plate to investigate its effect on the ballistic limit. It is important to run mesh sensitivity study to get the best and optimum element size for ballistic limit analysis. Unfortunately, the material model was not able to run on flat projectile. The failure criterion results in a fluctuating graph instead of convergence. It was shown that the predicted damage behaviour is almost similar to that observed in the experiments. High strain formations were clearly seen on the target plate. Analytical equation was adopted to run the ballistic limit for flat projectile which shows good agreement after modification of stress values for applied pretension.
CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

7.1 Conclusions

This thesis presented the experimental results related to high velocity impact of aluminium alloy 2014-T6 and carbon-fibre reinforced plastic (CFRP). Numerical model and analytical equations were used to simulate the same problem. The main objective was to understand the behavior of the materials with various pretension effects. Emphasis was placed on the determination of ballistic limits and damage by two different projectile types i.e., flat and hemispherical.

An experimental impact test was done using flat and hemispherical projectiles on aluminium alloy 2014-T6 with the effects of pretension. A special rig was fabricated to be used along with the gas gun for pretension loading purposes. The rig is capable of avoiding any vibrations from the impact, whereby it only allows displacement in the axial direction. Target impacted by the hemispherical projectile have shown large petals number and small plug on its nose while flat projectile results in large plug with very small edge. The geometrical hemispherical projectile shapes perforate by pushing the target sideway which delays the damage process thus affecting the results in the ballistic limit. Pretension reduces the ballistic limit for flat projectiles of 8% difference while increasing the hemispherical projectile ballistic limit of only 3% difference.

The ballistic limit of the CFRP panel with pretension decreases by 12% and 16%, thus showing reduction for flat and hemispherical projectiles respectively. Pretension activates fibre displacement which allows the hemispherical projectile to perforate through the material easily. Crack was observed after each impact, followed by the target moving forward and backward before a catastrophic failure would sometimes occur. Pretension contributes to catastrophic failure, mostly, for the hemispherical projectile target that occurred within the partial perforation as compared to the flat projectile, where the failure occurred in complete perforation with a difference of 10m/s lower.

It has been found that a suitable numerical model to perform high-speed impact analyses on both materials requires an accurate description of the material response and
Chapter 7: Conclusions and Recommendations

definition of the contact between the target and projectile. Parametric studies using FE simulation on aluminium alloy 2014-T6 shows that when pretension is increased to 10%, the ballistic limit gives very small difference, however with further increase in pretension, the ballistic limit reduced dramatically. Petalling and plugging have shown good agreement, while the ballistic limit prediction shows a very close value between the simulation and experimental results.

Hashin’s model in Abaqus/Explicit for the impact on orthotropic material is only suitable for hemispherical shaped projectiles whereas flat projectiles unsuccessfully gives good mesh sensitivity results. The failure only occurred in the tensile direction while the flat projectile fails in shear direction. Good agreements of ballistic limit between FE and experimental results in terms of ballistic limit and material damage for CFRP panels impacted by hemispherical projectile were observed. Another material characteristic found in the study is both materials start to stretch until it reaches a certain limit to fail.

An analytical equation has been adopted and used on the flat projectile target. Elastic limit compression value was modified to suit the pretension target value. With 30% pretension, the results have shown reduction of the ballistic limit value which is similar to the experimental with 1% difference.

7.2 Future Work

The following tasks are recommended for future investigation

- The image capture using high speed camera may be improved by modifying the pretension rig, which currently blocks the best view path of the camera from the side due to the unavailability of space in the laboratory.
- The damage and delamination of the panels may be analysed using C-Scan images to understand the characteristics of the impact damage and compare it with FE predictions.
- Hashin’s failure criterion needs to be extended to 3D elements in Abaqus. The existing model only allows the use of shell and continuum shell element, but not for the use of solid 3D element. This limits the capability of the FE model in Abaqus to the in-plane membrane damage and failure; while the out-of-plane shear failure, which is needed for flat nose projectile impact, cannot be modelled.
• The delamination between composite layers needs the use of a cohesive element, which might improve the numerical simulation of the ballistic behaviour of CFRP panels.
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