Finite Element Analysis of Composites Integral Armour

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ABSTRACT

This thesis is focussed on a numerical method to analyse the ballistic performance of multi-material armour system. The overall objective of this work is to develop numerical models to be used within MSC.DYTRAN capable of accurately predicting the ballistic response of multi-material composite armour, the effect of impact type on the damage and to help improve the armour design.

The research presented in this thesis includes a review of the existing ceramic and composite damage models, combine, modify and optimize them to investigate the type and extent of damage response of the materials used in ballistic protection. The numerical model leads to insight into the parameters governing the penetration and deformation response of laminated composite subjected to ballistic impact. The effect of various model parameters on the predicted ballistic response of the ballistic plate is intensively investigated. It was found that the through thickness properties used in the numerical model have a large effect on the predicted ballistic response.

A detailed study of the effect of mesh density on the numerical solution has shown that the numerical predictions are highly influenced by the element shape and size. The smaller the element the sooner the failure occurs, the less energy is absorbed and the smaller the time step becomes leading to a larger simulation time.

The accuracy of the composite numerical model was evaluated by comparing the numerical prediction to experimental data obtained from ballistic impact trials. Very good agreement has been found between the experimental and numerical results for both observations of damage and deformation. Further, values of measured ballistic limit are in very good agreement with the values gained from the simulations. This correlation forms a verification of our finite element simulations. Fibre breakage is generally acknowledged as the main energy absorption mechanism in damage due to ballistic impact; in this work the delamination and matrix failure have been shown to increasingly contribute to the energy absorption mechanism by reducing the matrix strength.

Further study of multi-layered ceramic composite armour has shown that use of ceramic tiles can improve the ballistic protection of the armour within an optimum ceramic composite ratio.

Finite element simulation has been shown to be a very powerful technique to predict the behaviour of composite and ceramic panels under ballistic impact.
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ABBREVIATIONS

FEA: Finite Element Analysis
FEM: Finite element Method
CIA: Composite Integral Armour
V50: Ballistic Limit Velocity
FSP: Fragment Simulating Projectile
Symbols

Symbol | Description |
--- | --- |
$M_p$ | the projectile Mass |
$a_p$ | the Projectile radius |
$h_1$ | the ceramic plate thickness |
$h_2$ | the backing plate thickness |
$S$ | Ultimate tensile strength of the backing plate |
$\varepsilon_c$ | is the breaking strain of backing plate |
$d_1$ | Ceramic Density |
$d_2$ | Backing plate density. |
$V_{50}$ | Ballistic Limit Velocity |
$E_{xx}, E_{yy}, E_{zz}$ | Normal Material stiffness |
$G_{xy}, G_{yx}, G_{zz}$ | Shear Material stiffness |
$X_{xx}, X_{yy}, X_{zz}$ | Tensile Fibre Failure |
$S_{xy}, S_{yx}, S_{xx}$ | Matrix Strength |
$S_{FC}$ | Fibre Crush Strength |
$S_{FSS}, S_{YS}$ | Fibre Shear Strength |
$P$ | Pressure |
$\sigma_y$ | Yield Stress |
$D$ | Material damage |
$\Delta\sigma_p$ | Plastic Strain increment |
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Chapter 1 Introduction

1 INTRODUCTION

1.1 General

Traditional armoured vehicles have been protected by metal-based armour. As weapon designers were constantly trying to improve the terminal effect of their projectiles the armour become thicker and heavier. That led to the evolution of ground fighting vehicles of 70+ tonnes (Fink 2000). The increase in armour weight reduced the mobility of it users. This led to the conclusion that the traditional armour materials have reached the limit of their usefulness. By the end of the twentieth century the strategy, tactics, and survivability requirement have changed from strong heavy vehicles to smaller ground forces that can be deployed and operate within a wide range of terrain and environmental conditions against an equally wide range of potential threats from over-matched force-on-force, open-terrain armies to urban-terrain guerrilla warfare. Army requirements for the twenty first century point to lightweight highly mobile and transportable-armed vehicles with a large increase in lethality and survivability, for light vehicles and individual soldiers to replace the more traditional heavyweight vehicles. To achieve that the army is looking to reduce the weight of the vehicles by half. Such a significant reduction on the weight will surely result in a reduction of level of static survivability compared to traditional heavy forces. However, the dynamic survivability of lightweight vehicles will be improved with the improvement of mobility speed and agility.

In search of improved armour performance (more strength less weight and less cost) it is safe to assume that the current materials have reached their limit. This encourages the scientist to look for new materials, not new in the sense of never been used before but to combine and use them in new manner.

To reach these goals, advances in lightweight armour are required to close the gap between lightweight and heavy more lethal forces. A concept involves an integration of several materials where the best of each material combined is allowed to contribute to overall structural performance.
The development of multi-layer integral armour began in the 1960s Fink (2000) when it was first realised that ceramic tiles backed by glass reinforced plastic provide good light weight armour system capable of defeating a projectile travelling at a high velocity.

One application of this new technique was demonstrated in the 1980s in the USA (Fink 2000) where polyester/glass composite hull was developed to replace the aluminium hull of the Bradley infantry-fighting vehicle. The resulting vehicle, with a thick section composite hull and appliqué armour tiles, became known as the Composite Infantry fighting vehicle and demonstrated the ability of composite to perform well structurally in an armed vehicle.

1.2 Composite Integral Armour

In the multi-layer structure each layer serves a purpose, yet combined together they provide a role sharing multi-functionality. Figure 1.2 (Gama et al. 2001), shows the components of composite integral armour (CIA).
1.3 Objectives

The objective of this study is to develop a numerical model that can effectively determine the dynamic response of multi-layered ceramic composite or ceramic
metallic armour under ballistic impact by accounting for all the complex material damage effects.

In this study an evaluation of different damage and failure models for different materials will be investigated and the best models will be integrated together to model a more complicated multi-layered armour. Finite element methods is a powerful numerical tool for the prediction of the dynamic deformation and damage behaviour of structure, the numerical model presented in this study was developed within a finite element framework. There are some similarities between drop weight and ballistic impact damage. Both impact types damage consist of fibre failure, matrix crack and delamination; the extent of each of these modes depends on the type of impact. Since these damage modes often interact during the impact event, a continuum damage mechanics approach will be used to predict the evolution of individual damage modes together with their interaction. Details of the assumption on which the damage models are based will be explained. For composite material a distinction between intralaminar damage which includes fibre breakage, matrix cracking, shear punching and crushing and interlaminar damage which consists of delamination will be made. A parametric study will be carried out to investigate the effect of in-plane strength on the ballistic limit and amount of energy absorbed by the plate. Results from this study will be used to improve the ballistic response of the plate.

For ceramic, several constitutive failure models will be revised and reasons for the selection will be given. Two models a) Johnston-Holmquist 1 which is a constitutive damage model built out of two failure surfaces; one for intact and the other for completely damaged model will be compared with b) Mohr-Coulomb Model that uses accumulative damaged based on effective plastic strain to predict damage and failure on ceramic.

To assess the accuracy of the developed damaged models, numerical predictions will be compared to experimental results. Furthermore numerical models will be compared to other models from literature which have been used as base model and modified to assess the improvement in the results.
Chapter 2 Background

2 BACKGROUND

2.1 General

As weapon designers try to improve the lethality of their projectiles, armour is becoming thicker and heavier. In search to improve the armour design ceramic tiles were introduced as their high stiffness and hardness made them suitable for such task. On the other hand the ceramic tiles brittle behaviour and poor tensile strength (when unconfined) cause failure and prevent them from absorbing any significant amount of energy. However, ceramic tiles confinement improves their performance and their ballistic limit is increased (Lee 2005).

In the past few decades Composite materials have increasingly been used in a wide range of engineering application because of their stiffness to weight ratio and their tailorability which make them a prime hit with designers. Composite material has various damage modes that can occurs individually and often interact and lead to failure. Therefore to be able to take a full advantage of their strengths it is vitally important to understand the failure and damage modes to account for it in design.

2.2 Composite

Historically, metallic materials have been dominant in the study of penetration and perforation (Lee & Sun 1993). A large number of publications, references and a comprehensive survey can be found in Zukas (1982) and Zukas (1990). However advances in material design in particular to fibre reinforced composite led to a shift in interest from metallic based materials to composites. In metallic structures the energy is usually absorbed by the large plastic deformation the structure undergo, whereas in composite fragmentation is the mechanism by which composite structure absorb energy during impact event (Belingardi et al. 1998). Damage in composite material due to impact can be fibre failure, matrix cracking, delamination, a combination or all of the above modes depending on the nature of impact. Abrate, (1998) indicated that the kinetic energy of the
projectile is an important parameter to consider but there are other factors to consider when predicting the damage and the response of the structure. The damage caused by the energy of a large mass low velocity impact will not necessarily be the same as the damage caused by the same energy of a small mass large velocity impact. For the high velocity impact Will et al (2002) reported that the overall compliance and the strain absorbing capacity of the laminate was not expected to play a significant role. They quoted that at very high rates of strain the structure respond in a local mode and the strain energy absorbing of the fibres and structure is less important. At lower strain rates the magnitude of the energy dissipated in the mechanism such as delamination and debonding may become important (Cantwell et al. 1991). Abrate (1998) defined low velocity impact as impact that does not result in complete penetration of the plate, he reported, based on experimental observations that the damage mainly consist of delamination, matrix crack and some fibre breakage. Will et al (2002) considered that an impact on Carbon Fibre reinforced Polymer is deemed to be of high velocity type if the impact velocity exceeds 1% of the speed of sound in the laminate thickness direction.

The material response of a composite target to ballistic impact is characterised by the shorter time of applied load (the projectile-target interaction time), when compared with the low velocity impact load time. Ballistic impact studies focus on the extent of the damage concentration (localisation of the damage) against the impact velocity. There is a connection between the material mechanical properties and the ballistic performance (the damage resistance to ballistic impact).

There are a large number of impact studies for targets made of composite materials. For examples Van Hoof (1999), Abrate (1998), Resnyansky (2006) are some of these publications that thoroughly outline the literature related to damage mechanism in composite during impact and the residual strength after impact. The failure modes are frequently analysed using post mortem examination. However, methods of damage assessment due to impact damage vary significantly from one publication to another. Evaluation methods may involve visual inspection, by transmitted light, C-scanning or X-ray photography.

Fujii (2002) reports on delamination of different CFRP samples with different fibre strength, which were analysed with post-mortem examination. His study has shown that impact delamination for laminates with stronger fibres and larger failure strain (the high strength-fibre CFRPs) is larger and deeper then low strength fibre. This occurred because the damage mechanism for the thick low
strength-fibre CFRP samples is plugging failure (in comparison, the damage mechanism for the high-strength-fibre CFRPs is delamination). He also showed that within the range of high velocities (from 500 up to 1230 m/s), fracture occurs in a fluid manner for thin 2 mm-samples. This 'fluid-like' fracture is characterised by stress levels which are much higher than the Hugoniot elastic limit, so strength effects could be neglected when considering the penetration process. For thicker 6 mm-samples, the front layers of the target were damaged in a fluid-like manner as before, but the rear layer was damaged in an extrusive manner with a plugging mechanism and delamination. The delamination width increased with impact energy for thick laminates but remained constant for thin laminates.

Naik (2004) numerically investigated the effect of ballistic impact on plain weave glass/epoxy and twill weave carbon fibre/epoxy. The analysis showed that the glass/epoxy plate provide a better ballistic protection. The analysis showed that the tensile failure of the yarn under the projectile contact area is the main energy absorbing mechanism for this composite. The tensile failure mechanism is high for glass epoxy composite because glass fibre has higher shear strength. For carbon/epoxy composite the yarn deformation in the surrounding contact area along with the shear plugging are found to be the major absorbing mechanism for this composite plate.

Bartus (2005) studied the effect of fibre orientation on the ballistic impact response of the composite plate. He tested randomly orientated fibres and he reported that the cracks propagate into area where fibres are highly coordinated and stop in the area where the fibres are grouped in chaotic orientations.

Damage mechanisms of a composite laminate (Kevlar fabric) have been analysed numerically in Silva (2005) when the composite targets are subject to ballistic impact. The damage character of the laminate plies in the through-thickness direction (from the frontal side down to the distal side of the target) changed from a matrix cracking mechanism at the frontal side to a pure delamination mechanism at the rear side of the target, if the impact velocity was below the ballistic limit velocity. Higher localisation of damage was observed at higher impact velocities, in which case the primary damage mechanism was fibre failure at the projectile/plate contact point. In contrast to the results presented by Silva (2005), when a flexible fabric such as Spectra Shield (polyethylene filaments in epoxy resin), is subjected to impact larger damage area is obtained and more energy is absorbed Tan (2005). The damage and the energy both increased with increasing impact velocity regardless of the projectile shape.
A study of the damage mechanism of unidirectional and quasi-isotropic carbon-fibre composites, which were impacted by spherical steel projectiles (the projectile diameter was 12.7 mm) at an impact velocity of 470-480 m/s, has been undertaken by Hammond (2004), using in-situ high-speed photography. The fine-grid technique was used during photographic observations of the target's rear side and the composite target's thicknesses varied from 2 to 3 mm. The observations revealed that initially (at the moment of the projectile's entrance into the target), the target was damaged just in the vicinity of the projectile diameter. Major damage spread occurred after the projectile exited the target.

This damage was associated with target flexure after the penetration. For quasi-isotropic composite targets, cracking occurred in the outer ply both in the fibre direction and orthogonally to the fibre direction, which resulted in the ply's delamination. From the observations, the remaining material out of the deformation zone (the 2-3 projectile diameter zone) did not appear to be significantly deformed. For unidirectional composite targets, cracking occurred in the fibre direction and quickly spread along the whole sample with deformation across the fibres (orthogonally to the fibre direction).

Van Hoof (1999) Blackman et al (1995) (1996) reported delamination to be the predominant mode of failure in composite. Delamination can be defined as the separation of the layers that makeup the composite structure. Separation occurs in the thin matrix layer that exists between each ply.

The resistance against the initiation and growth of delamination is usually weak as Briscoe and William reported (Van Hoof 1999). Moreover, delamination is found to significantly reduce the strength of the laminate to well below that of predicted by in-plane failure Blackman et al. (1995) and Abrate (1998). Until recently research into composite armour was predominately experimental; it seems that the main concern in armour design is to prevent the plate penetration. Different armour manufacturers have different ballistic measurement methods. Due to the complexity of the composite failure depending in the area of interest (if it is delamination, matrix etc) different tests to evaluate the ballistic phenomena are used, which will inevitably lead to different ballistic results. The most common method used in evaluating the ballistic response of a composite structure is Ballistic limit velocity $V_{50}$. An impact that may result in a complete penetration or perforation of the laminate is often called a Ballistic Impact. For a given projectile and target it is important to know the minimum velocity that will result in a complete penetration; that velocity is usually called the ballistic limit velocity. There are several definitions of ballistic limit used in
the literature as described in Figure 2-1. The ballistic limit velocity is a criterion of the target protective properties. However, this criterion is not completely defined. For example, the US defence department uses at least three ballistic limit criteria: the Army Ballistic Limit (ABL), Navy Ballistic Limit (NBL), and Protection Ballistic Limit (PBL). They differ from each other in the extent of target penetration by a projectile and in the extent of damage to the behind-target witness plate. For the ABL criterion, the projectile's nose should be visible from the back of the target. For the NBL criterion, the projectile's full passage through the target is the key observation (from the viewpoint of the ship's survivability, when the ship's wall is subject to the ballistic impact). The PBL criterion requires that a sheet of aluminium alloy (0.05 to 0.5 mm thickness located 15.24 cm behind the target) should be pierced at the ballistic limit velocity.

Since there are several complex and interactive failure modes involved in the penetration process and since a degree of variability is always present, Frissen et al (Van Hoof 1999) defined $V_{50}$ as the projectile impact velocity for which 50% of the laminate tested samples are completely perforated.

Ballistic impact results in two damage types:

- Damage to the target (armour)
• Damage to the behind-target objects (personnel or equipment) due to the debris resulted in the case of complete penetration which can have a high kinetic energy.

In this section an overview of the behind target damage is reviewed. In the case of perforation the composite plate may absorb some impact energy and affect the residual penetration capability of the projectile.

The most popular definition of ballistic impact is the ballistic limit velocity $V_{50}$ this definition is based on a 50 % probability of penetration of the armour. The method used in obtaining this velocity is by performing 6 shots three penetrable and three non penetrable. The coefficient of variation for all the six shots will need to be within 40 m/s (Bourke 2007). The average of these six shots is called the ballistic limit velocity ($V_{50}$).

The methods to access the penetration efficiency involve the following criteria:

- Perforation or non-perforation of the target.
- The depth of the penetration into the target
- The ballistic limit velocity
- The magnitude of the residual velocity after the projectile perforate the plate.
- The minimum projectile oblique angle at which it was stopped by the target.

In ballistic impact study the residual velocity and the ballistic limit velocity are usually the primary interest. Therefore many theories have been developed linking the ballistic limit velocity to the striking and residual velocity. Hetherington and Rajagopal (1991 and 1992), Tale (1967), Kasano et al (1997), Chocron (1998) and many more developed theories predicting the ballistic limit velocity. The simplest way to estimate the ballistic limit velocity is to use law of conservation of energy assuming a rigid projectile (non-deformable).

\[ KE_r = KE_i - KE_{AB} \]  \hspace{1cm} \text{Equation 2.1}

\[ \frac{1}{2} m v_r^2 = \frac{1}{2} m v_i^2 - \frac{1}{2} m v_{50}^2 \]  \hspace{1cm} \text{Equation 2.2}
Resnyansky (2006) reported some of these theories. In general the equations are usually based on the laws of conservation of energy and momentum:

\[ M_0 v_i = M_0 v_r + m_0 v_r + I \]  
Equation 2.4

\[ \frac{1}{2} M_0 v_i^2 = \frac{1}{2} M_0 v_r^2 + m_0 v_r^2 + E_p \]  
Equation 2.5

Where \( M \) is the mass of the projectile, \( m \) is the mass of the plug pushed from the target by the projectile, \( v \) is the velocity, \( I \) is the momentum transferred to the target and \( E_p \) is the energy lost during perforation. Subscripts \( 0, i \) and \( r \) represent initial and residual velocities.

Depending on the law of conservation used, the relation between the ballistic limit and the residual velocity will be different:

Model 1: By using the law of conservation of momentum the ballistic limit velocity \( V_{50} \) will be:

\[ v_{50} = \sqrt{v_i^2 - av_r^2} \]  
Equation 2.6

Model 2: By using the law of conservation of energy the ballistic limit velocity \( V_{50} \) will be:

\[ v_{50} = \sqrt{v_i^2 - a^2 v_r^2} \]  
Equation 2.7

Where \( a = \frac{M}{(M + m)} \)  
Equation 2.8

Kasano (1997) used CFRP and aluminium to verify the both models. He demonstrated that model 1 best describe the ballistic impact response of the CFRP plate and model 2 best describe the ballistic response of the aluminium plate. Resnyansky (2006) suggested that the reason the first model better describe the CFRP is due to the brittle nature of the CFRP plate which results in a smaller momentum and energy contribution to that of the aluminium plate where the plug is well formed. This means that \( a \) in (equation 2.8) will be close to 1 in the case of CFRP plate. In the case of aluminium \( a \) will be smaller which will have a larger influence in the second model.
The term critical energy ($E_c$) was introduced by Takahashi (1997) where he studied the ballistic response of polyethylene fibre textile. The critical energy (absorbed energy) was estimated using the ballistic limit velocity.

$$E_c = \frac{1}{2}mv_{so}^2$$  \hspace{1cm} \text{Equation 2.9}

This can be estimated from the projectile kinetic energy before and after impact similar to equation 2.1. Resnyansky (2006) reported that the critical energy $E_c$ is maximum at the ballistic limit $V_{so}$.

As the initial velocity of the projectile increases above the ballistic limit, the residual velocity becomes of interest as it will cause threat to the equipment or occupant behind the structure. On the other hand as the ballistic limit velocity is approached complete perforation of the plate may be prevented but the projectile kinetic energy may be sufficient enough to cause a large deformation and reduce the structure strength dramatically. Considering the energy balance reveals important features of ballistic impact including the effect of plate thickness, projectile size, shape and initial velocity.

The cost of putting together a prototype and testing it under conditions similar to that of real life can be expensive both in terms of cost and time. A better way is to use computer simulations. A wide range of design option can be tested and the final design can be chosen even before the first prototype is constructed. Clearly computer simulation can holds the upper hand in engineering design. In the past thirty years numerous physical and numerical models of impact and penetration have been published. However the majority of them study impact on isotropic materials especially metals Zukas (1982) and Zukas (1990). Only in the past decades focuses on composite and ballistic impact has been numerically studied. Out of these only a few focuses on impact on multilayer such as ceramic, composite, rubber and aluminium foam.

This research presents a combination of several models combined together to try to simulate the penetration of different projectiles. The ultimate goal is to use existing laws as baseline modifying and mixing them to build a model capable of prediction how the different material mode interact and to suggest new technique to improve the energy absorption capability of the structure which will ultimately lead to improved ballistic limit and protection.

A better numerical model requires understanding of the mechanisms involved in penetration and failure of the plate. As mentioned above only a small amount of
data is available in the literature for the penetration and failure mechanism of composite under ballistic impact and even less literature deals with the post failure and delamination as it is considered to be a low velocity impact phenomenon. As mentioned earlier delamination is found to be one of the causes of reducing the in-plane laminate strength, so it is of great importance and should be studied if post failure strength is to be addressed.

In the next paragraphs theoretical experimental and numerical approaches are discussed.

2.2.1 Penetration mechanisms

In general punching failure, fibre failure, matrix cracking and delamination are the main failures occurring during a ballistic impact event. Abrate (1998) and Tan (2003) reported that the penetration largely depend on the projectile shape which influence the perforation energy.

Abrate (1998) have reported that the ballistic limit is often proportional to the areal density of the plate. This statement is not entirely accurate as Abrate (1998), Bless et al (1990) and Tan (2003) have shown. As the energy loss during penetration is also strongly affected by the projectile nose shapes, which affect the failure mode and make it significantly different. Yen (2002) have reported that punching failure, fibre failure, matrix cracking and delamination are the main failure that occurs during the ballistic event. Further, more these modes of failure often interact and are dependent on impact condition. In the case of large mass, low velocity delamination seems to be the dominant failure where as in the case of small mass high velocity impact fibre failure is the dominant form of energy absorption.

Zee and Hsieh (1993) designed a set of experiments to determine the effect and contribution of each failure mode on the amount of absorbed energy for different materials. They found that delamination were a major factor for graphite epoxy, but had only a minimum effect on Kevlar and polyethylene fibre (Abrate1998).

Failure modes involved during the penetration of the target can be different at different locations through the target thickness. Will (2002) showed that at high velocity impact the damage tend to be located within a "fir tree" where delamination size increases from impacted surface to the rear surface of the laminate. Cheng and Langlie (2003) developed a model showing these failures occurring in sequence the relative thickness of each stage depend on the overall plate thickness.
Van hoof (1999) provided further detailed description of the various damage modes described above.

During the initial stages of the impact the laminate material is compressed under the force of the projectile. The through thickness compression results in crushing of the material. Whereas the through thickness shear deformation result in a plug of laminate material being pushed away.

As the projectile progress through the plate, it forces the fibre to extend beyond their tensile limit, causing the fibre breakage.
As the projectile advance through the plate. The in-plane compression results in inter-laminar shear stresses, whereas the out-of-plane compression causes interlaminate normal stresses. Both types of stresses can cause the initiation and the propagation of delamination.

Figure 2-5: Delamination

The damaged caused by impact strongly depends on the plate properties, environmental effect and boundary conditions. Lopez and Navarro (2002) investigated the influence of temperature on the damage produced on CFRPs by intermediate and high velocity spherical projectile impact. Their results showed a clear dependence of damage on temperature, impact velocity and type of laminate. Flanagan (1999) reported based on a detailed investigation carried out by Cunniff (1992) (1996) on ballistic response of fabric armour using FSP for fabric systems such as Spectra, Kevlar and Nylon subjected to impact velocities ranging between 400 to 1600 m/s. He reported that out of these fabrics spectra has the highest energy absorption capacity. He also compared woven to braided three dimensional E-glass. In addition to usual failure modes the woven laminate suffered from delamination, while the three dimensionally braided composite did not delaminate.

The energy loss during the penetration mechanism can be attributed to energy absorbed by the material, projectile deformation and heat generation due to friction (Flanagan et al 1999). Results presented indicate that energy lost due to projectile deformation is similar for all ten materials studied. Furthermore the heat generation due to friction is generally negligible.

Van Hoof (1999) reported on an investigation on the effect of ballistic impact on polyethylene and found that the ballistic limit velocity strongly depend on the projectile size and the areal density of the plate. Segal (1991), Van Hoof (1999) studied the effect of impact on several fibre types and concluded that the ballistic limit mainly depends on the energy absorption limit of the fibre more than anything else. He also showed that a higher areal density and fibre volume will result is a better ballistic performance. Similar conclusions were presented by Flanagan et al (1999) with the addition of fabric type and weave.
Guoqi et al (1992) studied the unidirectional and woven fabric. As expected the ballistic limit of woven Kevlar 29 varies linearly with the thickness, they found neither lay-up nor matrix volume fraction had any effect on the plate response.

Wu and Chang (1995) studied the effect of initial velocity on the fibre breakage and concluded that the projectile velocity does influence the amount of fibre breakage.

Flanagan et al (1999) reported on Lee, Song and Ward work (1994) where they investigated fibre composite subjected to multiple ballistic impact and concluded that vinyl ester resin composite outperformed polyurethane composite for impact velocity ranging between 150 m/s to 300 m/s. Van Hoof also reported similar results based on Lee et al (1994) where they reported that the matrix stiffness did have an influence on the ballistic impact resistance of Spectra composite.

In an attempt to improve the ballistic response of composite armour new models are needed to be developed, which means a better understanding of composite damage is required. Since ballistic test can be expensive and time consuming several attempts to study and compare the damage models of high and low velocity impact have been carried. Most of the studies reported a difference in the damages pattern. However, assuming that the impactor is considered to be the main influence in an impact event. In quasi-static test (assuming load is limited) the impactor usually does not penetrate the plate but if the velocity is increased a little and the plate is allowed to be penetrated the damage mechanism involved will be similar to that of ballistic impact and the results and observations can be used to gain an insight into the ballistic study.

### 2.2.2 Delamination

Although delamination is usually acknowledged as one of the main damage mechanism in impacted composite plates, information about the extent of delamination and the mechanism involved in their initiation and growth under ballistic impact are limited. The majority of research into the impact induced delamination has been focussed on the low velocity/ high mass impact.

Ballistic impact tests tend to be difficult and very expensive, so most of the composite studies have been published based on low velocity impact. In contrast to ballistic impact a large amount of information is available from drop impact test. Even though ballistic and drop weight impact differ from the point of view of loading characteristics. Where Ballistic impact is influenced by velocity, whereas drop weight is influenced by weight. Under low velocity impact loading
conditions, the contact between the projectile and the target are relatively long allowing the whole structure to respond which also enables the kinetic energy to be dissipated and accommodated at a point far from the impact area. Under these loading conditions the elastic energy absorbing capacity of the structure is very important. On the other hand a high velocity impact tends to produce a more local type of response resulting in energy dissipation over a small and local area. Under these conditions the geometrical parameters have little effect (Cantwell and Morton 1989). However the assumptions that the cause of damage and delamination initiation and growth observed in drop weight impact can be valid for ballistic test (Van Hoof 1999).

In the next paragraphs an outline summary of the current understanding of delamination mechanism is presented and discussed.

**Low Velocity Impact**

The most common damage characteristics of Low velocity impact or drop weight impact damage are matrix cracking, delamination and fibre breakage. These three modes or states of damage usually occur in the order listed above with increasing the impact energy. They also depend on the geometry of the structure, type of fabrics and material properties, loading conditions, and boundary conditions.

Matrix cracking is usually the first major damage mode associated with drop weight impact. The propagation of the matrix crack is strongly influenced by the orientation of the fibre with respect to loading direction (Bartus 2005). The cracks usually propagate into the areas where fibres are highly coordinated. A matrix crack that propagates all the way to the ply interface has been referred to a critical matrix crack. Choi (1991), Van Hoof (1999) reported that there is an impact energy threshold associated with the energy required to initiate the first critical crack.
Chapter 2 Background

Abrate (1998) describe delamination as the debonding between adjacent laminates and it is of most concern since it significantly reduces the strength of the laminates. Experimental studies consistently report that delamination only occurs at interface between plies with different fibre orientations. If two adjacent plies have the same fibre orientation, no delamination will be introduced at the interface between them. For a laminate impacted on its top surface, the delamination area will have an elongated ellipse or "peanut" shape with a section that narrows at the impact point see Figure 2-6. The elongated portion of the delamination is aligned with the fibre direction in the lower part of that interface.

The delamination area usually is plotted against the kinetic energy of the impactor, and after a small threshold value is reached, the delamination size increases linearly with the kinetic energy (Abrate 1998). Straznicky et al. reported that the delamination area increases with impact energy up to a critical level and then remain constant (Van Hoof 1999).

After impact the damage process is initiated by matrix cracks which then induce delamination at ply interface. Abrate (1998) reported two matrix cracks: tensile
cracks and shear cracks Figure 2-7. The tensile cracks are introduced when in-plane normal stresses exceed the transverse tensile strength of the ply. Shear cracks are at an angle from the mid surface, which indicates that the shear stresses play a significant part in their formation.

Figure 2-7: Two types of matrix cracks, (a) and shear crack (b) tensile crack (Abrate 1998)

The plate thickness also plays a significant role in the type of damage that occurs during the impact. In thick plates, the matrix cracks are first introduced at the first layer impacted by the projectile for the high localised contact stress. The damage progresses from the top down resulting in a fir-tree like damage pattern Figure 2-8. In a thin laminate, the bending stresses at the back of the laminate introduce matrix cracks in the lowest layer which will lead to a reversed matrix and delamination pattern (b).
The delamination area is usually narrow below the impact zone and expands as it moves away from the impact centre. The conical shape of the matrix crack and delamination is caused by the high transverse shear stress that occurs during the impact.

**High Velocity Impact**

In drop weight impact, the damage is usually distributed over a large area, well beyond the point of impact. The damage in plates impacted with a velocity above the ballistic limit is usually very small and local and there is hardly any deformation. For ballistic impact, the damage and delamination is in between and resembles the drop weight impact damage.

Van Hoof (1999) compared the matrix damage and delamination mechanism observed in the drop weight impact to that of the ballistic impact and concluded that they are similar. Both type of impact result in the same major damage modes (matrix cracking, fibre failure and delamination).

- In ballistic impact the maximum delamination occurs on the back side of the impacted specimen (Guoqi et al 1992). This is similar to the delamination pattern observed in drop weight impact.

- In ballistic impact the specimen exhibit bulging deformation underneath the impactor (Guoqi et al 1992) Figure 2-9. This is similar to the
lamine deflection in drop weight impact with the exception that it is smaller in size and localised around the impactor.

- In the impacted area the material deforms downwards and laterally, which cause in-plane and out of plane compression (Guoqi et al 1992). The out of plane compression causes interlaminar normal stresses and the in-plane compression leads to interlaminar shear stresses. Both these stresses cause delamination growth.

- The delamination at the bottom of the specimen can be further extended when the projectile separates the underlying plies from the rest of the laminate (Figure 2-10)

- The experimental observation of ballistically impacted specimen indicates that the damage mechanisms are similar to those found in drop weight impact. It is reasonable to assume that in ballistic impact the delamination is initiated by matrix cracks extending into the ply interface similar to drop weight impact.

Based on the above it is reasonable to assume that the information available on delamination from drop weight impact can be used in prediction laminate behaviour under ballistic impact. With the exception that in ballistic impact the penetration mechanism are much more important.

![Figure 2-9: Bulging of laminate underneath the projectile during ballistic impact](Van Hoof 1999)
2.3 Appliqué Armour

An important factor influencing the ballistic response of the target is the properties of the target. The question how the target decomposition into several layers may influence the ballistic response and increase the absorption energy of the plate has been studied.

Partom (2001) studied the effect of ballistic impact on ceramic backed by aluminium plate. He showed that a doubled spaced target (two ceramic/aluminium target each made of 4.6 mm of ceramic and 3.1 mm of aluminium separated by 8.2 mm gap) provide a worst ballistic protection than a single assembly 9.2 mm of ceramic backed by 6.6 mm of aluminium.

Prior (1986) numerically investigated the ballistic response of a ceramic composite plate impacted by a 7.62 mm calibre ball round of 9.33 g mass. The surface target was made of (Al2O3) and the backing plate was made of GFRP. The ceramic thickness was varied from 4.5 to 5.5 mm whereas the composite thickness was kept constant at 9.5 mm. the ballistic limit velocity was estimated to vary between 800 and 900 m/s.

Ceramic tiles are used in composite armour to blunt the projectile and absorb kinetic energy (Jovicic 2003). He compared the ballistic response of different layers of ceramic spheres embedded in epoxy and backed by composite with monolithic ceramic backed by the similar composite plate. He concluded that ceramic spheres embedded in epoxy exhibit slightly lower energy absorption. However, they provide an advantage of ease of complex shape comfortable manufacturing.
Fujii (2002) reported on ballistic response of CFRPs plate with plies of different carbon properties:

i) high stiffness and high strength,

ii) a relatively low stiffness & same strength,

iii) high stiffness but strength lower than (i).

Different combinations of cross ply laminate has been studied, the plate strength has been assessed based on the absorbing energy capability. The absorbed energy was measured as the difference between the initial and residual kinetic energy of the projectile.

The absorbed results revealed that the samples with laminate type (i) at the rear absorb more energy the choice of the front laminate did not affect the result. This is followed by samples with laminate type (i) in the centre. The choice of front and rear laminate did not affect the results. These results led the author to conclude that the rear laminates is the key one in ballistic protection in term of energy absorption.

As mentioned earlier the development of multi-layer armour began in the sixties when it was first realised that ceramic reinforced armour provides a good protection. Ceramics have been used in armour design because of it high effectiveness in absorbing kinetic energy under extreme loading conditions when confined. Ceramic can sustain a significant compressive strength even when crushed and pulverized by a projectile under impact. But the most important reason is the materials lightweight compared to traditional armour materials. However ceramic has one major disadvantage which could eliminate or narrow it use in armour design to areas that only undergo small deformation. That drawback is it brittleness.

Computational methods can be used in design to try to extend the usage of ceramic to other structural areas, which means an understanding of the fundamentals of material behaviours of ceramic under impact is necessary to efficiently explore the potential of any design option.

Based on experimental observation ceramic shows a different behaviours under tension to that under compression. Lee (2005) reported that ceramic under tension exhibit a linear elastic behaviour and a sudden rupture. However it is a different case under compression where the failure tend to be more gradual and
initial failure does not necessarily mean a complete lose of load carrying capability.

It is widely accepted that the material behaviour of ceramic strongly depends on hydrostatic pressure. As the pressure increases, the frictional force on the pressure applied surface increases hindering any slipping of the grain boundaries. This led to a significant increase in shear strength of ceramic material. As a result shear strength became the popular way of predicting damage in pressure sensitive material (Lee 2005).

As for composite material extensive experimental work has been done to understand ceramic behaviour under impact and to evaluate its resistance to penetration. The type of experiment carried out can fall under one of two categories. Uniaxial stress (Bar impact), or uniaxial strain (Plate impact). Most of the current work has been developed to try to simulate and predict the ceramic behaviour and effect and to describe the damage and failure behaviour.

Armour vehicles have been traditionally protected by steel or metallic base armour, which is why most of the published research deals with penetration on isotropic metallic targets. Zukas (1982), Abrate (1998), Zukas (1990) and many other publications give an extended review of ballistic impact on isotropic material. Only limited amount of information is available at least in open literature on ballistic impact on composite armour mainly because it is still a newly developed area, and whatever is available is protected for commercial interest. Impact event into ceramic composite armour can be explained by simplifying it and separating the entire process into two stages.

During impact a compressive wave is generated by the projectile and it travels from the front toward the rear face of the ceramic at the speed of sound, then it reflects and turns to tensile breaking the ceramic in tension on its way back. This stage is in order of few microseconds. The outcome of this stage can be the shattering or erosion of the projectile and degradation of ceramic. For ceramic shown in Figure 2-11, a shock above the Hugoniot elastic limit is known to introduce permanent damage and signal the beginning of material degradation. Den Reijer (1991) has predicted that the ceramic cone will be generated at

\[ t = 6 \left( \frac{h}{c} \right) \]

Equation 2.10
Where: \( c \) is the speed of sound, \( t \) is time and \( h \) is the thickness of the ceramic (Woodward 1990). During the formation of the cone the ceramic does not move and the projectile is being eroded.

Figure 2-11: Phase one

The second stage starts after the end of the first one at \( t = \frac{h}{c} \), now the whole armour contributes to the slowing down of the projectile see Figure 2-12. The rear of the projectile moves at speed of \( v \), the ceramic/projectile interference at \( u \) and the cone at \( u_0 \), the erosion rate is given by the penetration of the projectile into the ceramic \( v-u_0 \).

Figure 2-12: Phase two

The effectiveness of ceramic faced armour is demonstrated by Jovicic (2003) where the ballistic limit velocity of 11.4 mm thick tile of Alumina AD-85 is experimentally determined to be 390 m/s. whereas the ballistic limit of a 6.35
mm of ceramic faced armour backed by 6.35 mm of Aluminium, which have the same areal density is found to be 650 m/s.

The conclusion from this experiment was the necessity for multi-materials armour systems consisting from a hard facing layer to shatter or blunt the projectile and a backing plate to absorb the kinetic energy and support the structure.

In general ceramic failure models can be expressed as a function of time, pressure and effective stress. The models predict damage and failure via comparing certain functions with other measured quantities. There are several models available in the literature. Below a brief description of the most popular models is given.

Johnston and Homlquist (1990) have developed a model known as (JH1) which is considered to be one of the popular models Figure 2-13(a). It is widely used in ballistic impact studies as LS DYNA has included the damage theory and material behaviour into their main material library. In this model they used two surface strength curves to model intact and completely damaged ceramic. They later improved it and proposed (JH2) Cronin (1999), where they introduced another variable curve to model the degradation of the ceramic as the damage evolves Figure 2-13(b). Johnston, Holmquist and Beissel (2003) proposed another model similar to Johnson Holmquist 1. The only new feature in this model is the capability to present material strength and damage as smooth function of the pressure Figure 2-13 (c).
Figure 2-13: Johnson Holmquist ceramic models for high pressure, high strain and high strain rate conditions

For the JH-1 and JHB model, the intact material curve is used prior to fracture (D < 1). Once fracture has occurred (D = 1) the failed material curve is used. The JH-2 model also has an intact and failed material curve, but the model is gradually softened as damage accumulates. The strength of the material is assumed to vary with pressure, strain rate and tensile strength.

For intact material, the strength is assumed to increase linearly from $\sigma=0$ at a tensile pressure of $-T$ to a strength of $\sigma=\sigma_t$ at a pressure of $P=P_t$. $T$ is the maximum hydrostatic tension the material can withstand. When subjected to tensile pressure, the material responds elastically until brittle failure at a specified effective stress value. This corresponds to a complete instantaneous damage. Once fracture has occurred the element cannot carry tensile loading for the remainder of the analysis. It still can carry compressive loading as described by strength of failed material (D=1) curve.

A phenomenological model of the response of a ceramic material under impact loading conditions was developed by Simha et al. (Lamberts 2007) (see Figure 2-14). The yield stress, $\sigma_y$, is a function of the pressure $p$ and the strain rate. During plastic deformation, damage accumulates until failure (D = 1). The yield stress of the material is a weighted sum of the intact material strength, $\sigma_{\text{intact}}$, and the failed strength, $\sigma_{\text{failed}}$. Because $0 \leq D \leq 1$ all intermediate states of failure can be described and the material is softened gradually.
Chapter 2 Background

\[ \sigma_y = \sigma_{\text{intact}} (1 - D) + \sigma_{\text{failed}} D + \frac{3 \varepsilon}{2 \gamma} \]

Equation 2.11

Where:

\[ \sigma_{\text{failed}} = \min[\alpha \sigma, \sigma_{\text{max}}] \quad \gamma = \gamma_0 \exp[\gamma_1 (p - P_{\text{HEL}})] \]

Equation 2.12

Figure 2-14: Simha strength model (without strain rate effect).

With \( \alpha \) the slope of the curve shown in \( \gamma_0 \) and \( \gamma_1 \) material parameters and \( P_{\text{HEL}} \) the pressure at the Hugoniot elastic limit, which is the onset of inelastic behaviour. The term \( \gamma \) controls the contribution of the deviatoric strain rate \( \varepsilon^d \) to the strength of the material. Taking this rate-dependent term into account is a phenomenological contribution of micro-crack sliding, dislocation activity and grain boundary sliding within the material during deformation. This model is used for plate impact simulations, depth of penetration simulations and interface defeat computations. A very characteristic feature of this model is the higher material strength of failed material with respect to intact material.

The above ceramic material models describe the material response, intact and failed strength, as well as damage accumulation as functions of pressure. However as damage originates from an existing distribution of micro-cracks, several other models used to study ballistic impact into ceramic Rupert et al (1998), Cater et al (1999), Liu and Rajendran (2006), Lo (2008) uses failure models based on Griffith failure criterion [Griffith (1920) & (1924)]. Rajendran and Grove (1996) and Addessio and Johnson (1990) developed microphysical
models where damage is described by a crack density parameter. Crack nucleation and growth are based on a generalised Griffith criterion. Due to this microcracking, a shear modulus and bulk modulus reduction was modelled.

Griffith developed a criterion for crack propagation for completely brittle materials for which there is no plastic deformation. He demonstrated that the critical stress required for crack propagation is described by Callister (1996):

\[ \sigma_c = \left( \frac{2E\gamma_s}{\pi a} \right) \]  

Equation 2.13

Where:

\( \sigma_c \) = Critical Stress

\( E \) = Modulus of elasticity

\( \gamma_s \) = Specific Surface Energy

\( a \) = one half of the length of an internal crack

These models were used to successfully reproduce velocity histories under one dimensional strain conditions. Modelling steel projectile impact on ceramic targets resulted in less acceptable results, especially for unconfined experiments.

Failure models based on Mohr-Coulomb damage model (Ref1 & Ref2) has been introduced to describe the macroscopic behaviour of material such as ceramic and concrete. Results show a good correlation between the experimental results and numerical predictions.

Many ceramic models are available in literature most of them focused on predicting the material behaviour of ceramic armours, the penetration, the plate resistance and the damage area. These models are often designed based on specific experiments and are for specific materials. To improve them, calibration coefficients are often used. If for any reason the geometry or boundary conditions change, these coefficients become void and invalid. It is however necessary to conclude that most of this models are pressure-dependent and the strength is strain-rate dependent to some extent.
2.4 Ceramic/ Composite

Composite integral armour design is a very complicated task. Traditionally experimental method was used to study the penetration of the armour. However, with the emergence of computers several models and simulations were introduced. Most of these models were analytical. With the advance technologies and fast development of computer processing power it became feasible to use the computer simulation a step further which led to the introduction of numerical models which later become more advanced and complicated.

Over the years only few analytical models stood the test of time, one of the most popular models is Florence Model (Florence 1969). This model was first developed in 1969 to predict the ballistic limit of ceramic faced armour; it is based on the assumption that ceramic does not contribute to the energy absorption of the plate. Ceramic is assumed to only distribute the load over a larger area of that of the plate, whereas all the kinetic energy is absorbed by the backing plate.

![Figure 2-15: Description of Florence Fracture Conoid](image)

The ballistic Limit Velocity as predicted by Florence Model is:

\[
V_p = \frac{\left(\varepsilon, S\right)}{\sqrt{(0.91 f(a) M_p)}}
\]

Equation 2.14

Where:
\[ f(a) = \frac{M_p}{(M_p + (h_1d_1 + h_2d_2)\pi a^2)\pi a^2} \]  
\text{Equation 2.15}

\( M_p \) is the projectile Mass

\( a_p \) is the Projectile radius

\[ a = a_p + 2h_1 \]  
\text{Equation 2.16}

\( h_1 \) is the ceramic plate thickness

\( h_2 \) is the backing plate thickness

\( S \) is Ultimate tensile strength of the backing plate

\( \varepsilon_c \) is the breaking strain of backing plate

\( d_1 \) is the density of the ceramic

\( d_2 \) is the density of the backing plate

Hetherington and Rajagopalan (1991) have investigated the amount of energy absorbed by a ceramic/ composite plate Impacted by a projectile during perforation using analytical models and compared the results with the experimental data. The graph plotted by Hetherington and Rajagopalan (1991), comparing the actual energy absorbed by an armour system as determined by experiment with that predicted in the following manner:

The ballistic limit velocity for the combination is estimated using Florence model.

The residual velocity is assumed to equal \((V_t - V_p)\) and the residual kinetic energy is thus evaluated assuming the mass remains unchanged.
Chapter 2 Background

Figure 2-16: Comparison of Theoretical prediction with measured values of Energy absorbed (Hetherington and Rajagopalan 1991)

In this model the projectile is assumed to be cylindrical and impact the target at high velocity. It is assumed that when the projectile impact the ceramic a cone made of fractured ceramic is generated this spread the impact load over a larger area. No energy is absorbed by the ceramic fracture. As the projectile penetrates the plate the ductile deforms absorbing energy in the process.

Hetherington and Rajagopalan (1991 and 1992) further reassessed the model. Chocron (1998) proposed a two stage modelling where in the first stage the projectile erosion is considered. In the second stage both the projectile and ceramic cone is considered to become one part and both penetrate the backing plate. Den Reijer (1991) predicted the time taken by the ceramic cone to be generated equation 2.10 and the angle of it (65°).

In many analytical models the projectile is usually considered to be rigid. Tale (1967) proposed a model that takes the projectile erosion and mushrooming into account.

Cortes et al (1992) and Navarro (1993) investigated the effect of stress wave propagation through ceramic/ composite plate. They have shown that upon impact, compressive stress wave is generated at the face of the armour and progresses through toward the back of the ceramic where it reflects back as a tensile wave at the ceramic/ composite interface. The amplitude of the wave depends on many factors and plays an important role in ceramic fracture.

impact, fine ceramic particles are created by the ceramic fracture ahead of the projectile, which leads to high internal pressure. The ceramic confinement provides protection from the wave damage and displays a high resistance to penetration. Gama (2001), Rajendran et al (1994, 1995 and 1996) have investigated normal impact on ceramic metallic armour using Lagrangian finite element codes. They have shown that once the ceramic tile is pulverised ahead of the projectile, the powder is pushed rather than penetrated. They also investigated the effect of coulomb friction and concluded that it did not have a large effect in the case of ballistic performance.

Navarro et al (1993) investigated the maximum dynamic deflection and the energy absorbed as a function of areal density of ceramic composite armour. The maximum dynamic deflection was found to be linearly decreasing and the energy absorbed linearly increasing as the ceramic/ composite armour areal density increases.

Most of the literature available on the numerical analysis investigation of composite armour is for two components ceramic/ metallic or ceramic/ composite armour. As for studies of armours with more than two components, the research and publications are very limited. Gama (2001), Mahfouz et al (2000) investigated the penetration of composite integral armour with a rubber layer between the ceramic tile and composite backing plate. They have shown that the dynamic deflection of the composite plate decreases with the increase of the rubber layer thickness. Gama has also used one dimensional numerical stress wave models to investigate the effect of the rubber layer on the three component ceramic rubber and composite plate.

Gama et al. (2001) investigated the penetration on composite integral armour with a rubber layer between the ceramic and the composite backing plate. They have shown that the dynamic deflection of the composite plate decreases with the increase of the rubber layer thickness. They also showed that the rubber layer delays the stress wave transfer and reduces the amplitude of transmitted stress wave to the backing plate.

Wang et al (1995) used finite element code DYNA 2D to simulate the impact on alumina ceramic/ Aluminium. They have shown that there are four different deformation mechanisms of the aluminium backing plate (petalling, plugging, partial penetration and indentation) as a function of the backing plate thickness.
Gama et al (2001) used finite element analysis to investigate the potential benefit of using rubber and aluminium foam to damp the stress wave. They have reported that aluminium foam has a unique capability in delaying stress wave propagation and attenuation. When the foam is still intact, the dispersion of the stress wave takes place at the cellular structure of the aluminium. As foam densification is partial, it acts as a stress wave filter, only after complete densification effective stress wave propagation take place.

Composites offer tremendous possibilities for part fabrication once few basic concepts are understood. The key lies in understanding the different materials available, their possible range of application and the best way to handle them. During a ballistic event a large amount of kinetic energy should be consumed by the shattering of the ceramic tile and deformation of projectile. The longer the armour tiles stay in front of the projectile the better the armour in defeating the projectile. Excellent armour will stop the projectile before it reaches the composite plate. The most advantageous ceramic tile has a hexagonal shape as this help to contain the ballistic damage with a minimum number of tiles and facilitate the repair of the tiles that fractured during the ballistic event Fink et al (2000). Ceramic tiles blunts and/or shatters the projectile whereas the backing plate absorb more kinetic energy, contains the damage in the ceramic and help stopping the fragments from travelling any further.

The rubber layer between the ceramic tiles and structural composite is used to absorb the impact energy through viscous damping and to add multi-hit capability to the armour. However delamination between rubber and ceramic and between rubber and composite backing plate are found to be a major failure mode of the armour during impact due to the transmission and reflection of the waves between rubbers layers especially that of rubber and brittle ceramic Mahfooz et al (2000).

2.5 Analytical Model

Although composite materials have been used in industry for several decades, until recently the dominant method of studying the impact effect was empirical. Attempts to save time and money led to a concentrated effort to be initiated to understand the material behaviour under impact and to find a comparable techniques for design of advanced composites against foreign-object impact.
When designing for impact response it desirable to have criteria to determine how the various properties of the projectile and target will influence the material response.

Over the years only few analytical models for the complete composite ceramic armour have been presented in literature the most famous one is Florence model Florence (1969).

2.5.1 Advantages of Analytical Methods

1. Less data preparation time. This is a direct result of introducing simplifying assumptions into the governing equations, which reduce the problem into one or two-dimensional algebraic or differential. Therefore, the analysis time required for data preparation and data processing for a given problem is reduced.

2. Very useful in making prediction provided care is taken not to violate the simplifying assumptions introduced in their derivation.

3. Less computer time and storage. The Analytical method uses less numbers of equations because its deals only with a very simplified problem, which result in a smaller system of equations and reduction of data used.

4. Easily applicable and changeable. It is often very difficult to change the geometry and boundary conditions of a problem when using Finite Element. It is an important advantage in problems where changing the geometry and condition is required.

2.5.2 Disadvantage of Analytical method

1. Knowing the exact simplifying assumption that can be made without violating the geometry and material property of the problem

2. The solutions to the problem are approximate and not accurate depending on the amount of information used and the amount of simplification made.

3. The solution does not contain a great deal of information

4. Some analytical models failed to predict the accurate response around the ballistic limit.
2.6 Numerical Models

Over the past thirty years, the numerical analysis of structures using computers has been dominated by the finite element methods (F.E.M.). This is a general method technique, which involves a discrimination of the body into element of finite size; in much the same way as a brick house consists of many simple bricks. Within each element the structural behaviour can be described and expressed in a simple form. Assembling together the equation for the element, one large system of simultaneous equations describing the overall behaviour of the structural response to a given loading can be obtained and solved.

2.6.1 Advantages of Finite Element Methods

1. High resolution of stresses. Stress are accurate because no further approximation is imposed on the solution, solutions are exact and fully continuous inside the domain. This makes Finite element methods much more suitable for modelling impact problems.

2. Computer time and space can be saved by only using finer meshes only around the area of interest.

3. A great deal of information can be obtained from the finite element program and information can be obtained after each stage making it easier to predict the time of failure and the critical regions of the structure.

4. Familiar mathematics. The mathematics used in finite element formulations is familiar to engineers and if not, are not difficult to learn. Since it contains many numerical procedures that are commonly used such as numerical integration and treatment of boundary conditions.

2.6.2 Disadvantage of Finite Element Methods

1. More unwanted information. Usually the area of interest in ballistic Impact problem is known and small, modelling an entire three-dimensional complex body with finite element and calculating the stresses at each nodal point is very inefficient way of solving the problem.

2. Material Properties. Sometimes the material property is not known and is very difficult to obtain.
3. Time and space. The weakest aspect is that finite elements generate a mesh for the whole body. Discretization schemes which usually lead to a very large system of matrices to be solved even though some of these problems have been partially overcome by the introduction of very powerful computers it still can be a problem.

2.7 Method to use

To decide whether empirical, analytical or numerical solutions are more suitable for particular problem three factors must be taken into account:

1. The type of problem (linear or non-linear).
2. The degree of accuracy required.
3. The amount of time required for preparing and checking the data.
3 Key Aspects of Numerical Modelling

3.1 General

When a complete solution to an impact problem is required, numerical solution must be used. The computational process consists of three stages; a compact description of these computational processes is shown in Figure 3-1.

From the information provided by the user specifying the initial geometry, boundary condition and stress-strain relationship in both elastic and plastic region a description of the model will be generated in a format usable by the main processor.

In the main processor the laws of conservation of energy and momentum coupled to an equation of state, a failure and a post failure criterion cast into finite – element and integrated with respect to time into the next phase. This procedure is usually long and demands a long time and computer storage.

The results produced are usually quite long as a full description of each stage of each element of the problem are produced, which makes it very hard or impossible to read as it can run into thousands of pages of data. So the data is fed into the post-processor which graphically prepare and display the required information such as velocity, deformation, stresses.... at a given time.

The user needs at least 6 months training to be able run dynamic problems, during which a frequent contact must be kept with the code developer or an experienced user. Apart from the man month expenses, computational costs are negligible.

It must be kept in mind that the numerical results are a reflection of the capability of the software and the quality of the modelling fed to the computer, a better material description and modes leads to better results, a poor material description will lead to incorrect results and may also lead to a catastrophic failure.
Figure 3-1: Computational process
Chapter 3 Key Aspect of Numerical Modelling

3.2 Software

There are many references in literature to software capable to simulate ballistic impact into armour. Most of them claim a good correlation between the experimental results and numerical predictions. In this research the sponsor insisted in using MSC Software (Patran & Dytran). In this section a summary of a pepper comparing available software capable of simulating impact is presented.

Nguyen et al (2005) described the investigation of three commercial explicit finite element analysis packages, LS-Dyna, MSC.Dytran and Pam-Shock, to determine their capability in predicting barely visible impact damage (BVID) in composite structure. The investigation was conducted by first determining the suitability of the code in constructing an FE model of a stiffened, solving for BVID and retrieving results. The results were intern compared to experimental data in order to gauge the suitability of the codes for composite design and analysis. Comparison of the FE analysis to experimental data includes damage development and degradation, as well as the time history response. The Chang-Chang failure theory (MSD.Dytran Manual) with brittle degradation was used for both LS-Dyna and MSC.Dytran, while the biphase model was used for the Pam-Shock.

Table 3-1 indicates the standard composite failure criteria that are available in the codes reviewed. Table 3-2 shows the associated damage degradation associated with the different material constants.

Table 3-1: Composite Failure Criteria available in explicit FE code

<table>
<thead>
<tr>
<th>Code</th>
<th>Tsai-Hill</th>
<th>Tsai-Wu</th>
<th>Modified Tsai-Wu</th>
<th>Maximum stress</th>
<th>Maximum strain</th>
<th>Chang-Chang</th>
<th>Hashin</th>
<th>Biphase</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSC.Dyran</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LS-Dyna</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pam-Shock</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

Table 3-2: Default degradation rules in MSC.Dytran

<table>
<thead>
<tr>
<th>Code</th>
<th>Tsai-Hill</th>
<th>Tsai-Wu</th>
<th>Modified Tsai-Wu</th>
<th>Maximum stress</th>
<th>Maximum strain</th>
<th>Chang-Chang</th>
<th>Hashin</th>
<th>Biphase</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSC.Dyran</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LS-Dyna</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pam-Shock</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

64
Results indicated that in general all the three FE packages were capable of creating a composite damage model, solving for damage and degradation, and then post processing the damage information. An important capability in these programs was the ability to view the composite damage modes in individual plies. Comparison of the force-time curves as well as the peak forces indicated that general trend and shape of the curves were predicted reasonably well. However the largest difference was found in the duration of the impact event which all simulations predicted a shorter time for contact.

The comparison of the BVID prediction by the three FE codes to the experimental test results are shown in Figure 3-2. The results showed that similar damage areas were predicted using the Chang Chang failure criterion with degradation using MSC.Dytran and LS-Dyna. However, Pam—Shock standout from the other software. The authors attributed that to the failure theory used (Bi-Phase) which require extensive property degradation data compared to the other failure theories which was difficult to obtain. The other factor influencing the pam—shock results was the interpretation of the damage. The biphase theory used in Pam—Shock predicts damage development and corresponding degradation of the properties from the initial strain level well below the ultimate strain of the material. Whereas; the other failure theories assume elastic behaviour until failure.

![Figure 3-2: Comparison between test and post failure degradation foe damage area.](image)

The conclusion that was be made from this paper is that both LS-Dyna and MSC.Dytran are similar and capable of modelling impact damage in composite, with MSC.Dytran having a larger composite failure criteria available (Table 3-1) and better predict the total damage area.
For the inexperienced this statement is somewhat misleading as the damage model comparison presented in this study is for shell elements which are usually used in the aerospace and automotive industries. However in the case of armour design where the composite plates are usually very thick solid element are used.

3.3 Discretization Methods

In computer analysis a continuous physical system is usually replaced by a discretized system – a computational mesh-.

The problem is divided into a finite number of regions or element using imaginary lines. Then the problem is simplified and reduced into displacement at the nodes, which are the only interaction point between the elements.

The displacement at any point within an element is defined in term of nodal displacement using set of functions.

These displacement functions define the state of strain within each element. These together with other properties are used to define the state of stress.

Systems of forces applied at the nodes that are proportional to the external forces are determined. This procedure results in a stiffness relationship-equation relating external loads, internal loads, and nodal displacement. The conventional technique for large system of algebraic equation is used to assemble the local element data into global ones and solve for nodal displacement.

The computer code used in prediction the material behaviour under contact can be divided into three categories:

3.3.1 Lagrangian Methods (for structure modelling)

Lagrangian codes are the most common finite element processing techniques for engineering application. Grid points are located on the body being analysed. Elements of material with constant (invariant) mass connect the grid points, forming a mesh. As the body deforms, the computational grid is fixed with the material and move with the body and elements (mesh) distort. The Lagrangian processor uses explicit formulation and allows large deflections with material and geometric non-linearity. The main advantage of such method is:
The equations of mass, momentum, and energy conservation are simpler because they are not transferable from one element to another. So they can be computed faster as a fewer computations are required.

Straightforward boundary condition because of the material interface and free surfaces are stationary in the material coordinate frame.

Some constitutive equations require time histories of material behaviour. It is easily and accurately accounted for in the Lagrangian method.

3.3.2 Eulerian Modelling (Fluid Modelling)

The Eulerian processor is essentially an explicit computational fluid dynamics code. The grid points remain fixed in space, defining fixed volumes, or elements, as the fluid moves through these Eulerian elements, or mesh, the mass, momentum and energy of the fluid is transferred from one element to another.
3.3.3 Arbitrary Lagrange Euler Coupling (ALE-formulation)

The ALE-formulation is a coupling between the two formulations described before. This formulation allows the Eulerian material to move and coincide with the interface nodal points of the Lagrangian mesh by means of ALE coupling surfaces. The interface can be seen as a boundary condition for the Eulerian mesh on which it can exert a pressure for example. This pressure is then applied to the Lagrangian structure.

3.3.4 Smooth Particle Hydrodynamics (SPH)

SPH is a mesh free technique that can be applied for non-linear problems with large deformations. The SPH overcomes the disadvantages of the Lagrange and Euler approaches. In the SPH formulation free movable points with a fixed mass, called particles, have coherence by means of an interpolation function. A kernel estimate allows describing the conservation of mass, momentum and energy in terms of interpolation sums. A physical object is than defined by a field of SPH points instead of elements. The problems of this formulation are the large velocity oscillations in single particles.

3.3.5 Structure – Structure Interaction

In the case of interaction between two separate Lagrangian meshes to model a contact problem, the sliding side is designed as a master surface and the other as slave surface. As the name indicate the master surface dictate the behaviour of the slave surface. The important steps in the sliding interface techniques are as follows:

1. Identify a series of nodes that makes up the master surface
2. Identify a series of nodes that makes up the slave surface.
3. The equation of motion for both master and slave nodes are applied for each integration time increment.
4. The interference between master surface and slave nodes is checked. All free slave nodes not on the master surface are searched for penetration at each time step. If penetration is found the time step is scaled back in such manner that the potential intruder just reaches the master surface at the end of the time step. At the beginning of the next time step, the slave node is constrained to slide on the master segment it impacted.
5. Once penetrating slave nodes are returned to master slave nodes, momentum balance is invoked. Frictional forces are applied. If tensile forces exist at the interface, slave nodes are released and voids permitted to form.

Steps 3-5 are repeated for each time step.

When mesh distortion became very large the level of error increases to an unacceptable level. Some codes allows of the problem to be re-meshed.

### 3.4 Modelling Technique

There are several methods available to model composite material; in this chapter, a brief description to the most common ones will be given.

#### 3.4.1 Fibre-Composite Material with Failure

Multilayered composite elements can be built using orthotropic materials model in shell elements (Dytran 2005). The fibre and matrix stress and strain relation is described by the elastic stress-strain relation:

\[
\begin{bmatrix}
\sigma_{11} \\
\sigma_{22}
\end{bmatrix} = \frac{1}{(1 - \nu_{12}\nu_{21})} \begin{bmatrix}
E_{11} & \nu_{21}E_{11} \\
\nu_{21}E_{11} & E_{22}
\end{bmatrix} \begin{bmatrix}
\varepsilon_{11} \\
\varepsilon_{22}
\end{bmatrix}
\]  

Equation 3.1

This method can be used effectively to model thin layers of composite and it is widely used in aerospace and automotive industry.

#### 3.4.2 Orthotropic Material

Composite can also be modelled as 3D orthotropic linear elastic material. This type of material can only be modelled with Lagrangian solid element.

![Solid Elements](image)
HEXA: Six-sided solid element with eight grid points.

PENTA: Five-sided solid element with six grid points.

TETRA: Four-sided solid element with four grid points.

The relation between the stress and the strain is given by:

$$\sigma = [C] : \varepsilon$$

Equation 3.2

Where:

$$[C] = [T] [C_L] [T]^{-1}$$

Equation 3.3

$$[T]$$ = The transformation matrix between the material coordinate system (x, y, z) and the basic coordinate system.

$$[C_L]$$ = The local constitutive matrix defined in the material coordinate system

$$[C_L] = \begin{bmatrix}
1/E_x & -\nu_{yx}/E_y & -\nu_{zx}/E_z & 0 & 0 & 0 \\
-\nu_{xy}/E_x & 1/E_y & -\nu_{zy}/E_z & 0 & 0 & 0 \\
-\nu_{xz}/E_x & -\nu_{zy}/E_y & 1/E_z & 0 & 0 & 0 \\
0 & 0 & 0 & 1/G_{xy} & 0 & 0 \\
0 & 0 & 0 & 0 & 1/G_{yz} & 0 \\
0 & 0 & 0 & 0 & 0 & 1/G_{zx}
\end{bmatrix}$$

Equation 3.4

Where:

$$E_x, E_y, E_z$$  Young’s modulus in the principal directions.

$$\nu_{xy}, \nu_{xz}, \nu_{yz}$$  Poisson ratio between the x and y-axis, the z and x-axis, the z and y-axis.

$$G_{xy}, G_{yz}, G_{zx}$$  Shear modulus in the xy, yz, and zx planes.
Chapter 3 Key Aspect of Numerical Modelling

3.5 Composite Damage Model

During the duration of this research (which extended from 11/2003 to 06/2007); several damage models of ceramic and composite has been reviewed. Base models (Hashin for composite and JH1 for ceramic) were selected and modified using techniques implemented in other models to optimize and calibrate final models that were used in this project.

During a ballistic event, fibre failure, matrix failure and delamination should be taken into account as they are considered the principle damage mechanisms in a ballistically impacted laminate. These damage modes are accumulative and are usually dependent on the impact condition.

3.5.1 Damage in fibre direction

Stresses in the fibre direction are transmitted mainly through the fibres because of their strength and stiffness compared to the properties of matrix. Under high tension the fibre straightens, which may contribute to the damage in the matrix even in the absence of fibre damage. However, matrix damage can hardly effect the transmission of tensile stresses in the fibres.

In compression, the load carrying capacity is affected by the effective stiffness and strength of the surrounding matrix that acts as an elastic foundation for the fibre. Buckling of the fibre associated with damage to the resin matrix, as a result all material properties are degraded.

3.5.2 Fibre Damage in Transverse direction

Shear and normal stresses acting transverse to the fibres are transmitted through both fibres and matrix. The damage effects arising from these stresses take place only in the matrix or in the matrix-fibre interface, which leads to delamination. In composite materials, the fibre-resin interface has the weakest strength properties. Advancing cracks in the matrix soon passes into the fibre-matrix interface and propagate along it without damaging the fibre. In the case of transverse loading, there is a progressive opening of the existing cracks. In the case of compression in transverse direction crushing in the sense of fragmentation of brittle matrix will occurs.
3.5.3 Damage model

A brief description of the numerical damage models for both unidirectional and woven fabric is presented below. Although only woven fabrics results were presented in this thesis. The damage and failure model was based on Hashin UD fibre model (Matzenmiller et al. 1995). Hence Hashin model is summarised below.

Traditional damage models for composite material do not include any residual strength capability once the material strength has been exceeded. This means that once the material strength in a particular direction has been exceeded the stiffness value related to that direction will be immediately reduced to zero. These models are referred to as the instantaneous failure models.

In reality, composite material retains some residual strength once the material strength has been exceeded. This strength can be included in the post-failure models. This type of damage models allow for a gradual decrease in the material strength once the material strength has been exceeded. Recent application of these model showed that it can improve the ballistic response prediction of the composite material and reduce mesh sensitivity in models (Van Hoof 1999)

3.5.4 Instantaneous Failure Model

To describe the failure criteria in the lamina, a methodology similar to that developed by Hashin was used. Hashin failure criteria was initially developed to predict damage and failure in unidirectional fabrics, where failure planes are introduced to split the general failure criteria into four separate criteria for the above-defined modes:

- The failure is assumed to be caused by normal and shear stresses, acting on the fibre plane. The general failure criterions are applied to matrix and fibre modes, providing two algebraic expressions.

- For both fibre and matrix each of this failure criteria is subdivided to tensile and compression mode.

- Four strength parameters $X_t$, $X_c$, $Y_t$ and $Y_c$ are obtained using results from simple uniaxial tension and compression tests.

- After all the plane stress assumptions are applied to the four failure criteria, Hashin has introduced these simple equations:
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**Tensile fibre mode I: \( \sigma_{11} \geq 0 \)**

\[
e_m^2 = \left( \frac{\sigma_{11}}{X_1} \right)^2 - r \begin{cases} 0 \text{ failed} \\ \phi_{\text{elastic}} \end{cases}
\]

Equation 3.5

**Compressive fibre mode II: \( \sigma_{11} < 0 \)**

\[
e_c^2 = \left( \frac{\sigma_{11}}{X_c} \right)^2 - r \begin{cases} 0 \text{ failed} \\ \phi_{\text{elastic}} \end{cases}
\]

Equation 3.6

**Tensile matrix mode III: \( \sigma_{22} \geq 0 \)**

\[
e_m^2 = \left( \frac{\sigma_{22}}{Y_1} \right)^2 + \left( \frac{\tau}{S_c} \right)^2 - r \begin{cases} 0 \text{ failed} \\ \phi_{\text{elastic}} \end{cases}
\]

Equation 3.7

**Compressive matrix mode IV: \( \sigma_{22} < 0 \)**

\[
e_c^2 = \left( \frac{\sigma_{22}}{Y_c} \right)^2 + \left( \frac{\tau}{S_c} \right)^2 - r \begin{cases} 0 \text{ failed} \\ \phi_{\text{elastic}} \end{cases}
\]

Equation 3.8

Where \( \sigma \) denote the stress, \( X \) denote fibre strength, \( Y \) & \( S \) denote matrix strength. The subscripts 11 and 22 indicate the in-plane direction (longitudinal or transverse). The subscripts t and c denote tensile and compression respectively.

**3.5.5 Woven material**

Hashin failure criteria for unidirectional laminate (described above) has been used as a baseline in this study. Additional term referring to contribution of the fill and warp fibre shear damage have been added to the damage model. Hashin failure criteria has been generalizes and the damage has been described by the quadratic interaction between the associated axial and through the thickness shear strains (Yen 2002).

**Tensile/shear fibre mode: \( \sigma_{x}; \sigma_{y} \geq 0 \)**

The fill and the wrap fibre tensile/shear failure is given by the quadratic interaction between the associated axial and through the thickness shear strain...
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\[
\left( \frac{E_x(\varepsilon_x)}{S_{xT}} \right)^2 + \left( \frac{G_{xx}e_{xx}}{S_{xxS}} \right)^2 = r 
\]  
Equation 3.9

\[
\left( \frac{E_y(\varepsilon_y)}{S_{yT}} \right)^2 + \left( \frac{G_{yy}e_{yy}}{S_{yyS}} \right)^2 = r 
\]  
Equation 3.10

Where \(<\>\) is Macaulay Brackets, which means that if the value inside turns negative total value becomes Zero.

**Compressive fibre mode: \(\sigma_{xx}; \sigma_{yy} < 0\)**

\[
\left( \frac{E_x(\varepsilon_x)}{S_{xc}} \right)^2 = r 
\]  
Equation 3.11

\[
\left( \frac{E_y(\varepsilon_y)}{S_{yc}} \right)^2 = r 
\]  
Equation 3.12

**Fibre Crush damage Mode: \(E_{zz} \geq 0\)**

The crush failure due to the high through the thickness compressive pressure is modelled using:

\[
\left( \frac{E_z(\varepsilon_z)}{S_{zc}} \right)^2 = r 
\]  
Equation 3.13

**Matrix Shear Failure Mode**

As explained above the layer can be damaged under in-plane shear stressing without damaging the fibre. This in-plane matrix failure mode is given by:

\[
\left( \frac{G_{xy}e_{xy}}{S_{xy}} \right)^2 = 1 
\]  
Equation 3.14
Where $\varepsilon$ denotes the strain, $E$ and $G$ denote the elastic modulus and $S$ denote the strength. The subscripts $x$, $y$ and $z$ represent the in-plane fill, in-plane wrap and the through thickness direction respectively. $T$, $C$ and $FC$ denote the tensile, compression and fibre crush.

The failure model predicts the in-plane tensile failure by relating either the longitudinal or the transverse tensile strain to the corresponding strength. In the case of unidirectional laminate the longitudinal tensile failure represent fibre breakage (Equation 3.6) and transverse failure represent matrix failure (equation 3.8). In the case plain woven composite, both longitudinal and transverse tensile failure corresponds to the fibre brakeage (Equation 3.10 & 3.11). $r$ corresponds to the failure thresholds which are set to equal to 1 in the case of instantaneous failure. This means that once the material strength has been exceeded the stresses are immediately set to zero, which is equivalent to reducing the stiffness to zero.

### 3.5.6 Continuum Damage Mechanics

Continuum damage mechanics is a relatively new discipline that focuses on predicting the effect of progressive degradation of material properties. Since the continuum damage mechanics is the adopted approach for the numerical model presented in this thesis a description is provided in this section. This approach was first proposed by Matzenmiller et al (1995) to describe the accumulation of damage in composite materials. Several other researchers have investigated and adopted this approach Van Hoof (1999), Deslauriers, Cronin and Duquette (2004), yen (2002). Numerous contributions have been made to model impact on composite using this approach which is also known as Matzenmiller, Lubliner and Tylor (MLT). However the majority of this work is published on the application of DYNA3D.

Matzenmiller et al (1995) applied the CDM theory to model damaging unidirectional composite material. The MLT damage approach is based on the principal that the damage is accumulated within a material based on the deformation and loading in deferent directions. The onset and growth of damage to stiffness losses in the material are quantified by the introduction of damage variable ($\sigma$).
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\[
S = \begin{bmatrix}
\frac{1}{(1 - \sigma_{11})E_{11}} & -\frac{\nu_{12}}{E_{11}} & 0 \\
-\frac{\nu_{12}}{E_{22}} & \frac{1}{(1 - \sigma_{22})E_{22}} & 0 \\
0 & 0 & \frac{1}{(1 - \sigma_{12})G_{12}}
\end{bmatrix}
\]  
Equation 3.15

The inverse of the compliance matrix is the stiffness matrix which will always exist as long as the damage variables are less than unity.

This means that the following criteria are used to predict fibre and matrix failure respectively:

**Fibre failure:**

\[
f_1 = \left( \frac{\sigma_{11}}{(1 - \sigma_{1})c_{1,t}X_{11c,t}} \right)^2 - r_{1c,t} = 0
\]  
Equation 3.16

**Matrix Failure:**

\[
f_2 = \left( \frac{\sigma_{22}}{(1 - \sigma_{2})c_{2,t}Y_{22c,t}} + \frac{\tau_{12}}{(1 - \sigma_{12})c_{2,t}\sigma_{2,yc,t}} \right)^2 - r_{2c,t} = 0
\]  
Equation 3.17

The notation \(c_{t}\) is used to indicate the compression and tension. It is important to note that the damage threshold \(f_i\) is calculated in the current time step \((t)\) where as the \(r_i\) is calculated in the previous time step \((t-\Delta t)\).

The damage function \(\sigma\) is

\[
\sigma_i = 1 - \exp\left( -\frac{1}{me} \left( \frac{\varepsilon}{\varepsilon_f} \right)^m \right)
\]  
Equation 3.18

\(m\) is a damage parameter used to describe the post failure behaviour.

This approach was used by Deslauriers et al (2004) to model damage in woven carbon composite. The MLT formulation has been used to simulate damage in composite using shell elements. In this thesis a three dimensional model based on the MLT model has been used, hence extra terms has been added to the material stiffness matrix. A set of damage variables \(\sigma_i\) are introduced with
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The compliance matrix $S$ is related to the damage variables as given in Yen (2002) and Matzenmiller et al (1995).

$$
\begin{bmatrix}
\frac{1}{(1-\sigma_1)E_x} & -\nu_{yx} & -\nu_{xz} & 0 & 0 & 0 \\
-\nu_{xy} & \frac{1}{(1-\sigma_2)E_y} & -\nu_{yz} & 0 & 0 & 0 \\
-\nu_{xz} & -\nu_{yz} & \frac{1}{(1-\sigma_3)E_z} & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{1}{(1-\sigma_4)E_{xy}} & 0 & 0 \\
0 & 0 & 0 & 0 & \frac{1}{(1-\sigma_5)E_{yz}} & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{1}{(1-\sigma_6)E_{xx}}
\end{bmatrix}
$$

The damage thresholds $\sigma_i$ are continuously increasing functions with increasing damage. The damage threshold has an initial value of 1 which results in zero damage in the associated direction. This provides an elastic region initially. The non linear response is modelled by damage growth represented as an increase in the damage variable $\sigma_i$. The damage variables are then used to reduce the material stiffness in the corresponding directions.

The material parameters required to describe a composite material are available from various publications including material data published by the various fibre/resin manufacturers. This includes the modulus, strength and Poisson's ratio. However determining the damage exponent to use in ballistic impact simulation can be very tricky.

The effect of damage exponent is described in many publications such as Matzenmiler et al (1995) Yen (2002), Van Hoof (1999). A low value of $m$ will describe a material that absorb more energy prior to complete damage and failure, with significant stiffness degradation prior to failure and more gradual loss of stiffness after failure. A high value of $m$ will causes similar response to brittle material, with little or no loss in stiffness prior to failure and full damage correspond to zero stiffness shortly after failure.
The selection of \( m \) is very difficult as it was found to be a function of the material and loading rate (Deslauriers et al. 2004). Van Hoof et al (1999) studied the ballistic impact on woven Kevlar and found out that \( m=8 \) provide a reasonable prediction of the material response. In a study of unidirectional CFRP laminate by Williams (Deslauriers et al. 2004) he achieved a good correlation between experimental results and numerical prediction by using \( m=10 \) for low to medium impact energy and \( m=20 \) provided a better results for high impact energies. In a study of ballistic impact on plain woven glass/ Epoxy Yen (2002) used \( m=4 \) and reported a good correlation between the experimental and numerical predicted results. Since the material properties used in simulating the ballistic response on glass epoxy are obtained from literature (Yen 2002) the value of \( m=4 \) has been used in this study.

### 3.5.7 Strain Rate Effect

The effect of strain rate on the layers strength values of the composite failure modes is modelled by multiplying the associated strength values \( S_{STR} \) by a scale factor as Brown (2005):

\[
S_{STR} = S_0 \times \left( 1 + C_{nse} \ln \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right)
\]

Equation 3.19
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\[
S_{STR} = \begin{bmatrix}
S_{ST} \\
S_{ST} \\
S_{ST} \\
S_{ST} \\
S_{ST}
\end{bmatrix} \quad \text{And} \quad \dot{\varepsilon} = \begin{bmatrix}
\dot{\varepsilon}_x \\
\dot{\varepsilon}_y \\
\dot{\varepsilon}_z \\
\dot{\varepsilon}_{xz} \\
\dot{\varepsilon}_{yz}
\end{bmatrix}
\]  
\text{Equation 3.20}

Where

\( C_{rate} \) is the strain rate constant for the strength properties.

\( S_0 \) is the quasi-static reference strength value of \( S_{STR} \) at the reference strain rate \( \dot{\varepsilon}_0 = 1 \text{s}^{-1} \).

\( S_{STR} \) is the rate dependent strength value

\( \dot{\varepsilon}_0 \) is the quasi-static reference strain rate value.

\( \dot{\varepsilon} \) is the associated strain rate value.

Figure 3-7 shows the effect of the strain rate on the axial stress strain response for \( C_{rate} = 0.02 \).

Figure 3-7: Axial tensile stress-strain curve for damage model under various constant strain rates loading.
3.5.8 Delamination

In this section the numerical techniques that can be used to model delamination is been discussed. There are several techniques that have been developed over the past two decades to predict delamination behaviour in composite plate. As discussed in section 2.2.2 the assumptions that the cause of damage and delamination initiation and growth observed in drop weight impact can be valid for ballistic impact also. In general, the analysis of delamination is commonly divided into the study of the initiation and the analysis of the propagation of an already initiated area. Delamination initiation analysis is usually based on stresses and use of criteria such as the quadratic interaction of the interlaminar stresses in conjunction with a characteristic distance (Camanho et al 2001). This distance is a function of specimen geometry and material properties, and its determination always requires extensive testing.

Crack propagation, on the other hand, is usually predicted using the Fracture Mechanics approach. The Fracture Mechanics approach avoids the difficulties associated with the stress singularity at a crack front but requires the presence of a pre-existing delamination whose exact location may be difficult to determine. When used in isolation, neither the strength-based approach nor the Fracture Mechanics approach is adequate for a comprehensive analysis of progressive delamination failure.

The early work to predict delamination saw different authors focusing on interlaminar normal and shear stresses to predict when delamination was more likely to occur. This technique assumes an intact laminate free of any defects and numerical determine stresses in the region of interest which are used to predict failure. The main advantage of the material strength approach is its ability to predict the initiation of delamination however; this approach cannot accurately predict the size and the delamination growth in composite.

The majority of work in predicting delamination growth in composite uses the fracture mechanic methodology which involves the calculation of the strain energy release rate. This approach is similar to the classic fracture mechanic crack growth proposed by (Griffith 1920). However this approach cannot be applied without an initial crack. This means that the delamination initiation does not have the same meaning as that of material strength approach. The best way to describe the meaning of delamination initiation in the fracture mechanics approach is the growth of a pre-existing small crack.
The delamination growth in composite material can be presented using the three fracture mode components: Mode I, the opening mode due to stress normal to the fracture plane. Mode II, the in-plane shear mode occurring due to shear stresses in the direction of crack propagation and Mode III, shear mode due to stresses parallel to the propagating crack front.

![Mode I, Mode II, Mode III](image)

Figure 3-8: Mode I, Mode II and Mode III crack propagating modes (Travesa 2006).

Most of the publications on the growth of delamination focus on mixed modes I-II. The following criterion is often used

$$\left( \frac{G_I}{G_{IC}} \right)^m + \left( \frac{G_{II}}{G_{IIc}} \right)^n = 1$$

Equation 3.21

Where $G_{IC}$ and $G_{IIc}$ are the critical energy release rates for mode I and II respectively. m and n are constants determined using curve fitting of experimental data. The problem with using the fracture mechanic approach is the calculation of fracture parameters such as the stress intensity factor and energy release rates requires nodal variable and information from the node before and behind the crack front. Such calculations can be done with some effort for stationary cracks, but can be extremely difficult when progressive crack propagation is involved (Travesa 2006). The other point about using this approach to predict delamination growth is type of failure criterion is not based on physical or morphological principles, but simply a relationship to fit the data (Van Hoof 1999, Whitney, 1989).

The virtual crack closure technique is one of the most widely used procedures to predict crack propagation. This technique is based on Irwin’s assumption that when a crack extends by a small amount, the energy released in the process is equal to the work required to close the crack to its original length. If the energy
released per unit area is greater than or equal to the critical value, $G_c$, the crack will propagate. The mode I, mode II and mode III energy release rates, $G_I$, $G_{II}$ and $G_{III}$, respectively, can be computed from the nodal forces and displacements obtained from the solution of a finite element model.

In a finite element model such as shown in Figure 3-9, the energy released is the work done by the nodal forces required to close the crack tip, therefore:

$$G_I = \frac{1}{2b\Delta a} F_{cd}^z (v_c - v_d)$$  \hspace{1cm} \text{Equation 3.22}

$$G_{II} = \frac{1}{2b\Delta a} F_{cd}^z (u_c - u_d)$$  \hspace{1cm} \text{Equation 3.23}

$$G_{III} = \frac{1}{2b\Delta a} F_{cd}^z (w_c - w_d)$$  \hspace{1cm} \text{Equation 3.24}

Where $b$ is the specimen thickness, $F_{cd}^x$, $F_{cd}^y$, $F_{cd}^z$ are the magnitude of the nodal forces pairs at nodes c and d in the x, y and z direction respectively. $v_c, u_c, w_c$ and $v_d, u_d, w_d$ are the nodal displacement before node c and d are pulled together.

Figure 3-9: Calculation of the energy release rate using Virtual Crack Closure Technique (Travesa 2006)

The analysis can be done in two steps, using the first step to compute the values of the nodal forces $F_{cd}^x$, $F_{cd}^y$ and $F_{cd}^z$ necessary to hold the nodes c and d together, while the relative displacement components between nodes c and d are computed in the second step. However the analysis can be simplified using the assumption made by Rybicki and Kanninen (Travesa 2006), who suggested that
the values of the nodal forces in equations (3.20), (3.21) and (3.22) can be replaced by the corresponding components of nodal forces $F_{xy}$, $F_{xz}$ and $F_{yz}$.

After calculating $G_I$, $G_{II}$ and $G_{III}$, the total energy release rate reads:

$$G_T = G_I + G_{II} + G_{III}$$  

Equation 3.25

Crack propagation is predicted when the computed energy release rate equal to the fracture toughness of the material $G_c$:

$$G_T = G_c$$  

Equation 3.26

The main advantage of such technique is that it is based on the energy release rate rather than stress.

The need to improve modelling of composite materials in impact analysis has long been recognized. All commercial finite element packages lack full composite description. Delamination is a critical feature of composite material. Several researches have implemented models of delamination behaviour using crash codes. Figure 3-10 shows the result of impact on a composite plate. From the picture it is not clear whether delamination occurs or not and if so the location and the extent.

Figure 3-10: Delamination: a comparison between numerical and experimental results (Yen 2002)
3.5.9 Modelling Delamination

The delamination method chosen to be used in this project is similar to the tie-break contact algorithm in LS-Dyna3D. This approach has been successfully used by Hung et al (1995) to model delamination due to drop weight impact. Van Van Hoof (1999) has reported a good agreement on the numerical prediction and experimental data.

By this method, nodes on opposite sides of an interface where delamination is expected are tied together using spring elements. The interface spring resists the motion in the normal and shear direction.

![Spotweld/Spring elements](image)

**Figure 3-11: Spotweld/Spring elements**

If the constraint forces exceed some criterion, the constraint is released and the delamination grows. The spring elements are used to hold together two sub-laminates. This property calculates the forces generated in the rod elements as it ties two nodes together, and predicts failure if the magnitude of the total force or its components exceeds specified strength value.

During a contact problem, the sliding side is designed as a master surface and the plate as slave surface. As the name indicates, the master surface dictates the behaviour of the slave surface. The first steps in the sliding interface techniques are:

- Identify a series of nodes that makes up the master surface: FSP.
- Identify a series of nodes that makes up the slave surface: Plate.

However, in this case that would not be enough, as modelling delamination requires that the interference between each layer should be modelled. Therefore in addition to the above:

- One layer of the plate is also defined as master and the others as slave.
3.5.9.1 Concluding Remarks

The need for accurate, predictive finite element models of composite structures is increasing due to the increased use of composites structures in both the automotive and aerospace industries. However, modelling composite impact behaviour is a challenging problem.

It seems clear that one of the key areas requiring additional attention is the role of delamination. Various methods for modelling delamination growth as part of impact model have been evaluated. Accurate modelling can be achieved. However, Fleming (1999) & Van Hoof (1999) gave two factors that make the use of such models difficult. First, the mesh size required for accurate delamination prediction is small by the standards of engineering crash models. This may impose a prohibitive computational burden, particularly when using an explicit code, such as MSC Dytran. Second, the dynamic property data required to predict delamination growth are not easily obtained. Critical energy release rates may vary as a function of loading rate; may have different initiation, propagation and arrest values; and are difficult to apply for mixed-mode loading conditions. Until these modelling and material characterization issues are overcome, the simple "spring" method of modelling an interface may present the best choice for use in a crash model. However, a substantial amount of experimental correlation may be required to provide confidence in its use for any specific material/geometry combination.

3.6 Ceramic Damage Models

The response of ceramic material to ballistic impact loading is of complex nature and depends on a large number of variables. The material model should be capable of accurately predicting the failure and damage evolution due to the large stresses. The model should also have the ability to provide some compressive strength after the material has failed. Such material model does not exist in MSC Dytran.

The standard available material models available in MSC Dytran, do not meet the necessary requirements to simulate ballistic impact on ceramic. Therefore several suitable material models available in literature have been reviewed. This section describe damage model for ceramic which is pressure dependent. Two
failure models will be introduced each have different failure surface based on experimental observations.

### 3.6.1 Material Model Selection

For ceramic materials, a change in physical (especially mechanical) properties can be observed with different physical environments. Compressive strengths and ductility may be enhanced under an increased pressure, due to the suppressing or favouring of certain slip systems Lamberts (2007). Besides that, strength increases with increasing strain rate.

Damage models based on Mohr-Coulomb failure criteria (Ref1-2 2003) has been introduced to describe the macroscopic behaviour of material such as ceramic and concrete. Results of depth of penetration simulations were in reasonable agreement with the experimental data.

The ceramic model of Simha appears to be suitable. Computational results are within a few percent of experimental results. One part however of the model is not consistent with any other constitutive model. In the Simha model it is assumed that failed material in compression is stronger than intact material. The explanation given for this unusual behaviour is that failed material consists of more (but smaller) particles with therefore more surface area that interacts during deformation Lamberts (2007). This increase the internal friction results is higher strength. This is contradicting with what is to be expected, as failed material has less strength than intact material. Because of this inconsistency, this model will not be selected.

Microphysical modelling, which is based on evolving microcracks, is one way of modelling ceramic material. But since this theory is only based on a single crack propagation and no crack interaction is considered, this way of describing the ceramic material response remains to be more phenomenological than properly micromechanical based. Therefore, this type of constitutive modelling will not be adopted for computations of ceramic impact simulations.

The Johnson-Holmquist models are frequently used in ballistic research of brittle materials because of their relatively easy theory and implementation. In AUTODYN and LS Dyna the first two Johnson-Holmquist models (i.e. JH1 and JH2) are implemented. These softwares are similar to MSC Dytran as they are especially developed for simulating impact loading on various types of structures, like spacecrafts, armour material or brick walls. However AUTODYN and LS Dyna have additional advantages as the material library contains more suitable
models to describe brittle material behaviour. In both program codes the Johnson-Holmquist models generate agreeable results which therefore can provide good insight in the ceramic material response. The latest model however, the Johnson Holmquist Beissel model (JHB), has not yet been implemented in any of these codes since it is rather new. This model is very similar to the JH1 model, both having a discrete damage model. The JH2 model is somewhat different since it has a continuous damage model. To model the correct material behaviour, the intact strength of the JH2 model is always higher than that of the JH1 or JHB model, because the damage reduces the strength as plastic strain accumulates. This eventually results in similar material strengths for all three models.

However determination of the JH2 parameters is more difficult, since the damage evolution has to be taken into account. Therefore the JH1 model will be selected to be implemented into MSC.Dytran to model the ceramic material behaviour. This model is more favourable than the JH2 model, since it has less functions analytical functions.

3.6.2 Mohr-Coulomb Model

This model is an attempt to capture the material behaviour of pressure dependent material or materials that contain voids and crush or compact under pressure. Examples of such material where strength significantly degrade by crushing include soils, foams, concrete, wood and ceramic.

A ceramic maintains its compressive strength as the hydrostatic pressure increases, which makes it easy to model using Mohr-Coulomb model which used yield strength as a function of local hydrostatic pressure.

![Mohr-Coulomb Model: Yield Stress as Function of Pressure](image)

Figure 3-12: Mohr-Coulomb Model: Yield Stress as Function of Pressure
As the hydrostatic pressure increases the ceramic crushes and damage start accumulating; to capture this phenomenon a damage factor is introduced. This damage factor reduces the elastic moduli and the strength of the ceramic. Initially this damage factor $D$ is set to zero for all elastic deformation. The factor remains constant for all plastic deformation for which the effective strain value is less than Effective Plastic Strain 1 ($\text{EPS}_1$). As the effective plastic strain increases above $\text{EPS}_1$ the damage starts accumulating and the damage parameter increases linearly until it reaches a maximum damage $D_{\text{max}}$ at an effective Plastic strain value of ($\text{EPS}_2$) and remains constant after that as shown in Figure 3-13.

![Figure 3-13: Accumulative Damage Function $D$ of Effective Plastic Strain](image)

$$D = D_{\text{max}} \times \left( \frac{\text{EPS} - \text{EPS}_1}{\text{EPS}_2 - \text{EPS}_1} \right)$$

Equation 3.27

The progressive damage is modelled by reducing the yield strength using the damage factor $D$. The material has no residual strength in tension. However in compression the damaged ceramic maintain some residual strength.

When the hydrostatic pressure is positive, the yield strength is calculated as follows:

$$Y_{\text{Dam}} = Y \times (1 - D)$$

Equation 3.28
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When $D$ is maximum, the residual strength is greater than zero.

When the hydrostatic pressure is negative, the yield strength is calculated as follows:

$$ Y_{\text{dam}} = Y \times \left( 1 - \frac{D}{D_{\text{max}}} \right) $$

Equation 3.29

When $D$ is maximum, the residual strength is zero.

Figure 3-14: Yield Strength as a function of accumulative damage

In compression, Bulk Modulus and shear modulus are unaffected. However in tension they are progressively reduced to zero.
3.6.3 Johnson Holmquist 1

The Johnson Holmquist model JH-1 was first proposed to describe the brittle behaviour of ceramic subjected to large deformation, it is a very simple model, which consists of an intact strength and a failed strength surfaces that are functions of the pressure, the strain rate, and the damage. Pressure, bulking and damage are other aspects of the model. This is the first of three closely related models, JH-1 Johnson Holmquist (1990), JH-2 Cronin (1999) and Johnson Holmquist Beissel (2003).

3.6.3.1 Pressure

The Johnson Holmquist constitutive model requires several material variables to describe the response of certain material. Initially the material response is considered elastic where the material is described by the following equation of state.

The pressure before failure is simply:

\[ P = K_1 \mu + K_2 \mu^2 + K_3 \mu^3 \]  

Equation 3.30

In Tension
\[ P = K_1 \mu \]  

**Equation 3.31**

Where

\[ \mu = \frac{\rho}{\rho_0} - 1 = \frac{V_0}{V} - 1 \]  

**Equation 3.32**

\( P \) = the pressure  
\( K \) = Constant  
\( \rho \) = Density  
\( V \) = Volume

**Figure 3-16 Pressure in Johnson Holmquist Model (JH1)**

After complete failure has occurred, bulking can occur because of a pressure increase and/or volumetric strain increases (Johnson Holmquist 1990 and 2005). This can be described physically as the larger volume a fractured material occupies compared to the intact material. Constrain or confinement from surrounding material results in local increase in pressure. Therefore, an
additional pressure, $\Delta P$, is added to equation 3.30. This pressure increase is determined by energy considerations. The loss of internal elastic energy, $\Delta U$, is converted into potential hydrostatic energy.

$$P = K_1 \mu + K_2 \mu^2 + K_3 \mu^3 + \Delta P$$  \hspace{1cm} \text{Equation 3.33}$$

The pressure increase is determined from energy conservation. Figure 3-17 is shown that a decrease in material strength occurs when the material changes from an intact ($D < 1$) state to a failed state ($D = 1$). This represents a decrease of the internal elastic energy of the deviator and shear stress. The general expression of this internal energy is

$$U = \frac{s_x^2 + s_y^2 + s_z^2 - 2\nu(s_x^2 + s_y^2 + s_z^2)}{2(1 + \nu)} + \frac{2(1 + \nu)(r_{xy}^2 + r_{yz}^2 + r_{zx}^2)}{2E}$$  \hspace{1cm} \text{Equation 3.34}$$

Where $\sigma_x, \sigma_y, \sigma_z$ are the normal deviator stresses; $r_x, r_y, r_z$ are the shear stresses; $\nu$ is Poisson’s ratio; and $E$ is modulus of elasticity.

Equation 3.34 can be expressed as:

$$U = \frac{\sigma^2}{6G}$$  \hspace{1cm} \text{Equation 3.35}$$

Where $\sigma$ is the von Mises stress and $G$ is the shear modulus of elasticity.

The decrease in internal elastic energy can be expressed as:

$$\Delta U = U_i - U_f$$  \hspace{1cm} \text{Equation 3.36}$$

Where $U_i$, elastic energy of the material before failure ($D < 1$) and $U_f$ is the elastic energy after failure ($D = 1$).

This loss of deviator and shear stress (internal energy) is converted into potential hydrostatic energy by adding $\Delta P$. An approximate equation for energy conservation is:

$$\Delta P \mu_f + \frac{\Delta P^2}{2K_1} = \beta \Delta U$$  \hspace{1cm} \text{Equation 3.37}$$

Where $\mu_f$ is $\mu$ at failure and $\beta$ is the fraction of the elastic energy lost converted to hydrostatic energy.
The first term \((\Delta P\mu_j)\) is the approximate potential energy for \(\mu > 0\) and the second term \(\left[\frac{\Delta P^2}{2K_1}\right]\) is the corresponding potential energy for \(\mu < 0\).

Solving for \(\Delta P\) gives

\[
\Delta P = -K_1\mu_j + \sqrt{(K_1\mu_j)^2 + 2\beta K_1 \Delta U}
\]

Equation 3.38

It should be noted that \(\Delta P = 0\) for \(\beta = 0\), and that \(\Delta P\) increases as \(\Delta U\) for \(\beta = 0\) increases and/or \(\mu_j\) decreases.

3.6.3.2 Strength

A summarized overview of the strength model is provided Figure 3-17. Figure 3-17 shows that the strength (von Mises stress) \(\sigma\) is dependent on the pressure \(P\). The graph also shows that as the pressure increases, the material strength increases significantly. This is consistent with the well-known fact that brittle materials are much stronger in compression than they are in tension.

The equivalent stress (strength) is a function of pressure strain rate, and damage \(D\), for undamaged material \(D=0\), and for totally damaged material \(D=1\). For the partially damaged material, the strength is taken to be equal to the intact strength.

For intact material, the strength is assumed to increase linearly from \(\sigma = 0\) at a tensile pressure of \(-T\) to strength of \(\sigma = S1\) at a pressure of \(P = Pl\). \(T\) is the maximum hydrostatic tension the material can withstand. When subjected to tensile pressure, the material responds elastically until brittle failure at a specified effective stress value. This corresponds to a complete instantaneous damage. Once fracture has occurred, the material lose all its capability to carry any tensile loading. The damaged material however maintains some of its compressive strength and can still carry some compressive loading as described by strength of failed material (\(D=1\)) curve.
Chapter 3 Key Aspect of Numerical Modelling

Intact Material Strength

\[ S_1 \]

\[ S_2 \]

\[ S_3 \]

Fractured

\[ T \]

\[ P_1 \]

\[ P_2 \]

Pressure P

\[ \dot{\varepsilon} > 1.0 \]

\[ \dot{\varepsilon} = 1.0 \]

Figure 3-17: Effective Stress as Function of Pressure

T is the maximum hydrostatic pressure the material can undergo.

S1 and S2 are the intact Material strength at compressive pressure P1 and P2 respectively.

After the material has fractured (D = 1) the slope of the fractured strength is given by C6, and the maximum fractured strength is S3.

3.6.3.3 Damage

The JH1 model has a pressure dependent damage model included. Damage is accumulated in a similar manner as in the Johnson Cook failure model and is defined as:

\[ D = \sum \frac{\Delta \varepsilon}{\varepsilon_f} \]

Figure 3-18: Damage in Johnson Holmquist (JH1)
\[ D = \sum \frac{\Delta \varepsilon}{\varepsilon_f^p} \]  

Equation 3.39

Where \( \Delta \varepsilon^p \) is the plastic strain during a cycle of integration.

\( \varepsilon_f^p = f(p) \) is the plastic strain to fracture under constant pressure \( P \) referred to in the damage graph. The material does not undergo any plastic strain at the maximum hydrostatic tensile pressure \( T \) and increases to \( \varepsilon_f^p = EFMAX \) at compressive pressure \( P = DP1 \).

Most of the constants used in the JH1 model are obtained from Hopkinson bar tension compression or torsion tests.

### 3.7 Concluding Remarks

#### 3.7.1 Composite Material

The composite plate will be modelled using 8-noded 3D orthotropic Lagrangian solid elements with single point integration. The model consists of up to 24 layers; each layer is 0.5mm thick resulting in a maximum thickness of 12 mm.

In this research a distinction between the intralaminar and interlaminar failure modes will made, and each type of this type of failure modes was treated in a separate part of the software.

The intralaminar failure modes (fibre breakage, matrix cracking, through thickness crushing and shear failure) will be modelled within the element constitutive routine and defined using material subroutines.

**Tensile/shear fibre mode: \( \sigma_{xx}, \sigma_{yy} \geq 0 \)**

\[
\left( \frac{E_x(\varepsilon_x)}{S_{xT}} \right)^2 + \left( \frac{G_{xy} \varepsilon_{xy}}{S_{sfs}} \right)^2 = r \]  

Equation 3.9

\[
\left( \frac{E_y(\varepsilon_y)}{S_{yT}} \right)^2 + \left( \frac{G_{yx} \varepsilon_{yx}}{S_{sfs}} \right)^2 = r \]  

Equation 3.10
Chapter 3 Key Aspect of Numerical Modelling

**Compressive fibre mode:** $\sigma_x, \sigma_y < 0$

$$\left( \frac{E_x (\varepsilon_x)}{S_{xc}} \right)^2 = r,$$  
Equation 3.11

$$\left( \frac{E_y (\varepsilon_y)}{S_{yc}} \right)^2 = r,$$  
Equation 3.12

**Fibre Crush damage Mode:** $E_z \geq 0$

$$\left( \frac{E_z (\varepsilon_z)}{S_{zc}} \right)^2 = r,$$  
Equation 3.13

**Matrix Shear Failure Mode**

$$\left( \frac{G_{xy} (\varepsilon_{xy})}{S_{sy}} \right)^2 = 1,$$  
Equation 3.14

The interlaminar failure mode included delamination; the method chosen to be used in this project is similar to the tie-break contact algorithm in LS-Dyna3D. This approach has been successfully used by Hung et al 1995 to model delamination due to drop weight impact. Van Hoof (1999) has reported a good agreement on the numerical prediction and experimental data.

By this method, nodes on opposite sides of an interface where delamination is expected are tied together using spring elements. The interface spring resists the motion in the normal and shear direction.

![Figure 3-19: Spotweld/ Spring elements](image)

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If the constraint forces exceed some criterion, the constraint is released and the delamination grows. The spring elements are used to hold together two sub-laminates. This property calculates the forces generated in the rod elements as it ties two nodes together, and predicts failure if the magnitude of the total force or its components exceeds specified strength value.

3.7.2 Ceramic

For ceramic damage models, Mohr-Coulomb and Johnson-Holmquist 1 models have been selected for this study as are frequently used in ballistic research of brittle materials because of their relatively easy theory and implementation. The JH1 uses two surface strength curves to model intact and completely damaged ceramic where as the MC model has a continuous damage model where the strength is assumed to be a reduced using a damage factor D. Both models have been described in details in chapter 3.6.
4 MODEL CALIBRATION

4.1 Model Description

MSC Dytran is a three-dimensional finite element code that has been used in this study (as requested by the sponsor) to simulate the ballistic impact loading of different composite and isotropic materials. This program is an explicit finite element code dedicated to analyse dynamic problems associated with large deformation, high velocity impact, and ballistic propagation. MSC Dytran seeks a solution of the momentum equation satisfying the traction and displacement boundary conditions on the exterior and interior boundaries respectively.

The energy equation is integrated in time and is used for equation of state evaluation, and for a global energy balance. The velocities and displacements are updated accordingly. The principal limitation during integration is the size of the time step, which should be small enough so that a second wave cannot travel across the smallest element during one integration step. Finite element models for the projectile and the plate were built using MSC Patran; the plates are modelled using eight-noded three-dimensional solid orthotropic elements, whereas the projectiles are modelled using rigid four nodded shell elements.

For composite damage and failure prediction, MSC Dytran has a variety of models available (MSC Dytran Manual, 2003 & 2005). The first class of models contains the interactive models that predict the onset of failure, but not the failure mode. This class contains the Tsai-Hill and Tsai-Wu failure theories. The second class not only predicts the onset of failure, but provides the fibre compression (fibre buckling), matrix tension (matrix cracking), matrix compression, or in-plane shear failure. Theories that fall in the latter class are the Chang-Chang, maximum stress, modified Tsai-Wu, and Hashin failure theory. However all these failures are only available for orthotropic shell elements that are widely used in aerospace and automotive industry.

As for 3-D orthotropic element, (FAILxxx) entry can be referenced to define a failure model for the material. The failure model can be based on a maximum stress limit, or maximum pressure limit, which are not usually used to obtain accurate results and predicts ways to improve ballistic protection of the
materials. To achieve that detailed study of the effect of each material property on the ballistic response of the plate is to be carried out. The only other option where more details can be included is to use external user subroutines.

4.1.1 User subroutine

User subroutines are a powerful feature in MSC Dytran that allows the program to be customised to provide capabilities that are not possible with standard program. Within certain subroutines, there is easy access to the data stored for the elements and grid point. The restriction is that the user-written subroutine must have the list of the user numbers of the elements and grid points involved. That way the grid point can be stored and retrieved.

A user-subroutine allows for the description of a more detailed failure mechanism for a more complicated material such as composite. The subroutine must ultimately return the failure flag for the element that has been processed. The failure flag indicates either failure or no failure. MSC Dytran processes the resulting failure flags and sets the element stresses to zero when the failure flag indicates that material has reached its limit. In addition to ultimate failure, property degradation prior to complete material failure can be defined. Property degradation means that the material properties that describe the material's elastic behaviour are allowed to degrade up to zero before the material completely fails. Effectively, property degradation influences the element's capability to carry loading as it gets weaker during this process. Depending on the described model in the subroutine, all properties can degrade completely before material failure occurs or when a certain property reaches a limit, material failure occurs.

MSC Dytran uses a Fortran 90 compiler so a working knowledge of FORTRAN and a full understanding of the processes to be simulated are essential in describing the problem. Yet care must be taken when using user-subroutine compiler as it is possible to corrupt the data stored within the MSC Dytran, rendering the results meaningless.

4.2 Energy Balance and Single Cell Study

During a ballistic impact, the kinetic energy of the projectile is transferred to the plate and absorbed through various damage mechanisms, increasing the internal energy of the system. The accuracy of the simulation can be verified by the
conservation of energy of the system. The energy transferred from the projectile to the plate can be expressed by equation:

\[ E_{\text{Tran}} = IE_{\text{Plate}} + KE_{\text{Plate}} + HGE_{\text{Plate}} + E_{\text{Eroded}} \]  

Equation 4.1

Where E, IE, KE, HGE denote total energy, internal energy, kinetic energy and hourglass energy. Subscript tran and plate denote transferred and plate. Law of conservation of energy is observed in any physical phenomena. The kinetic energy of the projectile is spent increasing the kinetic energy, internal energy of the plate other part are lost in the form of eroded material. The hourglass mode (HG) is a non physical, zero energy mode of deformation that produces zero strain and proper HG coefficient can help reduce hourglassing.

![Energy History Graph](image)

Figure 4-1: Energy History for 5 mm plate impacted with 0.22" FSP

The initial kinetic energy of the impacting projectile is computed as:

\[ KE = \frac{1}{2} mv^2 \]

The variation in energy history of the projectile kinetic energy, the plate energies are presented in Figure 4-1. During the impact process, a significant amount of
the projectile kinetic energy is transferred to the target and converted into internal, kinetic, eroded and hourglass energies. During the impact process a small variation between the energy lost by the projectile and the total energy transfer to the plate was noticed. The slight total energy variation (approximately 1%) was assumed to be caused by the energy contributed to the system during the removal of the penetration. Since the energy variation was less than 1% of the total energy which appears to be insignificant no modification has been applied to the system.

### 4.3 Single cell Study

To verify that the model complies with the represent damage and failure laws described in the subroutines it was necessary to use a single cell model and compare the results with hand calculations. In this study only one element is modelled using the composite 3D orthotropic element properties and only a single failure is defined each time. At each time step the stress and the element response to that failure is extracted and checked manually to make sure the correct failure has been predicted. The purpose of this exercise is simply to make sure that when the stresses in the element reach the failure value described in the subroutine the element will fail.

#### 4.3.1 Boundary Conditions

![Single cell schematic and boundary condition](image)

ABCD Const in Z-Axis  
ABFE Const in Y-Axis  
ADHE Const in X-axis

Figure 4-2: Single cell schematic and boundary condition
4.3.2 Tension

In the first test only tensile failure has been implemented in the user subroutine. The maximum tensile strength is set to 740 MPa. The element is then subjected to dynamic tensile force.

![Figure 4-3: single element response to tensile force](image)

Figure 4-3 shows the element tensile stress continues to increase until the maximum tensile strength is reached, when failure occurs the stresses are set to zero.

4.3.3 Compression

In the second test only compressive failure has been described in the user subroutine. The maximum compressive strength is set to 390 MPa. The element is then subjected to compressive stress.
Figure 4-4: single element response to Compressive stress

Figure 4-4 shows the element compressive stress continues to increase until the maximum compressive strength is reached, once the failure occurs the compressive stress is set to zero.

4.3.4 Shear

In the third test only shear failure has been described in the subroutine. The maximum shear strength is set to 48 MPa
Figure 4-5: Single Element response to shear stress

Figure 4-5 shows the element shear stress continues to increase until the maximum shear strength is reached, and then failure occurs.

4.3.5 Concluding remarks

The finding of this single cell element studies indicates that the model complies with the failure mechanism described in the user subroutine. And the Program accurately processes the resulting failure flag from the subroutine and sets the stresses to zero when the failure flags indicate material failure.

4.4 Mesh

Based on information obtained from literature and from firsthand experience it is well documented that damage failure and energy absorption by the plate during ballistic impact strongly depend on the type of mesh used. The smaller the mesh the sooner the failure occurs. There are many studies of ballistic impact on composite plate available in the literature (See Van Hoof 1999, kamel et al 1998) however most of these references do not give detailed descriptions of the mesh size effect on energy absorbed during the ballistic event. Further, to the author's
knowledge none of tests studies have been carried out using MSC Dytran. Most of these studies do not reveal the size of the element used in their studies, and if the size is mentioned no explanation is given to justify their use. In this chapter all aspect of meshing technique will be studied in a bid to obtain and justify the optimum element size and meshing technique.

**4.4.1 Components of the model**

*Fragment Simulating Projectile, FSP*

The projectile used in this study is a 0.22" FSP Threat as shown in Figure 4-7; it has been modelled using four node rigid shell elements. The total number of FSP elements is 300.

*Composite Plate*

![Figure 4-6: Schematic of the FSP and Composite Plate](image)

![Figure 4-7: Fragment Simulating Projectile](image)
4.5 Full and Quarter model

When trying to carry out mesh sensitivity study using 3D-orthotropic element two very important factors need to be considered and taken into account. First the plate thickness: when using a thin plate the ballistic limit difference for small and large elements may not be big enough to cause any concern, which may not necessarily, be the case for the thick plate. It is therefore decided that the plate should have a considerable thickness. That leads to the second problem which is the number of element used in the simulation. These must be kept to a minimum. The proposed solution is to model only a quarter of the plate and use symmetry; however it is necessary to make sure that the new boundary condition will not affect the outcome of the simulation. Table 4-1 gives the details of the full and quarter plate used in this simulation.

Table 4-1: summary of two models used.

<table>
<thead>
<tr>
<th>Model Type</th>
<th>Number Elements</th>
<th>Initial Velocity</th>
<th>Residual Velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Model</td>
<td>125189</td>
<td>550</td>
<td>297</td>
</tr>
<tr>
<td>Quarter Model</td>
<td>31461</td>
<td>550</td>
<td>294</td>
</tr>
</tbody>
</table>

Boundary Condition

ABCD: fully constrained
E: constrained in X-axis
F: constrained in Y axis

Figure 4-8: Full and quarter plate boundary conditions
Figure 4-9 shows the velocity profiles of the full and quarter plate. It is clear that the velocity profiles are almost identical and therefore it is safe to assume that the use of only a quarter model with symmetry will not compromise the results of the ballistic simulation.

4.6 Mesh Size Study

As mentioned earlier it is well known that numerical simulation of ballistic impact using explicit software is highly mesh dependent. Based on work done by Van Hoof (1999) it is concluded that element failure is not only material property dependent, but also depends on the element size. In general the smaller the element the sooner the failure occurs. In this section a study of the effect of in-plane mesh size on the ballistic limit, energy absorbed, time step, failure size and shape is presented.

Since there is no mention on the element dimensions that can be used in finite element simulation several element size were studied see Table 4-2.
Since a wide range of element size will be studied in this investigation it was decided that a thickness should be kept to a minimum however since the change on ballistic limit heavily depend on the thickness of the plate it was decided on 5 mm of composite plate. Each layer has a length and width of 50 mm and a thickness of 0.5 mm resulting in 10 layers. The details are shown in Table 4-2.

Table 4-2: Summary of meshed used in this investigation

<table>
<thead>
<tr>
<th>L (mm)</th>
<th>Qtr Plate Elem No.</th>
<th>Calculated time step</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50</td>
<td>100000</td>
<td>1.2 E-7</td>
</tr>
<tr>
<td>0.40</td>
<td>156250</td>
<td>9.8e-8</td>
</tr>
<tr>
<td>0.30</td>
<td>277222</td>
<td>7.3e-8</td>
</tr>
<tr>
<td>0.25</td>
<td>400000</td>
<td>6.12e-8</td>
</tr>
<tr>
<td>0.20</td>
<td>625000</td>
<td>4.80e-8</td>
</tr>
<tr>
<td>0.15</td>
<td>1108890</td>
<td>3.6e-8</td>
</tr>
<tr>
<td>0.10</td>
<td>2500000</td>
<td>2.4e-8</td>
</tr>
</tbody>
</table>

Table 1.2 shows a summary of the element size, the number of element used in the quarter plate simulation and the theoretically estimated time step during the simulation. The table shows that as the element size decreases the number of element used in the simulation significantly increases and the time step decreases. In MSC. Dytran the time step is determined by the following equations:

\[ \Delta t = \frac{SL}{c} \]  
\[ c = \sqrt{\frac{\text{Young's Modulus}}{\text{Density}}} \]

Equation 4.2  
Equation 4.3
Where

\[ c = \text{the speed of sound in the plate} \]

\[ S = \text{Constant} \]

\[ \Delta t = \text{time step} \]

\[ L = \text{Element dimension} \]

As expected increasing the number of elements used in the simulation coupled with a reduction in the time step will inevitably result in an increase in the processing time.

![Figure 4-10: Effect of mesh size on the amount of energy absorbed](image)

Figure 4-10 summarise the effect of varying the in-plane mesh density. The graph shows that the predicted amount of energy absorbed by the plate decreases significantly as the mesh density increases, and it continues to do so. When the element dimensions are large the residual velocity is low which means that the elements absorb more energy before they fail. Hence the plate absorbed more kinetic energy as a result the predicted ballistic limit of the plate is higher. As the in-plane element dimension decreases the residual velocity increases.
That leads to a lower ballistic limit velocity which means that the element failed sooner.

As the element size becomes smaller the changes in energy absorption becomes less and less significant. The graph also shows that the difference in the amount of energy absorbed by the plate for element size 0.20 mm and 0.15 mm is almost negligible. It is therefore assumed that as far as energy absorption mechanism is concerned once the element size reach 0.20 mm the energy level will be constant and any further reduction will have no significant effect on the results. It is also worth mentioning that increasing the mesh density any further will cause the model to stop as the mesh would far exceed the computer capability.

![Graph](image)

**Figure 4-11: Effect of mesh size on the simulated ballistic event time**

Figure 4-11 summarise the effect of element size on the simulated time of a ballistic event. The graph shows that for the same number of cycles the simulated time has been significantly reduced as the element size is reduced. For element size 0.50 mm the total simulated time was 18 μs that was reduced to just 5 μs for element size 0.4 mm and continues to do so as the element dimension is reduced. In contrast to the effect the mesh density has on the energy absorption where it stops at 0.20 mm, the time reduction continues throughout the investigation. So the ballistic event simulated time will always decrease with the element size. This means that the CPU time required to
simulate a ballistic event of \((x \, \mu s)\) will be much longer if smaller elements are used. This is better demonstrated in Figure 4-12.

![Figure 4-12: Effect of mesh size on average time step](image)

Figure 4-12 shows the effect of element size on the time step. It is clear from the graph that the element size has a strong influence on the average time step and that the time step decreases as the mesh density increases. The graph shows that the actual time step is much smaller than the calculated one. In general the time step is calculated using Equation 4.2 and equation 4.3 for both cases. However when the element is subjected to loading the element dimension changes hence the time step changes as it depends on the length of the smallest element dimension.

The effect of in-plane mesh density on the predicted back-plane displacement is summarised in Figure 4-13. It is clear that element size has a large influence on the plate response. When element size are large, a large back-plane response was predicted that continue to decrease as the mesh density increases until element size reached 0.30 mm where it was noticed that the back-plane response was becoming constant.
Figure 4-13: Effect of mesh size on the backplane response

Figure 4-14: Effect of mesh density on damage pattern top view. a) 0.50 mm mesh; b) 0.20 mm mesh.
Figure 4-15: A 3D view of the Effect of mesh density on damage pattern side view. a) 0.50 mm mesh; b) 0.20 mm mesh.

Figure 4-16: Effect of mesh density on damage pattern Bottom view. a) 0.50 mm mesh; b) 0.20 mm mesh.

Figure 4-14 to Figure 4-16 shows the effect of varying the in-plane mesh density on the damage size and pattern of a composite plate. The figures show that the element size influences the damage size. When the element dimensions were 0.50 mm Figure 8-12-14 a) the damage size was bigger which explains the result obtained in Figure 4-10; where it was shown that plate with bigger element absorbed more energy. As the mesh density increases the damage area size decreases which are consistent with results obtained in Figure 4-10; the damage size continues to decrease as the mesh density increases until the element dimensions become 0.20 mm and then the damage pattern remains largely unchanged.
Comparing the damage size and pattern between the top and bottom side of each plate shows that the damage size at the point of entry (top side Figure 4-14) is smaller than that at point of exit (Bottom side Figure 4-16), which is consistent with experimental observations.

The different colours shown in Figure 4-14 to Figure 4-16 represent different failure times. In the simulation where element dimensions were 0.50 mm there were only three colours representing the failure time. That increases to five colours when 0.20 mm elements were used to simulate the ballistic impact. That indicate that the smaller the element dimension used the more detailed time history and result can be obtained. However it also indicates the smaller the mesh used the smaller the time step becomes.

4.7 Effect of Meshed area

Another problem that arises when modelling ballistic impact on composite structure is the dimensions of the modelled area. Different researchers use different dimensions. Usually the size of the modelled plate is taken to be equal to that used in the experiment to verify the results. In high velocity impact the damage area is small and local as the plate thickness increases the area of visible damage and full penetration may remain small but delamination may become larger depending on the type of fabric used. In this section the plate dimension effect on the ballistic response and the amount of absorbed energy was be studied.
Figure 4-18: Effect of the size of modelled area

Figure 4-18 shows the effect of the modelled size on the amount of energy absorbed by the plate. The graph indicates that the amount of energy absorbed by the plate increases as the plate dimensions increase. These increases could be explained by the in-plane stress waves. When the plate dimensions are small the in-plane stress waves quickly reach the edges of the plate reflecting back and causing peak in the stress waves which cause failure. As the plate dimensions increase and the edge of the plate become further from the point of impact the in-plane stress wave take longer to reach the edges and reflect back. Once the plate dimensions reach 30 mm; the difference on the amount of energy absorbed by the plate becomes constant. Since the plate thickness will be varied between 2mm to 12mm and the impact velocity will also be varied, a larger plate dimension (50mm x 50mm) was selected to accommodate any increase in the size of the damage and delamination.

4.8 Bias Mesh

As seen earlier, explicit codes are mesh dependent. In contact problems it is crucial to have a mesh as small as possible. However, meshing the entire plate
with small mesh will lead to undesirable problems. Usually the area of interest in a ballistic impact event is small and located exactly under the impactor. Modelling the entire three-dimensional complex bodies with small mesh and calculating the stresses at each nodal point is very inefficient way of solving the problem, especially if spotweld or spring elements are added and subroutines are used to describe material behaviour.

Since the area of interest in a ballistic event is located exactly under the impactor and the surrounding area, only a small area will be meshed with fine constant mesh. The elements size is gradually increased when moving away from the centre toward the edges of the plate. Initially four solid bodies were used to model each composite layer and result of initial trial is shown in Figure 4-20. At point of entry the damage area is small and local compared to a larger damage area at the point of exit. In addition, the delamination only occurs at the rear of the plate. These results are consistent with experimental observations. However, the figure also shows some additional damage areas [A, B & C], which are not consistent with experimental observations.

![Figure 4-19: First design option; Bias mesh](image)

The cause of these failures could be a sudden increase in the mesh density, the reflecting wave from the edge of the plate.
Chapter 4 Model Calibration

The first design option with bias mesh predicted additional failure around area [A] (see Figure 4-20) which is not consistent with experimental observation. It seems that there is a distinct possibility that the element quality used away from the impact area is so poor that a severe distortion of the stress wave due to numerical reflection is created. It is well known that increasing the element dimension too quickly will cause internal reflections and create odd results.

Since this problem only appeared when bias mesh was used, it is possible that the problem with such model is the sudden change or increase in the mesh density. When using such technique care must be taken so that only a gradual increase in element size is allowed.

Another problem with this technique is the elements size and shape near the edge of the plate Figure 4-20 [C&B]. These have large length to width ratio; elements can quickly deform reducing the accuracy of the calculation, reducing the time step and ultimately cause failure when the length of the side of the elements becomes zero.

Based on these observations it was concluded that the main problem with such technique is the sudden increase in the mesh and elements size. In the next design option the issues of sudden increase in mesh density and the large length to width of the elements near the edge of the plate have been addressed.

Figure 4-20: Numerical simulation of ballistic impact on composite plate
4.9 Effect of Mesh Density of Contact

Previously, the effect of mesh density of the plate has been investigated. In this section the effect of varying the mesh density between the FSP and the plate will be studied. The projectile is modelled with three different element dimensions 1.0mm 0.5 mm 0.3mm and 0.1mm, which is smaller than the plate mesh.

![Graph showing the effect of varying FSP mesh density on energy absorbed.](image)

**Figure 4-21:** Effect of varying FSP mesh density on energy absorbed.

Figure 4-21 shows the energy absorbed by the plate impacted with 0.3" FSP travelling at 900 m/s. In the cases where the mesh density of the projectile is larger or equal to that of the plate the amount of energy absorbed is constant. Whereas in the case where the projectile mesh is smaller than that of the plate, there is an increase in the amount of absorbed energy. When the master element is larger than the slave it may penetrate an element without been detected, but when it is detected in the next integration time it will be trapped hence a larger force is required to push it through.
Chapter 4 Model Calibration

Figure 4-22 shows that FSP penetrated the plate but some elements did not fail. This indicates that the Master nodes went through the slave without being detected.

The mesh density of the slave surface should always be finer than that of the master surface because the slave points are checked for penetration of the master segments but not vice versa. If the mesh density of the master is finer than the slave surface then, penetrations can occur with the master surface going through the slave without being detected.

4.10 Effect of Mesh Under The Impact Region

The element type used in area meshed with small and constant element is investigated in the section. Two options have been studied:

Option 1: This area had a cylindrical shape with constant Hex Element of 0.20 mm dimension as shown in Figure 4-23.

Option 2: This area was modelled using four solid bodies as seen in Figure 4-24, the area exactly under the impactor was given a cubical.
Figure 4-23: Design Option 1

Figure 4-24: Design Option 2
The ballistic response of both models of the composite plates and the amount of energy absorbed by the plates during the ballistic event remain unchanged. However the effect of element shape under the projectile on the duration simulated is shown in Figure 4-25. It is clear that the quality of the element has a great influence on the time step. In both cases the element dimension were kept at 0.20 mm. however, in the case of circular plate the time step has been halved. That can be explained by the quality of element at the centre of the plate (option 1), where the element has a pancake like shape. During the analysis, the element shape (which is used in defining the time step) may be severely distorted changing it dimensions, causing the time step becomes smaller as it depends on the smallest element side (Eq. 4.1 - 4.2).

The effect using spotweld to model delamination on the total time of the process per cycles is shown in Figure 4-26. The graph indicates that the spotweld/spring effect on the time step far exceeds the effect of the element size and quality. In the above analysis the plate length, thickness and all boundary condition were kept the same. The element dimension remained 0.2mm. Spotweld are introduced to the plate with rectangular elements to tie together the nodes of the opposite sides where delamination is expected. The figure shows that in this case plate with spotweld the time step more than halved. Which means that the CPU time, number of time steps and the data produced will
increase dramatically. However this problem cannot be avoided if delamination is to be taken into consideration in this simulation.

![Graph showing the effect of spotweld on time step](image)

**Figure 4-26: Effect of spotweld on time step**

The effect using spotweld to model delamination on the total time of the process per cycles is shown in Figure 4-26. The graph indicates that the spotweld/spring effect on the time step far exceeds the effect of the element size and quality. In the above analysis the plate length, thickness and all boundary condition were kept the same. The element dimension remained 0.2mm. Spotweld are introduced to the plate with rectangular elements to tie together the nodes of the opposite sides where delamination is expected. The figure shows that in this case plate with spotweld the time step more than halved. Which means that the CPU time, number of time steps and the data produced will increase dramatically. However this problem cannot be avoided if delamination is to be taken into consideration in this simulation.

**Figure 4-27** shows the result of a 7 layers of S2 Vinyl Ester composite plate impacted with 0.88g ball at a velocity of 900m/s. As expected the damage is small and local and a small delamination occurs at the back of the plate.
Figure 4-27: Ballistic Impact Simulation of 14 layers of composite impacted with 0.88g ball above ballistic limit velocity.
Figure 4-28: Ballistic Impact Simulation of 14 layers of composite impacted with 0.88g ball below ballistic limit velocity.
Figure 4-28 show the result of the same plate impacted with a speed below the ballistic limit velocity. The time taken by the projectile to come to rest is longer than the time it took clear the plate in the case of high velocity impact. That is clearly demonstrated by the colour index, where there are more colours in the case of below ballistic impact velocity. The total fibre damage is small compared to that of high velocity impact; however the delamination is larger. In this case the projectile's kinetic energy is low and not enough to penetrate the fibre. But it is sufficient enough to cause matrix failure and delamination.

4.11 Summary

To verify the validity and accuracy of the model two separate studies has been carried out; Energy balance and Single cell study. The energy balance study was designed to verify the accuracy of the simulation by the law of conservation of energy of the system. Whereas the single cell study was designed to verify that the model complies with the damage and failure laws described in the subroutines.

The energy study showed that during the impact process, a significant amount of the projectile kinetic energy is transferred to the target and converted into internal, kinetic, eroded and hourglass energies. However a small variation between the energy lost by the projectile and the total energy transfer to the plate was noticed. The slight total energy variation (approximately 1 %) was assumed to be caused by the energy contributed to the system during the removal of the penetration. Since the energy variation was less than 1 % of the total energy which appears to be insignificant no modification has been applied to the system.

The finding of this single cell element studies indicates that the model complies with the failure mechanism described in the user subroutine. And the program accurately processes the resulting failure flag from the subroutine and sets the stresses to zero when the failure flags indicate material failure.

A detailed study of the effect of mash size and shape on the plate response to ballistic impact was carried out. The finding of this section indicate that element size has a great influence on the plate response to ballistic impact as it determines the accuracy of the ballistic limit, energy absorption, time step, damage area and the accuracy of the information obtained. Based on the above
results it was concluded that numerical simulation when the element size is 0.20
mm or less is used will provide an accurate answer not influenced by element
dimension and also help obtain better and more detailed information. However
reducing the element dimensions below 0.2 mm will result in a decrease in the
time step size which will cause four problems: a) in a large increase in the
number of element used. b) a large increase in the CPU time of the problem. c) a
large increase in the size of data produced which will make it difficult to process
and store. d) Sometimes when small element are used element can became
severely distorted which could cause the program to stop.

Explicit codes are shown to be mesh-dependent. Meshing the entire plate with
small mesh will lead to undesirable problems. Since the area of interest in a
ballistic event is located exactly under the projectile and the surrounding area,
only a small area was meshed with fine constant mesh. The elements size was
gradually increased when moving away from the centre toward the edges of the
plate.

The shape of the elements under the projectile was also investigated, results
showed that the ballistic response of the composite plate and the amount of
energy absorbed by the plate during the ballistic event remain unchanged.
However the time step was found to be largely influenced by the element shape.

The delamination method chosen to be used in this project is similar to the tie-
break contact algorithm in LS-Dyna3D. This approach has been successfully
used by Hung et al (1995) and Van Hoof (1999) who has reported a good
agreement on the numerical prediction and experimental data.

The effect using spotweld to model delamination on the total time of the process
per cycles is shown in Figure 4-26. The graph indicates that the spotweld effect
on the time step far exceeds the effect of the element size and quality. The figure
shows that in this case plate with spotweld the time step more than halved.
Which means that the run time, number of time steps and the data produced
will increase dramatically. However this problem cannot be avoided if
delamination is to be taken into consideration in this simulation.

In an attempt to reduce the number of elements used in a simulation only a
quarter of the problems was modelled and symmetry was used. Simulations
show that the different in velocity profile of full and quarter plate is very small.

In summary the composite plate was modelled using:
- Quarter plate and symmetry was used.
- Delamination was modelled using rod elements
- Only a small area was meshed with fine constant mesh (0.2 mm)
- The elements size is gradually increased when moving away from the centre toward the edges of the plate
- The mesh density of the plate should always be smaller than the projectile's.
To evaluate the accuracy of the numerical model a series of ballistic tests have been designed and executed. Due to several constrictions, only relatively thin composite plates have been tested. The manufacturing of thick composite plate was not a problem; however reaching a velocity high enough to penetrate the thick ballistic plate was difficult. Three types of projectiles have been used in this series of ballistic tests: 0.44g, 0.88g spherical ball and 0.3" FSP. The maximum velocity and kinetic energy that was achieved depended on the type of projectile used and it varied between 35J for 0.44g spherical ball and 54J for 0.3" FSP which was not high enough to penetrate a thick plate.

Attempts to measure residual velocity of the projectile were later abandoned due to interference from the debris from the back of the damaged composite plate. This problem was eliminated by the introduction of spall liner. However changes to the projectiles angle when leaving the back of the plate made it difficult to accurately estimate the residual velocity.

The selection of the material to be used in the ballistic impact study and verification of the composite model was based on the availability of the fabric and resin. Plain woven E-glass fabric was used in this study due to the large amount available during the course of this study.

In the case of ceramic composite armour the ballistic limit could not be obtained for the lack of fire power. When the spherical balls were used to impact the composite/ ceramic armour, there was hardly any visible damage to the plate and the projectile completely shattered. In the case when the ceramic/ composite plate was impacted with 0.3" FSP at the highest possible velocity, the projectile was severely damaged and it could not even clear the ceramic tiles. The backing composite plate was untouched. For these reasons the case of ceramic only the damage will be compared to the numerical simulations from literature -which intern were compared to experimental results- to see if the model is capable of predicting the damage patterns.
5.1 General

Composites are made of fibrous material infused in a tough plastic. Resin Transfer moulding and Vacuum infusion are techniques that use pressure/vacuum to drive resin into a laminate. Materials are laid dry into the mould and wetted using low viscosity resin via carefully placed tubing.

5.1.1 Resin Transfer Moulding

The Resin Transfer Moulding, RTM, is a well known technique that uses liquid resin to impregnate fabric. It is traditionally used in the manufacturing of large parts in various applications. The results obtained usually have a good surface finish and the production rate is quite reasonable.

During the RTM the preform is laid on the mould cavity, the mould is then closed and the resin is injected into the cavity under pressure (Ref3, Minaie, Lin, 2001). Once the liquid resin fills the cavity it is left to cure. A typical RTM is illustrated in Figure 5-1.

![Figure 5-1: Schematic of Resin Transfer Moulding](image-url)
5.1.2 Vacuum Assisted Resin Transfer Moulding

Recently there has been a major shift in the manufacturing of large and complex fibre reinforced structure. This shift is centred around the adoption of completely based vacuum process. This process is known as Vacuum Assisted Resin Transfer moulding (VARTM).

The VARTM is a process where dry fabric is placed into a mould, covered by a vacuum bag and sealed tight. The preform is wetted with low viscosity resin with the aid of vacuum. A distribution medium is usually placed on the top of the fabric to make sure of the even distribution of resin throughout the panel (Rigas 2001). A typical VARTM is illustrated in Figure 5-2.

![Figure 5-2: Vacuum Assisted Resin Transfer Moulding](image)

The resin infusion processes are a group of composite processing techniques that enable the manufacture of large composite structure with high mechanical properties. It is closed mould technique in which fibrous material in impregnated by a resin flow (Brouwer 2003). Vacuum injection uses vacuum at the outlet side, whereas resin transfer moulding (RTM) uses increased pressure at the inlet.

To achieve repeatable high quality product careful process design is needed as fibre architecture; resin viscosity and temperature of the operation all influence the wetting of the fabric.

The VARTM method was used in the manufacturing of the composite plate as it provides a good fibre to resin ratio.
5.2 Ballistic Samples

Table 5-1: Material used in Ballistic plate.

<table>
<thead>
<tr>
<th>Material</th>
<th>Description</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D Fabric</td>
<td>Plain woven E-glass fabric with areal density of 400 g/m²</td>
<td>PWEG</td>
</tr>
<tr>
<td>Resin</td>
<td>Vinyl Ester</td>
<td>VE</td>
</tr>
</tbody>
</table>

Table 5-2: Resin description

<table>
<thead>
<tr>
<th>Name</th>
<th>Manufacturer</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vinyl Ester Resin</td>
<td>Reichhold</td>
<td>NORPOLDION 9102-500</td>
</tr>
<tr>
<td>Catalyst</td>
<td>Kerox Chemicals Ltd</td>
<td>Methyl ethyl ketone peroxide</td>
</tr>
</tbody>
</table>

Table 5-3: Specimens used in the ballistic impact

<table>
<thead>
<tr>
<th>No of Layers of fabric</th>
<th>Thickness (mm)</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>1.19</td>
<td>PWEG-VE-4</td>
</tr>
<tr>
<td>6</td>
<td>1.75</td>
<td>PWEG-VE-6</td>
</tr>
<tr>
<td>8</td>
<td>2.37</td>
<td>PWEG-VE-8</td>
</tr>
<tr>
<td>12</td>
<td>3.27</td>
<td>PWEG-VE-12</td>
</tr>
<tr>
<td>14</td>
<td>4.04</td>
<td>PWEG-VE-14</td>
</tr>
</tbody>
</table>
Once the composite panels are cured, ballistic impact specimens of E-Glass Vinyl ester were obtained by cutting the different thickness plates into 100mm x 100mm panels using a high diamond tipped slitting wheel. A summary of the specimens used in the ballistic impact test is presented in Table 5-3.

5.2.1 Fibre Volume Fraction

The fibre glass volume fraction was calculated using the following equation (Zhu 2009):

$$V_f = \frac{AD_f \times N_f}{\rho \times t}$$  \hspace{1cm} Equation 5.1

Where $V_f$ is the fibre volume fraction, $AD_f$ is the areal density of the glass fabric, $N_f$ is the number of fabric layers, $\rho$ is the fabric density and $t$ is the composite thickness.

It is assumed that there are no voids in the composite plate which is not always true. Usually the void content in vacuum infusion is small (0.1 – 0.3%). Hence there is a small margin of error which was ignored in the calculation. The results are listed in Table 5-4.

Table 5-4: volume fraction of the plain woven E-glass fabric.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Fibre Volume Fraction $V_f$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PWEG-VE-4</td>
<td>52.32</td>
</tr>
<tr>
<td>PWEG-VE-6</td>
<td>53.36</td>
</tr>
<tr>
<td>PWEG-VE-8</td>
<td>52.54</td>
</tr>
<tr>
<td>PWEG-VE-12</td>
<td>57.12</td>
</tr>
<tr>
<td>PWEG-VE-14</td>
<td>53.94</td>
</tr>
</tbody>
</table>

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Table 5-4 shows that the average fibre volume fraction of the E-glass/VE is approximately 54%.

5.3 Ballistic Impact Test

The ballistic tests were carried out in collaboration with a colleague who is investigating the ballistic impact on 3D textile composite material Zhu (2009). To evaluate the accuracy of the numerical model, ballistic tests were performed and results were compared to the finite element predictions. To be certain that no further model calibration is needed, the impact conditions were varied. That was achieved by using two different projectiles of different mass and geometry. As well as varying the initial impact velocities. The ballistic Impact tests were carried out at the Composite Technology Centre (CTC) laboratory at Queen Mary University of London (QMUL). The details of the ballistic test setup, equipment used, measuring techniques and results obtained are presented in the rest of this chapter.

5.3.1 Experimental setup

During the ballistic trial the samples were mounted in the test framework and orientated normal to the angle of attack. The samples were supported by the fixture shown in Figure 5-3. The support frame is made from steel, the bottom, left and right sides are fixed. However, the top can move up and down to allow for samples with different sizes to be tested. The composite panels were clamped to the support fixture using several pins along the top and bottom sides of the frame.

The composite panels were impacted by steel projectiles. In the first set of tests the projectile used had a spherical shape to avoid scattered results due to the change in the yawing angle which usually results in a change in the oblique angle. In the second sets of tests ceramic/ composite plate were impacted by the 0.30" Fragment Simulating Projectile (FSP) shown in Figure 4-7. In both sets of test, a gas gun was used.
Figure 5-3: Gas Gun setup: (a) Gas Cylinder pressure chamber and firing valve (b) Chronograph' (c) Composite Plate support.

The gas gun consists of pressure chamber, barrel, a nitrogen tank, a burst diaphragm, a pressure relief valve, nozzle and a steel chamber. As shown in Figure 5-4
A range of velocities were achieved by varying the pressure in the chamber. Gas was fed into the pressure chamber located at the end of the barrel. A simple diaphragm made of thin plastic or aluminium sheet is used to restrain the nitrogen gas until the pressure build-up in the chamber reaches the predetermined level. Then the diaphragm is busted allowing the nitrogen air to accelerate the sabot and FSP down the barrel to strike the supported specimen. The projectile was released after the sabot collapsed at a predetermined location inside the barrel prior to impact. The actual impact took place inside the experimental steel chamber. In principal the gas gun used in this sets of experiment was capable of launching a 0.44g projectile with a velocity up to 500 m/s. Usually the gas guns maximum velocity depends on the maximum pressure, the length of the barrel used to accelerate the projectile and the initial mass of the projectile and sabot. Therefore it was not possible to achieve the maximum velocity in all cases.

5.3.2 Ballistic limit velocity \( (V_{50}) \)

The projectile velocity was estimated immediately before the impact using the chronograph which was positioned close to the target. After the impact the specimens were removed, photographed and C-Scanned for damage analysis.

The method used in obtaining the experimentally measured ballistic limit velocity is by firing six shots within 10% range at the same plate at the same angle under
similar condition for which three must fully penetrate the armoured panel. The average is the final ballistic limit velocity. Table 5-5 present an example of obtaining the ballistic limit velocity for 2.37 mm plate impacted by a 0.44 g steel ball.

Table 5-5: Gas gun test to determine the ballistic limit velocity (V50) of 0.44g for PWEG-VE-8.

<table>
<thead>
<tr>
<th>Status</th>
<th>Shots No</th>
<th>Impact Velocity (m/s)</th>
<th>Impact Energy (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perforating</td>
<td>1</td>
<td>254</td>
<td>14.20</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>245</td>
<td>13.21</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>243</td>
<td>13.00</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>240</td>
<td>12.67</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>239</td>
<td>12.56</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>238</td>
<td>12.46</td>
</tr>
<tr>
<td>Non Perforating</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 5.4 Results

The results obtained from the ballistic trials are presented in this section. Table 5-6 shows the ballistic limit velocity of different plate thicknesses impacted with 0.44g ball and 0.88g ball.

Ballistic Limit velocity is defined as the velocity of a particular projectile at which it is expected to penetrate a composite armour plate of a given thickness and physical properties at a specific angle of obliquity for which the probability of penetration is 0.5.
Table 5-6: Ballistic limit velocity (V50) of 0.44 g and 0.88 g

<table>
<thead>
<tr>
<th>Group</th>
<th>plate</th>
<th>Projectile</th>
<th>Ballistic limit velocity (m/s)</th>
<th>Areal Density (kg/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DB-1</td>
<td>PWEG-VE-4</td>
<td>0.44g Ball</td>
<td>176.66</td>
<td>2.08</td>
</tr>
<tr>
<td></td>
<td>PWEG-VE-8</td>
<td>0.44g Ball</td>
<td>284.93</td>
<td>4.23</td>
</tr>
<tr>
<td></td>
<td>PWEG-VE-12</td>
<td>0.44g Ball</td>
<td>349.68</td>
<td>6.61</td>
</tr>
<tr>
<td>DB-2</td>
<td>PWEG-VE-4</td>
<td>0.88g Ball</td>
<td>152.72</td>
<td>2.08</td>
</tr>
<tr>
<td></td>
<td>PWEG-VE-6</td>
<td>0.88g Ball</td>
<td>200.89</td>
<td>3.21</td>
</tr>
<tr>
<td></td>
<td>PWEG-VE-8</td>
<td>0.88g Ball</td>
<td>236.10</td>
<td>4.23</td>
</tr>
<tr>
<td></td>
<td>PWEG-VE-12</td>
<td>0.88g Ball</td>
<td>301.68</td>
<td>6.31</td>
</tr>
<tr>
<td></td>
<td>PWEG-VE-14</td>
<td>0.88g Ball</td>
<td>320.07</td>
<td>7.36</td>
</tr>
</tbody>
</table>
Figure 5-5: Ballistic limit velocity of E-glass/ VE impacted by 0.44 g and 0.88 g steel ball.

Figure 5-6: Energy absorbed by the different thicknesses of E-glass/ VE impacted by 0.44 g and 0.88 g steel ball.
Results presented in Figure 5-5 show that the ballistic limit velocity was affected by the type of projectile used in the experiments. For the same plate thickness the ballistic limit for different projectile used were different. The ballistic limit for 0.44g ball was higher than that of the 0.88g. The effect of the projectile includes the effect of mass.

The effect of the projectile mass can be conceded using kinetic energy rather than ballistic limit velocity. The kinetic energy was calculated using $V_{50}$ using:

\[ KE = \frac{1}{2} m V_{50}^2 \]  

Equation 5.2

The kinetic energy $E_{50}$ is usually referred to in literature as the ballistic limit energy or the perforation energy $E_p$.

Figure 5-6 show the results. It can be seen that type of the projectile used also affect the energy results. For the same plate thickness the ballistic limit energy of different type of projectile are in order of their mass.

A linear relationship was obtained between the ballistic limit energy and the areal density of the plate. This was not the case for the ballistic limit velocity. As the area density increase the increase in energy becomes bigger.

### 5.5 Model Validation

The objective of the gas gun tests on composite plates was to validate and calibrate the numerical model presented in this research. Two types of projectiles were used in these ballistic experiments (0.44g and 0.88g balls) to make sure that the calibrated model was not dependent on the one type of projectile. The damage and failure modes used in the numerical model are described in details in chapter (3, 4 and 6)

#### 5.5.1 Material Properties

The material of ballistic panels used in this study is plain woven E-Glass/ VE. The material properties for the woven E-Glass/ VE were obtained from data published in the literature. Scida et al (1999), Boh et al (2005), Deka et al (2006). Mesoscopic homogeneity is assumed and the orthotropic material properties are defined, as shown in Table 6-4, where $x$ and $y$ are the in-plane directions and $z$ is
the out-of-plane direction. The strength properties are defined using the model described in Chapter 3; the values used are shown in Table 5-7.

Table 5-7: Elastic properties adopted for E-Glass/VE in the numerical model

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$</td>
<td>1391 (Kg/m$^3$)</td>
</tr>
<tr>
<td>$E_x$</td>
<td>17 (GPa)</td>
</tr>
<tr>
<td>$G_{xy}$</td>
<td>4 (GPa)</td>
</tr>
<tr>
<td>$\nu_{xy}$</td>
<td>0.13</td>
</tr>
<tr>
<td>$E_y$</td>
<td>17 (GPa)</td>
</tr>
<tr>
<td>$G_{yx}$</td>
<td>4 (GPa)</td>
</tr>
<tr>
<td>$\nu_{yx}$</td>
<td>0.28</td>
</tr>
<tr>
<td>$E_z$</td>
<td>7.48 (GPa)</td>
</tr>
<tr>
<td>$G_{zx}$</td>
<td>4 (GPa)</td>
</tr>
<tr>
<td>$\nu_{zx}$</td>
<td>0.28</td>
</tr>
</tbody>
</table>

Table 5-8: Strength properties adopted for E-Glass/VE in the numerical model.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_x^C$</td>
<td>220.0 (MPa)</td>
</tr>
<tr>
<td>$X_y^C$</td>
<td>220.0 (MPa)</td>
</tr>
<tr>
<td>$X_F^C$</td>
<td>500.0 (MPa)</td>
</tr>
<tr>
<td>$X_x^T$</td>
<td>300.0 (MPa)</td>
</tr>
<tr>
<td>$X_y^T$</td>
<td>300.0 (MPa)</td>
</tr>
<tr>
<td>$S_{xy}$</td>
<td>40 (MPa)</td>
</tr>
<tr>
<td>$S_{yx}$</td>
<td>31.6 (MPa)</td>
</tr>
<tr>
<td>$S_{xf}$</td>
<td>300.0 (MPa)</td>
</tr>
<tr>
<td>$S_{x}^S$</td>
<td>31.6 (MPa)</td>
</tr>
</tbody>
</table>

Delamination Strength (section 2.2.3) = 80 MPa

The strength parameters have been modified by up to +10% to provide the best fit of the $V_{50}$ value of the 4 mm plate.
5.5.2 Ballistic Limit Velocity

Figure 5-7: Ballistic Impact Limit Comparison of Experimental data with Numerical prediction of Plain Woven E-glass/ VE impacted with 0.44g Ball.

Figure 5-8: Ballistic Impact Limit Comparison of Experimental data with Numerical prediction of Plain Woven E-glass/ VE impacted with 0.88g Ball.
Figure 5-7 and Figure 5-8 show experientially measured and numerically predicted ballistic limit velocities as functions of areal density. Excellent agreement is found between experimental and predicted results for both masses of ball bearing. Taking into account the expected experimental errors, the results can be described as in complete agreement. These results verify the finite element approach used. These methods will be applied composite and ceramic/composite armour.

Results of experimentally measured ballistic limit velocity and numerical predicted shows that the ballistic limit increases with increasing areal density. Increasing the mass of the ball bearing reduces the ballistic limit. However, this reduction is small and does not reflect the large increase in projectile mass. This indicates that the ballistic limit velocity is not only influenced by the kinetic energy of the projectile but also influenced by the projectile geometry (contact area). As the mass of the projectile increases the projectile diameter also increases leading to a larger surface area of contact spreading the load over a larger area.

5.6 Damage

Damage introduced to laminate composites during a ballistic impact can significantly vary depending on the projectile type and the impact velocity. It is therefore important to be able to detect the type and the extant of the damage to compare it to the numerical simulation. In this section, results relevant to the ballistic impact damage detection and quantification are presented. In 5.6.1 the use of Non Destructive Techniques and in particular Ultrasonic is demonstrated for damage detection. In 5.6.2 the use of digital photography for damage sizing is demonstrated.

5.6.1 Non Contact C-Scan

In the case of ballistic impact where the plate is usually very thick the impacted and surrounding area of damage has been shown to result in partial or complete loss of translucency Berketis (2006). Visual inspection and photography become inadequate for detecting the type of damage and it size.

Non contact or air-coupled ultrasonic is a relatively new field. The principle of operation of the ultrasonic system is to excite and collect response data from the
interaction of ultrasonic waves at different interfaces. In the case of delamination in an impact damaged plate, waves travel fast through undamaged material and then lose velocity when travelling through air-spaces formed by the cracks. A set of delamination on an impact damaged plate specimen absorb energy from the wave and result in signal loss Berketis (2006).

Figure 5-9: the configurations for a dual probe system. Normal straight through transmission.

The system used is designed by AirStar 2000. The software used for motion control and results presentation is Winspect. The ultrasonic hardware setup and the initial signal filtering are handled by BOPLA 2000, a piece of software developed by AirStar. The system uses a set of two probes in transmit-receive roles for single through transmission.

One problem associated with non-contact C-Scan is that any small gaps around or between specimens scanned, that can create a direct path for the waves can lead to serious reduction in the signal to noise ratio. Also scattering of the waves on the edges of the specimens increases the area for which inadequate information is given. A practice to minimize signal leaks and the signal deterioration associated at edges of the specimens and the specimen support is to use acoustic coupling gel.
Figure 5-10: Damage on the composite plate when impacted at a velocity below V50 including the ball (dimensions in mm)

Figure 5-10 and Figure 5-11 show the difference in damage size for the same composite plate impacted at velocity below the ballistic limit Figure 5-10 and above the ballistic limit velocity Figure 5-11. The damage size in the case of high velocity is smaller than that of low velocity. However the type and extent of the damage is not clear. This made it difficult to compare the damage between the experimental results to the numerical predictions.

Figure 5-11: Damage to the composite plate impacted at velocity higher than V50 no ball (dimensions in mm)
5.6.2 Photography

One of the advantages associated with the use of glass fibres as reinforcement in composite laminates is the ease of damage detection by visual means. The impact damaged area can be sized from photographs and then measured accordingly. For specimens of the impacted composite panels, a digital photograph was taken to assess the damage size. Halogen white spot-light was used at the back of the specimens to illuminate them. A ruler was placed near / under the damaged area in each composite sample. The digital camera was then used to capture images of the damaged textile composite. The damaged part absorbed light more than the undamaged part, results are shown in Figure 5-12 and Figure 5-13.

This effect was used to measure the damage size as a horizontal diameter and total area. In the case of full penetration, total failure (Fibre and resin) is clear. However in the surrounding area, the type of the damage is not clear only the extant the damage is measured; the total damage area is presented Table 5-9. Whereas in the case where the plate stopped the ball the total damage area is presented in Table 5-10. Both set of results agrees with numerical simulation presented in section 6 where it was shown that the damage area increases as the impact velocity is reduced.

![Figure 5-12: Damage on composite plate impacted by 0.88g ball above ballistic limit velocity.](image-url)
Table 5-9: 2D Damage area of composite plate after ballistic impact.

<table>
<thead>
<tr>
<th>Section</th>
<th>Area (mm²)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>30.2</td>
<td>Complete failure of fibre and resin</td>
</tr>
<tr>
<td>B</td>
<td>396</td>
<td>Resin failure and some delamination</td>
</tr>
<tr>
<td>C</td>
<td>855</td>
<td>Resin failure</td>
</tr>
</tbody>
</table>

Figure 5-13: Damage on composite plate impacted by 0.88g ball below ballistic limit velocity.
Table 5-10: 2D Damage area of composite plate after ballistic impact.

<table>
<thead>
<tr>
<th>Section</th>
<th>Area (mm²)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>30.2</td>
<td>Complete failure and projectile embedded in the plate</td>
</tr>
<tr>
<td>B</td>
<td>586.5</td>
<td>Resin failure and some delamination See Figure 5-14</td>
</tr>
<tr>
<td>C</td>
<td>1477</td>
<td>Resin failure</td>
</tr>
</tbody>
</table>

Figure 5-14: 4.04 mm plate impacted with 0.88g ball travelling at 300 m/s (below ballistic limit velocity).

Comparing Figure 5-14 to Figure 5-15 where simulation of 4.2 mm plate impacted with 0.88g ball travelling at velocity below ballistic limit (300m/s) shows a similar damage size and delamination length. The total delamination damage length shown in Figure 5-14 is 24 mm where as the size of the damage in Figure 5-15 is 26 mm.
Figure 5-15: 4.2 mm plate impacted with 0.88g ball travelling at 300 m/s (below ballistic limit velocity).

5.6.3 Ceramic Composite Armour

Figure 5-16: Damage to ceramic/Composite armour impacted with 0.3” FSP

The damage caused to a Ceramic/Composite plate impacted with 0.3” FSP is shown in Figure 5-16. The shattering of ceramic and formation of ceramic Cone is clearly visible. But the damage is located only in the ceramic and the composite backing plate remains untouched. The slight difference in the damage in both cases is caused by a difference in the initial angle of contact. It was difficult to control the FSP yawing angle. In Figure 5-16 (a) the damage is almost symmetrical indicating the plate was impacted at an oblique angle. Figure 5-16 (b) shows the right-hand side is more damaged than the lift hand side, indicating that the FSP struck the plate at an angle.
Figure 5-17 shows the state of the 0.33" FSP after impacting the ceramic composite plate. Usually when 0.33" FSP is used in a ballistic impact on composite plate it remains undamaged. This figure demonstrates the advantage on using ceramic tiles to blunt the projectile and protect the composite plate.

5.7 Summary

To evaluate the accuracy of the developed numerical model it was necessary to compare the numerical prediction to experimental data obtained from ballistic impact trials. Due to the limitation of the firing power of the gas gun only relatively thin composite plates have been tested (up to 4 mm). Composite sample were manufactured using vacuum assisted resin transfer moulding (VARTM). The average fibre volume fraction of the E-glass/VE was approximately 54%. The material properties and strength used in the simulation are presented in Table 5-7 and Table 5-8.
The method used in obtaining the experimentally measured ballistic limit velocity is by firing six shots within 10% range at the same plate at the same angle under similar condition for which three must fully penetrate the armoured panel. The average is the final ballistic limit velocity.

Two types of projectiles were used in the ballistic test 0.44g and 0.88g round ball. Excellent agreement is found between experimental and predicted results for both masses of ball bearing. Taking into account the expected experimental errors, the results can be described as in complete agreement. These results verify the finite element approach used. These methods will be applied composite and ceramic/composite armour.

Results of experimentally measured ballistic limit velocity and numerical predicted shows that the ballistic limit increases with increasing areal density. Increasing the mass of the ball bearing reduces the ballistic limit. However, this reduction is small and does not reflect the large increase in projectile mass.

Two methods of damage detection have been used in this study. A non contact air coupled c-scan was used to determine the extent of the damage caused to composite material. The c-scan showed the total damage caused to the composite plate projectile. However, data on delamination could not be compared between the numerical model and the c-scan as it was not possible to identify the type and extent of the damage from the c-scan photos.

In the second method a digital photograph was taken to assess the damage size. Halogen white spot-light was used at the back of the specimens to illuminate them. The damaged part absorbed light more than the undamaged part. The total damage caused by impact velocity below ballistic limit is larger than that caused by impact velocity higher than ballistic limit.

To measure the extent of delamination, the plate was cut at the centre of the impact area Figure 5-14. The comparison of the measured damage size and the numerically predicted shows that the total delamination damage length is 24 mm whereas the size of the numerically predicted delamination damage is 26 mm.
6 BALLISTIC IMPACT

6.1 Simulation

The model used in this investigation is presented in chapter 3 and 4 where different models have been studied, calibrated and the final design option is selected. The chosen model has been validated in chapter 5 where numerical predictions were compared to experimental data. In this chapter the model will be used to predict the ballistic limit velocity for various composite plates thicknesses impacted with different projectiles. The material properties will be varied to investigate the effect of each property on the ballistic response of the plate in a bid to try to improve the amount of energy absorbed by the plate and improve the ballistic protection of the composite plate.

6.1.1 Simulation

Plate

Ballistic impact is simulated using the numerical package described in chapter 4. Finite element models for the projectile and the plate were built using MSC Patran. The geometry of the plate is shown in Figure 6-1.

Figure 6-1: Schematic of the FSP and Composite Plate

The composite plate is 100 x 100 mm². In order to obtain the ballistic limit velocity of a range of Areal densities the plate thickness was varied between 4
mm and 12 mm. The support and boundary conditions remained unchanged throughout the simulations. The plate was fully constrained on all four sides. To reduce the size of the problem hence the simulation time, only one quarter of the plate is modelled (see chapter 4 for more details). The plate is modelled using 8-noded 3D orthotropic Lagrangian solid elements with single point integration. The model consists of up to 24 layers; each layer is 0.5 mm thick resulting in a maximum thickness of 12 mm. Delamination is simulated using discrete interfaces inserted between the laminate ply mesh. The nodes on opposite sides of an interface where delamination is expected are tied together using 1-D elements as described in 3.5.9. If the constraint forces exceed some criterion, the constraint is released and the delamination grows. The number of elements depends on the plate thickness. Table 6-1 gives a detailed description of the number of element used per thickness. Figure 6-2 shows the plate mesh used in this study.

Figure 6-2: Finite Element Mesh of Plain Woven composite plate
Table 6-1: Model details

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Layers</th>
<th>HEX Elm</th>
<th>QUAD Elm</th>
<th>1D Elm</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 mm</td>
<td>24</td>
<td>90600</td>
<td>382</td>
<td>84778</td>
<td>177760</td>
</tr>
<tr>
<td>10 mm</td>
<td>20</td>
<td>75500</td>
<td>382</td>
<td>70034</td>
<td>145916</td>
</tr>
<tr>
<td>8 mm</td>
<td>16</td>
<td>60400</td>
<td>382</td>
<td>55290</td>
<td>116072</td>
</tr>
<tr>
<td>6 mm</td>
<td>12</td>
<td>45300</td>
<td>382</td>
<td>40546</td>
<td>86228</td>
</tr>
<tr>
<td>4 mm</td>
<td>08</td>
<td>30200</td>
<td>382</td>
<td>25802</td>
<td>56384</td>
</tr>
<tr>
<td>2 mm</td>
<td>04</td>
<td>15100</td>
<td>382</td>
<td>11132</td>
<td>26614</td>
</tr>
</tbody>
</table>

**Projectile**

Four different types of projectiles were used in this study to determine the effect of projectile shape and mass on the ballistic response of the plain woven composite plate. In addition to the two different types of round ball bearing used in the ballistic impact experiment (see chapter 5), the panel was impacted with two of the most commonly used Fragment Simulating Projectiles (FSP) that are used to assess the ballistic protection of the composite armour. The composite panel was impacted with 0.22" and 0.30" Calibre FSP. Figure 6-3 represent the FSP geometry, where as Table 6-2 and Table 6-3 shows the different projectiles properties.
Chapter 6 Ballistic Impact

Figure 6-3: Fragment Simulating Projectile (FSP)

Table 6-2: FSP Properties

<table>
<thead>
<tr>
<th>Parameter</th>
<th>0.22&quot; FSP</th>
<th>0.30&quot; FSP</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>0.005461 m</td>
<td>0.007493 m</td>
</tr>
<tr>
<td>L</td>
<td>0.00635 m</td>
<td>0.008839 m</td>
</tr>
<tr>
<td>A</td>
<td>0.00254 m</td>
<td>0.003454 m</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>35°</td>
<td>35°</td>
</tr>
<tr>
<td>m</td>
<td>0.0011 Kg</td>
<td>0.002751 Kg</td>
</tr>
</tbody>
</table>

Table 6-3: Round ball Properties.

<table>
<thead>
<tr>
<th>Properties</th>
<th>0.44g Round ball</th>
<th>0.88g Round Ball</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>0.00473 m</td>
<td>0.0060m</td>
</tr>
<tr>
<td>mass</td>
<td>0.00044 kg</td>
<td>0.00088 Kg</td>
</tr>
</tbody>
</table>

The projectiles used in this study have been modelled using rigid 4-noded shell elements. Figure 6-4 shows a close up of the 0.44g and 0.88g round ball bearing.
The Lagrangian method is used; this is the most common finite-element processing technique for engineering applications. Grid points are located on the body being analysed. Elements of material with constant mass connect the grid points, forming a mesh. As the body deforms, the grid points move with the body and the elements (mesh) distort. The software has the capability to remove the failed elements from the mesh. This element removal was used in this analysis to allow the projectile to penetrate the composite plate.
Material Properties

As S2-Glass fabric is more commonly used in the armour protection, ideally it should have been used throughout this project. However due to the lack of the material during the experimental stage, E glass fabric was used to calibrate and validate the model. In this chapter relatively thick plates was simulated. Since the available gas gun was not capable of firing projectiles at velocities high enough to penetrate thick plates other source of experimental results were required. Ballistic limit velocity of different thickness of plain woven S2-Glass/Epoxy was obtained from literature Yen (2002). Furthermore Yen used failure model similar to the one described and used in this project. The difference is in the way delamination was modelled. In this research a distinction between the intralaminar and interlaminar failure modes was made, and each type of this type of failure modes was treated in a separate part of the software.

The intralaminar failure modes (fibre breakage, matrix cracking, through thickness crushing and shear failure) were modelled within the element constitutive routine and defined using material subroutines. The interlaminar failure mode included delamination, which was modelled using discrete interfaces inserted between the layers of the elements. This allows the formation of a discrete delamination backplane during the penetration process.

The material of ballistic panels used in this study is plain woven S2-Glass/Epoxy. The material properties for the woven S2 Glass-epoxy were obtained from data published in the literature. Yen (2002) used these properties to simulate ballistic impact on 12.5mm thick S2 glass epoxy plate. The ballistic limit velocity of the two different models were compared and checked against experimental results. Mesoscopic homogeneity is assumed and the orthotropic material properties are defined, as shown in Table 6-4. The strength properties are defined using the model described in Chapter 3; the values used are shown in Table 6-5.

Table 6-4: Elastic properties adopted for S2-Glass/Epoxy in the numerical model

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$</td>
<td>1783 (Kg/m$^3$)</td>
</tr>
<tr>
<td>$E_x$</td>
<td>24.10 (GPa)</td>
</tr>
<tr>
<td>$G_{xy}$</td>
<td>5.90 (GPa)</td>
</tr>
<tr>
<td>$\nu_{xy}$</td>
<td>0.12</td>
</tr>
<tr>
<td>$E_y$</td>
<td>24.10 (GPa)</td>
</tr>
<tr>
<td>$G_{yx}$</td>
<td>5.90 (GPa)</td>
</tr>
<tr>
<td>$\nu_{yx}$</td>
<td>0.40</td>
</tr>
<tr>
<td>$E_z$</td>
<td>10.40 (GPa)</td>
</tr>
<tr>
<td>$G_{zx}$</td>
<td>5.90 (GPa)</td>
</tr>
<tr>
<td>$\nu_{zx}$</td>
<td>0.40</td>
</tr>
</tbody>
</table>
Table 6-5: Strength properties adopted for S2-Glass/Epoxy in the numerical model. (See notation table)

<table>
<thead>
<tr>
<th>$X_C^C$ = 350.0(MPa)</th>
<th>$X_T^T$ = 590.0(MPa)</th>
<th>$S_{xy}$ = 48.3(MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_C^C$ = 350.0(MPa)</td>
<td>$X_T^T$ = 590.0(MPa)</td>
<td>$S_{yz}$ = 48.3(MPa)</td>
</tr>
<tr>
<td>$X_C^F$ = 690.0(MPa)</td>
<td>$S_P^S$ = 550.0(MPa)</td>
<td>$S_{zx}$ = 48.3(MPa)</td>
</tr>
</tbody>
</table>

Delamination Strength (section 2.2.3) = 80 MPa

6.2 Original Strength Parameters

6.2.1 Effect of Velocity on Damage Area

To demonstrate the approximate proportion of energy absorbed by each failure a view of the simulation is presented in Figure 6-6 and Figure 6-7. The figures show a 0.88g Round ball penetrating 14 layers of S2-Glass/Epoxy composite plate, at two different velocities, a velocity higher than the ballistic limit and a velocity below the ballistic limit velocity.

Figure 6-6: Ballistic Impact Simulation of 14 layers of composite impacted with 0.88g ball above the ballistic limit velocity.
Figure 6-6 shows ballistic response of the composite plate subjected to a velocity higher than the ballistic limit. As a result, the damage area is small and local. The size of the damaged area is equal to the size of the projectile and there is only a small visible delamination.

Figure 6-7 shows a simulation of the same composite plate impacted with a velocity below the ballistic limit. The visible damage caused by the projectile is larger than that caused by high velocity. That is because the projectile does not possess enough kinetic energy to break the fibre and further penetrate the plate. But it still has a considerable amount of energy, enough to cause further damage in the weaker fibre matrix interface, causing more matrix failure and delamination.

**Figure 6-7: Ballistic Impact Simulation of 14 layers of composite impacted with 0.88g ball below ballistic limit velocity.**

**6.2.2 Ballistic Limit Velocity**

The $V_{50}$ ballistic limit velocity for a material is defined as that velocity for which the probability of penetration of the chosen projectiles is exactly 0.5. The technique used in obtaining $V_{50}$ is usually to perform a ballistic simulation using striking velocity for FSP that is high enough to perforate the target. Successive
simulations are then performed by reducing the striking velocity by 25 to 50 m/s depending on the plate thickness until there is no perforation. Similar technique to that described earlier is used to obtain $V_{50}$.

![Graph of residual velocity for 10 mm plate S2-Glass/Epoxy](image)

**Figure 6-8: Plot of residual velocity for 10 mm plate S2-Glass/Epoxy**

Figure 6-8 shows the velocity profile of 0.22 FSP impacting a 10 mm S2-Glass/Epoxy. The figure indicates that as the ballistic limit velocity is approached a large drop in the residual velocity is observed. The residual velocity for 700 m/s is about 250 m/s. Reducing the impact velocity by 50 m/s, resulted in the plate completely resisting the projectile.

### 6.2.3 Ballistic Limit

Figure 6-9 shows the ballistic limit velocity of different plate thickness. As expected ballistic limit increases with increasing the plate thickness.
Figure 6-9: Ballistic limit velocity for different S2-Glass/Epoxy thickness

Figure 6-10: Ballistic limit velocity for different Areal Density
Figure 6-10 shows the ballistic limit velocity for the same plate impacted with the same projectile. This time the results are plotted as a function of Areal density. As expected the ballistic limit velocity increases with the areal density.

![Graph showing ballistic limit velocity vs. areal density](image)

**Figure 6-11: Predicted Ballistic Limit Velocity of Several Areal Density plates subjected to Impact with different projectiles**

Figure 6-11 shows the predicted ballistic limit velocities of different threats as a function of areal density. As expected the ballistic limit velocity of each threat increases with areal density. As the level of threat increase the ballistic limit velocity of the plate is reduced. The graph shows that threats fall under four categories; round ball bearings and Fragment Simulating Projectiles. This indicates that the ballistic response of the composite plate is not only influenced by the Kinetic energy and surface area of the projectile and contact, but could also be influenced by the projectile (FSP) sharp edges that can cause more damage.
The ballistic limit energy of each projectile type is presented in Figure 6-12. Results show that as the areal density of the composite plate increase, the rate of change in the ballistic limit energy increases.

Figure 6-11 shows the ballistic limited velocity of the 0.22” FSP to be smaller than that of 0.88g ball, which is to be expected as the mass of the 0.22 FSP is greater than the 0.88g ball. Figure 6-12 reveals that the ballistic limit energy of the 0.88g ball is equal or greater than that of 0.22” FSP. This is interesting as it further verify that the ballistic performance of the plate is not only influenced by the projectile mass but also influenced by the projectile geometry and shape.
6.3 Results: Study of effect of material properties

The effect of varying the material properties and strength is presented in this section. It is assumed that the ballistic resistance of a composite plate is greatly influenced by the fibre properties. In this study material properties will be varied to find out which material parameter has the greatest influence on the energy absorbed, ballistic limit and damage area. And make sure that the new material properties will not affect model stability.

Table 6-6: Input parameters used to investigate the effect of material properties

<table>
<thead>
<tr>
<th>Failure Mode</th>
<th>In-plane</th>
<th>Through</th>
<th>In-plane</th>
<th>Through</th>
<th>In-plane</th>
<th>Through</th>
<th>Through</th>
<th>Through</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Strength</td>
<td>Thickness shear</td>
<td>Strength</td>
<td>shear</td>
<td>Stiffness</td>
<td>Strength</td>
<td>shear</td>
<td>Stiffness</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(E_s/E_t)^2</td>
<td>+ (G_s/3)^2</td>
<td>Fibre tensile mode</td>
<td>S_x = 1180MPa</td>
<td>Fibre shear mode S_w = 1100MPa</td>
<td>Fibre tensile and compression stiffness</td>
<td>E_f = 97 GPa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(E_s/E_t)^2</td>
<td>+ (G_s/3)^2</td>
<td>Fibre compression mode</td>
<td>S_x = 700MPa</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Layer shear Stiffness G_w = 11.8 GPa</td>
</tr>
<tr>
<td>(E_s/E_t)^2</td>
<td></td>
<td>Fibre crush S_c = 1380MPa</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(E_s/E_t)^2</td>
<td></td>
<td>Matrix strength S_w = 97MPa</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(G_s/3)^2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Layer shear Stiffness G_w = 11.8 GPa</td>
</tr>
</tbody>
</table>
Table 6-6 shows the links between the parameters used in the model damage and failure predictions and their physical meanings. The table also gives the new property values used in the investigation (double the stiffness & strength).

6.3.1 In-plane Strength

![Graph showing the effect of varying in-plane strength on the energy absorbed by the plate](image)

Figure 6-13: Effect of varying in-plane strength on the energy absorbed by the plate

![Graph showing the effect of varying in-plane strength on backplane displacement](image)

Figure 6-14: Effect of varying in-plane strength on backplane displacement
Figure 6-13 summarizes the effects of varying the in-plane strength ($S_{xx}$ and $S_{yy}$) properties on the amount of energy absorbed by the composite plate during ballistic impact event. The in-plane strength in the model represents the layer axial tensile and compressive strength in the fill and wrap direction. Doubling the in-plane strength results in a lower residual velocity of the projectile. This indicates an improvement in the ballistic properties of the composite plate.

Figure 6-14 represents the effect of varying the in-plane strength on the backplane displacement of the composite plate. The curve representing double the strength appeared to resist the projectile more than the other design options. Panels with normal strength have small backplane deflection suggesting quicker penetration.

Figure 6-15: Delamination and backplane displacement of composite plate impacted with a projectile travelling at 900 m/s. a) Normal composite material. b) Double in-plane strength.
6.3.2 Through Thickness strength

Figure 6-16 summarizes the effects of varying the through thickness strength ($S_{zz}$) on the velocity profile of the projectile and the amount of energy absorbed by the composite plate during ballistic impact event. The through thickness strength in the model represents the fibre crush strength. Doubling the through thickness strength dramatically increases the amount of energy absorbed by the plate.

The curve representing the energy profile of the composite plate with double the in-plane strength is shorter than that of plate with normal material properties. In both simulations the numbers of cycles was kept constant at 6000 cycles. However the graph suggests normal plate simulation proceeded further. From the following observation:

- The points on the curves represent the time steps.
- The points on the curve representing the plate with double the in-plane stiffness are denser.
- The time step is proportional to the smallest element dimension.
It is concluded that in the simulation where the strength was doubled the element got distorted much faster causing the time step to become smaller which in turn led to smaller run time. The graph suggests that the through thickness strength have the greatest effect on the ballistic response of the plate and on the time step.

Figure 6-17: Effect of varying through thickness strength on backplane displacement

Figure 6-17 represents the effect of varying the through thickness stiffness and strength on the backplane displacement of the composite plate. The curve representing the double strength appeared to resist the projectile more.

Figure 6-18: Delamination and backplane displacement of composite plate impacted with FSP travelling at 900 m/s  a) Normal composite material. b) Double through thickness strength
6.3.3 In-plane shear Strength

Figure 6-19: Effect of varying in-plane strength on the energy absorption.

Figure 6-19 summarizes the effect of varying the in-plane shear strength on the amount of energy absorbed by the composite plate during a ballistic impact event. The in-plane strength used in the model represents the layer shear strength due to matrix failure. Increasing the in-plane shear strength slightly reduces the amount of energy absorbed by the composite plate. The figure also suggests varying the in-plane shear strength reduces the time step.

The effect of varying the in-plane shear strength on the backplane response of the plate is presented in Figure 6-21. The graph shows that increasing the matrix strength reduced the backplane displacement of the plate indicating that the damage in the matrix did no spread and remained in a local area. This could explain the slight reduction in the amount of energy absorbed by the plate.
Figure 6-20: Effect of varying in-plane shear strength on velocity profile and penetration depth

Figure 6-21: Effect of varying in-plane strength on backplane displacement.
6.3.4 Through Thickness Shear Strength

Figure 6-22: Effect of varying through thickness shear and strength on absorbed energy.

Figure 6-23: Effect of varying through thickness shear strength on backplane displacement.
Figure 6-22 summarizes the effect of varying the through thickness shear strength \((S_x, \text{ and } S_y)\) on the amount of energy absorbed by the composite plate during a ballistic impact event. The through thickness strength in the model represents the layer shear strength due to fibre failure in the fill and wrap direction. The figure shows that increasing the through thickness shear strength slightly reduce the energy absorption capability of the plate. This defers to equation 3.9 predictions. The equation predicted that increasing the through thickness strength should increase the failure strain values hence improving the ballistic capability of the plate.

Figure 6-23 represents the effect of varying the through thickness shear strength on the backplane displacement of the composite plate. The curves indicate increasing the through thickness shear strength reduces the backplane deflection indicating a quick penetration.

![Figure 6-24: Delamination and backplane displacement of composite plate impacted with a projectile travelling at 900 m/s](image)

- a) Normal composite material.  
- b) Double Through thickness shear strength
6.3.5 Stiffness

Figure 6-25: Effect of varying the in-plane stiffness on Energy absorbed by the composite plate.

Figure 6-26: Varying through thickness stiffness effects on energy absorbed
Figure 6-27: Effect of varying in-plane shear stiffness on energy absorbed

Figure 6-28: Effect of varying through thickness shear stiffness on energy absorbed

Figure 6-25 and Figure 6-26 summarise the effect of varying the in-plane ($E_{xx}$, $E_{xy}$) and through thickness stiffness ($E_{zz}$) on the amount of energy absorbed during ballistic impact event. The in-plane and through thickness stiffness in the...
model represents the layer shear stiffness due to fibre in the fill, wrap and out of plane direction. The graphs indicate that doubling the stiffness reduces the amount of energy absorbed by the plate. This means that increasing the in-plane and through thickness stiffness reduces the ballistic protection of the composite plate.

Figure 6-27 summarizes the effect of varying the in-plane \((G_x)\) and through thickness \((G_{yZ}, G_z)\) stiffness on the projectile penetration during a ballistic impact. Doubling the in-plane shear stiffness had a little effect on the ballistic properties of the composite plate. The effect of varying the through thickness shear stiffness on the projectile penetration during a ballistic impact is summarized in Figure 6-28. Doubling the through thickness shear stiffness improved the ballistic properties of the composite plate and further resisted the projectile perforation.

6.3.6 Summary

The findings in this chapter indicate that the material properties influence the composite plate response to ballistic impact.

- Increasing the in-plane strength increase the amount of energy absorbed by the plate, improves the ballistic limit velocity, increases the backplane deformation and causes a larger delamination.

- Increasing the through thickness Strength increases the energy absorbed by the plate, improve the ballistic limit velocity and increases the backplane deflection.

- Increasing the in-plane shear strength resulted in a small reduction on the amount of energy absorbed by the plate.

- Increasing the in-plane stiffness will results in less energy absorbed by the plate, a deeper penetration and causes a smaller delamination.

- Increasing the through thickness stiffness reduces the amount of energy absorbed by the plate, reduces the ballistic limit velocity, result in a smaller backplane deflection and smaller delamination.

- Varying the in-plane shear stiffness does not have much influence on the ballistic response on the composite plate.
Increasing the through thickness shear stiffness surprisingly increases the amount of energy absorbed by the plate.

Figure 6-29 summarises the effect of varying the material properties on the percentage of energy absorbed by the plate during ballistic impact event. The figure indicates that the thought thickness strength $S_{zz}$ representing the fibre crush strength has the greatest effect on the ballistic properties of the plate.

![Figure 6-29: Effect of varying Material properties on the energy absorbed by the composite plate.](image)
6.4 Improving the Armour Design

6.4.1 Statement

The most attractive feature of composite material is the ability to design and tailor the material properties to suit our need. Figure 6-29 shows that the fibre crushing strength $S_{zz}$ has the greatest influence on the ballistic response of the composite plate. Doubling this strength resulted in more than doubling the amount of energy absorbed by the composite plate.

![Figure 6-30: Effect of Through Thickness Strength of Plate Absorbed Energy](image)

Increasing the through thickness strength representing the fibre crushing strength would mean improving or changing fibre. The next material property that had an influence on the ballistic response of the composite plate is the in-plane shear strength. This property represents the matrix strength.

Increasing the in-plane shear strength has been shown to slightly reduce the ballistic performance of the composite plate. Chapter 6.3.3 showed that although the energy absorbed by the plate was slightly reduced when the matrix strength has been doubled, the backplane response was noticeable. This led to the conclusion that reducing the matrix strength may allow the damage to spread.
over a larger area and allows the plate to deform more absorbing more energy in the process. The matrix strength is a controlling factor of the trough thickness and in-plane shear strength. In this analysis the failure model used assumes that the matrix strength is represented only by the in-plane shear strength. The through thickness shear strength was used in conjunction with the in-plane strength to represent the layer tensile and shear strength in the fill and wrap directions of the plain weaved fabric and to describe the interaction between the associated axial and through thickness strain presented in equation 3.9 and 3.10.

In this study, the in-plane matrix shear strength has been reduced and the effect on ballistic limit and energy absorption mechanisms has been investigated. Four values of in-plane matrix shear strength have been used $S_{xy} = 48.3 \text{ MPa}$, $S_{xy} = 38.3 \text{ MPa}$, $28.3 \text{ MPa}$ and $18.3 \text{ MPa}$; representing 0: 20; 40 and 60% reduction in the matrix strength. All other strength properties remained unchanged.

Table 6-7: variation in matrix Strength

<table>
<thead>
<tr>
<th>Strength Value (MPa)</th>
<th>Reduction (%)</th>
<th>Strength (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>48</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>38</td>
<td>20</td>
<td>80</td>
</tr>
<tr>
<td>28</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>18</td>
<td>60</td>
<td>40</td>
</tr>
</tbody>
</table>

6.4.2 Ballistic Limit

The $V_{50}$ ballistic limit for the different thickness plates with the different values of in-plane shear strength are presented in Figure 6-31. The reduction in shear strength increases the ballistic limit for all plate thicknesses.

The difference in the amount of energy absorbed by a thin plate is small but increases as the plate thickness increases. As the reduction in the matrix
strength increases the plate absorbs more and more energy leading to a higher ballistic limit velocity.

Figure 6-31: Ballistic limit velocity Vs Areal Density for different in-plane shear strength.

Figure 6-32: Ballistic limit Energy Vs Areal Density for different in-plane shear strength.
6.4.3 Energy absorption for different thicknesses

The effects of in-plane shear strength on energy absorption have been investigated. Figure 6-33 shows the effect of matrix shear strength for an 8 mm thick plate. The results show that there is only a small change in the amount of energy absorbed by 8 mm thick plates for different matrix strength.

![Figure 6-33: Energy absorbed by 8 mm Plate](image)

Figure 6-33: Energy absorbed by 8 mm Plate

Figure 6-34 shows the effect of matrix shear strength on a 12 mm thick plate. The results show that the difference in the amount of energy absorbed by 12 mm thick plates has increased and become more visible for all in-plane strength in contrast to the 8 mm where the difference was only visible for 18 MPa. The figure also show that the section of curves referred to [A] is the same for all the strength and that the change on the curves values only appears at later stages. This can be explained by the facts that at the initial stages of impact the velocity is high and the damage response is local, most of the energy is absorbed by the fibre failure and since the fibre strength remained unchanged this part of the curve also remain unchanged. Only at later stages when the velocity is reduced and the rest of the plate start contributing to the energy absorption mechanism damage through delamination and matrix breakage that the difference in energy level becomes visible.
The results presented in this section demonstrate the effect of resin strength on energy absorption mechanism during ballistic impact. The reduction in matrix strength has been shown to increase the energy absorbed by the plate and improve the ballistic limit velocity. These results demonstrate that the effect of in-plane shear strength on energy absorption is dependent on both plate thickness and velocity. Particular sensitivity to velocity is found around the ballistic limit. These results also show that the effect of reduced in-plane shear strength is more marked at low velocities. The effect is larger for thicker plates.

6.5 Summary

The material of ballistic panels used in this study is plain woven S2-Glass/Epoxy. The material properties for the woven S2 Glass-epoxy were obtained from data published in the literature (Yen 2002). Ballistic limit of four different projectiles were obtained for various areal densities. As expected the ballistic limit velocity of each projectile increases as the areal density increases and decreases as the mass of the projectile is increased. Increasing the projectile mass from 0.44g to 0.88g did not have the same ratio of effect on ballistic limit
velocity. This indicates that ballistic response of the composite plate is not only influenced by the projectile mass and kinetic energy. But also the projectile’s diameter. Increasing the projectile diameter increases the contact area, which distribute the load over a larger area; it could also be influenced by the projectile (FSP) sharp edges that can cause more damage.

A detailed parametric study of the effect of varying all material properties on the amount of energy absorbed by the plate and penetration is carried out and results are presented in Figure 6-35.

![Figure 6-35: Effect of varying Material properties on the energy absorbed by the composite plate.](image)

Varying the material properties of composites shows that the fibre crushing strength had the greatest effect on improving the armour ballistic properties.

Increasing the in-plane shear strength has been shown to slightly reduce the ballistic performance of the composite plate. Chapter 6.3.3 showed that although the energy absorbed by the plate was slightly reduced when the matrix strength has been doubled, the backplane response was noticeable. This led to the conclusion that reducing the matrix strength may allow the damage to spread over a larger area and allows the plate to deform more absorbing more energy in the process. The matrix strength is a controlling factor of the trough thickness
and in-plane shear strength. In this analysis the failure model used assumes that the matrix strength is represented only by the in-plane shear strength. For plain woven fabric the through thickness shear strength is the interaction between the wrap and fill of the fabric and the resin. Since the strength of the fibre is higher than the resin the through thickness shear strength will be represented by the fibre shear failure in the fill and wrap direction.

In this study, the in-plane matrix shear strength has been reduced and the effect on ballistic limit and energy absorption mechanisms has been investigated. Four values of in-plane matrix shear strength have been used $S_{xy} = 48.3$ MPa, $S_{xy} = 38.3$ MPa, 28.3 MPa and 18.3 MPa; representing 0; 20; 40 and 60% reduction in the matrix strength. All other strength properties remained unchanged.

The reduction in matrix strength has been shown to increase the energy absorbed by the plate and improve the ballistic limit velocity. These results demonstrate that the effect of in-plane shear strength on energy absorption is dependent on both plate thickness and velocity. Particular sensitivity to velocity is found around the ballistic limit. These results also show that the effect of reduced in-plane shear strength is more marked at low velocities. The effect is larger for thicker plates.
7 CERAMIC AND CERAMIC COMPOSITE ARMOUR

7.1 Ceramic

Ceramic has been used in armour design since the sixties when it was first realized that ceramic tiles backed by armour plate provide a better protection against projectiles. The analysis of ceramic subjected to impact is of significant importance because of their wide use in the body armour, lightweight vehicles, and heavy armoured vehicles or tanks. Ceramic materials make excellent armour because of their high strength to low mass which is a key parameter in any armour design. While there are many constitutive models in the literature that describe the response of ceramic to different loading conditions the Mohr Coulomb and Johnston Holmquist models appear to be the most popular and allege to provide good results which were in reasonable agreement with experimental data and capture the essential components of ceramic response to ballistic impact Rosenberg (1997) Lamberts (2007).

It is important to recognize that all constitutive models contain assumptions based on experimental results and observations. It should be appreciated that experimental testing for ballistic impact on ceramic panels will give a considerable degree of scatter. The key to a successful constitutive model is its ability to achieve a proper balance between accurate representations of the physical phenomena while maintaining computational efficiency.

Ballistic impact simulation on ceramic tiles is carried out using the finite element package and techniques described in chapters 4 and 6.

During a ballistic event the ceramic tiles blunt and/ or shatter the projectile; it may therefore be more accurate to include the deformation of the projectile which means using 3-D solid elements with failure to model the projectile. Since the objective of this investigation (section 7.1 only) is to study the effect of ballistic impact on ceramic plate, not the projectile. Including a deformable projectile may increase variables it is therefore decided that the projectile will continue to be modelled as a rigid body only for the preliminary study. This assumption should not affect the studies curried out in this chapter as accurate
ballistic limit velocity was not of interest since it was not possible to obtain the experimentally measured value of the ballistic limit velocity of a ceramic plate impacted with 0.22 FSP. The ceramic tiles are modelled as one continuous plate using eight nodes isotropic materials. Since ceramic material is not included in Dytran library Failure. Two theories have been used to predict the damage and failure on ceramic plate see chapter 2 and 3 for more details. The two models were designed based on experimental results. Therefore each of the models has its own calibration coefficients which have been obtained from literature as shown in tables Table 7-1 and Table 7-2.  

7.1.1 Mohr-Coulomb Model

A simplified Mohr-Coulomb strength model and linear equation of state are used to model the ceramic plate response to ballistic impact. The material constants used in modelling the ceramic plate are shown in Table 7-1.

Table 7-1 Mohr-Coulomb Damage model

<table>
<thead>
<tr>
<th>Mohr-coulomb Ceramic model</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Equation of state: Linear</td>
<td>Pressure 1: -3.00 E8 Pa</td>
</tr>
<tr>
<td>Reference Density: 3430 Kgm⁻³</td>
<td>Pressure 2: 0.00 Pa</td>
</tr>
<tr>
<td>Bulk modulus: 1.54E11 Pa</td>
<td>Pressure 3: 1.01 E20 Pa</td>
</tr>
<tr>
<td>Shear modulus: 8.30 E11 Pa</td>
<td>Pressure 4: 1.01 E20 Pa</td>
</tr>
<tr>
<td>Failure: Cumulative Damage</td>
<td>Yield Stress 1: 0.0 Pa</td>
</tr>
<tr>
<td>Reference temperature: 300 K</td>
<td>Yield Stress 2: 3.80 E9 Pa</td>
</tr>
<tr>
<td>Strength: Mohr-Coulomb</td>
<td>Yield Stress 3: 3.8 E9 Pa</td>
</tr>
<tr>
<td></td>
<td>Yield Stress 4: 3.8 E9 Pa</td>
</tr>
<tr>
<td></td>
<td>Failure : Accumulative Damage</td>
</tr>
<tr>
<td></td>
<td>Eff. Pls. Strain at Zero Damage: 0.01</td>
</tr>
<tr>
<td></td>
<td>Eff. Pls. Strain at Zero Damage: 0.03</td>
</tr>
<tr>
<td></td>
<td>Maximum Damage: 0.7</td>
</tr>
</tbody>
</table>
Since this simulation was carried out using a rigid FSP; the ballistic limit and the amount of energy absorbed obtained from these simulations are not true reflection of the real values. Therefore these results will only be used evaluate different effect of ceramic material properties on the plate response during a ballistic event.

7.1.1.1 Simulation
Figure 7-1: Back and side view Simulation of Ballistic Impact on 5mm of Ceramic using Mohr Coulomb Model.
Figure 7-1 shows the simulation of ballistic impact on 5 mm of ceramic. The model is based on Mohr Coulomb yield model.

Figure 7-2: (Ref1-2) "Ballistic impact simulation using LSDyna" (www.dec.fct.unl.pt/projectos/impacto/Public_Papers/Report%20on %20Ceramic)

Figure 7-2 shows simulation of ballistic impact on ceramic plate carried out using LS-Dyna. Mohr Coulomb model is used to model the damage and failure in both cases. There are similarities between the both results indicating that the ceramic model used is capable of accurately predicting damage and failure.
7.1.2 Johnston Holmquist 1

The JH-1 model is summarized in chapter 3. This model incorporate linear segments, two curves describe the strength surfaces of the material one is for intact ceramic and the other is for completely damaged ceramic. The material constants used in modelling the ceramic plate are shown in Table 7-2.

Table 7-2 Johnston Holmquist 1 Damage model

<table>
<thead>
<tr>
<th>Johnston Holmquist 1 Ceramic model</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kgm^{-3})</td>
<td>3700</td>
</tr>
<tr>
<td>Shear Modulus (GPa)</td>
<td>90.16</td>
</tr>
<tr>
<td>Equation of State:</td>
<td></td>
</tr>
<tr>
<td>K1 (GPa)</td>
<td>130.95</td>
</tr>
<tr>
<td>K2 (GPa)</td>
<td>0</td>
</tr>
<tr>
<td>Beta</td>
<td>1.0</td>
</tr>
<tr>
<td>Strength Constants:</td>
<td></td>
</tr>
<tr>
<td>T (GPa)</td>
<td>0.30</td>
</tr>
<tr>
<td>P1 (GPa)</td>
<td>0.00</td>
</tr>
<tr>
<td>P2 (GPa)</td>
<td>25.0</td>
</tr>
<tr>
<td>Pf (GPa)</td>
<td>2.50</td>
</tr>
<tr>
<td>S1 (GPa)</td>
<td>1.75</td>
</tr>
<tr>
<td>Si (GPa)</td>
<td>7.80</td>
</tr>
<tr>
<td>Sf (GPa)</td>
<td>2.90</td>
</tr>
</tbody>
</table>

A study of the effect of different strength constants into the ballistic response of ceramic is performed. In this section the ceramic models will be modified to establish the principal energy absorbing mechanism and the cause of damage and crack which is a phenomenon always associated with ceramic failure.
7.1.3 Detailed Study of Johnson Holmquist 1

Figure 7-3: Full Johnson Holmquist model

Figure 7-3 describes the full Johnson Holmquist 1 model used to simulate ballistic impact on ceramic plate. Figure 7-4 shows in details the progression of the stress, Equivalent stress, pressure and failure during ballistic impact of 0.22' rigid FSP travelling at 900m/s on 5 mm ceramic plate.

The initial gap between the projectile and the ceramic plate is 0.5 mm. the time taken by the projectile to impact the plate is 0.55µs. Figure 7-4(a) shows the state of the plate at 0.32µs just before impact as expected pressure and stress are zero. Figure 7-4(b) shows the state of the plate at 0.673µs (0.12µs after initial contact). A stress wave is generated and starts travelling outward the stress wave have a negative sign indicating that it is compressive. Figure 7-4(c) shows the state of the plate after 1.025µs (0.45µSec from initial contact) under the point of impact the stresses are too high the equivalent stress reaches it maximum value and failure starts occurring. The failure progress outward from the point of impact toward the back of the plate. Although the compressive stress wave has reached the back of the plate it is not powerful enough to break ceramic. Figure 7-4(d) shows the state of the ceramic plate after 1.377µs (0.82µs from the initial contact) the stress wave turned tensile at the free surface and the back of the ceramic plate is completely broken. Figure 7-4(e) shows the state of the ceramic plate after 1.73µs (1.17µs from initial contact) the stress wave continue to expand radially and the area under the impactor is completely damaged. Figure 7-4 (f) represent the ceramic plate state after 2.08µs (1.5µs from initial contact) the stress waves continue to travel radially outward from the impact causing further damage to the ceramic plate.
Figure 7-4: Failure, Pressure and Equivalent Stress progress during ballistic impact of 0.22" FSP travelling at 900 m/s on 5 mm of ceramic at: (a) 0.00 µs; (b) 0.673 µs; (c) 1.025 µs; (d) 1.377 µs; (e) 1.73 µs; (f) 2.08 µs.
7.1.4 Failure due only to –VE Pressure

Figure 7-5: (a) Full JH1 Model and (b) FH1 no positive pressure

Figure 7-6: Top and Bottom view of the failure progress during ballistic impact of 0.22" FSP travelling at 900 m/s on 5 mm of ceramic when only strength due to (-VE) pressure is used at: (a) 1.025μs; (b) 1.377μs; (c) 1.73μs; (d) 2.4μs; (e) 3.4μs; (f) 5.6μs.
Figure 7-5: shows the modification made to the Johnson Holmquist model to investigate the effect of using the strength due only to negative pressure on the ballistic response of the ceramic plate. This means that infinite compressive strength is assumed.

Figure 7-6 shows in details the failure progression during ballistic impact of 0.22" rigid FSP travelling at 900m/s on 5 mm ceramic plate. Figure 7-6(a) shows the state of the plate after 0.475μs no damage occurs to the plate as the critical stresses are not yet reached. Figure 7-6(b) shows the state of the ceramic plate after 0.827μs. A small damage area appears at the free surface of the plate shaped exactly as the blunt side of the FSP. This indicates that the pressure and stress wave have reached the back of the plate and the wave turned tensile. Figure 7-6(c) shows the state of the ceramic plate after 1.23μs, the back of the plate has failed while the front is still intact. Figure 7-6(d) shows the state of the plate after 1.377μs, there is a total failure under the initial area of contact and the damage continue to grow radially. Figure 7-6(e) shows the state of the ceramic after 2.25μs, the failure continues to grow radially following the path of the stress waves, cracks start appearing at the back of the plate. Figure 7-6(f) the final damage state of the ceramic after 5.05μs. When the full JH1 model is used the total damage area was small and local in this case the damage continues to grow and the final damage area is very large.

7.1.5 Failure due only to +VE Pressure

Figure 7-7: (a) Full JH1 Model and (b) FH1 No Negative Pressure

Figure 7-7 shows the modification made to JH1 model to investigate the effect of using only the strength due to +VE pressure on the ballistic response of ceramic. This means that infinite tensile strength is assumed.
Figure 7.8: Failure progress in ceramic plate impacted with 0.22" FSP travelling at 900 m/s when only strength due to +VE pressure is used at: (a) 0.67 µs; (b) 1.025 µs; (c) 1.37 µs; (d) 1.73 µs; (e) 2.08 µs; (f) 6.13 µs.

Figure 7.8(a) shows the state of the plate after 0.123 µs from initial contact. Figure 7.8(b) shows the state of the plate after 0.475 µs, at the point of impact failure start occurring indicating that the stresses are too high at this point and reaches it maximum allowable value. Figure 7.8(c) The failure progress outward from the point of impact toward the back of the plate. By this time the compressive stress wave has reached the back of the plate but it is not powerful enough to break ceramic. When full JH1 model was used the back of the plate is totally damaged by now; however in this occasion the back of the ceramic plate is still intact which indicates that tensile stress is responsible for breaking the back of the ceramic plate. Figure 7.8(d) shows the state of the ceramic plate after 1.18 µs the stress wave continue to expand radially however only a small increase in failure is noticed this further indicates that tensile stress wave is responsible for breaking the back of the ceramic plate. Figure 7.8(e) represent the ceramic plate state after 1.53 µs, the damage slowly progress downward. Figure 7.8(f) shows the state of the damage after 5.58 µs the damage slowly progressed downward and the final damage area is small and local.
Chapter 7 Composite Integral Armour

7.1.6 Effect of Velocity

Figure 7-9: Side and back view of simulation of Damage growth in 5 mm ceramic plate impacted with rigid 0.22" FSP travelling at 400 m/s.

Figure 7-9 shows the damage growth in 5 mm ceramic plate impacted at 400 m/s. The figure shows that upon impact damage started under the impact area due to compressive stress. The stress travelled outward toward the back of the ceramic, reflecting at the free surface and become tensile breaking the back of the plate. Figure 7-9(e) shows the formation of the ceramic cone. And Figure 7-9(f) shows the formation of cracks.
7.1.7 Low Velocity Impact

Figure 7-10: Failure progress in 5 mm ceramic impacted with 0.22" FSP travelling at 100m/s at: (a) 5.95 µs; (b) 6.3 µs; (c) 7.01 µs; (d) 8.77 µs

Figure 7-10 shows in details the failure progression during ballistic impact of 0.22" rigid FSP travelling at 100m/s on 5 mm ceramic plate. The initial gap between the projectile and the ceramic plate is 0.5 mm. the time taken by the projectile to impact the plate is 5µs. Figure 7-10(a) shows the state of the ceramic plate after (0.95µs from the initial contact) when the compressive stress wave has reached the back of the ceramic plate, turned tensile and starts making it way up toward the front of the plate. A small failure initiate at the back of the ceramic plate and making its way back toward the front of the ceramic plate. The time taken by a stress wave to reach the back of the ceramic plate is approximately 0.55µs from initial contact. To reflect back and make it way up half the ceramic plate is approximately 0.85µs this shows that the failure predicted by the model is caused by the tensile stress wave. Figure 7-10(b) shows the state of the ceramic plate after 1.3µs from initial contact, the stress wave continues to expand radially and the damage is growing from the back of the plate toward the front of the ceramic plate. Small crack start appearing at the free surface of the ceramic. Figure 7-10(c) shows the state of the ceramic after 1.6µs, the stress wave continues to travel radially and the damage and cracks continue to grow. The damage under the impactor is not symmetrical that could be explained by the shape of the projectile the extra damage is located under the
blunt edge of the projectile which is an accurate reflection of impact damage one would expect. Figure 7-10(d) shows the final damage at the back and side of the ceramic plate. A large number of cracks can be seen at the back of the plate. And the side of the plate shows

7.1.8 Comparison of both models

Figure 7-11: Simulation Run Time

Figure 7-11 shows the computer running time for the same plate impacted at the same velocity under similar boundary conditions. It is clear that the Johnston Holmquist model take longer time to run compared to the simplified Mohr Coulomb model. JH1 model is not included in the material library of MSC Dytran therefore the model is described using Fortran Subroutines (See Chapter 4 for more details). And most of the parameters used in this model are not described in the subroutine. Therefore it is required to describe them, call them, write them, use them, and then store them. These processes need to be done for every parameter of each element at each timestep. Thus the simulation time and storage needed are increased.
Chapter 7 Composite Integral Armour

7.2 Ceramic Faced Composite Armour

The requirement of any effective armour system is low density and effectiveness in defeating threats. It is well known that ceramic has an important role to play in ballistic protection. Ceramic have three important factors that make it a suitable candidate: low density to provide low mass; high bulk and shear modulus to prevent deformation and high compressive strength to resist penetration. However ceramic is very sensitive to tensile loading. An integrated system where high resistance of ceramic mixed with ductility of other material will make an effective protective shield. In the system presented in this section ceramic will provide hardness whereas the composite provide confinement and energy absorption.

The composite armour system consists of two materials, ceramic and composite, the areal density is constant.

Table 7-3: Ceramic Composite Armour systems

<table>
<thead>
<tr>
<th>Ceramic Thickness/m</th>
<th>Composite thickness (m)</th>
<th>Areal density (Kg/m²)</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.012</td>
<td>21.4</td>
<td>0.00</td>
</tr>
<tr>
<td>0.001</td>
<td>0.0095</td>
<td>20.44</td>
<td>0.105</td>
</tr>
<tr>
<td>0.002</td>
<td>0.0075</td>
<td>20.37</td>
<td>0.267</td>
</tr>
<tr>
<td>0.003</td>
<td>0.0055</td>
<td>20.30</td>
<td>0.545</td>
</tr>
<tr>
<td>0.004</td>
<td>0.004</td>
<td>21.12</td>
<td>1.00</td>
</tr>
<tr>
<td>0.005</td>
<td>0.002</td>
<td>21.06</td>
<td>2.50</td>
</tr>
<tr>
<td>0.006</td>
<td>0.00</td>
<td>20.99</td>
<td>-</td>
</tr>
</tbody>
</table>
Chapter 7 Composite Integral Armour

7.2.1 Numerical Analysis

In this section the finite element analysis of ceramic composite armour is presented. One of the main reasons for using the ceramic front armour is the ability of ceramic to blunt and shatter the projectile; to develop a model capable of capturing the entire failure it is therefore essential to include the deformation of the projectile in this new model. The steel projectile was modelled using 3-D solid elements with failure. The projectile properties are presented in Table 7-4.

Table 7-4: Projectile Properties (Ref 1-2)

<table>
<thead>
<tr>
<th>4340 Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Equation of State:</strong> Linear</td>
</tr>
<tr>
<td><strong>Reference Density (kg/m³):</strong> 7830</td>
</tr>
<tr>
<td><strong>Bulk Modulus (kPa):</strong> 1.59E+7</td>
</tr>
<tr>
<td><strong>Reference temperature (K):</strong> 300</td>
</tr>
</tbody>
</table>
7.2.1.1 Johnson Holmquist Model
Figure 7-12: Ballistic Impact response of on Ceramic Composite Plate to 0.33" FSP threat.

Figure 7-12 shows the ballistic response of (ceramic composite Plate) impacted with velocity below ballistic limit. Upon impact a small and local damage area is generated exactly under the projectile followed by the formation of a cone shaped damaged area on the ceramic. As the projectile penetrates the plate it deforms and erodes, the damage in the plate expand horizontally but remains confined to the ceramic and does not extend to the composite backing.
Figure 7-13: Ceramic Composite Armour Response to High Velocity Impact
Figure 7-13 summarises the ballistic response of ceramic composite plate to 0.33" FSP travelling at 900 m/s. To be able to capture the finite details of the penetration and damage process a very small time step has been used which resulted in large CPU time and output files. Upon impact a small and local failure is generated at the area of contact below the projectile indicating that the ceramic maximum equivalent stress limit has been reached. For the next few frames the initial damage area remains small (or very small changes) indicating that the ceramic failure criteria have not been satisfied. In Figure 7-13(d) a small damage appear at the rear of the ceramic layers between the ceramic and composite interface, this damage start to spread horizontally and make it way up toward the front of the ceramic tile. As the projectile penetrates the plate it starts deforming and eroding. During this process the damage does not advance to the backing plate instead it grows horizontally in a cone shape. The tip of the projectile is blunted by the ceramic layer as it penetrates the plate. During this time the only visible damage to the composite plate is delamination. As the projectile approaches the backing plate the composite start deforming and failing.

Figure 7-14: Velocity profile of different Ceramic/ Composite ratios

Figure 7-14 shows the velocity profiles of ceramic composite armours with a constant areal density (approximately 21 kg/m²) but different ceramic to
composite ratios. The results show that introducing ceramic in the face of composite improved the ballistic response of the plate. The effect was almost instantaneous. As the number of ceramic layers increase the ballistic limit improved until a ceramic composite ratio of (1:1). The graph shows that although the projectile still had some energy it was not penetration the plate any further. Indicating it has come to rest. The shapes of the curves suggest that the time step decreases as the ceramic thickness increase. Figure 7-15 shows the improvement in ballistic limit velocity as the ceramic layer thickness increases. For ceramic composite ratio above (1:1) the projectile has come to rest when it was impacted with 900 m/s.

![Graph showing ballistic limit energy for different ceramic-composite ratios](image)

**Figure 7-15: Ballistic Limit Energy of different Ceramic/Composite ratios**

### 7.3 Summary

In this section the finite element analysis of ceramic composite armour was presented. Two models have been used to show how some of the ceramic parameters affect the results. In both examples the composite model remains unchanged. However the ceramic model was be slightly altered.

When the ceramic material is subjected to ballistic impact a compressive stress wave was generated under the contact area and start travelling radially outward.
if the magnitude of the stress wave exceeds the dynamic strength of the ceramic material the elements fails. If not damage may start accumulating causing the ceramic to lose some of it strength. The compressive stress wave continues to travel radially outward damaging and breaking the ceramic when the stress limit is exceeded. Once the stress wave reach the back of the plate or the free surface, it reflects back as tensile stress wave and leads to the formation of spall damage if the dynamic tensile strength is exceeded. Usually this stage takes place in few microseconds depending on the plate thickness. Once the stress wave become tensile it starts making it way up toward the front of the plate causing more damage and failure.

Results of ballistic impact simulation on ceramic plate based on modified Mohr-Coulomb model were compared to results obtained from literature using LS-Dyna. Both simulation predicted similar damage and crack pattern the only difference was the size of the damage area under the projectile. This difference is due to the shape of the projectile used to impact the plate. In the LS Dyna example the damage area was circular because a bullet is used to impact the ceramic plate. While an FSP have two sharp edges.

To establish the effect of each material parameter on the ballistic response of the ceramic plate the JH1 model has been modified to include limited effect each time.

When using full JH1 model usually the area under the projectile fail due to compressive stress wave. When the failure due to positive pressure is removed from the model area under the projectile did not fail and the plate continued to resist the projectile during the first stages of impact until the pressure and compressive stress wave reached the free surface and reflect back causing the plate to fail in tensile. The failure started at the back of the plate and made it way up to the front of the plate.

When the failure due to negative pressure is removed from the model the cracks did not appear in the ceramic and the damage was small and local.

The introduction of ceramic in the face of composite improved the ballistic response of the plate. The effect was almost instantaneous. As the number of ceramic layers increase the ballistic limit improved until a ceramic composite ratio of (1:1). Where Figure 7-14 shows that although the projectile still had some energy it was not penetration the plate any further. The figure shows that the time step was getting smaller due to the severe deformation of the projectile.
and ceramic elements increasing the CPU time. Figure 7-15 shows the improvement in ballistic limit velocity as the ceramic layer thickness increases. For ceramic composite ratio above (1:1) the projectile has come to rest when it was impacted with 900 m/s.
Composite materials are relatively new class of material. Their main advantages are the ability to design and tailor the laminate to serve the designers need. These advantages are also the biggest disadvantage as design and mixing of different combinations of materials restrict the ability to unify all the different damage and failure modes in a simple theory. The damage mechanism, failure modes and mechanical behavior of composite material under different loading conditions are still under continuous development and improvement.

The objective set at the beginning of this project is to successfully simulate the ballistic response of ceramic composite armour using finite element packages MSC.DYTRAN and MSC.PATRAN. These packages were insisted on by the sponsor. To the Author's knowledge such work has never been attempted using MSC.DYTRAN during the project duration (11/2003 to 06/2007). The first publication referring to the use of MSC.DYTRAN in ballistic impact on armour was a 2007 thesis which was published in 2008. To date there are only two publications on ballistic impact simulation on armoured vehicles using MSC.DYTRAN. None of them deals with composite material. Adams (2007) investigated ballistic impact on metallic structure whereas Lamberts (2007) investigated ballistic impact on ceramic material. Both authors concluded that the standard material models available in MSC.DYTRAN do not suffice for simulating ballistic event. In both project Eulerian solver was used. The Eulerian solver is used for fluid or materials that undergo very large deformations. And because ballistic impact experiment on ceramic shows that the material undergo a large deformation and may behave like fluid the Eulerian solver was used. However, they still had to use user subroutines as the damage and failure models were not available in the Eulerian solvers within MSC.DYTRAN.

Fujii (2002) showed that for velocities above the ballistic limit fracture occurs in fluid manner for thin composite plate. This can be used as good argument for using Eulerian Solver. However, for thick plates the front layers of the target were damaged in fluid lake manner but not the rear of the plate.
At the beginning of this project the use of Eulerian solver was discussed with 
MSC.DYTRAN support group; however planes were later abandoned as it became 
clear that the Eulerian solver will require set of material and strength different to 
that used within Lagrangian solver. Also modelling composite failure using 
Eulerian method will not reach the required standards of accuracy especially if 
accurate damage and delamination predictions are required.

As the main focus of this work is to develop and use a numerical model capable 
of simulating and predicting the ballistic impact response of composite and 
ceramic composite armour using MSC PATRAN and DYTRAN. And since no 
failure model within MSC.DYTRAN capable of accomplishing that was available. 
A review of the existing damage and failure models was undertaken to 
understand, optimize and develop a new model capable of predicting the ballistic 
response of composite ceramic armour. To develop a new model, not in the sense 
of never been used before, but to combine different model and use them in new 
manner.

The study of ballistic impact response of composite armour is still 
predominantly experimental, with primitive objectives that only focuses on the 
prevention of projectile penetration. The experimental method used in developing 
new and better armours can be very expensive and time consuming. Since the 
composite failure is interactive and complicated the degradation and post failure 
of the material is usually ignored as it is harder to study. In this study several 
models were combined and tested in an attempt to provide a fast and more 
reliable prediction of the ballistic impact response. Also to try and gain insight 
into parameters that affects the ballistic limit velocity of the composite armour.

In this investigation existing failure model have been modified and/ or combined 
in an attempt to provide a better and faster means of predicting the failure and 
damage on different materials and to investigate the effect of some material 
properties on the ballistic response of the armour.

MSc Dytran is an explicit three dimensional finite element software dedicated to 
analyse problems where time step is important. The first version was released on 
June 1991 by combining MSC Dyna and MSC Pisces in an attempt to solve 
problems for structure fluid interaction such as blast loading or bird strike on 
aircraft.

In an attempt to carry a detailed study of parameters governing the damage and 
failure mechanism user subroutines were used. Subroutines allows for detailed
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description of material behaviour, damage and failure. The only restriction is that the user subroutine must have the list of user numbers of elements and grid points involve, to have an easy access to data and storage. In the case of ceramic the subroutine did not have this list which means that each variable used had to be defined, recall, stored used, and stored again for future use. This put a big burden on processor in term of time and space. This limits the parameters and element numbers used and affected the model selection.

8.1 Material model selections

8.1.1 Composite

Hashin failure criteria for unidirectional laminate has been selected and used as a baseline in this study. Additional term referring to contribution of the fill and warp fibre shear damage have been added to the damage model. Hashin failure criteria has been generalizes and the damage has been described by the quadratic interaction between the associated axial and through the thickness shear strains. This approach is similar to the composite damage model used by Yen (Yen 2002). The difference is in the way delamination was modelled Yen's model did not have a distinction between the intralaminar and interlaminar failure modes.

Figure 8-1: Delamination: a comparison between numerical and experimental results (Yen 2002)
Figure 8-1 shows a comparison between experimental results and numerical predictions. The predicted ballistic limit velocity (Yen 2002) of a 12.5 mm S2 Glass/epoxy impacted with 0.22" FSP was 731 m/s whereas the experimental value was 842 m/s which is approximately 13% higher than the predicted value. The extent of the predicted delamination is not visibly clear when using Yen's damage model.

In general, the analysis of delamination is commonly divided into the study of the initiation and the analysis of the propagation of an already initiated area. Delamination initiation analysis is usually based on stresses and use of criteria such as the quadratic interaction of the interlaminar stresses in conjunction with a characteristic distance. Crack propagation, on the other hand, is usually predicted using the Fracture Mechanics approach. The Fracture Mechanics approach avoids the requirement of the presence of a pre-existing delamination whose exact location may be difficult to determine. When used in isolation, neither the strength-based approach nor the Fracture Mechanics approach is adequate for a comprehensive analysis of progressive delamination failure.

In this research a distinction between the intralaminar and interlaminar failure modes was made, and each type of these failure modes was treated in a separate part of the software.

The intralaminar failure modes (fibre breakage, matrix cracking, through thickness crushing and shear failure) were modelled within the element constitutive routine and defined using material subroutines. The interlaminar failure mode included delamination, which was modelled using 1-D elements inserted between the layers of the elements. This allows the formation of a discrete delamination backplane during the penetration process. This approach has been successfully used by Hung et al (1995) to model delamination due to drop weight impact. Van Hoof (1999) has reported a good agreement on the numerical prediction and experimental data of ballistic impact on composite plate.

8.1.2 Ceramic

For ceramic damage models, Mohr-Coulomb and Johnson-Holmquist 1 models have been selected for study as they are frequently used in ballistic research of brittle materials because of their relatively easy theory and implementation.

Both models are similar in the sense that both models use strength as a function of pressure to describe the damage model. The JH2 model is somewhat different
then JH 1 since it has a continuous damage model. To model the correct material behaviour, the intact strength of the JH2 model is always higher than that of the JH1 model, because the damage reduces the strength as plastic strain accumulates. However determination of the JH2 parameters is more difficult, since the damage evolution has to be taken into account. Therefore the JH1 model has been selected to be implemented into MSC.Dytran to model the ceramic material behaviour. This model is more favourable than the JH2 model, since it has less functions analytical functions.

8.2 Model calibration

To verify the validity and accuracy of the model energy balance study has been undertaken. The energy study showed that during the impact process, a significant amount of the projectile kinetic energy is transferred to the target and converted into internal, kinetic, eroded and hourglass energies. However a small variation between the energy lost by the projectile and the total energy transfer to the plate was noticed. The slight total energy variation (approximately 1 %) was assumed to be caused by the energy contributed to the system during the removal of the penetration. Since the energy variation was less than 1 % of the total energy which appears to be insignificant no modification has been applied to the system.

A detailed study of the effect of mesh size and shape on the plate response to ballistic impact was carried out. The numerical predictions were found to be highly influenced by the element size. The amount of energy absorbed by the plate depended on the element size.

To eliminate the effect of mesh size on the energy absorbed by the plate a detailed mesh sensitivity study was carried out. Since there is no mention on the literature on the element dimensions that can be used in finite element simulation several element size were investigated and results have been presented in Figure 4-10. Results show the effect of varying the in-plane mesh size on the amount of energy absorbed by the plate. This figure revealed some important points.

- The amount of energy absorbed by the plate is dependent on the mesh size. The plate absorbed more energy when the elements were bigger. This results are similar to results from work done by Van Hoof (1999) where
he concluded that element failure is not only material property dependent, but also depends on the element size. In general the smaller the element the sooner the failure occurs.

- The elements size did not have a large influence on the damage pattern (Figure 4-14). However, for larger elements the damage area was bigger. This could explain why the smaller the elements the less energy the plate absorbed during penetration.

- The size of the element has influence on the time step. Since the time step is proportional to the smallest elements side. Reducing the element size caused a reduction in the time step value. Comparing the theoretical calculated time step to the actual one obtained from the simulation showed a large discrepancy. That could be explained by the deformation the elements undergo when subjected to loading.

- Elements size 0.2 mm were selected to be used in this study for two reasons:

  - The difference in the amount of energy absorbed by the plate when meshed with 0.20 mm and 0.15 mm is very small.
  
  - Reducing the elements size any further caused the problem to stop as the mesh far exceeded the computer capability.

![Figure 8-2: Velocity profile of full and quarter plate](image)
In an attempt to reduce the number of elements used in a simulation only a quarter of the problems was modelled and symmetry was used. Simulations show that the difference in velocity profile of full and quarter plate is very small. It is therefore decided that quarter plate can be used for the rest of the study.

Explicit codes are known to be mesh dependent. In contact problem it is important to use small mesh. However meshing the entire plate with small elements will put large pressure on the computer. In a ballistic impact the damage area is usually small and local. Modelling the entire plate with small mesh is an inefficient way of solving the problem. Since the area of interest in a ballistic impact is located exactly under the impactor and on the surrounding areas. Bias mesh was used to model the plate because it allows for different mesh densities. Several design options were investigated and it was found that bias mesh sensitive to several factors in particular the changes in mesh density. That was best demonstrated in the areas near the edge of the plate where the elements had large length to width ratio. In that cases the element quickly deform when load was applied causing failure when the length of one side became zero.

The numerical simulation displayed a considerable degree of hourglassing; initially the stiffness control provided a solution as they proved to be the most efficient way of controlling this numerical problem. However, increasing the hourglass stiffness also stiffened the plate response affecting the ballistic response of the plate and resulting in smaller backplane estimation.

The proposed solution is to model the area under impactor with small mesh allowing the elements sizes to gradually increase both in length and width when moving away from the centre of the plate.

The final two design options are presented in Figure 8-3.

Option two is chosen where the area under the impactor was modelled using eight nodes cubic elements for following reasons:

- Changing the element shape under the projectile had no influence on the amount of energy absorbed by the plate.

- When cylindrical shape is used some elements in the middle of the plate have pancake shapes which were found to have large effect in reducing time step (Figure 8-4).
- When ceramic plate was modelled these elements get distorted very quickly causing the problem to stop.

Figure 8-3: Final Design Option, (1) the quarter cylindrical area is meshed with constant elements size 0.2mm; (2) quarter cylindrical area has a squared shape area meshed with constant mesh.

Figure 8-4: Effect of both design option on time step
The effect of mesh density of contact was also investigated. Varying the element size of the projectile while keeping the plate mesh constant was found to have no effect on the amount of energy absorbed by the plate as long as the plate mesh was smaller than the projectile's. However, when the projectile is meshed with elements smaller than the plate's the amount of energy absorbed by the plate changes. The mesh density of the plate should always be smaller than the projectile's. Because slave nodes are checked for penetration of master segment not vice versa. If the element size of the master are smaller than the slave surface, penetration may occur with master surface going through the slaves without been detected.

8.3 Ballistic Impact Experiment

To evaluate the accuracy of the developed numerical model it was necessary to compare the numerical prediction to experimental data obtained from ballistic impact trials. Due to the limitation of the firing power of the gas gun only relatively thin composite plates have been tested (up to 4 mm). The gas gun was only capable of firing 0.88g ball at the maximum velocity of 400 m/s. Composite sample were manufactured using vacuum assisted resin transfer moulding (VARTM). The advantages of such technique are reduction in pollution because the entire process take place in a close controlled system, time and cost reduction because of the single step process.

The fibre glass volume fraction was calculated using the following equation:

\[ V_f = \frac{AD_f \times N_f}{\rho \times t} \]  

Equation 8.1

Where \( V_f \) is the fibre the volume fraction, \( AD_f \) is the areal density of the glass fabric, \( N_f \) is the number of fabric layers, \( \rho \) is the fabric density and \( t \) is the composite thickness.

The average fibre volume fraction of the E-glass/VE was approximately 54%.

In the case of composite material only of 0.44g and 0.88g round ball were used, for two reasons:

- The gas gun limitation described above which means only relatively small ball can be fired at high velocity.
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- The difficulty in controlling the yawing angle of FSP or any cylindrical shape projectile. When the projectile is released from the sabot it tends to rotate which make it difficult to control the impact angle. Due to the spherical nature of the round ball that problem was eliminated.

8.3.1 Ballistic Limit Velocity

The method used in obtaining the experimentally measured ballistic limit velocity is by firing six shots within 10% range at the same plate at the same angle under similar condition for which three must fully penetrate the armoured panel. The average is the final ballistic limit velocity.

A number of ballistic impact test were performed to evaluate the accuracy of the model. All results were plotted as functions of areal density.

Figure 8-5 and Figure 8-6 show experientially measured and numerically predicted ballistic limit velocities as functions of areal density. Excellent agreement is found between experimental and predicted results for both masses of ball bearing. Taking into account the expected experimental errors, the results can be described as in complete agreement. These results verify the finite element approach used. These methods will be applied composite and ceramic/composite armour.

Results of experimentally measured ballistic limit velocity and numerical predicted shows that the ballistic limit increases with increasing areal density. Increasing the mass of the ball bearing reduces the ballistic limit. However, this reduction is small and does not reflect the large increase in projectile mass. This indicates that the ballistic limit velocity is not only influenced by the kinetic energy of the projectile but also influenced by the projectile geometry (contact area). As the mass of the projectile increases the projectile diameter also increases leading to a larger surface area of contact spreading the load over a larger area.
Figure 8-5: Ballistic Impact Limit Comparison of Experimental data with Numerical prediction of Plain Woven E-glass/ VE impacted with 0.44g Ball.

Figure 8-6: Ballistic Impact Limit Comparison of Experimental data with Numerical prediction of Plain Woven E-glass/ VE impacted with 0.88g Ball.

The effect of the projectile mass can be considered using kinetic energy rather than ballistic limit velocity. The kinetic energy was calculated using $V_{50}$.
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\[ KE = \frac{1}{2}mv^2_0 \]

Equation 8.2

The kinetic energy \( E_{50} \) is usually referred to in literature as the ballistic limit energy or the perforation energy \( E_p \) (Takahashi 1997).

![Figure 8-7: Energy absorbed by the different thicknesses of E-glass/VE impacted by 0.44 g and 0.88 g steel ball.](image)

A linear relationship was obtained between the ballistic limit energy and the areal density of the plate. As the area density increase the increase in energy becomes bigger.

### 8.3.2 Damage

Damage caused to composites during a ballistic impact can change depending on the initial impact velocity, plate thickness and projectile shape. It is important to be able to detect and quantify the extent of the damage. Two methods of damage detection have been used in this study. A non contact air coupled c-scan was used to determine the extent of the damage caused to composite material. The c-scan showed that the total damage area caused to the composite plate by impact velocity below ballistic limit is larger than that caused by impact velocity above the ballistic limit. However, a detailed comparison between types of damages obtained from the c-scan and numerical simulation was not possible as the exact location of each type of failure was not clear from the c-scan picture.
In the second method a digital photograph was taken to assess the damage size. Halogen white spot-light was used at the back of the specimens to illuminate them. The damaged part absorbed light more than the undamaged part, as shown in Figure 5-14. This effect was used to measure the damage size as a horizontal diameter and total area. Figure 5-12 and Figure 5-13 shows that the total damage caused by impact velocity below ballistic limit is larger than that caused by impact velocity higher than ballistic limit.

The results also showed that for high velocity impact (above the ballistic limit) the damage at the face and the back of the plate is small and local. Whereas for velocity impact less than the ballistic limit the damage at the face is small and local, but increases toward the rear of the plate. The damage also changes from fibre failure and matrix crack at the front to delamination toward the back of the plate. Similar results were reported by (Silva 2005)

Figure 8-8: Damage on composite plate impacted by 0.88g ball above and below ballistic limit velocity

Figure 8-9: Damage on composite plate impacted by 0.88g ball above and below ballistic limit velocity.
Table 8-1: 2D Damage area of composite plate after ballistic impact.

<table>
<thead>
<tr>
<th>Description</th>
<th>Area (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Perforated</td>
</tr>
<tr>
<td>Complete failure of fibre and resin</td>
<td>30.2</td>
</tr>
<tr>
<td>Resin failure and some delamination</td>
<td>396</td>
</tr>
<tr>
<td>Resin failure</td>
<td>855</td>
</tr>
</tbody>
</table>

Table 8-1 shows a comparison of the measured damage size as a horizontal diameter and total area for the perforated and non perforated plate. The visible damage area of the non-perforated plate far exceeds that of the perforated plate. That is consistent with numerical prediction.

Figure 8-10: 4mm plate impacted at velocity less than ballistic limit

Comparing Figure 5-14 to Figure 5-15 where simulation of 4.2 mm plate impacted with 0.88g ball travelling at velocity below ballistic limit (300m/s) shows a similar damage size and delamination length. The total delamination damage length shown in Figure 5-14 is 24 mm where as the size of the damage in Figure 5-15 is 26 mm.
8.4 Ballistic Impact Simulation

As S2-Glass fabric is more commonly used in the armour protection, ideally it should have been used throughout this project. However due to the lack of the material during the experimental stage, E glass fabric was used to calibrate and validate the model. In this chapter relatively thick plates was simulated. Since the available gas gun was not capable of firing projectiles at velocities high enough to penetrate thick plates other source of experimental results were required. Ballistic limit velocity of different thickness of plain woven S2-Glass/Epoxy was obtained from literature Yen (2002). As revealed in section 8.1.1. The same material properties have been used in Yen (2002) and this project, but modified damage and failure model. As mentioned in section 8.1.1. the predicted ballistic limit velocity of 12.5mm thick S2 Glass/epoxy plate impacted with 0.22" FSP was 731 m/s whereas the experimental value was 842 m/s which is approximately 13% higher than the predicted value.

The predicted ballistic limit velocity of a 12 mm think plate using the same properties but different delamination damage model was 780 m/s. this demonstrate the improvement of using a distinction between the intralaminar and interlaminar failure modes.

This method also demonstrates the capability of this model to visibly show delamination. The paper (Yen 2002) did not refer to the size or extend of damage and delamination so that it can be compared to the model developed in this project.
8.4.1 Ballistic Limit

After evaluating and calibrating the accuracy of the numerical model, Ballistic impact simulation of different projectiles on different plate thicknesses were studied to investigate the effect of each material parameter on the failure mechanism and the amount of energy absorbed by the plate.

8.4.2 Ballistic Limit Prediction

Ballistic limit of four different projectiles were obtained for various areal densities. As expected the ballistic limit velocity of each projectile increases as the areal density increases and decreases as the mass of the projectile is increased. Doubling the projectile mass from 0.44g to 0.88g did not halve the ballistic limit velocity. This indicates that ballistic response of the composite plate is not only influenced by the projectile mass and kinetic energy. But also by the projectile diameter. Increasing the projectile diameter increases the contact area, which distribute the load over a larger area.
Figure 8-12 shows that the amount of energy absorbed by the plate increases with the increase of areal density and projectile type. The figure also shows that the plate critical energy increases as the ratio of the projectile's mass to diameter increases.

To eliminate the effect of projectile on the predicted ballistic limit velocity for a given areal density a parameter R has been introduced.

\[
R = \frac{E_{\text{critical}}}{a} = \frac{\left( \frac{1}{2} m_p V_{50}^2 \right)}{a}
\]

Where \( E_{\text{critical}} \) is the critical energy of the plate (energy absorbed by the plate), \( a \) is the surface area of the projectile, \( m_p \) is the projectile mass and \( V_{50} \) is the ballistic limit velocity.
Figure 8-13: Predicted critical energy per unit area of Several Areal Density plates subjected to impact with different projectiles.

Figure 8-13 indicates that the critical energy per unit area for a given areal density is approximately constant for all projectiles. This technique can be useful in predicting the ballistic limit velocity of any threat for a given areal density.

**8.4.3 Material Parameter Effect**

To be able to improve the armour designs a full understanding of the effect of the material properties on the ballistic response of the composite plate is required. A detailed study of the effect of varying all material properties on the amount of energy absorbed by the plate and penetration is carried out.

**8.4.3.1 Fibre Strength**

*In-plane normal strength*

Doubling the in-plane strength increased the amount of energy absorbed and improved the ballistic impact properties of the plate. The in-plane strength in the
model \((S_x \text{ and } S_y)\) represents the layer axial tensile and compressive strength in the fill and wrap directions it also caused an increase in the backplane displacement of the plate indicating a further projectile resistance. The in-plane normal strength had little effect on the time step.

**Through thickness strength**

The through thickness strength in the model \((S_z)\) represents the fibre crush strength. Doubling the through thickness strength is equivalent to doubling the fibre crushing strength leading to a very large increase in the amount of energy absorbed by the composite plate and arrested the projectile. Increasing the through thickness strength also had a large effect of the reducing the time step.

**Through thickness shear strength**

The through thickness strength in the model \((S_{xz} \text{ and } S_{yz})\) represents the layer shear strength due to fibre failure in the fill and wrap direction. Increasing the through thickness shear strength had little effect on reducing the ballistic properties on the composite plate and the size of the time step. A small decrease in the backplane response is also observed.

**8.4.3.2 Resin Strength**

**In-plane shear strength**

The in-plane shear strength in the model \((S_{xy})\) represents the layer shear strength due to matrix failure. Increasing the in-plane shear strength slightly reduced the amount of energy absorbed by the plate and the backplane displacement.

**8.4.3.3 Fibre Stiffness**

**In-plane stiffness**

Increasing the in-plane stiffness resulted in a reduction in the failure strain of the material which reduces the amount of energy absorbed and the ballistic protection of the plate. Doubling the in-plane stiffness caused an increase in element distortion which led to a decrease in the time step size. Doubling the in-plane stiffness resulted in a smaller backplane displacement. That indicates that the plate did not resist the projectile and was quickly perforated.
Through thickness stiffness

Increasing the through thickness stiffness significantly reduced the amount of energy absorbed and ballistic protection of the composite plate. Doubling the through thickness shear stiffness is equivalent to halving the fibre crushing strength. This reduces the plate resistance to punching failure. Varying the through thickness stiffness had little effect on the time step. Doubling the through thickness stiffness reduced the backplane displacement indicating the plate failed sooner.

Through thickness shear stiffness

Doubling the through thickness shear stiffness increased the amount of energy absorbed and improved the ballistic protection of the composite plate. Increasing the through thickness shear stiffness also reduced the time step as the plate resist the projectile the element distort further causing the element size and time step to decrease.

8.4.3.4 Resin Stiffness

In-plane shear stiffness

Changing the in-plane shear stiffness had almost no effect on the amount of energy absorbed by the plate. The only noticeable effect of increasing the in-plane stiffness is the reduction in backplane displacement.

8.4.4 Armour design improvement

Varying the material properties of composites shows that the fibre crushing strength had the greatest effect on improving the armour ballistic properties. Increasing the in-plane shear strength has been shown to slightly reduce the ballistic performance of the composite plate. Chapter 6.3.3 showed that although the energy absorbed by the plate was slightly reduced when the matrix strength has been doubled, the backplane response was more noticeable. This led to the conclusion that reducing the matrix strength may allow the damage to spread over a larger area and allows the plate to deform more absorbing more energy in the process. As seen from the experimental results, the energy absorbed by the plate during a ballistic event depends on many factors. One of which is the speed of the projectile. At high impact velocity (above the ballistic limit), the damage is usually local and the primary damage mechanism is matrix and fibre failure at the projectile/plate point of contact Figure 8-8 and Figure 8-9. These damage
modes changes to fibre failure and matrix cracking mechanism at the frontal side and matrix cracking and delamination mechanism at the rear side of the target if the impact velocity was below the ballistic limit velocity Figure 8-9 and Figure 8-10.

This means that as the ballistic limit velocity is approached failure modes will change from local fibre failure to the matrix cracking and delamination spread over a larger area. This led to the idea of reducing the matrix strength to allow for the damage to propagate which will allow the plate to absorb more energy in the process.

Changing the material property such as in-plane strength which represents the matrix strength, in a complicated material such as the composite is a complex issue as it will have an impact on other strength parameters as the damage and failure modes in composite material usually interact.

The matrix strength is a controlling factor of the trough thickness and in-plane shear strength. In this analysis the failure model used assumes that the matrix strength is represented only by the in-plane shear strength. For plain woven fabric the through thickness shear strength represent the layer shear strength due to the fibre shear strength in the fill and wrap directions. Since the strength of the fibre is higher than the resin the through thickness shear strength will be represented by the fibre shear failure in the fill and wrap direction.

Figure 6-31 shows the effect of varying the in-plane shear strength on the ballistic limit velocity of different areal densities. The ballistic limit velocity continues to increase as the strength is reduced. As expected the improvement becomes more noticeable as strength become smaller or as the plate become thicker. This improvement could be explained: As the in-plane strength is reduced the matrix damage area increases absorbing more energy in the process. Also as the plate thickness increase the total damage area increases leading to more energy been absorbed. For thin plate the changes in ballistic limit velocity is relatively small and only become visible when the strength is more than halved. As the plate thickness increases the changes in energy absorbed by the plate increases for all three strengths. The amount of energy absorbed by the plate during the initial stages of impact is the same for all strength values. That could be due to the relatively high velocity of impact where the failure is local and most of the energy absorbed at this stage is due to fibre failure. This agrees with Silva (2005) observation, where he noticed that when the composite targets are subject to ballistic impact. The damage character of the laminate plies in the
through-thickness direction (from the frontal side down to the distal side of the target) is highly localised and the primary damage mechanism was fibre failure at the projectile/plate contact point. And since the fibre strength remains unchanged the amount of energy will be constant. The changes become clearer in the later stages of the impact when the velocity is reduced and the rest of the plate start contributing to the energy absorption mechanism through delamination and matrix failure. Silva (2005) reported that in the case when impact velocity is below the ballistic limit velocity the damage changed from a matrix cracking mechanism at the frontal side to a pure delamination mechanism at the rear side of the target.

The changes in the amount of energy absorbed by the plate when the in-plane shear strength is changed are also dependent on the impact velocity. In particular around the ballistic limit velocity where the plate absorbs more energy because of the failure of a large matrix area.

The outcome of this investigation demonstrates the effect of resin strength on energy absorption mechanism during ballistic impact. The reduction in matrix strength has been shown to increase the energy absorbed by the plate and improve the ballistic limit velocity. Results also demonstrate that the effect of in-plane shear strength on energy absorption is dependent on both plate thickness and velocity. The effect is larger for thicker plates.

Table 8-2: increase in ballistic limit velocity and energy.

<table>
<thead>
<tr>
<th>$S_{xy}$ Strength (%)</th>
<th>$V_{50}$ (m/s)</th>
<th>Improvement (%)</th>
<th>$E_{50}$ (J)</th>
<th>Improvement (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>775</td>
<td>0</td>
<td>330</td>
<td>0</td>
</tr>
<tr>
<td>80</td>
<td>803</td>
<td>3.6</td>
<td>354</td>
<td>7</td>
</tr>
<tr>
<td>60</td>
<td>830</td>
<td>7.1</td>
<td>378</td>
<td>14</td>
</tr>
<tr>
<td>40</td>
<td>870</td>
<td>12</td>
<td>416</td>
<td>26</td>
</tr>
</tbody>
</table>
In this research a distinction between the intralaminar and interlaminar failure modes was made, and each of these types of failure modes was treated in a separate part of the software. This resulted in the matrix strength been represented in both part of the model.

The damage model used in representing the intralaminar failure modes (fibre tensile, shear, crushing and matrix failure) meant that the matrix damage and failure models was represented only by the in-plane strength ($S_{11}$). And the matrix through thickness tensile and shear strength was modelled on the interlaminar failure model. The through thickness shear strength ($S_{xx}$ and $S_{yy}$) used in the model represents the layer shear strength due to fibre failure in the fill and wrap direction.

In reality the matrix strength is a controlling factor for both in-plane and through thickness shear strength, reducing the matrix strength will affect both of them. In this research it has been shown that the ballistic response of the composite plate will continue to improve as the matrix strength ($S_{11}$) is reduced. Whereas in reality there may be an improvement up to a stage where the effect of in-plane shear strength and through thickness tensile and shear may cancel each other out. The model may not have been able to accurately predict that could be due to the failure model used in predicting delamination which was based on strength-based approach only.

Despite the fact that delamination is closely related to matrix cracking, coupling effects between matrix cracking and delamination were not accurately represented in the numerical model. An accurate prediction of delamination and precise amount of energy absorbed in the process will requires the use of strength-based approach and the Fracture Mechanics approach (chapter 3.5.8.). Furthermore ballistic experimental results for composite plates with reduced matrix strength are required to validate the findings.

### 8.5 Ceramic

Modelling ceramic using MSC software has proved to be a challenge as the ceramic material behaviour is not included in the material library of MSC Dytran. Therefore subroutines have to be used to describe the material behaviour, damage and failure. Fortran subroutines are also used to describe composite material response to ballistic impact; in the case of composite material
the subroutines had easy access to the data stored for most of the elements and grid point within the subroutines. In the case of ceramic the user-written subroutine didn't have the list of the user numbers of the elements and grid point involved. That meant that for every element at every time step the required parameters need to be defined recall used and stored, this procedure immensely increased the processing time of the simulation. These restricted our study of ceramic composite armour as number of elements and parameters used needed to be kept to a minimum and failure and damage model needed to be simplified. In armour design ceramic is used to blunt and shatter the projectile; therefore it is more accurate to used deformable 3-D solid element with failure to simulate impact on composite ceramic armour.

8.5.1 Mohr Coulomb

As mention above MSC Dytran does not have the full Mohr-Coulomb available in the material library. Therefore a simplified version is used where linear equation of state is used in conjunction with Mohr-Coulomb yield model. The model does not allow for material degradation as damage accumulates. Therefore the material is assumed to main full strength until failure.

Results of ballistic impact simulation on ceramic plate based on modified Mohr-Coulomb model were compared to results obtained from literature using LS-Dyna. Both simulation predicted similar damage and crack pattern the only difference was the size of the damage area under the projectile. This difference is due to the shape of the projectile used to impact the plate. In the LS Dyna example the damage area was circular because a bullet is used to impact the ceramic plate. Where as an FSP have two sharp edges.

8.5.2 Johnson Holmquist

A detailed study of Johnson Holmquist model has been carried out. In general when the ceramic material is subjected to ballistic impact a compressive stress wave is generated under the contact area and start travelling radially outward if the magnitude of the stress wave exceeds the dynamic strength of the ceramic material the elements fails. If not damage may start accumulating causing the ceramic to lose some of it strength. The compressive stress wave continues to travel radially outward damaging and breaking the ceramic when the stress limit is exceeded. Once the stress wave reach the back of the plate or the free surface, It reflects back as tensile stress wave and leads to the formation of spall damage if the dynamic tensile strength is exceeded. Usually this stage takes place in few
microseconds depending on the plate thickness. Once the stress wave becomes tensile it starts making its way up toward the front of the plate causing more damage and failure.

To establish the effect of each material parameter on the ballistic response of the ceramic plate the JH1 model has been modified to include limited effect each time.

8.5.3 Failure due to –Ve pressure

Figure 8-14 shows the effect of removing failure due to positive pressure from the JH1 Model. This means that infinite compressive strength is assumed. When using full JH1 model usually the area under the projectile fail due to compressive stress wave. When the failure due to positive pressure is removed from the model the plate did not fail under the compressive wave and continue to resist the projectile during the first stages of impact until the pressure and compressive stress wave reached the free surface and reflect back causing the plate to fail in tensile. The figure shows the failure starting at the back of the plate and making it way up to the front of the plate.
8.5.4 Failure Due to +VE pressure

Figure 8-15: Effect of only using strength due to +VE pressure on the amount of energy absorbed by the ceramic plate.

Figure 8-15 shows the effect of positive pressure on the amount of energy absorbed by the plate during a ballistic impact event. This means that infinite tensile strength is assumed. Initially the energy absorbed by the ceramic plate is the same which indicate that the failure of the area under the projectile is due to maximum equivalent stress. The change in energy starts occurring between 1.025\(\mu s\) and 1.37\(\mu s\) that coincide with time taken by the compressive stress wave to reach the back of the plate 1.087 \(\mu s\) reflect and become tensile. This indicates that the tensile stress wave is responsible for the failure that usually occurs at the back of the plate.
8.6 Ceramic Composite Armour

The introduction of ceramic to the composite armour has been found to provide a better ballistic protection. All the theories used in the analytical and numerical analysis predicted that. However, the different theories provided different results.

Although there has been some research concerning the failure in ceramic there are no data that provide for a description of the failure process. Johnson and Holmquist (2002) have shown some indications that the JH1 model could be more accurate to use. They have shown that the plate impact results provided a constant strength under high pressure and significant plastic strain. This indicates that the significant softening does not occur under damage (plastic strain) until the material is fully damaged. This led to the conclusion that JH1 will be more suitable to model the composite ceramic armour as the MC model uses the damage factor D to model the progressive damage by reducing the yield strength (chapter 3.6.2)

The numerical analysis of ballistic impact on ceramic composite armour that was carried out provided some good results and failed to predict some important ones. When the full Johnson Holmquist 1 theory was used the model predicted that upon impact stress wave is generated at the area on contact and start travelling radially outward. If the projectile velocity is high enough and the maximum equivalent stress limit is reached failure will occur at the ceramic front. Once the stress wave reaches the back of the ceramic layer at the ceramic composite interface it turn tensile and failure start occurring. The failure at the ceramic/ composite interface is usually large and grows very fast this is due to the brittle nature of the ceramic which is very sensitive to tensile stress. Pictures of the simulation shows that the model can predict most of the failures associated with this type of impact and reported in the literature from the formation of ceramic cone, erosion of the projectile, ceramic sensitivity to tensile failure, delamination of the composite, large delamination at the interface etc.. However the model did not predict the large deformation and the larger damage that occurs to the backing plate which is associated with this type of impact.

In reality, as the projectile impact the target a compressive stress wave is generated and starts travelling radially outward toward the rear of the ceramic layer where it turns tensile at the ceramic composite interface. Usually if the impact velocity is high enough the generated compressive wave will be sufficient enough to cause damage in the front of the ceramic layer. But the majority of the
damage is usually caused by the failure due to tensile wave at the rear of the ceramic layer.

JH1 predicted all these behaviours and once failure occurs the ceramic element is deleted from the model. MSC Dytran uses Lagrangian methods which is based upon fixed mass elements which means that when a structure deforms, so does the attached mesh. The element failure in Lagrangian method is the measure of the maximum allowable stress/ deformation of an element before is it deleted from the calculation. A direct consequence of using this is that as the elements are deleted, they no longer contribute to the physics of the simulated event. This means that the global system will lose mass, momentum and energy, which can severely affect the evolution of a simulation.

In reality as the ceramic reach it strength limit failure occurs but the ceramic does not disappear from the armour instead it breakdown to fine debris which remain between projectile, the intact ceramic and the backing plate. As the projectile penetrates the plate it pushes this debris towards the backing plate which causes damage to composite plate. It is the failure of the Lagrangian method to predict this behaviour that led to failure of predicting the large damage in the composite plate.

![Figure 8-16: Ballistic Limit Energy of different Ceramic/ Composite ratios](image-url)

Figure 8-16: Ballistic Limit Energy of different Ceramic/ Composite ratios
The effect of varying the ceramic composite thickness is presented in Figure 8-16. The results show that introducing ceramic in the face of composite improved the ballistic response of the plate. The effect was almost instantaneous. As the number of ceramic layers increase the ballistic limit improved until a ceramic composite ratio of (1:1). Where Figure 7-14 shows that although the projectile still had some energy it was not penetration the plate any further. The figure shows that the time step was getting smaller due to the severe deformation of the projectile and ceramic elements increasing the CPU time. This is the most challenging problem faced when trying to simulate ballistic impact into ceramic composite armour. The number of subroutine and parameters used within each subroutine in describing the damage and failure severely obstruct the progress of the model. Figure 8-16 shows the improvement in ballistic limit velocity as the ceramic layer thickness increases. For ceramic composite ratio above (1:1) the projectile has come to rest when it was impacted with 900 m/s.
9 CONCLUSION AND FUTURE WORK

9.1 Conclusion

The main objective of this study was to use finite element package, MSC Dytran, to investigate the response of a composite plate during a ballistic event and to try to determine the effect of material parameters on the amount of energy absorbed by the plate and the effect it has over the ballistic limit velocity of the armour. The following conclusions have been reached:

a) Excellent agreement between experimental test and numerically predicted results for ballistic impact on composite laminates.

b) Comparison of the model used in this project with similar ones has shown a slight improvement in predicting the ballistic limit and delamination extent.

c) Simulations show some improvement of the ballistic performance of composite laminates with reduced in-plane shear strength, but energy absorption is critically dependent on the plate thickness and matrix strength.

d) The numerical model was found to be mesh sensitive and results greatly depend on the area and size of the mesh density. The master element always needs to be larger than the slave elements.

e) The numerical simulation indicates that there is a linear relation between the ballistic limit energy and the areal density of the composite plate.

f) Model for ceramic failure for ballistic impact have been implemented however further work is needed to assess and develop a simpler model to be used with MSC.DYTARN.

g) Although the accuracy of the model is not completely established in the case of composite integral armour, the results are in agreement with experimental observations. The use of composite plate to confine the ceramic tiles was found to improve the ballistic properties on the plate.

h) Detailed study of the effect of each ceramic material parameter separately enabled a better understanding of the ballistic response of the ceramic plate. This could provide and understanding in armour improvement.

i) The ballistic response of the ceramic/ composite armour has been numerically investigated. The performance of the composite armour has been
compared to that of composite plate. Results have shown that the introduction of ceramic plate improved the ballistic resistance of the plate. However, the increase in ballistic protection is not linear and depend on the ceramic composite thickness ratio.

j) Comparison of the numerical simulation with the experimental results have shown that the numerical model on the impact response captures many aspects of the physical phenomena and provide more information on the effect of different properties on the material behaviour during a ballistic event. However; the ceramic model failed to predict some important behaviour associated with the ballistic impact on ceramic composite armour such as the extensive damage to the backing plate. This failure could be due to the nature of the Lagrangian code used in this simulation.

k) The absence of ceramic from Dytran material library made the ballistic impact simulation on ceramic extremely difficult and time consuming. It is the author's conclusion that MSC software is not suitable to for simulating high velocity impact on ceramic material.

l) Despite apparent need for further model improvements, this work has shown a clear advantage of numerical analysis over the traditional methods based on empirical work.

m) Finally it is concluded that the numerical simulation provide a better understanding of the interaction of the different individual material properties and their effect on the ballistic response of ceramic/ composite armour which could help improve modern armour.
9.2 Future Work

Existing damage models have been combined and used in this research. This work is meant to be a first step in the development of a numerical model capable of accurately predicting the ballistic response of composite and multi-layered ceramic composite armour. Together with experimental validation, this work could be very important in practical design and development of new composite armours. Despite the good agreement between the numerical prediction and the experimental data, there is need for further research in some areas.

a. Despite the good results obtained using the current mesh a new better meshing technique will need to be adapted when modelling multi-layered composite and ceramic plate as both the delamination and ceramic cracks are mesh sensitive.

b. Because of the quasi-static nature of the material parameters used in this simulation some disagreement with the experimental results were noticed. The study has shown the need for a better material model capable of predicting the plate response over a range of velocities. The condition encountered involved large strain and strain rate ranges. Strain rate effect is taken into account in the case of composite material. A more detailed study to investigate the effect of threat level on the strain rate values is needed. Also in future work it will need to be accounted for in all the material models.

c. Even though the experimental results obtained from literature are valuable further ballistic test are required using different projectiles and high energy to examine the extent of the damage area in the plate.

d. Alumina tiles have been of the greatest interest to armour designs because it provides good strength at a small cost. However due to the lack of required experimental data and the absence of proper material library in the MSC Dytran the development of the damage model has been hindered. A source for material properties need to be found other ways experimental test will be needed to obtain the required data.

e. However Johnston-Holmquist has provided more accurate relatively good results. Further work need to be done to better asset other models and may be combining the models.

f. Before any further work is done in the development of a new model for multi-layer composite ceramic armour a source for ballistic limit and
Chapter 9 Conclusion and Future Work

damage assessment for ballistic impact on ceramic/ composite is needed to enhance the calibration of the model.

g. The material properties used to date have been obtained from various literature sources with modifications enabling the model to run. The present failure model is for removal of the element as soon as the failure criterion has been reached; it will be more accurate to develop a more sophisticated failure model including residual strength especially for the ceramic where the model fail to predict the large damage area in the composite caused by the ceramic debris.
10 Reference List


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