Engineering Design of Composite Military Helmet Shells Reinforced by Continuous 3D Woven Fabrics

A thesis submitted to the University of Manchester for the degree of

Doctor of Philosophy

in the Faculty of Engineering and Physical Sciences

2016

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Abstract

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Doctor of Philosophy
Engineering design of composite military helmet shells reinforced by continuous 3D woven fabrics
July 2016

The present research aims at engineering design of military helmet shells with continuous 3D woven fabric reinforcements for improved protection at a lighter weight and a reduced cost. The research was carried out using both the experimental and numerical methods. The results proved that the designed 3D woven wadded through-the-thickness angle interlock (TTAI) fabrics can be successfully moulded as continuous reinforcements for the doubly curved military helmet shells; therefore, costs in pattern cutting in the current composite helmet making process are eliminated. An improved ballistic performance was also demonstrated in the continuously reinforced composite structures.

The wadding yarns added into the conventional TTAI fabrics enhanced the mechanical properties along the warp direction significantly. Improved composite in-plane isotropy was achieved by using the wadded TTAI fabrics as reinforcements. The locking angle method was modified based on the deformation behaviour of TTAI fabrics and was used to predict and evaluate the mouldability of both conventional and wadded TTAI structures. Mouldability factor, defined from the locking angle, assists the design and selection of continuous reinforcements that are of the appropriate mouldability. The mouldability limit of a PASGT (Personnel Armour System for Ground Troops) helmet shell was determined as 25.54. Thus, TTAI fabrics with mouldability factor no larger than this value are capable of continuously reinforcing the doubly curved shape.

Ballistic tests and post-mortem examinations through ultrasonic C-scan and X-ray computed tomography (CT) demonstrated the advantages of the continuously reinforced composite in energy absorption. Up to 19.3% more of the kinetic energy was absorbed by the continuously reinforced panel through generating a delamination volume that was twice as large as that of the discontinuously reinforced one, and the delamination damages were distributed over a wider area. Under the same level of fabric mouldability and composite areal density, the panels reinforced with fewer plies of heavier fabrics performed better. The wadded TTAI reinforced composite panel demonstrated the optimal ballistic resistance by showing a 25.5% thickness increase and 55.3% penetration through the thickness. The 3D wadded fabric and 2D plain weave fabric continuously reinforced flat panels presented an equivalent ballistic performance. Meanwhile, further numerical analyses were conducted based on the digitally obtained geometry of a PASGT helmet. Although the ballistic limits varied from location to location, an equivalent ballistic limit of the helmet shell was noticed for the PASGT shell when compared to its flat counterparts.

The military helmet shells reinforced by 3D wadded TTAI fabrics continuously offer improved ballistic performance. This is attributed to the preserved reinforcement continuity and the enhanced through-the-thickness properties. The research provides a novel reinforcing strategy for the construction of future composite military helmet shells.
Declaration

I declare that no portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.
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Acknowledgements

First of all, I wish to express my sincere thanks to my supervisor, Dr Xiaogang Chen, for his guidance, the valuable discussions and his patience throughout my PhD research.

I would also like to thank Dstl and University of Manchester for providing full financial support for my PhD research through the Knowledge Transfer CASE scholarship. Special thanks to Dr Garry Wells from Dstl for his technical advice and guidance on this project. I also thank Teijin® Ltd for providing the Twaron® yarns used in current research.

I am thankful for all the staff members from the University of Manchester who provided me with experimental and technical supports. In particular, my appreciations go to Mr Tom Kerr and Mr Mark Chadwick for their help on fabric weaving; Mr Stuart Morse on the evaluation of composite mechanical properties; Dr Alan Nesbitt and Mr Barry Gleave from the NCCEF (Northwest Composite Certification and Evaluation Facility) for their assistance in making and the characterisation of composites; Dr Tristan Lowe and Dr Fabien Leonard from MXIF (Henry Moseley X-Ray Imaging Facility) for helping me with X-ray imaging; and Dr Robert Heinemann and Dr Simeon Gill on the regeneration of the helmet geometry.

Special thanks to my academic colleagues and friends in the Protective Textiles Research Group, who are, over the years, Dr Ying Wang, Dr Yanyan Chu, Dr Yanfei Yang, Dr Yi Zhou, Mr Haoxian Zeng, Mr Zishun Yuan, Ms Nan Wang, Ms Yue Xu, Mr Yuan Chai, Mr Hang Zhou, Mr Kaichen Wang, Mr Jiawen Qiu, Mr Yan Wang and Mr Wang Xu who accompanied me during my study and gave me much inspiration.

Finally, I would like to express my deepest gratitude to my dearest parents and other family members for their unconditional support and encouragement during my PhD study.
List of publications


S. Min, Y. Chai, X. Chen, F. Leonard, Engineering of Military Helmet Shells with Continuous Textile Reinforcement, Proceedings to the 89th Textile Institute World Conference 2014

With love and gratitude to my dearest parents and other family members
Chapter 1 Introduction

1.1 Background

Different forms of military helmets have been used for head protection for soldiers for thousands of years, and the design of helmets has evolved alongside the advances in life-threatening weaponry and material sciences together with the increasing protection and comfort requirements from the wearers.

In ancient times, threats were mostly from low-velocity weapons like hammers, rods, swords, axes and spears. The ancient Greeks made their helmets from leathers and linked animal bones, and heavy metals were moulded into helmets under heat and pressure for the Roman gladiators. As the firearms arose, the steel helmets, such as the M1 helmets by the US Army, became an essential part of the personal armour system against shrapnel and fragmentation impacts.

Without a doubt, the rapid advancement of material sciences, manufacturing techniques and computer technology opened up a new era for the design and construction of military helmets. The introduction of high-performance synthetic fibres into helmet construction offered an opportunity for better protection when compared to their metal counterparts on a weight-to-weight basis, which also means a potential for lighter helmets. For instance, the aramid-reinforced helmets were introduced by the British government by 1984 \[1\] and succeeded with modifications on materials and coverage. It was reported that about 9000 composite helmets would be consumed by the British military from 2015 to 2018 \[2\].

Throughout the history of developments in military helmets over time, the constant pursuit of optimised protection at the lowest possible weight never changes. Therefore, the demands for improved head and neck protection against ballistic impacts, lightweight and wear comfort at an effective cost become the driving force for the present research.

1.2 Description of problem

Head protection of the modern composite helmets against high-velocity impacts is achieved through various forms of energy absorption and energy dissipation by the composite helmet shell, including the reinforcing fibres (such as aramids), reinforcement structure, resin and resin-fibre interface. Woven fabric using high-performance fibres is one of the most commonly employed methods for reinforcement handling. However, due to the limited mouldability of currently used plain weave fabrics, cutting and darting of the
reinforcing fabrics are unavoidable in order for them to be moulded into the shape of a doubly-curved helmet shell. Although the ballistic performance achieved using such methods are regarded as satisfactory, material discontinuity is believed to be a possibility which causes stress concentration and hence reduced performance against impacts. The cutting and darting methods for helmet shell formation are related to the following issues.

First of all, an unnecessary amount of time and labour are required during the shell making process [3, 4]. Meanwhile, discontinuity of reinforcing fabrics caused by cutting becomes a source of stress concentrations leading to ruptures at the joining locations upon impact loading [5, 6]. This is unfavourable for kinetic energy dissipation as the reinforcements would not be fully utilised, and it may also induce localised deformation and damage due to stress concentration. For this reason, continuous reinforcement is sought for improved performance and productivity, which also means lighter helmet weight and lower manufacturing cost.

Previous researches conducted in the Protective Textiles Research Group at the University of Manchester provide a possible route for producing continuous fibre reinforced military helmet shells. First of all, a three-dimensional (3D) woven fabric structure known as through-the-thickness angle interlock fabric (TTAI) was identified as being able to conform to doubly curved shapes without wrinkle formation [7]. The ballistic performance of the TTAI fabrics was then proved to be adequate for female body armour construction under NIJ testing standards [8, 9]. Further, the prototype of riot police helmet shell reinforced by one piece of woven fabric was produced using vacuum bagging method [10-12]. Both finite element (FE) simulation and experimental tests indicated the effectiveness of the continuous reinforcing method in terms of better energy absorbing capacity and wider stress distribution area when compared with the discontinuous counterparts against the low-velocity (blunt) impacts.

All these outcomes from previous studies lead to the exploitation of the 3D woven TTAI structure as continuous reinforcement for military helmet shells. However, the high-velocity ballistic impacts are the primary threats confronted by the wearers of military helmets. In order to provide effective ballistic protection, the TTAI fabrics as continuous reinforcements need to be tailored accordingly, with focuses on their predictable mouldability and enhanced ballistic resistance. The present study represents efforts to thoroughly explore this problem, targeting on the design of military helmet shells reinforced with a continuous 3D woven fabric with improved overall ballistic performance, and hence the possibility of weight reduction.
1.3 Research aims and objectives

The aim of current research is to design composite military ballistic helmet shells reinforced by continuous 3D woven fabrics for improved ballistic performance. The research is subdivided into three parts.

The first part of current research presents an experimental study on the ballistic performance of composites with both discontinuous and continuous reinforcing schemes, in order to explore the relationship between the reinforcement continuity and high-velocity impact performance of the composites. The two key objectives for this part of the work are:

a) to manufacture thick (above 5mm) composite panels reinforced by both continuous and discontinuous multiply plain weave fabrics using the modified vacuum-bagging method;

b) to study the ballistic performance of discontinuous and continuous plain weave fabric reinforced flat panels through experimental investigations. The perforated ballistic impact tests and the non-destructive tests (NDT) will be used for this study. The latter including the ultrasonic C-scan and X-ray computed tomography (CT) which evaluate the damage size.

The second part focuses on the study of 3D woven wadded TTAI fabrics in order to engineer and optimise woven textiles as the continuous reinforcements for the doubly-curved military helmet shells. The objectives in this part of work are:

a) to characterise the geometric and structural parameters of both conventional and wadded TTAI;

b) to produce conventional and wadded TTAI with designed weave specifications;

c) to evaluate the tensile properties of both conventional and wadded TTAI fabric reinforced composites. The results obtained will be used for FE analyses for the third part of the study;

d) to experimentally study the moulding behaviours of TTAI using the picture frame shear test and mouldability tester, in order to validate the mathematical model used for mouldability prediction;

e) to complete the mathematical model for theoretically predicting the fabric mouldability of TTAI by including wadded structures in addition to the conventional ones;
f) to carry out moulding experiments and define a mouldability threshold for continuous reinforcements with a PASGT (Personnel Armour System for Ground Troops) helmet shape.

The investigation into the ballistic response of continuously reinforced composite shells will be carried out in the third part of the research. This includes both experimental investigations on flat panels and numerical evaluations based on curved shells.

g) to study and compare the ballistic performance of continuously reinforced flat composite panels, in the hope to provide guidance on optimising the protection by having the required mouldability at low weight;

h) to digitally obtain the geometry of PASGT helmet shape using SolidWorks® for FE modelling in ABAQUS®;

i) to study the ballistic performance of the designed continuously reinforced military helmet shell through FE simulation of impacts at different locations; to propose suggestions for the design of future helmet shells.

1.4 Thesis layout

After the introductory chapter, the rest of this thesis is organised as following:

Chapter 2 presents a review of literatures in areas regarding: the impact response and failure mechanisms of textile reinforced composites against ballistic impacts, the influential factors for the ballistic performance of textile reinforced composites, characterisation of the mouldability of woven fabrics, the general functions and requirements of military helmets, limitations and innovations of advanced helmet construction and the implications for future designs.

Chapter 3 presents a preliminary study into the effects of textile reinforcement continuity on the ballistic performance of composite panels, in order to prove the advantage of continuous reinforcement for ballistic applications.

Chapter 4 presents analyses on the wadded TTAI fabrics and the composites reinforced by them. The design and fabrication of 3D woven TTAI fabrics on a shuttle loom will be described. The influences brought by adding straight wadding yarns into the conventional TTAI structures would also be confirmed both experimentally and numerically.

Chapter 5 presents an optimisation of the 3D woven TTAI fabric as continuous reinforcement for military helmet shells. Firstly, the mouldability of the wadded TTAI
fabrics would be theoretically predicted and the process of selecting continuous reinforcement for PASGT shaped shell would be demonstrated. Flat composite panels reinforced by TTAI fabrics with equivalent mouldability and areal density would be tested for their ballistic performance. The advantages of continuous 3D woven reinforcement over the currently used discontinuous reinforcing method will be further discussed.

Chapter 6 presents a finite element analysis on the ballistic response of wadded TTAI continuously reinforced military helmet shells. The effectiveness of the proposed continuous reinforcing scheme and the influence of shell curvature will be evaluated numerically in ABAQUS®.

Chapter 7 ends the thesis with conclusions and recommendations for future work.
Chapter 2 Literature review

The aim of the present research is to develop a continuously 3D woven fabric reinforced military helmet shell with improved protection at reduced weight and cost. The topic covers a wide range of knowledge and literature from ballistic impact physics to textile fabric design and composite material sciences.

This chapter reviews the advances in the study and engineering of military helmets from the following aspects: (1) mechanics of textile reinforced composites against ballistic impacts, (2) deformation behaviours of woven fabrics during moulding and theoretical methods for mouldability prediction, (3) design and evaluation of military helmets and implications for future military helmet engineering.

2.1 Mechanics of composite against ballistic impact

2.1.1 Advanced composites

Textile reinforced composites have been used in many advanced applications, including the ballistic armours, aerospace and automobiles. The advanced composites are composed of high-performance fibres and a matrix system [13]. The fibres are embedded within the matrix system but none of them would be soluble to another.

Composites have their distinctive advantages over metal. First of all, they have higher specific modulus and specific strength [13, 14], which are defined as the ratio of the Young’s modulus to the density of the material and the ratio of the strength to the density of the material, respectively. As shown in Table 2-1, the strength of unidirectional (UD) graphite/epoxy composite is twice that of the steel, while its specific strength is nearly ten times that of the steel. This means the mass of composite material required would be smaller than that of the steel when an equivalent strength value of a part is demanded. Therefore, the use of advanced composite materials offers more possibilities for weight reduction, which is critical in many applications.
Another advantage of the advanced composite material is their ability to combine the privileges of their components in producing properties that cannot be achieved by either of them on their own. The fibre reinforcements carry the loadings while the matrix holds the reinforcement in position and protect them against external environmental damages. The overall properties of the composite are determined by the amount and the property of each component. The ‘rule of mixture’ [15], as expressed in Equation (2-1), is well accepted to determine the modulus and strengths of the composite.

\[ E_c = E_f V_f + (1 - V_f) E_m \]  

(2-1)

where, \( E_c \), \( E_f \) and \( E_m \) are the Young’s Moduli of the composite, fibre reinforcement and matrix system, respectively; \( V_f \) is the fibre volume fraction.

Other advantages regarding the mechanical, thermal and physical properties of the advanced composites include their low thermal expansion properties, high dimension stability, and outstanding corrosion resistance [16].

### 2.1.2 Responses of composite against ballistic impact

#### 2.1.2.1 Ballistic impact on composite target

In order to prevent the projectile from penetrating the target or causing injury to the users by extensive deformation, the armour-grade composites are expected to absorb and dissipate the kinetic energy carried by the projectiles [17]. Upon ballistic impact loading, the kinetic energy carried by the projectile would deform the target. It is commonly understood that the deformation would strain the target material and stimulate stress waves
in the composite target [18]. As the stress wave propagates, the impact energy would be transformed into strain energy, kinetic energy and other forms of energy of the material it impacted into, with the strain and kinetic energy being the dominant forms. Damage and failure of the material will take place when the impact energy is sufficiently high to produce strain in fibre that exceeds the failure strain.

When a composite target is impacted by a projectile from the transverse direction, two types of stress waves would be stimulated. Propagating simultaneously within the composite target, are the longitudinal wave and transverse wave [18-22]. The longitudinal wave propagates away from the impact location along the composite plane. Intensive studies were carried out on the investigation of the stress wave propagation within single yarn [23] and soft armours made from woven fabrics [24, 25]. The velocity of longitudinal wave propagation \( c \) is determined by the modulus (E) and volume density (\( \rho \)) of the material, this being indicated in Equation (2-2).

\[
c = \sqrt{\frac{E}{\rho}} \quad (2-2)
\]

The transverse wave propagates away from the impact point at a lower speed \( u \), which can be evaluated by Equation (2-3).

\[
u = c \sqrt{\frac{\varepsilon}{1 + \varepsilon}} \quad (2-3)
\]

where the tensile strain \( \varepsilon \) is positively correlated with the transverse wave speed, it is the ratio of total deformation to the initial dimension [22].

This is why high-performance fibres like aramids, UHMWPE (ultra-high-molecular-weight-polyethylene) and carbon fibres are favourable for constructing ballistic armours. Such high-performance fibres would enable wider longitudinal stress distribution within a fixed impact duration, which allows more kinetic energy being absorbed by the target.

The warp and weft yarns in contact with the projectile directly are called the primary yarns, and the other yarns are secondary yarns. The impact on primary yarns produces transverse deflections. The secondary yarns which intersect the primary yarns are pulled out of the original fabric plane. Consequently, strain waves are developed like those identified in the primary yarns. The contribution of primary yarns in energy absorption is higher than that of the secondary yarns [25]. Efforts on getting the secondary yarns involved more in
energy absorption were made by previous researchers [26-30], in order to improve the ballistic performance of the soft armour panels.

The movement of the resin impregnated yarns is greatly constrained by the matrix for a woven fabric reinforced composite target. Following the basic theory on the transverse impact on compliant targets, more complex responses and damage mechanisms are involved.

2.1.2.2 Local and global responses

According to the impact velocity, impact loadings were classified into three categories, namely the low-velocity impact, high-velocity impact and hyper-velocity impact [18]. With different levels of impact mass, impact duration and the kinetic energy involved, the response of the composite targets would be different consequently. The boundaries between high and low-velocity impact regime were set by Robinson and Davies [31] as the ratio between the velocity of the impactor and the speed of sound in the plate thickness direction. Impacts of the ratio greater than the failure strain of the target are regarded as high-velocity impacts. Therefore, it is the speed of wave propagation through the thickness of the target instead of the velocity of the projectile that differentiates the response of the target.

![Diagram](image)

Figure 2-1 Local and global responses of targets under high or low-velocity impact: (a) High-velocity impact caused localised response; (b) Low-velocity impact related global response [32]

The ballistic impacts refer to high-velocity impacts by fragments and projectiles at the impact velocities ranging from 100 to 1000 m/s, and they often took place within a short time duration [33]. The ‘armour-grade composites’ [34] are engineered to convey
enhanced resistance to ballistic impact and widely employed for the construction of military helmet shells.

Comparisons between the responses of the composite materials against high and low velocities were conducted by Cantwell and Morton [32], Ursenbach et al. [35] on carbon fibre laminates and Shaker et al. [36] on Kevlar® woven fabric reinforced epoxy composites, respectively. Regardless of the differences in fibre materials and their architectures, all of the studies proved that the composites experienced localised deformation against high-velocity impacts; whereas the responses upon low-velocity impacts are often global. The local and global responses are illustrated in Figure 2-1. Further to that, the ballistic loadings by small projectiles under high impact velocities were found, by Olsson [37], to be more detrimental, and the dimension and boundary conditions of the target have barely any influences on the impact response. Therefore, it is crucial to identify and understand the failure mechanisms involved in ballistic impact events and engineer armours accordingly.

2.1.3 Damage mechanisms for energy absorption

The damages of composite directly contribute to the kinetic energy absorption. Hence, the damage of fibre reinforcement and matrix in a composite panel and the interface between them encourage energy absorption. Generally, the damage mechanisms involved in energy absorption in a polymer-matrix composite include fibre damage, matrix damage, delamination and friction [38].

Naik and Shrirao [18] established an analytical model to analyse the damage mechanisms of woven fabric reinforced composite targets. They assumed that the kinetic energy carried by projectiles is absorbed through cone formation on the back face of the target, deformation of secondary yarns, tensile failure of primary yarns, shear plugging, matrix cracking and friction during penetration. Figure 2-2 presents the strain distribution on primary yarns and the cone formed on the target upon the impact loading. Both the reinforcing yarns and matrix deform and cause energy absorption. The model predicted that energy absorption by delamination and matrix cracking is observed at very low levels, whereas the deformation and tensile failure of yarns are the main energy absorbing mechanisms.
Various failure modes, including matrix cracking, fabric breakage, shear-plugging on the impact face as well as progressive delamination and tensile fibre failure on the rear face were identified during the experimental studies carried out on all of the composite panels tested by Flanagan et al. [39]. Figure 2-3 plots the dominating failure modes involved at
different impact energy levels. Different failure modes were encountered at different impact energy levels. To avoid detrimental damages at the lower energy level, the properties related to the corresponding failure modes need to be enhanced accordingly.

Similarly, the suppression of certain failure modes for the trade-off of the others may also encourage more energy absorption. For example, the use of 3D woven reinforcements would restrict the spread of delamination, but enables better impact tolerance and improved post-impact mechanical properties. This would be further discussed in Section 2.2.2.1 later.

2.2 Factors influencing composite ballistic performance

The ballistic performance of a composite panel is influenced by factors including the properties of its components, the architecture by which the fibres are fabricated and assembled to form the reinforcement, the geometry and striking obliquity of the impactor, effect of strain rate, boundary conditions etc. It is impossible to control and isolate the role of each factor independently because the impact performance is influenced by all of these factors. This section endeavours to understand the roles of a few of the factors with major influences, providing guidance for the design of lighter ballistic composites.

2.2.1 Mechanical properties of the constituents

Based on the ‘rule of mixture’, the impact performance of the composite relies on the mechanical properties of its components, the reinforcing fibre, matrix and the strength at fibre/matrix interface.

2.2.1.1 Reinforcing fibres

High-performance fibres as reinforcements are responsible for carrying and transferring the impact loadings within a composite system [40]. The impact performance of a composite panel benefits directly from the use of high-performance fibres as reviewed previously in Section 2.1.1. Also, Cunniff [24] proposed a dimensionless property \( U^* \) to evaluate the ballistic performance of fibres, which is expressed in Equation (2-4).

\[
U^* = \frac{\sigma E}{2\rho \sqrt{\rho}}
\]  

(2-4)
In it, \( E, \rho, \sigma \) and \( \varepsilon \) are the Young’s modulus, volume density, ultimate tensile strength and ultimate tensile strain of the fibre, respectively. \( U^* \) combined the influences of the specific toughness of the fibre and the velocity of strain wave, as mentioned in Equation (2-2) and (2-3).

Table 2-2 Mechanical properties of high-performance fibres [40-43]

<table>
<thead>
<tr>
<th>Fibre</th>
<th>Density (g/cm(^3))</th>
<th>Specific tensile strength (GPa·cm(^3)/g)</th>
<th>Young’s modulus (GPa)</th>
<th>Elongation at failure (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kevlar® 29</td>
<td>1.43</td>
<td>2.03</td>
<td>70</td>
<td>3.6</td>
</tr>
<tr>
<td>UHMWPE</td>
<td>0.97</td>
<td>3.61</td>
<td>156</td>
<td>2.5</td>
</tr>
<tr>
<td>Zylon® (PBO)</td>
<td>1.56</td>
<td>3.72</td>
<td>280</td>
<td>2.5</td>
</tr>
<tr>
<td>M5</td>
<td>1.70</td>
<td>1.53</td>
<td>134</td>
<td>1.7</td>
</tr>
<tr>
<td>Carbon</td>
<td>1.78</td>
<td>1.91</td>
<td>240</td>
<td>1.4</td>
</tr>
<tr>
<td>E-glass</td>
<td>2.55</td>
<td>1.33</td>
<td>72.4</td>
<td>4.7</td>
</tr>
</tbody>
</table>

Based on Equation (2-4), fibres with large Young’s modulus and high fracture energy are considered as suitable reinforcements for ballistic applications. Such high performance fibres include aramids [39, 42], UHMWPE (ultra-high-molecular-weight-polyethylene) [41], PBO (Polybenzobisoxazole), [44, 45], M5 [43, 44], carbon fibres [32, 35, 46] and the hybrids of these fibres [47]. Comparisons between the specific strength of various materials are summarised in Table 2-2. Among them, the aramid and UHMWPE fibres are two of the most commonly employed high-performance fibres for constructing soft armours and as reinforcements for composite armours.

**Para-aramid fibres**

With the brand names as Kevlar® (by DuPont), Twaron® and Technora® (by Teijin), the para-aramid fibres are condensation polymers consisting aromatic groups.

DuPont [42] claims that the Kevlar® fibres contain highly oriented molecular chains and considerable numbers of intermolecular hydrogen bonds which add to its strength, as demonstrated in Figure 2-4. Kevlar® demonstrates superior properties over conventional high-performance materials by exhibiting high tensile strength at low weight (stronger than steel, stiffer than glass on the basis of the same weight), outstanding thermal and chemical resistance, low elongation at break, high modulus, high toughness and extraordinary dimension stability.
Summarised by Baker [48], aramid composites have the capacity to absorb large amounts of energy during penetration because of their ductile property against axial compression. In addition, the complex fibre failure modes, which include kinking in compression and defibrillation during final fracture, improve the energy-absorbing capacity of aramid composites under dynamic loading. All these benefits encouraged the use of para-aramid fibres, such as Kevlar® and Twaron®, for constructing lightweight ballistic body armours, reinforcements for helmets, tank panels and other military devices [40].

UHMWPE

UHMWPE fibres are made up of extremely long chains of polyethylene, as indicated in Figure 2-5. The molecular chains are highly oriented in the same direction and bonded to each other with a massive amount of van der Waals bonds, resulting in high intermolecular strengths. Dyneema® (developed by DSM) and Spectra® (developed by Honeywell) are the two brand names of UHMWPE.

Reported to be the world’s strongest fibre (together with Spectra® and Zylon®), Dyneema® fibres combine extreme strength with great softness and are manufactured through a gel-
spinning process [41]. With an over 95% molecular orientation and up to 85% crystallinity, Dyneema® is advertised to be 15 times stronger than steel, and 40% stronger than aramids on a weight-for-weight basis [49]. Dyneema® has a low specific gravity of 0.97, which allows it to float on water and provide the possibility for weight reduction [1]. UHMWPE fibres are also good at accumulating creep, which was utilised for helmet production by pressure moulding method [50].

### 2.2.1.2 Polymer matrices

The resin system binds the reinforcement together and acts as a stress-transfer medium. It also helps to dissipate the impact loading to the reinforcing fibres embedded inside [51]. Similar to fibre reinforcements, the choice of resin is related to the required properties, the intended application and the method of manufacture [14]. For the construction of armour-grade composites, the isotropic matrix system should have high tensile strength in order to resist high compressive loading and cracking [52].

Generally speaking, there are two types of polymer matrices in a composite system, thermoset and thermoplastic. Figure 2-6 illustrates the molecular structure of typical thermoplastic and thermoset matrices respectively. The properties of different types of cured matrix systems are listed in Table 2-3.

![Molecular structures of matrices: (a) Thermoplastic; (b) Thermoset](image)

**Figure 2-6 Molecular structures of matrices: (a) Thermoplastic; (b) Thermoset [53]**

**Table 2-3 Properties of different types of matrix [14]**

<table>
<thead>
<tr>
<th>Matrix</th>
<th>Density (kg/m³)</th>
<th>Young’s modulus (GPa)</th>
<th>Poisson’s ratio</th>
<th>Tensile strength (GPa)</th>
<th>Failure strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermosets</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Epoxy resins</td>
<td>1.1-1.4</td>
<td>3-6</td>
<td>0.38-0.40</td>
<td>0.035-0.1</td>
<td>1-6</td>
</tr>
<tr>
<td>Polyesters</td>
<td>1.2-1.5</td>
<td>2.0-4.5</td>
<td>0.37-0.39</td>
<td>0.04-0.09</td>
<td>2</td>
</tr>
<tr>
<td>Thermoplastics</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nylon 6,6</td>
<td>1.14</td>
<td>1.4-2.8</td>
<td>0.3</td>
<td>0.06-0.07</td>
<td>40-80</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>0.90</td>
<td>1.0-1.4</td>
<td>0.3</td>
<td>0.02-0.04</td>
<td>300</td>
</tr>
<tr>
<td>PEEK</td>
<td>1.26-1.32</td>
<td>3.6</td>
<td>0.3</td>
<td>0.17</td>
<td>50</td>
</tr>
</tbody>
</table>
Initially in their low-viscosity liquid state, thermosetting resins are converted into hard rigid solid through chemical cross-linking. The process of cross-linking to form a three-dimensional resin network is called curing and it’s often facilitated by curing agents or hardeners. The mechanical properties of the thermosetting resin are determined by the type of cross-linking chemical units and the length and density of these cross-links [14]. They are both controllable factors, with the former controlled by the type of chemicals used and the latter by the curing process. Relatively low viscosity in their uncured states makes thermoset resins suitable for impregnating high loadings of fibrous reinforcements [14].

Epoxy, unsaturated polyester and vinyl ester are the most commonly seen thermosetting resins. Among them, epoxy is the most popular one because it combines good chemical resistance, ease of process and good mechanical properties at an acceptable cost. Curing agents used for epoxy resin are amines and anhydrides, which form chemical bonds with epoxy following the reaction between amine-epoxy and hydroxyl-epoxy. Curing at room temperature during composite formation can be achieved in the case of using epoxy resin. The post-cure treatments at higher temperatures for stabilising the form are often followed [14]. This not only allows complex shapes to be processed but also saves energy by eliminating the high-temperature heating needed for curing.

Lee et al. [34] mentioned that the use of stiffer matrix would hold the fibres embedded more firmly, force the projectile to engage the fibres to a greater degree in breaking yarns. The fracture toughness of the brittle epoxy resin could be enhanced by introducing a second phase into the system, normally rubber [54]. With a higher modulus, thermoset composites are more rigid and durable under repeated loads. Spark [55] mentioned that helmet shells made from thermoset resin show better ‘ear-to-ear’ load rigidity in general.

Unlike thermoset resins, thermoplastics work as matrices by their inherited high molecular weight and strong intra-molecular bonds without cross-linking agents. Under heat treatment, molecules in their amorphous state disentangle, so that the initially solid prepregs are converted into viscous liquid and later solidified in the required shapes [14]. Thermoplastic resins including polypropylene, Nylon and PET exhibit high failure strain when compared to thermosets generally, as was found in Table 2-3. However, their use in the composites industry is quite limited. Because their high viscosity resulted from the high molecular weight and long molecular chains, makes it difficult for them to impregnate tightly fabricated reinforcing fibres. Dry spots and voids would significantly degrade the
performance of composites [56]. Also, difficulties may be encountered during processing because of their reliance on heating. In the current military helmet market, thermoplastic prepregs are used for heat-press shell moulding technique.

2.2.1.3 Delamination

Delamination or interlaminar fracture is often caused by the non-optimised curing and contamination during handling and developed from the out-of-plane stressing at the stress-free edges along the loading paths [5]. Upon transverse impact loading, the matrix cracks transform into delamination once the shear stress reaches a threshold [57] and continue to grow between the reinforcement plies [58].

The existence of delamination or interlaminar failure may induce a large reduction in composite stiffness and strength [59]. However, it is also regarded as one of the predominating mechanisms in energy absorption during ballistic impacts. Zee and Hsieh [38] compared the ballistic performances of multi-ply fabric reinforced composite panels and stacked composite sheets experimentally. They found that a large amount of the impact energy was released through delamination in brittle composites reinforced by carbon fibres, while the fibre and matrix damage contributed more for ductile composites which are reinforced with Kevlar® and Spectra® fibres.

Some researchers suggested that weak fibre-matrix bonding is desirable because it encourages ready delamination [19, 60]. That was proposed on the ground that separation of the fibre-matrix interface would not only absorb energy but also allow the fibres to extend to failure. Those composites are with high stiffness because the fibres in compliant laminates are already allowed for tensile failure [61]. As for the ballistic helmet shells, it should be rigid enough to prevent any excessive indentation and penetration of the projectile. This indicates that excessive delamination between reinforcement needs to be avoided.

2.2.2 Fabrication of fibre reinforcements

Fibres are of high aspect ratio, whose lengths are significantly longer than its width. In order to fully utilise their strength, the fibres need to be transformed into preforms that have them oriented for load carrying. Table 2-4 lists some of the typical reinforcement forms of polymer composites and their available processing methods [62]. An appropriate
choice of processing method needs to consider the form of reinforcement and the material properties.

Table 2-4 Typical reinforcement forms and their applicable processing methods [62]

<table>
<thead>
<tr>
<th>Material form</th>
<th>Pultrusion</th>
<th>Resin transfer moulding (RTM)</th>
<th>Compression moulding</th>
<th>Filament winding</th>
<th>Hand lay-up</th>
<th>Robotic lay-up</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unidirectional tape</td>
<td></td>
<td></td>
<td></td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Woven prepreg</td>
<td></td>
<td></td>
<td></td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Woven fabric/Neat resin</td>
<td>●</td>
<td>●</td>
<td></td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Stitched material/Neat resin</td>
<td></td>
<td></td>
<td></td>
<td>●</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prepreg roving</td>
<td></td>
<td></td>
<td></td>
<td>●</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roving/Neat resin</td>
<td>●</td>
<td></td>
<td></td>
<td>●</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Preform/Neat resin</td>
<td></td>
<td></td>
<td></td>
<td>●</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.2.2.1 Intra-ply architecture

2D laminates

Continuous fibres are aligned at designed orientations along the X-Y plane to form 2D laminates, as denoted in Figure 2-7. One distinguishing feature of 2D laminates is the lack of the through-the-thickness reinforcing fibres.

Figure 2-7 Fibre architecture of a 2D laminate [16]

The in-plane load carrying capacity of 2D laminates is largely influenced by the orientation of fibres during lay-up. The ‘quasi-isotropic’ 2D laminates balance the structure by laying-
up fibre tows in multiply directions. Tong et al. [63] experimentally proved that the quasi-isotropic laminates have higher transverse failure strain than its unidirectional counterparts.

Due to the absence of the Z-direction fibres, the 2D laminated structures have low through-thickness mechanical properties. The experimental results obtained by Tong et al. [16] proved that both the in-plane tensile and compressive strength of 2D laminates are at least 10 times of these tested along the through-thickness direction. The weaker through-thickness properties would result in poor transverse impact damage resistance and low post-impact mechanical properties.

Furthermore, the manufacturing process of 2D laminates is extremely time-consuming and expensive. Because the fibres are required to be stacked precisely according to the mould shape to avoid any voids and thickness variations. Foreign contaminants will significantly reduce the properties of the laminate [64]. To achieve complex shapes like the helmet shells and yacht hulls, multi-phase curing of the resin system will also be demanded to join the reinforcement patches where fibre continuity is hard to retain. All these disadvantages made the 2D laminates undesirable for the use as reinforcements of ballistic helmet shells under the conventional manufacture methods.

**2D woven fabrics**

Instead of arranging the continuous filament tows bi-directionally or multi-directionally across the X-Y plane to form 2D laminates, woven fabrics are characterised as two sets of yarns, namely warps and wefts, interlacing with each other perpendicularly [65]. The crimped warp and weft yarns in woven structure would tend to straighten themselves prior to fibre elongation when subjected to tensile stretch. The use of woven fabrics as composite reinforcements provides better structural integrity, ease of handle and longer shelf life when compared to chopped fibrous mats and unidirectional prepregs [66].
Woven fabrics have been used intensively as the basic components of soft armours. Figure 2-8 are the four commonly used 2D woven fabric structures as composite reinforcements [62]. Plain and basket weaves are considered as the most widely used because of their naturally balanced way of arranging wefts and warps within the fabric [19]. The plain weave structure has the largest number of crossovers per unit area, which according to Roylance [20] is helpful for the transmission and reflection of longitudinal strain wave during ballistic impacts.

Woven fabrics react to impact loadings differently when used in their dry state and as reinforcements of composites. As identified by Lee et al. [34], some primary yarns slipped off from the impactor on the dry fabric, as is indicated in Figure 2-9(a), but all of the primary yarns in the woven fabric reinforced composite are strained to break in Figure 2-9(b). This is because the movement of the yarns is largely constrained by the matrix, primary yarns in fabric reinforcements fail mainly through the fracture. Therefore, the crossovers act more as binders other than the medium for wave propagation onto secondary yarns.
Woven fabrics are often made into composites through wet lay-up process and as prepregs. Satin and twill weave fabrics are normally patterned for reinforcing parts with complex geometry, such as helmet shell and yacht hull [55]. The reduced number of the crossovers per unit area made them easier to conform to doubly curved shapes, although cutting and darting of the fabrics are still inevitable to avoid wrinkles.

**3D woven fabrics**

The development and application of 3D fabric reinforced advanced composites have been driven by the increasing demands to reduce fabrication cost, to enhance the through-thickness mechanical properties. The inter-laminar shear strength, fracture toughness and impact damage tolerance of the 3D fabric reinforced composites are expected to be higher than those of their 2D counterparts [67, 68].

The fabrication methods of 3D fabrics include weaving, braiding and knitting. Focuses will be placed on the woven preforms in the present study. Chen et al. [69] classified the 3D woven fabrics into four categories according to their configuration and geometry, as listed in Table 2-5. The 3D architectures mentioned in Table 2-5 are often manufactured on conventional looms, whereas some specially designed looms are required for complex shapes [68, 70-72].
Table 2-5 Classification of 3D woven fabrics

<table>
<thead>
<tr>
<th>Structure</th>
<th>Architecture</th>
<th>Shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid</td>
<td>Multilayer Orthogonal Angle-interlock</td>
<td>Compound structure, with regular or tapered geometry</td>
</tr>
<tr>
<td>Hollow</td>
<td>Multilayer</td>
<td>Uneven surfaces, even surfaces and tunnels on different levels in multi-directions</td>
</tr>
<tr>
<td>Shell</td>
<td>Single-layer Multilayer</td>
<td>Spherical shells and open box shells</td>
</tr>
<tr>
<td>Nodal</td>
<td>Multilayer Orthogonal Angle-interlock</td>
<td>Tubular nodes and solid nodes</td>
</tr>
</tbody>
</table>

According to the investigations conducted by Billaut and Roussel [73], the amount of impact energy absorbed by the 3D carbon/epoxy fabric reinforced composites is generally greater than that of the 2D laminates. This is due to the high delamination resistance of the 3D woven reinforced composites. The 3D angle-interlock fabric reinforced composites exhibited the smaller damage areas than the 3D orthogonal one did. Further to that, the 3D composites show significantly higher post-impact mechanical properties than their 2D laminate counterparts, including the higher flexural and compressive strength.

Bogdanovich [74] claimed that the composite panels reinforced with 3WEAVE®, which is a branded wadded 3D orthogonal woven structure, have much higher survivability under repeated drop weight impact applied at the same site and closely spaced multiple ballistic hits. It was due to the presences of the through-the-thickness warps which changed the dominating failure modes by restraining the matrix cracks and delamination from spreading into wider areas. However, he also mentioned that further experimental and numerical studies on the complex 3D transient deformation and failure processes in 3WEAVE® would be necessary, especially for the understanding the role of the through-thickness yarns.
Delamination damage in the 3D orthogonal composites was also found localised and strictly through-the-thickness of the panel by Grogan et al. [75]. The individual 3D woven lamina was considered as a ‘net’ to stop penetration, which acts more effectively than the 2D laminates. Experiments conducted by Brandt et al. [67] revealed that the composites reinforced by 3D woven through-the-thickness angle interlock fabric (denoted as 3X in Figure 2-10) have the highest interlaminar shear strengths, which indicate that the structure could offer the most integrity in forming the ‘net’ mentioned by Grogan et al. [75] in resisting the impacts.

Potluri et al. [76] calculated the damage resistance, which is the impact energy per unit damage area according to the definition given by Naik [77], of various type of composites. The 3D woven reinforced composites were found exhibiting higher damage resistance when compared to their UD (unidirectional laminate) and 2D woven counterparts. Among them, the angle-interlock fabric reinforced composite was of the highest compression strength both before and after the impact. This is because the wavy warp yarns decrimped and inclined at an angle to the loading direction.

Experimental studies by Bandaru et al. [78] also proved that the ballistic limit of the 3D angle-interlock fabric reinforced composite being the highest when compared to that of the
plain weave fabric and 3D orthogonal fabric reinforced composites. The advantages of 3D woven reinforcement in energy absorption are obvious. This is attributed to the existence of the through-the-thickness binding yarns. They bind the fibres in the failed layer to resist the impact. Otherwise, these fibres would be less engaged in energy absorbing and being separated from the rest of the layers.

In summary, the 3D reinforced composites were reported to exhibit improved impact resistance, damage tolerance and extended fatigue life because they restricted the spread of delamination to avoid structural fracture and improved the structural integrity in resisting the impacts on composite targets.

### 2.2.2.2 Inter-ply architecture

**Stitching**

Apart from the 3D weaving, 3D braiding and multi-axial warp knitting, the reinforcement plies stitching is also employed in binding the 2D laminated fibre reinforcements.

Tan et al. [79] and Kang [80] both proved that stitching would positively increase the interlaminar shear resistance. Also, non-destructive testing method X-ray radiography and ultrasonic C-scan were used to examine the effect of through-the-thickness stitching on the delamination propagation of impacted composites [81]. The role of stitching is found to be crack initiator and crack arrestor simultaneously. The presence of geometrical defects like resin-rich pockets and misalignment of in-plane fibres around stitching threads initiate matrix cracking upon impact loading, which will develop into delamination later. Meanwhile, the delamination growths are impeded by the stitches through bridging of the delamination cracks and arresting crack propagation. In order to achieve the maximum impact damage resistance, both the linear density of the stitching threads and the stitch density need to be carefully engineered.

The disadvantages of the stitching imply that the stress concentrated resin rich areas act as initiators for matrix cracking and delamination. Similarly, discontinuously reinforced composites would also provide such opportunities for delamination growth and detrimental damages under impact loading.
Hybridisation

Hybridisation allows composites to have mixed reinforcing materials and structures in order to deliver improved ballistic performances. Due to the variety of reinforcing materials, it is difficult to choose a suitable matrix and a proper processing temperature for the hybrid composite.

Walsh [82] demonstrated a successful application of the concept of reinforcing an aramid/graphite hybrid helmet by thermoplastic resin through a modified press-moulding method, as illustrated in Figure 2-11. Although a 10 to 25% weight reduction could be expected under the same level of protection, the requirements for the processing facilities and procedures are rigorous. Meanwhile, concerns over the discontinuity of reinforcing material are hard to resolve with the proposed procedures.

![Parallel fabrication cycle for hybrid helmet making](image)

Figure 2-11 Parallel fabrication cycle for hybrid helmet making [82]

2.2.3 Geometry of projectile

The responses of composite targets become differentiated when the impact velocities change. Meanwhile, the geometry of the impacting projectile would also affect the damage mechanisms of the composite, especially the first few plies that come into contact with the projectile initially.

![Effect of projectile shape on the penetration damage mode](image)

Figure 2-12 Effect of projectile shape on the penetration damage mode [83]
Iremonger and Went [83] found that the projectiles with sharp, right-angled edges cut the fibres in the first few nylon 6,6 reinforced plies, as illustrated in Figure 2-12. Signs of fibre melting with sheared fibre ends and bulbous rounding were traced at the cuts. While the oblique faces of the projectile stretch the fibres to their tensile failure instead. Providing the axial tensile strength of fibres much often one magnitude higher than their compressive and shearing strength, the energy absorption of the projectiles with oblique or round tips would be higher as a result.

With an understanding of the impact mechanics, it is essential to choose the suitable materials and architecture for constructing effective ballistic composites.

2.3 Fabric mouldability

For composite parts with complex geometries, including the helmet shells, cutting and darting of the reinforcing fabrics is inevitable. Although the procedures are highly labour and time consuming, as well as leaving the inferior composite overall performance, the use of discontinuous reinforcement is still the available solution.

Figure 2-13 Geometry of surface with double-curvature [84]

Figure 2-13 demonstrates the typical geometry of a surface with double-curvature. The curvature of each point on the doubly-curved surface is defined by two local curvatures about two normal planes. [85] Therefore, it is difficult to conform the conventional 2D woven fabrics and UD laminates onto those three-dimensional surfaces without wrinkle formation.

An important property of textile fabrics is their ability to conform to doubly curved shapes without applying large force [86]. This is the property that differentiates the textile fabrics
from other materials forms, such as paper, rubber or metal sheets. The expression of ‘moulding’ is preferred to describe the conforming of textiles under small force. The moulding of fabrics is also regarded as a process of ‘deforming’, where fabrics were forced to change their original configuration according to shaping requirement, with occasions of recoverable deformations. Moulded fabrics have a large range of applications which vary from clothing, upholstery to reinforcements for structural composites.

The use of textiles as reinforcements for constructing composites has made the evaluation of fabric’s ability to conform to required shapes more demanding than ever. Although used to characterise the process of fabric deformation, the terms ‘fitting’ or ‘drapability’, which are commonly applied in apparel and decoration applications are not accurate enough in the description. By ‘fitting’, it means the cloth is everywhere in contact with its backing without any wrinkles formed [86]. Whereas ‘draping’ is used to describe the final configuration of a cloth placed over a solid object [87]. ‘Drapability’ was used to define the deformation of fabric upon its own weight. Another term ‘formability’ means ‘the maximum compression a fabric can take up before it buckles, given a certain geometric arrangement’ [88]. The term does not describe the motions to adjust the relative positions of the yarns under the original fabric construction. Defined by Chen et al. [7], fabric ‘mouldability’ refers to ‘the fabrics’ ability to be moulded into three-dimensional shapes of double-curvature without wrinkle formation or applying large force’. The term ‘mouldability’ is considered to be more appropriate for describing the ability of textiles in reinforcing composites with complex shapes because it takes into account of the fabric deformation upon applied force.

2.3.1 Fabric deformation behaviour during moulding

It is essential to understand the mechanisms involved during fabric moulding, which indicates how the fabrics are deformed to form the required shapes. The interest of current study lies in woven fabrics.

Summarised by Hancock and Potter [89], there are four modes of fabric deformation involved in bi-directional fabric moulding: fibre straightening, in-plane shearing, fibre slip and fibre stretch. They also indicated that the mouldability of fabric is limited by the extent to which the individual tows of fibres can bend, shear and slide relatively to each other. Consequently, the moulding process can be characterised as a combination of motions
including fabric in-plane shearing, out-of-plane-bending and tensile stretching. The tensile stretch of the high-performance reinforcing fibres, such as aramids, UHMWPE, carbon and glass fibres, during moulding is normally negligible. However, the tensile force along the fibres may still lead to fibre straightening, and the tendency of structure compression also lead to wrinkle formation on the fabric surface [90].

Provided with adequate fibre flexibility only bending out of the plan is required to conform a piece of fabric to a shape with uniaxial curvatures, such as a cylindrical tube [91]. It is the fabric shearing motion that enables the fabrics to conform to doubly-curved shapes. The idea that ‘moulding of woven fabric upon surfaces with double curvatures is achieved mainly by shearing’ was brought about and testified by many other researchers [86, 88]. Therefore, shear motion shows the most significant effect on the determination of the fabric mouldability.

2.3.2 Locking angle method based on the pin-joint model

The mouldability of fabric is largely constraint by the freedom of yarn relative movement within the fabric plane under small shearing force. The visualisation of wrinkle formation on the surface of fabric reinforcement can be subjective. In order to make prediction objectively, various simulation models were developed.

2.3.2.1 Pin-joint fabric model

Given the rather coarse structure and complexity caused by yarn interlacing frictionally, the conventional continuum methods for predicting the bending and shearing of plate and shell structures are not applicable [92]. Simulation models that are better at describing the frictional bonding behaviour woven fabrics at yarn crossovers were sought to be developed for the prediction of wrinkle formation. The most popular model used for woven fabrics is the pin-joint model [85, 86, 93, 94]. Woven fabrics in this pin-joint model are regarded as a fibre network which joints at their interlacing points. As all the relative movements of adjacent yarns are restrained by the friction at their crossover points, these crossovers can be imagined as the pins, around which the yarn rotation occurs. Fabric in-plane shearing mechanism is well simulated through this model.
Figure 2-14 Wrinkle formation during shearing of plain weave fabrics based on the pin-joint model [95]

Figure 2-14 is an illustration of the pin-joint model of one unit cell of a plain weave fabric. Initially, the warp and weft yarns are interlaced perpendicularly (θ=90°) at four crossovers, forming a rectangular net. θ is the fabric angle, which is represented by the angle between warp and weft yarns at their interlacing point. After applying a pair of shear force parallel to the weft yarns, the fabric deforms in a way that the fabric angle θ between warp and weft gets smaller and smaller until it reaches the minimum angle θ_{lock}. Any further shearing will lead to the build-up of localised compression between adjacent yarns and soon compensated by out-of-plane deformations, which is when the wrinkles are formed. The angle θ_{lock} between adjacent warp and weft reached fabric shear limit is defined as the locking angle.

The mouldability of woven fabrics was also found to rely greatly on the shear rigidity of fabrics [7]. The reason why there are pinned points in the pin-joint model is because the high frictional resistance build-up at yarn crossovers, which made the relative movements
of yarns at the pin joints difficult. The term ‘shear rigidity’ [96] was determined as a function of the number of crossovers. The more crossovers within the fabric, the more difficult it is for the fabric to be sheared or moulded. Therefore, the use of a woven structure with fewer yarn crossovers is thought to be a way of increasing the fabric mouldability. Besides the influences from fabric structure itself, the frictional behaviour of material is also significant.

2.3.2.2 Locking angle

As described earlier, wrinkles or buckling appear only when the in-plane shear reaches its limit. According to Skelton [96], the limit of in-plane shearing is reached when the two adjacent elements of a unit cell come into ‘side-by-side contact’. At the shear limit position, there is no more space for the elements of a unit cell structure to rotate, but they will have to deform out-of-plane and appear as wrinkles on the fabric surface. In this way, the use of locking angle to determine and quantify the shear limit of fabrics offers a chance to predict the threshold for wrinkle formation. The threshold could be indicative for the selection of mouldable composite reinforcements.

With in-plane shearing as the major fabric deformation mode during moulding, the shear limit becomes an indicator for fabric mouldability. Further to that, the use of locking angle quantifies the shear limit of fabrics when moulding into certain shape is required. Any fabric with larger locking angle than the shear limit of the shape can be moulded into the required shape without buckling exactly. However, the use of locking angle to determine fabric mouldability is still influenced by fabric parameters such as thread spacing, friction, size and weave pattern.

2.3.2.3 Spacing factor

A term ‘Spacing Factor’ is defined by Prodromou and Chen [97]. It is determined by yarn thickness and yarn spacing, as expressed in Equation (2-5):

\[
\text{Spacing Factor} = \frac{\text{yarn thickness}}{\text{yarn spacing}} \quad (2-5)
\]

The deduction of the spacing factor is also based on the pin-joint model, but independent of the fabric construction.
A unit cell was taken from the fabric as shown in Figure 2-15(a). Figure 2-15 (b, i) and (b, ii) are quarter units at their initial and sheared states. In it, ‘L’ represents thread spacing, ‘t’ is the yarn thickness and ‘θ’ is the fabric angle at different shearing stages. According to the Pythagorean Theorem, the calculation of locking angle follows Equation (2-6).

\[ \theta_{lock} = \arcsin \frac{t}{L} \]  

(2-6)

Being consistent with the locking angle, the smaller the spacing factor is, the more freedom the yarns within fabric will have for in-plane shear, and consequently the more mouldable the fabric will be. However, unlike locking angle, ‘spacing factor’ is a normalised value for the evaluation of the mouldability of different fabric types. It is also proved to be helpful for designing and selecting fabrics as composite reinforcement moulding. With different combinations of yarn thickness and yarn spacing, it is possible to engineer fabric structure with required mouldability.

**2.3.2.4 Mouldability factor**

Roedel [98] proposed a term called ‘mouldability factor’ to evaluate the mouldability of the conventional through-the-thickness angle-interlock fabrics. Two jamming situations were assumed for predicting the locking angle of TTAI fabrics, namely the warp jamming and weft jamming. The mouldability factor ‘M’ is expressed as the larger locking angle between the two jamming situations. The smaller the mouldability factor is, more mouldable a convention TTAI fabric would be; and vice versa.
The mouldability factor can not only be used to predict the mouldability of conventional TTAI fabrics but also serves as a standard for quantifying the mouldability limit of certain shapes. In this way, the factor was used to identify the suitable reinforcement for riot police helmet construction successfully [98].

Both the spacing factor and the mouldability factor evaluate fabric mouldability based on the ratio of yarn thickness to yarn spacing. Only the use of mouldability factor is more accurate in the mouldability evaluation of conventional TTAI fabrics, as it took into account of the two different yarn jamming situations regarding the fabric structures. At the same time, mouldability factor shares a direct connection with fabric locking angles and fabric shear limits.

However, the prediction method provided by Roedel [98] is limited to the conventional TTAI fabrics only. In order to theoretically predict the mouldability of wadded TTAI structures at the same time, further development of this existing method is necessary and will be conducted in the present research.

### 2.4 Design and evaluation of composite military helmets

As a part of the personal armour system, head protection is of the prime importance. According to Carey et al. [99], up to 25% of all reported ‘projectile hits’ are received by the head and neck area, which counts for only 12% of a human body. This is because the soldiers need to check their surroundings constantly during military operations and certain law enforcement situations. Further to that, most combat fatalities result from head injuries. All these facts indicate that the design of military helmets should be able to convey maximum protection at lighter weight against a wide range of threats.

#### 2.4.1 Brief history of military helmet

Table 2-6 by Walsh et al. [82] outlined the development of US military helmets. The history of military helmets evolves with the level of threats the wearers faced to and the improvements in ballistic materials.
Table 2-6 Brief history of U.S. military helmets [55, 82]

<table>
<thead>
<tr>
<th>Threats</th>
<th>Areal Density (kg/m²)</th>
<th>Material</th>
<th>Design</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shrapnel</td>
<td>11.23-11.72</td>
<td>Rolled steel</td>
<td>WWI</td>
<td></td>
</tr>
<tr>
<td>Fragmentation</td>
<td>11.23-11.72</td>
<td>Hadfield steel</td>
<td>WWII/Korea/Vietnam</td>
<td></td>
</tr>
<tr>
<td>Fragmentation bullet</td>
<td>9.76-10.25</td>
<td>Kevlar 29 &amp; PVB Phenolic</td>
<td>PASGT</td>
<td></td>
</tr>
<tr>
<td>Fragmentation 9mm bullet</td>
<td>7.32-8.79</td>
<td>Kevlar 129 &amp; PVB Phenolic</td>
<td>MICH/ACH</td>
<td></td>
</tr>
<tr>
<td>Fragmentation 9mm bullet</td>
<td>7.32-8.79</td>
<td>Thermoplastic aramid UHMWPE hybrids</td>
<td>FFW</td>
<td></td>
</tr>
</tbody>
</table>
Contemporary military helmets need to offer a high level of protection against threats including random shrapnel and fragments at the lowest possible weight. Hence, the coverage of helmets extended from the top head to the side and back of the head. Considerations on the soldiers’ comfort, hearing acuity, mobility and the demand to mount operational devices encourage the improvements in helmet architecture.

Followed by the invention of Kevlar®, the 100% fibre-reinforced composite shell – PASGT (Personal Armour System for Ground Troops) was first introduced by the U.S. Army in the late 1970s and gradually replaced the ‘steel pots’. Nowadays, military helmet shells are often made from a pressure-moulded resin system, reinforced with ballistic resistance fabrics/fibres [55], such as aramids, UHMWPE and PBO.

2.4.2 Test standards

It was mentioned that the ballistic performance of a successful armour-grade composite is determined by its energy absorbing capability. The evaluation of the ballistic performance of the composites refers to that consequently. Summarised by Grujicic et al. [100], there are two commonly employed baselines for the qualification of an armour-grade composite, which are the ballistic limit and the damage morphology.

For the purposes of assuring the uniformity of helmets and the ease of international communication, test standards must be applied to all types of military helmet products. There are two most commonly recognised test standards, namely the NIJ Standard 0106.01 for Ballistic Helmets [101] and the $V_{50}$ requirement of U.S. military specification MIL-H-44099A [102].

2.4.2.1 NIJ Standard 0106.01

The NIJ standard was developed by the Law Enforcement Standards Laboratory of the National Bureau of Standards in U.S. It tests the helmets for their ballistic penetration and impact attenuation as indications for their ballistic protective performance.

According to the standard, the performances of the helmet are classified into three types differentiated by the projectile types and impact velocities. For instance, the Type II, which is employed by researchers including Tham et al. [103], Aare and Kleiven [104], tests the ballistic helmet against 9mm full metal jacket (FMJ) bullets with nominal mass of 8.0g at
the velocity of 358 m/s (equivalent to impact energy around 500 J). A qualified military helmet should be able to withstand at least four fair hits with no measured peak acceleration exceed 400 times the acceleration due to gravity.

The NIJ standard focuses on the ballistic side but provides no evaluation over blunt trauma deformation, which soldiers may also encounter in real situations.

### 2.4.2.2 U.S. Military Specification MIL-H-44099A

$V_{50}$ is defined as the average impact velocity of six fair hits at a 0-degree impact angle, with the three lowest velocities causing full penetration and the three highest velocities resulting in partial penetration. The test for $V_{50}$ demands adjustable striking velocity triggered from the shooting device. Hence a gas gun is normally employed in this case.

For the $V_{50}$ test standard, the U.S. military specified that the $V_{50}$ ballistic limit for a helmet to be 610 m/s under the impact of a 1.1 g 0.22 calibre type 2 fragment simulating projectile (FSP), which representing an impact energy around 200 J.

Besides the tests in ballistic performance, helmet durability is also tested in accordance with these testing standards. A water immersion test included in MIL-H-4409A was designed to test the quality of the coating on the outside surface of helmets; static structural tests are for the examination of helmet deformation under repeated loading.

Generally, these two standards focus on different types of projectiles with various impacting velocities, the choice over which standard to use depends on the level of protection required for the helmet.

### 2.4.3 Design aspects of military helmet

#### 2.4.3.1 Requirements of military helmets as head protection

The head, as the most important part of the whole human body, requires the protection of helmets in combats to reduce the severity or probability of head injury. Impact-induced head injuries include lacerations, abrasions, fractures, and other forms of tissue disruption to the brain, its container skull and the outer covering scalp, as illustrated in Figure 2-16. In another word, any excessive movement of one part of the head relative to another can be responsible for head injuries [105].
Tolerance to indentation

The head being protected by a helmet can help in avoiding the direct contact with projectiles. However, the transient deformation of the helmet during a non-penetrating impact may also result in severe head injury. Behind Armour Blunt Trauma (BABT) refers to the trauma introduced by the transient deformation of composite helmets [107]. Localised impact resulted from BABT creates fractures and high intracranial pressure [108]. The backface deformation (BFD) is regarded as a direct index for evaluating the BABT resulted from the non-perforated ballistic impacts.

Tolerance to peak acceleration

Unlike the visible injuries to scalp and skull, damage to the brain can cause complex, long-lasting symptoms without being noticed [109]. The physics motions responsible for the brain damage are the excessive head accelerations (including both translational and rotational accelerations), evaluated by ‘g’, or gravity unit [105]. European standard ECE 22.05 specifies that the peak acceleration of head could not be higher than 300g at any time, or 150g for more than 15ms [104].

One of the most commonly used criteria for predicting head injuries is the Head Injury criterion (HIC), which is an acceleration-based empirical method. It measures the likelihood of head injury arising from an impact [110]. The time duration set for the calculation of HIC is influential to the evaluation. Watson et al. [111] indicated that ballistic impacts imparted peak force at a 0.05ms time duration to the head, which is shorter than that of the low-velocity impacts.
Another frequently used acceleration-based brain injury tolerance measurement is PLA (Peak linear brain acceleration). It is the peak value of the translational acceleration measured at the centre of gravity of the test headform during impact [55]. Measured in g, PLA is determined by the maximum force received by head throughout the impact process.

### 2.4.3.2 Composition of military helmet

A typical military helmet consists of three basic components, namely the helmet shell, comfort padding and retention system. Optional accessories are often included in the system to fulfil any other requirements. Figure 2-17 displays these components of an LWH (Light Weight Helmet). The function of each component is discussed in detail.

![Figure 2-17 Typical compositions of a military helmet [112]](image)

**Helmet shell**

Summarised by Newman [113], the outer shell is to provide a hard, strong outer surface that distributes the impact load over a larger area. It also provides a penetration shield against high-speed objects and protects both the wearer and the underlying liner of the helmet. In addition, it should have a high strength-to-weight ratio and a smooth exterior finish. Deformation under impact force is allowed, but must be controlled to the limit, below which no fatal harm is caused to the head.

Mentioned by Carey [99], weight becomes a trade-off factor for thickness, coverage and even the equipment compatibility. Normally, the thickness of helmet shell is between 5 and 10 mm, depending on the material used and application. A spherical shell is often employed, due to its ability to distribute impact energy over a wide area with minimum impact friction and the ability to reduce tangential acceleration induced by the impact.
According to Salvaterra [114], rigid shells do better at diffusing impacts, thus leads to lower peak force. Normally, the outer surface of the helmet shell also includes chemical coatings for more protective functions, including self-extinguishing, chemical resistance and colour camouflage.

**Comfort padding**

A padding system is added for impact and shock energy absorption as well as creating a comfortable microenvironment between the helmet shell and the human head. They are usually made from open cell polyurethane foam, PVC (polyvinyl chloride) or polyethylene foam. The comfort paddings are largely insensitive to impact velocity and have the rebound characteristics [115]. According to Gilchrist and Mills [116], a good padding material can also deform to the shape of the head without exerting pressure over 10 kN/m², beyond which the wearer would suffer from headaches.

**Retention system**

A suspension and retention system helps to keep the helmet movement synchronised to that of the head without excessive constraint or freedom. From comfort points of view, the suspension and retention system are responsible for keeping a functional helmet-head interface. First of all, the centre of mass of the helmet should lie as close to that of the head as possible. This is to eliminate the turning movement to the head imposed by an unbalanced helmet. A balanced helmet allows the head and helmet to move as a single unit without being interrupted by any lagging. Secondly, the helmet suspension system must hold the helmet shell off the scalp to permit ventilation and heat dissipation, also leave a uniform space allowance for any minor helmet indentation [99].

**Optional accessories**

Given the basic protective functions, modern helmets are often equipped with some accessories for certain functions. For example, helmets for paratroopers are enhanced by modified chin straps without interfering with their overall performance. Also, different colour toned camouflage covers are used according to environmental characteristics. Not to mention the advanced electronic devices including audio-visual head gear, hands-free communication sets as well as real-time physical monitors are often mounted on modern helmets.
2.4.4 Manufacturing techniques for military helmet shell

The manufacture methods for military helmet shells depend largely on the materials employed. In this section, both the limitations in conventional press-moulding technique and other innovative methods for helmet shell making will be reviewed as inspirations for improved helmet designs.

2.4.4.1 Limitations in press-moulding technique

Unlike the shells curved on only one linear axis, helmet shell has a doubly curved hemispherical shape. Because of this, resin pre-impregnated sheet goods including fabrics or unidirectional fibre prepgs, cannot be moulded into the shape without cutting or overlapping.

Cunniff [4] deduced mathematical relations to prove the necessity of reinforcement patterning, under the assumption that no in-plane deformation on the reinforcement. As denoted in Figure 2-18, a difference between the circumference of the circle on the hemisphere $C_{sphere}$ and that of the circular sheet good $C_{sheet}$ could be calculated according to Equation (2-7), where $r_{sphere}$ is the radius of the hemisphere. This difference becomes larger as the central angle $\theta$ increases. In order to compromise the difference in circumferences, sheet goods need to be cut and patterned before moulding. Therefore, reinforcement discontinuity is inevitable.

$$C_{sphere} - C_{sheet} = 2\pi \cdot (\theta - \sin \theta) \cdot r_{sphere} \quad (2-7)$$

![Figure 2-18 Circular sheet goods conforming to a hemisphere shape [4]](image)

One of the major considerations behind the military helmet making is how to maintain a uniform coverage and evenly distributed thickness with minimised seams and reduced
waste at the same time. With press-moulding technique as a typical method for modern composite helmet production [55], the aforementioned considerations are achieved through the control over consolidation pressure, heating temperature and the pattern size of the flat sheet goods. Various reinforcement patterning approaches were patented as guidance for military helmet manufacture, including the eight-legged pinwheel by Alesi et al. [117] (Figure 2-19(a)), the six-legged pinwheel hexagonal blanks by White [118] (Figure 2-19 (b)), the rectangular four-legged pinwheel by Cheese [119] (Figure 2-19 (c)), the zig-zag cut preform by Medwell [120] (Figure 2-19 (d)) and so on. The marking and cutting process to obtain designed pattern shapes take 60% of the total manufacturing time [55].

Figure 2-19 Patterning approaches for helmet preforms: (a) 8-legged pinwheel [117]; (b) 6-legged pinwheel hexagonal blanks [118]; (c) Rectangular 4-legged pinwheel [119]; (d) Zig-zag [120]

Despite the intensity of labour involvement during preform patterning, the radiographic results provided by Cunniff [4] still demonstrated discontinuity in a Kevlar® helmet shell. The light thin lines are locations of discontinuity, as indicated in Figure 2-20. The light and dark areas across the helmet surface correspond to the variations in thickness or density of the shell. The discontinuity in reinforcing material results from the pattern seams and wrinkles during moulding of the planned patterns. Cunniff further characterised the wrinkled areas being low in modulus but high in elongation because of the local crimping, and the seams were rather randomly distributed.
Although the uniformity of coverage and distribution of seams could be optimised through the patterned preforms for the discontinuously reinforced helmet shell, the non-uniformity of performance is inevitable, not to mention the potential decrement to the ballistic resistance of the helmet. Thus, it is preferable to have a continuous reinforcing scheme for ballistic helmet making.

![Figure 2-20 Radiographic of quarter helmet section showing discontinuity of prepreg [4]](image)

2.4.4.2 Innovative techniques for continuous reinforcement

The difficulty of manufacturing continuously reinforced helmet shell lies in the design of preform with adequate mouldability. Efforts have been made by researchers in both modifying the material handling approaches as well as explore new material arrangements for mature manufacture methods.

Making use of the continuous filaments from their initial state is the most straightforward approach to make continuous reinforced helmet shells. Tracy et al. [121] patented a spray-on method for making multiply continuous filament ballistic helmet, as demonstrated in Figure 2-21. Continuous Kevlar® 29 filaments and a phenolic resin were deposited onto a helmet-shaped porous screen before air-dried and press-moulded. Although the V50 ratings of the resulted continuously reinforced helmet shells indicated satisfactory ballistic performance, no evidence of weight reduction was reported. Furthermore, the distribution of reinforcing fibre and matrix cannot be controlled precisely through the hand spray method, which would also lead to non-uniformity of helmet performance as the discontinuously reinforced shells.
Marissen et al. [122] mentioned their attempt to build two helmet shapes simultaneously through winding UHMWPE yarns continuously onto an ellipsoid mandrel, as is illustrated in Figure 2-22. Thermal cutting formed the helmet edge, owing to UHMWPE’s ability to be fused under pressure at high temperature. There is no report regarding the ballistic performance of this shell. The axis around which the mandrel revolves would leave an area on top of the helmet shell with no reinforcement.

Except the methods that utilise the continuous filaments to build ballistic helmet shells, researchers also looked into moulding techniques incorporated with the suitable reinforcing material choice. Marissen et al. [50] reported a creep forming method for making UHMWPE prepreg reinforced ballistic helmet shells. The method takes advantage of
UHMWPE’s ability to accumulate a considerable amount of creep elongation, given enough time and heat. The resulted one-piece helmet shell maintained the integrity of fibres and left no wrinkles across the helmet surface. The research did not include any reports on the degradation of mechanical properties for the prepregs after the creep forming process. However, with the reorientation of the UHMWPE molecular chains under heat, the ballistic performance of such helmet shells is questionable.

Looking into the current ballistic helmet market, a company called Ceradyne Diaphorm [123] put forward their Seamless Ballistic Helmets (SBH), manufactured according to their proprietary forming and continuous fibre reinforced thermoplastic composite helmet moulding technology. The SBH presents a dramatic improvement in ballistic performance over the conventional helmets. It is also claimed that the continuous reinforcements utilised include raw tow, woven textile, braids, uni-directional and pre-consolidated laminates made from co-mingled or pre-treated yarns, each follows a unique processing procedure. The success of this SBH proved the superiority of using continuous reinforcement for ballistic helmet shell. Cartwright et al. [124] also proposed a similar double diaphragm deep-drawing thermoforming process, which claims to be able to turn the as-purchased, flat-form composite materials into 3D shapes. Focusing on the manufacturing techniques other than the design of reinforcement structures, the proposed process is available for a wide range of reinforcing preforms. However, the core design concept lies in their proprietary moulding technique which is kept confidential.

Zahid and Chen [10, 11] proposed a vacuum-bagging method for the manufacture of continuously reinforced riot police helmet shells. One-piece of the designed 3D through-the-thickness angle-interlock fabric from previous studies [98] was moulded into the riot police helmet shape continuously and infused with epoxy resin. The resulted helmet shell has a smooth finish and excellent impact resistance. This offers a route for the manufacture of continuously reinforced ballistic helmet shells. However, multiplies of the reinforcing
fabrics are required to achieve ballistic protection. To achieve thorough resin impregnation when the thickness of the shell increases would require modifications to the procedures.

2.4.5 Numerical evaluation the impact performances of military helmet shell

2.4.5.1 Advantages

Generally speaking, the study of ballistic impact upon textile reinforced composites can be achieved by three methods, namely the experimental, the analytical and the numerical methods.

For the experimental methods, the composite ballistic performance, including the ballistic limit, backface signature and depth of penetration need to be measured by scientific equipment. This method is considered effective when there are only small numbers of parametric variables to be studied individually or collectively. Although the process of the experimental methods is often time and money consuming, it is still essential for practically evaluating and validating the impact responses of composites.

Unlike the experimental method that gives results only according to specific testing conditions, both the analytical and the numerical methods enable the tailoring of predefined parameters for a more comprehensive understanding of the problem. Parameters related to the stress and strain, which are difficult to detect during experiments can be obtained through these methods.

The analytical method is established based on the general continuum mechanics formulas and laws. Naik et al [18, 125, 126] specified the kinetic energy absorbing mechanisms involved during the ballistic impacts using an analytical model which is based on the wave propagation theory and the energy balance between the projectile and the composite. However, the calculation could become increasingly complicated when more complex physical phenomena involve. Furthermore, the composite mechanical properties often require homogenisation [127].

Benefitted from the developments in computer sciences, the numerical methods have become more effective in the prediction and analyses. The numerical analyses are often conducted on the commercial finite element packages, including ABAQUS [128], ANSYS [129] and LS-DYNA. The first step of any finite element simulation is to discretise the
actual geometry of the structure into a collection of finite elements. Each finite element represents a discrete portion of the physical structure. The finite elements are joined by shared nodes. The collection of nodes and finite elements is called the mesh. In a stress analysis, the displacements of the nodes are the fundamental variables to be calculated. Once the nodal displacements are known, the stresses and strains in each finite element can be determined accordingly. Even though there have been no such models that can represent all the features in a real situation, these finite element packages are adequate for model construction, boundary condition and interaction setting, calculation and result visualisation.

The numerical method becomes increasingly popular when it comes to the simulation and analysis of the ballistic impact of composite structures [130]. In a ballistic impact scenario, the complex interaction between the projectile and composites, deformation and failure of the composites can all be simulated by these FE packages at a relatively low cost. Also, they allow user-defined material models to be imported into them when the potential materials are not included in the standard material library. The information about stress and strain distribution, which is hard to collect in experiments can be extracted and visualised directly.

2.4.5.2 FEA for ballistic impacts on helmet shells

Finite element analyses (FEA) were used to evaluate the ballistic performance of helmets by many researchers. Tham et al. [103] successfully simulated the impact of a 9mm FMJ (full metal jacket) projectile on a PASGT helmet as illustrated in Figure 2-24, and verified the effectiveness of this Kevlar® helmet by impacting at different impact positions against the V50 testing standard. Results defined the ballistic limit of a Kevlar® helmet being 358 m/s.

![Figure 2-24 FEA model for PASGT helmet impacted by 9mm FMJ [103]](image)
FE modelling established by Aare and Kleiven [131] took into account of the retention system and the head tissues to study the head response and head injury upon ballistic impacts. They gave the conclusion that producing a shell with enough stiffness is the major task for a successful military helmet shell design. At the same time, enough distance should be kept between the helmet shell and the human head to avoid the rear effect which causes large indentation towards the head. They also found that impacts with oblique angles are more likely to cause brain injuries.

Li et al. [132] built an FE model of the ACH shell with headform backings for the evaluation of the maximum BFD of the helmet shell with four different sizes at three primary locations and at different oblique impact angles. The frontal impact was revealed as the most destructive followed by the crown and lateral impacts. The smaller the helmet, the more vulnerable it will be. These all indicate that the curvature of the shells would influence the ballistic impact resistance in terms of resulting different deformation depth. However, the difference is not evaluated correlated to the values of curvature.

Obviously, the use of simulation tools is of great help in military helmet design, as it saves a considerable amount of time and effort for producing real helmet prototypes. Besides, information that cannot be achieved through experiments, like the stress and strain distribution, can be easily obtained. Therefore, the use of FEA in current research will not only improve the work efficiency but will also give guidance to the experimental work. The accuracy of FE results is highly dependent on the scale of modelling. Hence, it is necessary to validate the FE model against the experimental results.

2.4.6 Implications for future military helmet design

From the design aspects discussed above, a clear picture has been drawn regarding how the prototyping of a military helmet is performed. Aspects that need to be taken into consideration are from the choices of raw materials, including the reinforcing fibres and matrices, to the manufacturing techniques to employ; from the decision on helmet/head damage tolerance to the testing standard to follow; from the shortcoming of currently used helmets to its possible solutions. It’s clear about which combination of the above aspects can give the best helmet and the most suitable helmet processing route can be found according to the requirements of the helmet wearer.
Limitations of discontinuously reinforced helmet shells that are currently in use encourage the design and development of continuously reinforced shells for better ballistic performance and possibly lighter shell weight. Engineering of suitable woven structures that can be moulded into the doubly curved helmet shapes will save the time and the labour cost as well as the material wasted during pattern arranging. The success of using vacuum bagging shell composite process provides a cleaner method, for no direct contact with harmful chemicals is required. In addition to that, both the in-house firing device and FEA simulation could be used for shell ballistic performance evaluation, before the designed helmet is put into use.

2.5 Remarks

The literature review demonstrated the superiority of high-performance fibre reinforced composites as military helmet shells, in terms of offering high kinetic energy absorption and small impact indentations. Basically, there are two practical routes to improve the ballistic protection. One is to invent new materials for the construction of ballistic composites, the other is to exploit and further utilise the currently available materials by arranging them in an optimised manner.

The current research set its scope on the later with a comprehensive understanding of the advances in material sciences. Textile reinforced composites respond to high-velocity ballistic impacts locally at the impact location. The use of 3D woven fabrics as reinforcements would enhance the mechanical properties of composite along the through-thickness direction. This is considered to be beneficial for offering protection against transverse impacts, as the linear high-performance fibres are fabricated into 3D architectures that have the strong integrity to react against impact damages.

One major limitation of the current composite military shell would be the discontinuity in reinforcement caused by fabric patterning. Restricted by the insufficient mouldability of the conventional woven fabrics, such as plain and basket weaves, cutting and patterning of the reinforcing fabrics become inevitable. This is a time and labour consuming process, and the resultant composites are discontinuous, which are prone to stress concentrations during service.

The 3D woven TTAI fabrics provided a chance for continuously reinforcing the doubly curved military helmet shells. However, further analyses and evaluations of the design are
still necessary. This includes practically prove the advantage of continuous textile reinforcement for ballistic applications, characterising and tailoring the TTAI structure for enhanced mechanical properties, engineering design of TTAI fabrics that can demonstrate predictable mouldability and acceptable ballistic performance at the same time. All these aspects will be covered in the present research and presented in the chapters follows.
Chapter 3 Study on the effect of reinforcement continuity on the ballistic performance of multiply composites

Limited by the mouldability of the 2D woven fabric reinforcements, cutting and darting fabrics are inevitable in order for them to be conformed onto doubly curved surfaces. This is the case for the manufacturing polymer based composite military helmet shells where discontinuous fibre reinforcements had to be adopted [4, 133]. It was reported that the discontinuity in composite reinforcements is the source for out-of-plane stress concentrations from the interlaminar fracture point of view [5, 6] and from the compressive strength perspective [134]. The 3D woven through-the-thickness angle-interlock (TTAI) fabrics are capable of conforming to doubly curved surfaces without forming wrinkles and were prototyped into reinforcing riot police helmet shells using the vacuum-bagging method [7, 11, 135], which showed improved protective performance against low-velocity impact. For the same concept to be used for engineering military helmet shells, which is designed to offer higher level protection against high-velocity low-mass impacts, it is imperative to study the effects of reinforcement discontinuity on the ballistic performance of woven fabric reinforced composites and to confirm the effectiveness of multiply continuous reinforcement against ballistic impact [133].

The failure mechanisms of woven fabric reinforced composites under ballistic impacts have been studied by many researchers [18, 36, 136, 137]. Upon ballistic impacts, localised damage often occurs at the impact location [36], associated with damages including fibre breakage, matrix cracking, and delamination [18]. The ballistic performance of composites depends largely on their ability to absorb impact energy [18, 137] through the aforementioned damages as well as heat and frictional dissipation.

Gellert et al. [136] characterised the process of a projectile penetrating a composite target into two distinctive stages, i.e. the damage initiation stage and the penetration stage. Acceleration of target material, compression on the target material by the projectile and material shear are the predominant damage mechanisms at the impact initiation stage, whereas stretching of fibres, delamination and dishing continue during the second stage until target penetration. One possible route of engineering composites with improved ballistic performance is to develop and utilise better materials for matrices and reinforcements. It is also possible to take advantages of the currently available matrix and
fibre materials by arranging them in a manner that allows for more effective impact kinetic energy absorption.

This chapter describes the analyses on the effect of reinforcement continuity on the ballistic performance of composites reinforced by woven fabrics. Flat composites are employed for this investigation to eliminate the influence on ballistic performance by composite curvature. Composite samples with continuous and discontinuous aramid reinforcements are prepared using epoxy resin. Perforation ballistic impact tests will be used to evaluate the performance of the composite samples, and non-destructive test (NDT), including ultrasonic C-scan and X-ray computed tomography (CT), are planned to examine the damage morphology of the composite samples.

3.1 Manufacturing of thick composite panels with modified vacuum bagging method

3.1.1 Reinforcement

3.1.1.1 Manufacturing of plain weave fabrics

Plain weave is chosen as the textile structure in the current study because it has the most number of yarn crossovers per unit area which are the key elements responsible for impact energy dissipation. The specification of the plain weave fabric is stated in Table 3-1. The selection of fabric thread density will be referred to for the design of 3D woven TTAI fabrics, as mentioned in Section 4.3.1. There are 1000 filaments in each 93tex and 168tex Twaron® yarn [138].

Table 3-1 Plain weave reinforcement specifications

<table>
<thead>
<tr>
<th>Threads</th>
<th>Fabric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yarn</td>
<td>Linear density (tex)</td>
</tr>
<tr>
<td>Twaron®</td>
<td>93</td>
</tr>
<tr>
<td>Weave structure</td>
<td>plain</td>
</tr>
<tr>
<td>Thread density (threads/cm)</td>
<td>11.5</td>
</tr>
</tbody>
</table>

The high-performance Twaron® yarns employed in the current research are provided by Teijin® Ltd. All the plain fabrics were produced in the weaving lab based at The University of Manchester. In order to produce the woven fabrics with required specification and allow for a rapid change of design, a dobby shuttle loom was employed to fabricate the woven reinforcements in the present research. The whole process was carried out through two stages: warping/weft preparation and weaving.
Warping is to produce a parallel sheet of straight ends by unwinding a single end from the yarn package [65]. A warp beam containing a total of 540 ends, each with the length of 8 metres, was produced. Similarly, weft preparation is to wind yarns onto pirns for pick insertions on shuttle looms [65]. After accommodating the warp beam on the weaving machine, warp ends were drawn-in through heald frame wires and reed dents successively according to the draft in Figure 3-1, before tied onto the take-in roller. The movement of heald frames, which follows the lifting plan in Figure 3-1 formed sheds for pick insertions. The machines chosen to accomplish each procedure are listed in Table 3-2.

Table 3-2 Machine models for plain weave fabric manufacture

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Machine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warping</td>
<td>Warping machine MS-1800/8, model1988 (by Hergeth Hollingsworth GmbH)</td>
</tr>
<tr>
<td>Weft preparation</td>
<td>MSK pirn-winder (by Schweiter Ltd.)</td>
</tr>
<tr>
<td>Weaving</td>
<td>Dobby shuttle loom ‘Arbon 100W’ (by Adolphe Saurer)</td>
</tr>
</tbody>
</table>

3.1.1.2 Fabric reinforcement arrangements

For the continuously reinforced composites, plain weave fabrics were laid up in an aligned orientation due to the balanced nature of plain woven fabrics.
In order to create evenly distributed discontinuity in fabric reinforcements, the plain weave fabrics were cut into panels with the width of $L_p$ prior to lay-up. Figure 3-2 is a schematic cross-sectional view of a discontinuously reinforced composite panel. Joints with the size of $L_j$ 2.5 mm were left in each reinforcement ply in these composites. The distance between the neighbouring joints on the adjacent plies is noted as the overlapping length, $L_o$. The panel width $L_p$ is twice the size of overlapping length $L_o$ plus the size of a joint $L_j$.

In order to receive perforated results while having detectable delamination after impact for damage morphology analyses, the decision of using 20 plies of reinforcement for all the testing samples in the present study was made. This was based on an experiment where composite panel P10C reinforced by 10 plies of the same plain weave fabric absorbed an average of 34.84J impact energy, but the delamination damage was rather localised. Details of this 10-ply continuously reinforced panel are listed in Table 3-6. A trial of doubling the number of plies also led to a total perforation of the composite panel. In this 20-ply composite, the amount of delamination damage accumulated was more obvious and more widely distributed.

In making helmet shells, the discontinuity resulted from the patterning of reinforcing fabrics needs to be staggered away from each other to achieve an even thickness of the helmet shell. Considering that the length of each petal of a four-legged pinwheel fabric preform is 20cm in respect to the size of an actual helmet, an even distribution of 30 plies of the fabric preform around the helmet circumference would lead to an average overlapping length around 15mm to 20mm. In order to be more representative in evaluating the ballistic performance of the discontinuously reinforced composites, the overlapping lengths of 20mm and 45mm were chosen for the spliced panels.

### 3.1.2 Resin

Epoxym resin is a commonly used matrix material for aerospace and impact resistance applications. A warm-curing epoxy system based on Araldite® LY564 and formulated amine hardener XB3486 from Huntsman® [139] was chosen as the matrix for manufacturing Twaron® reinforced composite panels. The curing of the epoxy resin is achieved through an additional reaction between the amine groups in the hardener and the epoxide groups under the designed curing cycle [140]. A three-dimensional cross-linked network is formed by the end of the curing process.
The long pot life and low viscosity of their mixture enable not only enough time for vacuum bagging infusions to be conducted but also good fabric reinforcement wetting. Furthermore, this epoxy system shows good product mechanical properties and heat resistance, which all contributes to a good composite impact resistance.

The epoxy resin and hardener were mixed well at a ratio of 100:34 by weight before left in the vacuum oven for an hour to degas. According to the recommendation from the resin manufacturer, the temperature rising time is one hour before reaching 80°C from the room temperature. After maintaining this temperature for eight hours, the composite was then left to cool following the switch-off of the heating system until it reaches the ambient temperature.

### 3.1.3 Vacuum bagging setup

#### 3.1.3.1 Conventional vacuum bagging

Figure 3-3 illustrates the schematic cross-sectional view of a conventional vacuum bag. An air-tight cavity, with fabric reinforcement sealed inside, needs to be created first. The resin can then be infused into such cavity at a controlled rate and amount, followed by a designed curing cycle as mentioned earlier for structure consolidation. The consumables used in a conventional vacuum bagging setup are specified in Table 3-3.

![Figure 3-3 Cross-sectional view of the conventional vacuum bagging setup](image-url)
Table 3-3 Consumables in a vacuum bagging setup

<table>
<thead>
<tr>
<th>Identification</th>
<th>Material</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spiral tube</td>
<td>PP</td>
<td>Direct and distribution resin flow</td>
</tr>
<tr>
<td>Vacuum bag</td>
<td>Nylon</td>
<td>Air insulation for vacuum environment</td>
</tr>
<tr>
<td>Perforated releasing film</td>
<td>Nylon</td>
<td>Barrier between composite and bagging film; Uniform resin distribution</td>
</tr>
<tr>
<td>Infusion mesh</td>
<td>PTFE</td>
<td>Promote resin flow and distribution across the reinforcement surface</td>
</tr>
<tr>
<td>Peel ply</td>
<td>Nylon</td>
<td>Barrier between composite and the rest of the vacuum bagging stack</td>
</tr>
<tr>
<td>Releasing agent</td>
<td>PTFE</td>
<td>Facilitate demoulding</td>
</tr>
</tbody>
</table>

Firstly, this technique enables reinforcement preforming before resin impregnation. The reinforcing fabrics can be patterned and moulded into the designed shapes prior to the resin infusion at their neat states. Secondly, the infusion process demands no extra heat facilitation. The finishing of resultant composite surfaces is good as well.

**3.1.3.2 Double-mesh vacuum bagging**

Problems arose from the use of vacuum bagging for ballistic panel production when considering the quality of the final composite product. As large panel thickness, which is often the case for ballistic targets, will add to the difficulties in thorough resin impregnation. Dry spots or even voids in the composite structure, especially along its through-the-thickness direction, could be resulted from this uneven resin impregnation. Although the occurrence of voids is inevitable, the mechanical properties of composite fall dramatically with the increase in void contents [141]. The fibre volume fraction of the composite is another important parameter that monitors the mechanical properties of the final composite. It is greatly influenced by the processing methods and reinforcement types. Because of the large thickness (up to 10 mm) of multiply reinforcement stack, efforts are required to encourage the resin impregnation along the through-thickness direction of the composite panel.

As aforementioned, the use of degassed resin for infusion is an efficient way to reduce void formation. This will not only reduce the risk of outgassing directly from resin but also increase the capability of dissolving bubbles during infusion. The procedure of resin degassing is to subject the epoxy-hardener mixture into a partial vacuum (low air pressure environment, so that the gas solubility of resin is decreased (according to Henry’s Law – at absolute vacuum, the gas solubility is zero). A Heraeus Vacutherm was used to create this
low-pressure environment. The mixture is placed into this partial vacuum environment for 1 hour before infusion.

![Vacuum bagging setup with double-mesh scheme](image)

Figure 3-4 Vacuum bagging setup with double-mesh scheme

Besides, a double-sided mesh scheme, as illustrated in Figure 3-4, is employed in the panel making out of manufacturing experience. Instead of using the infusion mesh only on the top surface of the panel, a continuous piece of mesh wrapping around the spiral tube is used. The mesh on the bottom surface will be able to promote an additional channel below the reinforcing fabrics for the resin flow to proceed. All the composite panels in the present research were manufactured based on this double-mesh scheme, regardless of their reinforcement arrangements.

### 3.2 Characterisation of composite specimens

The properties of the reinforcing Twaron® yarn and the epoxy resin matrix are listed in Table 3-4, in the constructed composite panel. The mass and fibre volume fraction influence the mechanical properties of the composite panels manufactured. Therefore, the composite panels were experimentally characterised for their density and constituents.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Specific density (g/cm³)</th>
<th>Tensile strength (GPa)</th>
<th>Young's modulus (GPa)</th>
<th>Compressive strength (GPa)</th>
<th>Elongation at break (%)</th>
<th>Decomposition temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Twaron® yarn</td>
<td>1.44</td>
<td>2.40-3.60</td>
<td>60-80</td>
<td>0.58</td>
<td>3.00-4.40</td>
<td>500</td>
</tr>
<tr>
<td>Epoxy resin</td>
<td>1.25</td>
<td>70-74</td>
<td>2.86-3.00</td>
<td>0.03-0.04</td>
<td>4.60-5.00</td>
<td>80-84</td>
</tr>
</tbody>
</table>
3.2.1 Measurement of composite density

Ten composite specimens were taken from the 20-ply plain weave fabric reinforced panel by the dimensions of 2 cm by 2 cm, oven-dry equilibrium of the specimens are conducted at 70 °C for 7 days based on the descriptions in testing standard ASTM D5229 [143] prior to the composite density measurement.

The composite density $\rho$ is measured by the density determination balance, Mettler Toledo XP205 Delta Range® electronic balance including a density measurement kit. It ensures accuracy to 0.1 mg. To conduct a test the specimen weight in air $W_a$ is first recorded followed by the weight of specimen in distilled water $W_L$. Because the composite density is larger than that of the distilled water, the specimen density is readily calculated based on Archimedes’ principle in Equation (3-1) [14].

$$\rho = \frac{W_a}{W_a - W_L} \rho_w$$

(3-1)

where, $\rho_w$ is the density of distilled water, taken as 0.99823 g/cm$^3$.

The measurements and results are listed in Appendix Table 1. The average density of plain weave fabric reinforced composite was calculated to be 1.346 g/cm$^3$.

3.2.2 Measurement of fibre volume fraction

The amount of fibre in a textile reinforced composite is directly involved in the determination of the mechanical properties of the composite. For instance, the theoretical elastic properties of a unidirectional composite could be calculated based on the ‘rule of mixture’, as indicated in Equation (2-1).

Normally, the fibre volume fractions of fibre reinforced composites are in the range of 50% to 65% restricted by the manufacturing parameters. Inappropriate impregnation will lead to dry spots or voids in the composite structure.

The methods to determine fibre volume fractions include acid digestion, optical microscopy-based analysis, resin burn-off and calculation based on fibre volume and weight ratio relationship. In the current research, the calculation method is adopted. Details of the approach are described as follows:
a) Measure the areal density of the fabric reinforcement; calculate the weight of fabrics required to make a composite panel with the size of 160×160mm, ‘\(W_f\)’.

b) After processing, trim the excessive resin and measure the weight of the composite ‘\(W_c\)’.

c) The weight of resin matrix ‘\(W_m\)’ is the difference between the weights of composite and fibre:

\[ W_m = W_c - W_f \]  

(3.2)

d) Calculate the volume of the fibres in the composite ‘\(V_f\)’, where the density of Twaron\(^\text{®}\) fibre ‘\(\rho_f\)’, being 1.44g/cm\(^3\), is obtained from the Teijin\(^\text{®}\) datasheet [142].

\[ V_f = \frac{W_f}{\rho_f} \]  

(3.3)

e) Calculate the fibre-resin volume ratio, where the density of Epoxy resin used ‘\(\rho_m\)’, being 1.25g/cm\(^3\), is obtained from the Huntman\(^\text{®}\) datasheet [139], and ‘\(V_m\)’ is the volume of the resin matrix.

\[ \frac{V_f}{V_m} = \frac{W_f \cdot \rho_m}{W_m \cdot \rho_f} \]  

(3.4)

f) Calculate the fibre volume fraction. Assuming the void content is too small to be accounted, the fibre volume fraction is all except the volume fraction of the resin.

\[ F_F = 1 - \frac{1}{1 + \left(\frac{V_f}{V_m}\right)} \]  

(3.5)

Details of the measurements are listed in Appendix Table 2. The fibre volume fraction of the 20-ply continuous plain weave fabric reinforced composite is 56.61±0.90%.

### 3.3 Experimental evaluation of the ballistic performance of discontinuously and continuously reinforced composites

The composite panels manufactured and characterised with both continuous and discontinuous plain weave fabric reinforcements were subjected to experimental investigations in order to compare their ballistic performance. The evaluation was carried out through two types of tests: one is to test their ballistic resistance through perforated tests on the ballistic range; the other is to non-destructive tests, including C-scan and X-ray CT, for the damage morphology examination after impact.
3.3.1 Experimental methods

3.3.1.1 Ballistic impact test

Figure 3-5 is the ballistic range used for evaluating the composite panels’ ballistic resistance.

In a perforated test, the kinetic energy loss of the impacting projectile is considered to have been absorbed by the composite panel. The impact velocity \( V_i \) and residual velocity \( V_r \) can then be calculated based on the recorded time for the projectile to go through the two slots located both before and after the composite panel. A schematic of the ballistic range setup is illustrated in Figure 3-6.
Steel cylinders whose weight is 1 gramme and whose height and diameter both measured as 5.5mm are used as impact projectiles in all tests. The blank cartridges can propel the projectiles to velocities ranging from 450 m/s to 500 m/s. Regardless of the energy dissipated through air friction, the energy absorbed by composite panels ($E_a$) is considered equal to the projectile kinetic energy loss, which can be calculated according to Equation (3-6), where $m$ is the projectile mass in gramme, $V_i$ and $V_r$ are the impact and residual velocities (m/s) of the projectile.

$$E_a = \frac{1}{2} m (v_i^2 - v_r^2) \quad (3-6)$$

Due to the unpredictable impact velocity from each shooting and the limited impact velocity range, the standardised ballistic limit $V_{50}$ tests cannot be performed on the currently available ballistic range. Therefore, an estimated ballistic limit ($V_{50e}$) is calculated from the striking velocity and the residual velocity from Equation (3-7). [144]

$$V_{50e} = \sqrt{V_i^2 - V_r^2} \quad (3-7)$$

It estimates the striking velocity with which the projectile has the exact kinetic energy that can be absorbed during a perforation impact. Unlike $E_a$, the use of $V_{50e}$ can offset the influences from the variations of the striking velocities and the geometry or mass differences of the impactor from one shooting to another. Therefore, it can be used as an indicator for the ballistic resistance of the composite panels.

### 3.3.1.2 Ultrasonic C-scan

Because low-frequency ultrasound in a range from 0.2 MHz to 15 MHz can propagate through composite materials [145], the ultrasonic scan becomes a non-destructive testing (NDT) method for detecting the structural discontinuity of a part and is widely used in industry. Differentiated by the result presentation, there are three most commonly seen types of ultrasonic scans, namely the A-scan, B-scan and C-scan [146, 147]. Being the simplest among the three, A-scan only plots the amplitudes of reflections received by the transducer against time (or the propagation distance) at each point of a working surface. B-scan displays the time required for the ultrasonic wave to propagate against the movement of the transducers. A C-Scan is produced when the amplitude of a particular echo is monitored at each point on the surface of the specimen. C-scan produces a cumulated defect distribution
through-the-thickness but gives no information on their depth. Hence, C-scan can be used to characterise the in-plane damage distribution of composites after ballistic impact.

Ultrasonic C-scan tests of all the impacted specimens were performed on a Midas NDT C-scan system together with the Zeus V3.0 software. As presented in Figure 3-7, the ultrasonic sound wave is emitted continuously from the transmitter and accepted by the receiver through the nozzles ejecting water as the ultrasonic medium. The composite samples are mounted onto the holder in order to ensure their surface being always perpendicular to the ultrasonic path. The frequency of the transmitted ultrasonic sound wave used should be inversely proportionally to the thickness of the composite panels. In here, the frequency applied is 1 MHz.

The motions of the two relatively still transducers are precisely controlled to achieve high scan accuracy. Figure 3-8 demonstrates the raster movement manner of the transducers. The moving speed is determined to be 100 mm/s. Both the index step and the grid size were all set to be 100 μm in this study.
The ultrasonic signal attenuations are interpreted into the colour map, ranging from 0-100%. Due to the absence of a time-of-flight function, the damage distribution cannot be located through the thickness. Thus, the C-scan result can only qualitatively characterise the in-plane distribution of impact-induced damages in flat composite panels, but cannot support the quantitative analyses of their volume.

### 3.3.1.3 X-ray computed tomography (X-ray CT)

X-ray CT is a radiographic imaging technique that can reveal the three-dimensional inner features of an object non-destructively. Originated from computerised axial tomography (CAT), which is a well-established examination technique in medical science, X-ray CT gains its popularity as an NDT method in composite material sciences recently due to its capability of detecting and quantifying defects including voids and impact induced damages [148].

The X-ray CT is established on the basis that the linear X-ray attenuation coefficient being a sensitive measure of atomic composition and density [149, 150]. Figure 3-9(a) is the X-ray CT machine used in the current study for scanning composite plates. The X-ray beam passes through a 360° rotational object, projecting a series of two-dimensional images onto the ionisation detector. In order to visualise the inner features of an object, those 2D image slices are reconstructed into 3D volume following a mathematical algorithm, as illustrated in Figure 3-9(b) [151]. The resolution of results, which are represented by the pixel size for
2D images and the voxel size for 3D volume, are controlled over the relative distances between the X-ray source, object and the detector.

Figure 3-9 X-ray CT: (a) X-ray CT setup; (b) Schematic illustration of X-ray CT acquisition and reconstruction process [151]

Although the X-ray attenuation coefficient is similar between aramid fibres and epoxy, damaged vicinity has much lower attenuation coefficient than the bulk composite. Thus, the damaged volume could be easily distinguished from the composite due to the high contrast between them. In the current study, X-ray CT technique is employed in characterising the damages on Twaron®/epoxy composite after ballistic impacts.
The X-ray CT imaging of Twaron®/epoxy composites was conducted on the Nikon Metrology 320/225 kV Custom Bay located in HMXIF (Henry Mosley X-ray Imaging Facility). The full composite specimens were scanned for a complete viewing of the impact damages. Composite plates are of high dimensional aspect ratios, where their lengths and widths are often much larger than their thickness. This would lead to artefacts in the form of bright stripes and rings, which are attributed to the differences in the paths of X-ray through the composites while they rotate [152]. In order to reduce the dimensional aspect ratio of each piece of composite, the composite specimens were stacked together as shown in Figure 3-10 to maintain a close attenuation throughout the scan. Thin polystyrene foams were utilised to separate the neighbouring specimens.

![Figure 3-10 The stacking of composite specimens for X-ray CT scans](image)

To provide the optimum contrast between the specimen and background as well as within the specimen, the settings listed in Table 3-5 were applied under a 225 kV X-ray source and a Tungsten target.
Table 3-5 Machine settings for scanning perforated Twaron®/epoxy composite panels

<table>
<thead>
<tr>
<th>Imaging parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerating voltage (kV)</td>
<td>97</td>
</tr>
<tr>
<td>Filament current (μA)</td>
<td>100</td>
</tr>
<tr>
<td>Filter</td>
<td>2.5mm Aluminium</td>
</tr>
<tr>
<td>Exposure time (ms)</td>
<td>708</td>
</tr>
<tr>
<td>Projections</td>
<td>3142</td>
</tr>
<tr>
<td>Voxel size (μm)</td>
<td>56.5</td>
</tr>
</tbody>
</table>

After the scanning sessions, all the 2D projections were reconstructed using the Nikon Metrology software CT-Pro®. Firstly, the centre of rotation is determined by dual slices which located at the top and bottom respectively. To avoid the beam hardening artefact which leads to brighter edges, the beam hardening correction was valued as 1. The volume was then reconstructed at 100% quality with the dimensions of 2000 × 2000 × 2000 voxels. The volume files were later reformatted into an 8-bit floating point, for the sake of reducing their size and remapping the grayscale value before being segmented for volumetric visualisation and characterisation later.

3.3.2 Results and discussion

3.3.2.1 Ballistic impact resistance analyses

The perforation-based ballistic impact tests were conducted on the continuously and discontinuously reinforced composite panels, respectively. In order to achieve an even distribution of joints across the composite width and thickness, the composite panels were constructed with the specifications presented in Table 3-6. For each type of the reinforcing scheme, 5 samples were prepared and subjected to the ballistic impact tests.

Table 3-6 Specifications of continuously and discontinuously plain weave fabric reinforced composite samples for ballistic impact tests

<table>
<thead>
<tr>
<th>Composite panels</th>
<th>Reinforcement continuity</th>
<th>Number of plies</th>
<th>Overlapping lengths Lo(mm)</th>
<th>Panel width Lp (mm)</th>
<th>Thickness (mm)</th>
<th>Areal density (kg/m²)</th>
<th>Fibre volume fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P10C</td>
<td>Continuous</td>
<td>10</td>
<td>0</td>
<td>160</td>
<td>2.50</td>
<td>3.21</td>
<td>57.89</td>
</tr>
<tr>
<td>P20C</td>
<td>Continuous</td>
<td>20</td>
<td>0</td>
<td>160</td>
<td>4.80</td>
<td>6.50</td>
<td>56.61</td>
</tr>
<tr>
<td>P20DLo20</td>
<td>Discontinuous</td>
<td>20</td>
<td>20</td>
<td>40</td>
<td>4.80</td>
<td>6.51</td>
<td>54.70</td>
</tr>
<tr>
<td>P20DLo45</td>
<td>Discontinuous</td>
<td>20</td>
<td>45</td>
<td>90</td>
<td>4.80</td>
<td>6.51</td>
<td>56.08</td>
</tr>
</tbody>
</table>
The ballistic test results are listed in Appendix, from Table 3 to Table 6. Figure 3-11 plots the energy absorption $E_a$ and the estimated ballistic limit $V_{50e}$ calculated according to Equation (3-6) and Equation (3-7). No normalisation of the values is necessary, as the variations in areal densities between continuously and discontinuously reinforced composite are small enough to be neglected.

![Figure 3-11](image)

**Figure 3-11** Comparison of the ballistic performance for continuously and discontinuously plain weave fabric reinforced composite panels: (a) Energy absorption; (b) Estimated ballistic limit.

When compared between the two types of discontinuously reinforced composite specimens, it is found that P20DL$_{045}$ with longer overlapping length exhibited better ballistic performance than P20DL$_{020}$ by having an 8.9% higher $E_a$ and a 4.4% higher $V_{50e}$. The $p$ values obtained from T-tests are 0.0308 and 0.0310 for the obtained energy absorption and
estimated ballistic limit results respectively. This clearly suggests that discontinuously reinforced composite panels with longer overlapping length work more effectively in resisting ballistic impact.

Furthermore, when compared to their continuously reinforced counterparts, the discontinuously reinforced composite panels demonstrated inferior performance to the continuously reinforced ones for both energy absorption and estimated ballistic limit. The continuously reinforced composites P20C demonstrated better ballistic performance than the discontinuously reinforced ones through absorbing up to 19.3% more of kinetic energy carried by the projectile than the discontinuous P20DL_o20. The estimated ballistic limit of the continuous panel is up to 9.3% higher than that of the discontinuous counterparts. The $p$ values obtained from T-tests are 0.0026 and 0.0049 for the obtained energy absorption and estimated ballistic limit results respectively, indicating the obvious difference between the ballistic performances of the continuously and discontinuously reinforced composites. This means that when the same amount of reinforcing material is used, the continuously reinforced composites would provide more effective ballistic protection than the discontinuously reinforced composites. The reasons for this better ballistic performance of the continuously reinforced composites could be attributed to the reinforcement integrity, and further investigations are required to explain the accurate mechanism behind the phenomenon.

### 3.3.2.2 Ballistic impact damages analyses

In order to investigate the damage caused by the ballistic impacts, the damage morphology of continuously and discontinuously reinforced composites was visually examined through the NDT test results, including ultrasonic C-scan and X-ray CT. Three composite specimens were selected, one from each composite type P20C, P20DL_o20 or P20DL_o45. The three specimens were impacted with the same projectile velocity of 480 m/s, which represents 115.20J kinetic energy.

**Planar projected damage area**

As aforementioned, the through transmission C-scan is only capable of providing planar projected information of the damaged area. The raw data obtained from through transmission C-scan was processed by the scientific image processing programme ImageJ [153]. The damaged area was distinguished from the undamaged parts through the
differences in their grayscale. Figure 3-12 depicts the damage projections extracted. The dotted lines in (b) and (c) represent the locations of resin gaps for the discontinuously reinforced panels. With the resolution being 72×72 pixels per inch for all the three images, the damaged areas were counted based on the number of pixels in each area and included in Table 3-7.

Table 3-7 Planar projected damage areas from ultrasonic C-scan

<table>
<thead>
<tr>
<th>Composite panels</th>
<th>P20C</th>
<th>P20DLo20</th>
<th>P20DLo45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damage area (mm²)</td>
<td>5691.15</td>
<td>3875.41</td>
<td>2344.98</td>
</tr>
</tbody>
</table>

Figure 3-12 Projections of damage from through transmission C-scan: (a) P20C; (b) P20DLo20; (c) P20DLo45
Figure 3-12 shows that the projected damage areas of all three samples are close to circular, with the axis in the warp direction slightly longer. This can be attributed to the transverse isotropic nature of the plain weave reinforcement and the binding effect of the matrix. The uneven dimensions in the warp and weft directions could be due to the subtle structural differences, in particular, the yarn crimp levels between the warp and weft yarns. The phenomena demonstrated in Figure 3-12 suggest that the weft yarns crimped more in the reinforcing fabrics than the warp.

Under the same impact condition, the projected damage area of the continuously reinforced P20C is 1.47 and 2.43 times larger than that of P20DL020 and P20DL045, respectively. This implies that the continuity of the reinforcement plays an important role in distributing the strain, which leads to more energy absorption. However, panel P20DL045, which has longer overlapping length than P20DL020, was related to a smaller damage area than P20DL020, which is not in line with their evaluated ballistic energy absorption as shown in Figure 3-11. This confirms that the C-scan projections of the damage areas alone are unable to reveal the damages and their distributions through the thickness of composites. However, the planar damage area did reveal the distribution of the projected damage.

**2D cross-sectional view at impact locations**

X-ray CT is another NDT method intensively applied in composite quality and damage evaluation [154-157]. The X-ray CT imaging of Twaron®/epoxy composite specimens was conducted on the Nikon Metrology 320/225 kV Custom Bay located in Henry Mosley X-ray Imaging Facility at the University of Manchester. The full composite specimens were scanned using the settings listed in Table 3-5 under a 225 kV X-ray source and a Tungsten target. After the scanning sessions, all the 2D projections were reconstructed using the Nikon Metrology software CT-Pro® to form the 3D images of the damages in the composite specimens.

Figure 3-13 shows the cross-sectional slices of the reconstructed composite specimens about the impact locations, and the impact velocity was 480 m/s for all three. It is seen that all three specimens underwent localised deformations along the projectile penetrating path. This is supported by previous research where the response of target is localised to the point of impact and the majority of the energy is absorbed by dissipating over a small area [32, 36]. In Figure 3-13, the forms of composite damage, including fibre breakage, matrix crack
and composite delamination, are clearly visible. The delamination of the composites took place between the reinforcing fabric plies and propagated through the thickness in coned shapes, as indicated by the dotted lines, with smaller diameters on the impact face and larger diameters on the back face for all three cases. Greater delamination areas near the projectile exit are obvious for all three specimens, and this observation is supported by findings from previous studies [36, 136].

![Image of CT images showing impact induced damages]

Figure 3-13 2D cross-sectional CT images of the impact induced damages perpendicular to the central line: (a) P20C; (b) P20DLo20; (c) P20DLo45

It is obvious that the conical delamination of discontinuously reinforced panels was related to smaller bottom diameters comparing to that of the continuously reinforced panel P20C. This agrees with the ballistic performance results presented in Figure 3-11 that the continuously reinforced composites demonstrate improved energy absorption. However, the damages incurred were at different levels through the thickness of the composite panels, and the damage volume needs to be quantified for further analysis.

**3D damage volume**

Different components of the composites were segmented based on their range of grayscale. The damages in a composite panel are darker than the bulk Twaron®/epoxy composite itself, as indicated in Figure 3-14. The determination of grayscale thresholding will affect the result of damage quantification.
Figure 3-14(a) presents a slice image of the impacted composite panel P20 near the impact location. The grayscale value along the highlighted line which passes the delaminated areas is plotted and shown in Figure 3-14(b). The threshold for delamination damage in an impacted composite panel was estimated to be 44~73. This range of grayscale values was used for the labelling of the damage volume in all the impacted composite panels.

![Figure 3-14](a): Slice image of P20C with highlighted line; (b): Grayscale value change along the highlighted line

To be noticed, the determination of the upper limit of the threshold is based on subjective judgement. Although the damage volume was successfully quantified by the estimated threshold, further research on the determination of the threshold would offer more accurate evaluation.

Figure 3-15 displays the projection views of the damage volume of the panels based on the grey scale thresholding technique using the 3D visualisation software Avizo® [158]. The planar views give similar results to that obtained by the C-Scan, whereas the side and top views offer more information about how the damage distributes throughout the panel thickness.
Figure 3-15 Projection views of the voxels representing damage volume: (a) P20C; (b) P20DLo20; (c) P20DLo45

Table 3-8 Damage volumes extracted from X-Ray CT

<table>
<thead>
<tr>
<th>Composite panels</th>
<th>P20C</th>
<th>P20DLo20</th>
<th>(c) P20DLo45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damage volume (mm$^3$)</td>
<td>805.47</td>
<td>394.02</td>
<td>406.05</td>
</tr>
</tbody>
</table>

A full picture about the matrix cracking and composite delamination can be presented using the composite damage volumes. The damage volumes of all three composite specimens are listed in Table 3-8. Delamination in ballistic composites is an important mechanism for absorbing the impact energy, and the damage volume probably is the best indicator to evaluate the degree of delamination in composites. The damage volume in the continuously reinforced P20C is 805.47 mm$^3$, which is about twice as large as those in the two discontinuously reinforced composite specimens P20DL$\alpha$20 and P20DL$\alpha$45. This again confirms the superiority of the continuously reinforced composites for ballistic resistance. P20DL$\alpha$20 with shorter overlapping length and P20DLo45 with longer overlapping length are associated to damage volumes of 394.02 mm$^3$ and 406.05 mm$^3$ respectively, implying that panels with longer overlapping lengths are more energy absorbent than that with shorter overlapping length. Though in this case, the difference demonstrated is moderate. The results above support the findings from the perforation tests presented in Figure 3-11 that the shorter the reinforcement overlapping length is the less ballistic energy absorbent the composite will be.
Discussions

The findings from this research can also be interpreted using the theory governing the propagation of longitudinal stress wave in the ballistic panel. The work of Smith et al. [23, 159] on the stress wave propagation along single yarns and woven fabrics provides theoretical and practical support to the findings from this research and confirmed the basic science behind the phenomena revealed in the current study. A longitudinal stress wave is generated on the composite panels upon the ballistic impact. The wave travels along the epoxy impregnated aramid fibres in the case of continuously reinforced composites, and the wave propagates through the impregnated fibres and resin gaps for the discontinuously reinforced composites. The stress wave speed depends on many parameters including Young’s modulus and the specific density of the medium materials, as outlined in Equation (2-2). According to the information provided in Table 3-4, the propagation speed of the stress wave for the continuously reinforced composite will be higher than that in its discontinuous counterpart. This could lead to the understanding that the continuous composite is more energy absorbent than the discontinuous, which is in good agreement with the NDT results presented in Figure 3-13 and Figure 3-15. Further studies on the stress wave propagation for both continuously and discontinuously reinforced composites would be useful to provide more evidence for the superiority of the former. Yarn-level finite element modelling could be a possible approach to accomplishing this. Although the damage volume was successfully quantified by the estimated threshold, further research on the determination of the grayscale threshold would offer more accurate evaluation.

The study of reinforcement continuity is based on flat composite panels to eliminate the influence of the curvature. Composite helmet shells are of 3D shapes with a double curvature. The findings on the flat composites with continuous and discontinuous reinforcements are believed to be applicable to the helmet shell, as demonstrated by Roedel and Chen [135]. Their findings indicated that the disadvantages of using discontinuous reinforcements in both their flat and curved forms, only the composites were evaluated under low impact velocity. This would provide support for the engineering design of helmet composites with continuous reinforcements.
3.4 Summary

This chapter presented preliminary studies on the effect of reinforcement continuity on the ballistic performance of multi-ply composites reinforced with plain weave fabrics made from Twaron®. Previously, the responses of continuously and discontinuously reinforced composites were investigated under the low impact velocity [12, 98]. However, it is discussed in the literature review that the composites react differently to low and high velocity impacts. Ballistic impacts often result in localised deformation. Whether or not the reinforcement continuity would lead to variations in ballistic performance is worth investigating. Three types of the composite were made with 20 plies of a plain fabric, one with continuous fabric reinforcement, and two with discontinuous fabric reinforcements but with different overlapping lengths of 20mm and 45mm respectively.

Based on the ballistic test results, the continuously reinforced composites demonstrated up to 19.3% more energy absorption and 9.3% higher estimated ballistic limit than the discontinuously reinforced ones. The $p$ values returned from T-tests are 0.0026 and 0.0049 for the obtained energy absorption and estimated ballistic limit results respectively, indicating an obvious difference between the ballistic performances of the continuously and discontinuously reinforced composites. Also, the discontinuously reinforced composites with longer overlapping length showed better ballistic performance.

NDT techniques were also used to evaluate the projection of the damage and the volume of the damage, and the results indicated more widely distributed delamination through the thickness of the continuously reinforced composite panel. The damage volume obtained from X-ray CT proved to be an effective indication for evaluating the amount of damage resulted from the impact. Larger damage volume was contributed to the energy absorption and led to the better ballistic performance of continuously reinforced composites.

All these findings lead to the use of continuous fabric reinforcements for the construction of stronger ballistic composites instead of the discontinuous ones. The continuous reinforcing method would be adopted for the design of next generation helmet shells. Further research based on this idea will be presented in the following chapters.
Chapter 4 Study on 3D woven wadded through-the-thickness angle-interlock (TTAI) fabrics

As pointed out in the literature review chapter, the limited mouldability of the 2D woven and UD laminates leads to discontinuities in the doubly curved composites reinforced by them. The advantages of the continuously reinforced ballistic composites were also experimentally proved in Chapter 3. Previous research on the engineering design of one-piece riot police helmet shells demonstrated potentials of the conventional TTAI fabrics as continuous fabric reinforcements [12, 98]. However, the threats faced by soldiers are different from those faced by the riot police officers. In order to provide sufficient ballistic protection while ensuring the continuity and mouldability of the reinforcing fabrics, the design of an effective reinforcement structure based on the conventional TTAI fabrics becomes essential. The work described in this current chapter is devoted to studying the characteristics of TTAI fabrics, especially the wadded TTAI fabrics, providing an understanding of the reinforcement structure and parameters to establish the geometric models.

4.1 3D woven TTAI fabrics

4.1.1 Classification of TTAI fabrics

The angle-interlock fabric is one of the solid 3D woven structures [69]. They are commonly composed of two sets of yarns, the straight weft yarns and binding (or interlocking) warp yarns. The positions of straight weft yarns in different layers are alternate, which leaves enough space for binding yarns going through from top layer to bottom with a smooth path to bind layers together.

According to the variations in the paths or the interlocking depth of binding yarns, angle-interlock fabrics can be classified into two types, namely through-the-thickness angle-interlock fabrics (TTAI) and layer-to-layer angle-interlock fabrics (LLAI), as illustrated in Figure 4-1. The TTAI refers to structures with warp yarns bind diagonally from top to bottom. Whereas the binding warp yarns within LLAI only binds certain layers of weft yarns instead of through the full depth.
TTAI fabrics are highly mouldable because of their small resistance to shear deformation [98]. This frictional resistance associated with fabric shearing is dependent on the number of yarn reversal points per unit area under the same material system. Obviously, TTAI fabrics have fewer yarn reversal points, as shown in Figure 4-2. The reversal points only appear at the top and bottom layer within the 3D structure. All the other contacts between warp and weft yarns are of much smaller areas inside of TTAI fabrics. Therefore, the less reversal points per unit area and the weaker the frictional interaction between warp and weft yarns would be, offering TTAI fabrics with rather low shear rigidities, which makes them easy to be moulded into required shapes.

Research works done by Chen et al. [160] proved that the shear rigidity of TTAI fabrics is only half that of the stitched multilayer fabrics under the same thread density. It was also
pointed out that TTAI fabrics with more weft layers and smaller weave densities are more mouldable [7], which will be testified later through theoretical deductions. In the current research, TTAI fabrics are chosen to be the reinforcement for military helmet shell construction and the target is to form a continuous reinforcement without any wrinkles formed during their moulding process.

4.1.2 Wadded TTAI fabrics

Besides of the conventional structures mentioned previously, TTAI and LLAI could be enhanced by adding straight wadding warp yarns into the structures. Figure 4-3 is a 3D view of a 4-layer wadded TTAI structure generated from the textile design software, ‘Weave Engineer’. It is seen from the illustration that the blue binding warp yarns bound the four layers of weft yarns together, forming the basic structure of TTAI. In addition to that, three layers of wadding warp yarns, denoted by the red yarns in Figure 4-3, are inserted between the weft layers. In this way, a wadded 4-layer TTAI woven structure with enhancement along the warp direction can be achieved. The influences of these additional wadding warps on both the structure and the performance of the TTAI reinforced composites will be studied in detail in the following sections.

The structures of the wadded TTAI fabrics were observed under a Projectina optical microscope with PIA 4000 digital image analysing software to enable a large viewing field. Prior to that, multiplies of the 4-layer wadded TTAI fabrics were impregnated with a mixture of epoxy resin Araldite® LY564 and amine hardener XB3486 at the ratio of 100:34 by weight through the vacuum-bagging method mentioned in Section 3.1.3. To get the
cross-sectional view of the TTAI fabrics, composite slices along both the warp and weft directions were cut by a diamond saw and polished.

Figure 4-4 is the cross-sectional views of a multiply 4-layer wadded TTAI reinforced composite slice along both its warp and weft directions. Three sets of yarns, including the wefts, binding and wadding warps, were denoted on the figures. The four straight weft layers are highlighted by the green dotted lines. The paths of the weft yarns in Figure 4-4(a) and that of the wadding yarns in Figure 4-4(b) are both straight as was considered in the structural model of wadded TTAI structure illustrated earlier in Figure 4-3. The binding warps found their ways through the thickness of each TTAI fabric ply, holding the wefts and wadding warps together. The crimp level of the binding warps is found much higher than that of both the wadding warps and the wefts. Due to the inherent yellow colour of Twaron® yarns, the paths of the Twaron® filaments are generally brighter than the cross-sections. However, it is still noticed that the cross-section of all three sets of yarns demonstrates a lenticular shape. The cross-sections of the wefts, binding and wadding warps were highlighted in green, blue and red, respectively. This flattened cross-sectional shape results from the binding force during the fabric weaving and the vacuum pressure during the composite making, which is commonly the case for filament yarn reinforced composites [161].

Generally, the packing of these three sets of yarns agrees with the structural model in Figure 4-3 as well. From Figure 4-4(a), it is found that the wadding yarns stack into columns which are separated by the binding warps within each fabric ply. The area outlined by the dotted lines indicates a column consists of three wadding warps. The lenticular cross-sectional shapes of the wefts and their packing were also highlighted in Figure 4-4(b). The gaps between them are filled with the thickness of a weft yarn. Within each fabric ply, the thickness of the wadding warps defines the distance between the four weft layers. The four weft layers arrange themselves into columns consisting two picks each.
Chapter 4

Figure 4-4 Cross-sectional views of multiply 4-layer wadded TTAI reinforced composite: (a) along weft yarn paths; (b) along warp yarn paths

4.2 Characterisation of TTAI

The structural characterisation of TTAI provides the basic geometric information of the yarns and the fabric for FE model establishment. It also assists the selection of fabrics as composite reinforcements because various fabric designs could be represented and
compared by their structural characters mathematically. The present research attempts to complete the structural analyses for TTAI fabrics, for the sake of building the geometric model for FE analysis later and also specifying the structural parameters for the evaluation of fabric mouldability.

4.2.1 Weave specifications

The weave specifications of a conventional TTAI typically include the yarn linear density (tex), thread density (ends and picks/cm) and the number of straight weft layers within the structure. In the case of wadded TTAI fabrics, a wadding plan also needs to be specified regarding the arrangement and thread density of wadding yarns. The expression for a TTAI is ‘\( k – n_1 – n_2 \)’, in which, \( k \) is the number of straight weft layers, \( n_1 \) and \( n_2 \) are warp and weft density, respectively. For instance, a ‘5-10-30’ represents a piece of TTAI fabric with 5 straight weft layers, whose warp and weft density being 10 ends/cm and 30 picks/cm. Whereas, for the wadded TTAI structures, the straight wadding warp ends are inserted between adjacent interlocking warp ends as columns, which have been demonstrated in Figure 4-4(a). Wadding ends within each column are arranged in between each straight weft layers, i.e. a ‘4-6-(6*3)-28’ stands for a 4-layer wadded TTAI structure with an interlocking warp density of 6 ends/cm and wadding warp density of 18 ends/cm, its weft density is 28 picks/cm.

4.2.2 Geometric parameters

The Pierce geometrical model was the first to employ mathematical descriptions for the structural characterisation of woven fabrics. Prior to that, physical measurements based on observing the actual specimens was the only possible approaches [162]. The model described both the physical descriptions of a cloth, including the number of threads per unit length, crimp, yarn thickness of warp and weft, and the geometric descriptions of a cloth, including the yarn path along its central axes. The Pierce’s model enables the prediction of fabric mechanical behaviours through the structural parameters of fabrics mathematically. However, the Peirce models are more suitable for simulating the staple yarns with high twist levels, including cotton and wool.
In order to better mimic the yarn flattening within the fabric, especially for describing the filament yarns like Twaron® and Dyneema®, efforts have also been made to extend the model into non-circular yarns, such as the ellipse section by Peirce [162] himself, the racetrack (rectangular with semi-circle ends) sections by Kemp [163] and the lenticular (two symmetry arcs) sections by Hearle and Shanahan [161, 164]. Figure 4-5 is a Peirce model of the plain weave fabric with lenticular yarn cross-section [161]. Based on the figures obtained from microscopic observations, the lenticular yarn cross-section was found to be the most precise in interpreting the real status of filament yarns in composites. Therefore, the geometrical models of TTAI fabrics established in the current research are based on Pierce’s model under the assumption of yarns are rigid bodies whose cross sections being lenticular and non-deformable in all cases.

4.2.2.1 Yarn cross-section

The thickness of a single yarn is determined by ‘tex’, which is a unit of textile measurement for yarn linear density, or yarn thickness. Tex ($T_t$) is defined as the yarn mass in grammes per thousand metres.

$$T_t = S' \rho \times 10^3 \quad (4-1)$$

where $S'$ is the cross-sectional area of all the filaments within the yarn bundle (mm$^2$); $\rho$ stands for the volume density of yarn (g/cm$^3$). Regardless of the shape of the yarn cross-section, $S'$ should stay constant given the yarn linear density being the same.
Each Twaron® yarn is made of 1000 aramid filaments. The circular cross-sectional shape of the aramid filaments results from the round shape of the spinnerets during spinning. The variation in yarn linear density is because of the differences in the thickness of the filaments. Figure 4-6 illustrates the cross-sectional view of the packing of aramid filaments within a Twaron® yarn bundle. For filament yarns within dry fabrics, both the square and the hexagonal packings exist, lead to a fibre volume fraction, $P_f$ between 78.64% and 90.69% [165]. Consequently, the actual cross-sectional area of a single yarn $S$ should follow Equation (4-2),

$$S = \frac{S'}{P_f}$$  \hspace{1cm} (4-2)

Figure 4-7 illustrates the geometric relations regarding the lenticular shaped yarn cross-section. Because a lenticular cross section is made up of two symmetrical arcs, the area of a lenticular shape can be calculated according to Equation (4-3), (4-4) and (4-5),

$$R = \frac{a^2 + h^2}{2h}$$  \hspace{1cm} (4-3)

$$\theta = 4\arctan\left(\frac{h}{a}\right)$$  \hspace{1cm} (4-4)

$$S = 2\left[\frac{\theta R^2}{2} - a \cdot (R - h)\right]$$  \hspace{1cm} (4-5)

where $a$ is half the length of the long axis, $h$ is half the length of short axis, $R$ is the radius of the arc and $\theta$ is the central angle of arc.
4.2.2.2 Thread spacing

Thread spacing \( L \) (mm) refers to the distance between two adjacent warp or weft yarns. It is made up of the thickness of yarn and the gap between two yarns. The subscript number ‘1’ indicates the parameters along warp direction and ‘2’ the weft direction, in all cases.

For conventional TTAI fabrics, the warp and weft spacing, which are \( L_1 \) (mm) and \( L_2 \) (mm) respectively, is calculated according to Equation (4-6) and (4-7).

\[
L_1 = \frac{10}{n_1} \quad (4-6)
\]

\[
L_2 = \frac{10k}{n_2} \quad (4-7)
\]

where \( n_1 \) and \( n_2 \) are the warp thread density (ends/cm) and the weft density (picks/cm) respectively; \( k \) is the number of straight weft layers.
Figure 4-8 is the top view of a 4-layer wadded TTAI structure. The dotted frame outlined the smallest repeat of this structure. For the wadded TTAI fabrics, the warp spacing is related to both the thread densities of the binding warps and the wadding warps. While the binding warp spacing \( L_1 \) and the weft spacing \( L_2 \) are still calculated according to Equation (4-6) and (4-7), the calculation of wadding warp spacing \( L_1' \) (mm) follows Equation (4-8), to take into consideration of the wadding plan.

\[
L_1' = \frac{10(k - 1)}{n_1'} \quad (4-8)
\]

where \( n_1' \) is the thread density of wadding warps (ends/cm).

Because there are \( k \cdot (k + 1) \) straight weft picks in a weave repeat, the number of weft stacks \( m \) within a repeat is

\[
m = \frac{2k(k + 1)}{k} = 2(k + 1) \quad (4-9)
\]

‘\( p \)’ denotes the fabric length of a weave repeat and it can be expressed as

\[
p = \frac{10k(k + 1)}{n_2} \quad (4-10)
\]

From the Equation (4-6), (4-7) and (4-8) above, it is found that the warp spacing is determined by the warp thread density only, whereas the weft spacing is also affected by the number of weft layers within the structure. Within a TTAI structure, the weft yarns are distributed along both the fabric width and its thickness directions. Weft spacing only outlined the distance between adjacent wefts within the same layer. Along fabric thickness direction, weft yarns are bound by the tension of the binding warps in a most compact manner. Under the same weft density, TTAI fabrics with more weft layers will have larger weft spacing consequently.

**4.2.2.3 Binding warp path**

Within a TTAI structure, the straight yarns, including the wefts and wadding warps, are held together by the binding warps configuring through the thickness of the fabric at certain angles. Hence, the geometrical parameters of the binding warp including the interlocking angle and its length needs to be specified to determine a binding warp path. Both of them are closely related to the fabric thickness.
Figure 4-9 Cross-sectional view of a 4-layer TTAI along warp path: (a) Conventional; (b) Wadded

Figure 4-9 illustrates the cross-sectional view of half a weave repeat of both the 4-layer conventional and wadded TTAI fabrics. In both cases, the configuration of a binding warp consists of three parts: two arcs at the top and bottom layer respectively (P_1P_2 and P_6P_7) and a straight line (P_2P_6) through the fabric thickness. To form the arcs, the binding warp and weft yarns are tightly in contact with each other on fabric surfaces, while the straight line serves as a tangent line to the weft cross-section at each contact point, and a right triangle ΔO_2P_3P_5 is formed consequently. α is the interlocking angle which indicates the angle between binder path and horizontal line. The geometrical relations of the right triangle according to Pythagorean Theorem and the arc length formulae form the theoretical base of the calculation equations (4-11), (4-12) and (4-13).

\[ H = l \cdot \sin \alpha + 2r \cdot (1 - \cos \alpha) + 2h \]  
\[ p = 2[l \cdot \cos \alpha + 2r \cdot \sin \alpha] \]  
\[ r = R + h \]
where $r$ is the radius of an arc whose central angle being $2\alpha$; $l$ is the length of the straight line $(P_2P_6)$, $H$ is the thickness of the fabric. The value of $r$ is slightly larger than the radius of the arc that formed the lenticular shape.

In the case of the wadded TTAI, the thickness of the fabric $H_w$ satisfies Equation (4-14).

$$H_w = (2k + 1) \cdot 2h \quad (4\text{-}14)$$

For the conventional TTAI, the thickness of the fabric $H_c$ satisfies Equation (4-15)

$$H_c = (k - 1) \cdot \frac{L_2}{2} \cdot \tan \alpha + 4h \quad (4\text{-}15)$$

Therefore, the geometric model of a TTAI fabric is established given the linear density of the thread used, the thread densities and the weave structure (including the number of straight weft layers and the wadding plan) being specified. The calculation equations derived will later be used to establish the geometric models of TTAI for FE analyses.

### 4.2.3 Structural parameters

The geometric model described in the previous section takes into consideration of the real geometric parameters of the TTAI structures based on the optical observation. While for the analyses and prediction of the mechanical behaviours, certain idealisation of the real physical features will simplify the problem, only if the structural characters are well reflected in the analyses. This is because the size of the long axis of a lenticular shape is found similar to the thread spacing. Under the assumption of the non-deformable cross-section, it is difficult to predict the fabric tightness and mouldability if the gaps between yarns are filled with their own widths. A constant diameter of circular cross-section, which was used to represent the thickness of yarns, was defined according to the yarn linear density.

The assumption of the non-deformable circular cross-section is arbitrary, but it allows the characterisation of fabric mouldability regardless of the changes in cross-sectional shapes. Therefore, the fabric tightness and mouldability factor were evaluated based on circular yarn cross-section in the current study.

#### 4.2.3.1 Representative yarn thickness

In order to characterise the thickness of the yarns, the cross-sections of all three sets of yarns could be assumed as circular and non-deformable. The gaps between filaments within a single yarn bundle are also regarded as negligible. Consequently, the thickness of
yarn could be represented by its diameter $d$ (mm) under the assumption of a round cross-section, which is calculated by Equation (4-16) deduced from Section 4.2.2.1.

$$d = \sqrt{\frac{40T_t}{\pi \rho \times 10^{-2}}}$$

(4-16)

For example, the representative thickness of Twaron® filament yarns with different linear densities (tex) are calculated and listed in Table 4-1, where the density of Twaron® fibre is set to be 1.44 g/cm$^3$ according to the product datasheet by Teijin® [142].

Table 4-1 Calculated yarn diameters of Twaron® yarns

<table>
<thead>
<tr>
<th>Linear density (tex)</th>
<th>93</th>
<th>110</th>
<th>168</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameters (mm)</td>
<td>0.287</td>
<td>0.312</td>
<td>0.385</td>
</tr>
</tbody>
</table>

4.2.3.2 Weave tightness

The weave tightness is influential to the properties of fabrics, especially when the comparison between fabrics made from yarns with different linear densities is required. For the same weave structure, larger fabric tightness indicates a tighter compaction of threads, leaving narrower gaps between the adjacent yarns. The circular yarn cross-section is also assumed for the prediction of weave tightness because it reassembles the tightest configuration of the filament yarns within a woven structure.

Since both warp and weft yarns configure within a three-dimensional space, the tightness calculation is based on their projections onto the horizontal plane and is related to the calculation of fabric coverage. Peirce [162] suggested the use of ‘cover factor’, which is the ratio of the area covered by yarns to the area covered by fabric. On the basis of that, Love [166] defined the fabric tightness as the cover factor of the actual fabric to that of its maximum construction. Equation (4-17) and (4-18) are the warp tightness of conventional $E_I$ and wadded $E_I'$ TTAI respectively.

$$E_I = \frac{n_1 d_1}{10} \times 100\%$$

(4-17)

$$E'_I = \frac{n_1 d_1 + n'_1 d'_1}{k-1} \times 100\%$$

(4-18)

where $d_1$ and $d'_1$ are the representative thickness of warp and wadding yarn diameter in millimetre that is worked out according to Equation (4-16), $n'_1$ is the wadding warp density (ends/cm). When the column of wadding yarns are inserted between each weft layer at the
same thread density as the binding warps (where, \( \frac{n_1'}{k-1} = n_1 \)), Equation (4-18) for the warp
tightness of wadded TTAI fabrics \( E_1' \) can be simplified as Equation (4-19).

\[
E_1' = \frac{n_1(d_1+d_1')}{10} \times 100\% \quad (4-19)
\]

In the case of weft tightness, both conventional TTAI and wadded TTAI share the same
calculation formula. The weft tightness \( E_2 \) is derived from Equation (4-20)

\[
E_2 = \frac{md_2}{p} = \frac{2(k+1)d_2}{10k(k+1)} = \frac{d_2n_2}{5k} \times 100\% \quad (4-20)
\]

where \( k \) is the number of straight weft layers, \( m \) is the number of weft stacks and \( p \) is the
lengths of a weave repeat along the warp direction, as was defined in Section 4.2.2.2. From
the weft tightness calculation Equation (4-20), it is found that, in addition to the use of
finer yarns and smaller fabric density, the increase in the number of straight weft layers
used will also lead to smaller fabric tightness along weft direction. This is because the weft
yarns arrange themselves in a three-dimensional space. Under the same weft density, the
weft spacing would increase with the increase in the number of weft layers, based on the
definition in Equation (4-7). Therefore, by increasing the number of straight weft layers in
TTAI, looser fabrics with more space to allow yarn relative movement will be woven.

Based on the discussions above, the choices of yarn linear density, fabric thread density
and the numbers of straight weft layers will lead to different TTAI fabric tightness. In
general, the total tightness is the build-up of the tightness in both warp and weft directions.
The careful choice on fabric tightness could give the TTAI woven a good overall look. At
the same time, the effect of TTAI tightness on the ballistic performance of the composites
it reinforced is sought to be understood in the following studies.

4.3 Design and production of TTAI fabrics

4.3.1 Design of TTAI fabrics

As mentioned in Section 3.1.1.1, the plain weave fabric at the thread density of 11.5
threads per cm was woven from 93tex Twaron®. And composite panels reinforced by it
were also investigated for their ballistic performance. In order to provide comparable
subjects, TTAI fabrics are designed to share the similar fabric warp tightness as the plain
weave fabric used earlier. According to the calculation Equation (4-16) and (4-17), the
warp and weft tightness of the plain fabric both being 32.98%. With the tightness of this
plain weave fabric as a reference, TTAI structures with different geometrical parameters are designed as listed in Table 4-2.

Generally, those TTAI fabrics could be grouped into 4 groups (Group A-D, respectively). The weft tightness of each variety within each group is also designed to be at the same level. The warp tightness of all the specimens is controlled at an equivalent level to the plain weave reference, despite the yarn linear density, warp density, the number of weft layers and the wadding plan being different.

Table 4-2 Weave specifications of designed TTAI fabrics

<table>
<thead>
<tr>
<th>Fabric type</th>
<th>Number of weft layers</th>
<th>Yarn linear density (tex)</th>
<th>Thread density (thread/cm)</th>
<th>Warp tightness (%)</th>
<th>Weft tightness (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Warp density (epc)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Binding warp</td>
<td>Wadding warp</td>
<td></td>
</tr>
<tr>
<td>Plain I</td>
<td>-</td>
<td>168</td>
<td>8.5</td>
<td>8.5</td>
<td>32.73</td>
</tr>
<tr>
<td>(A1)</td>
<td>5</td>
<td>168</td>
<td>8.5</td>
<td>-</td>
<td>26</td>
</tr>
<tr>
<td>(A2)</td>
<td>5</td>
<td>168</td>
<td>8.5</td>
<td>-</td>
<td>28</td>
</tr>
<tr>
<td>(A3)</td>
<td>5</td>
<td>168</td>
<td>8.5</td>
<td>-</td>
<td>30</td>
</tr>
<tr>
<td>(A4)</td>
<td>5</td>
<td>168</td>
<td>8.5</td>
<td>-</td>
<td>32</td>
</tr>
<tr>
<td>(B1)</td>
<td>5</td>
<td>168</td>
<td>10</td>
<td>-</td>
<td>26</td>
</tr>
<tr>
<td>(B2)</td>
<td>5</td>
<td>168</td>
<td>10</td>
<td>-</td>
<td>28</td>
</tr>
<tr>
<td>(B3)</td>
<td>5</td>
<td>168</td>
<td>10</td>
<td>-</td>
<td>30</td>
</tr>
<tr>
<td>(B4)</td>
<td>5</td>
<td>168</td>
<td>10</td>
<td>-</td>
<td>32</td>
</tr>
<tr>
<td>Plain II</td>
<td>-</td>
<td>93</td>
<td>11.5</td>
<td>11.5</td>
<td>32.98</td>
</tr>
<tr>
<td>(C1)</td>
<td>4</td>
<td>93</td>
<td>11.5</td>
<td>-</td>
<td>28</td>
</tr>
<tr>
<td>(C2)</td>
<td>4</td>
<td>93</td>
<td>11.5</td>
<td>-</td>
<td>30</td>
</tr>
<tr>
<td>(C3)</td>
<td>4</td>
<td>93</td>
<td>11.5</td>
<td>-</td>
<td>32</td>
</tr>
<tr>
<td>(C4)</td>
<td>4</td>
<td>93</td>
<td>11.5</td>
<td>-</td>
<td>34</td>
</tr>
<tr>
<td>(D1)</td>
<td>4</td>
<td>93</td>
<td>5.75</td>
<td>17.25</td>
<td>28</td>
</tr>
<tr>
<td>(D2)</td>
<td>4</td>
<td>93</td>
<td>5.75</td>
<td>17.25</td>
<td>30</td>
</tr>
<tr>
<td>(D3)</td>
<td>4</td>
<td>93</td>
<td>5.75</td>
<td>17.25</td>
<td>32</td>
</tr>
<tr>
<td>(D4)</td>
<td>4</td>
<td>93</td>
<td>5.75</td>
<td>17.25</td>
<td>34</td>
</tr>
</tbody>
</table>
4.3.2 Fabric production

The warping and weft preparation for the production of 3D woven TTAI followed the similar procedures as that for the production of plain weave fabrics. Normally, the conventional 3D woven TTAI fabrics are produced on a dobby loom. Details about the machinery involved refer to the production of plain weave fabrics described in Section 3.1.1.1. In order to allow more wadding warp ends being accommodated in the structure under controlled tension, an extra warp beam, which contains the required wadding warp ends, needs to be added to the loom during weaving. The let-off rate of the ends on the wadding yarn beam and that of the binding yarn beam were adjusted independently to maintain a flat fabric finish.

As an example, the yarns required per weave repeat for conventional and wadded TTAI 4-layer and conventional 5-layer were denoted in Figure 4-10. The colour codes for binding warp, wadding warp and weft follows that used in Figure 4-3. As illustrated in Figure 4-10(b), the number of wadding warp ends on the additional warp beam is three times of that on the original binding warp beam for the wadded 4-layer TTAI. Following the denoted sequences, the weave designs used for producing TTAI fabrics are specified in Table 4-2, including the weave diagram, reed plan, harness plan and lifting plan, are displayed in Figure 4-11.

During the fabric weaving process, the alteration of fabric weft densities could be achieved through changing the take-up gear, as long as all the other specifications stay unchanged. Therefore, TTAI fabrics with only weft densities being different could be produced by drawing-in for just once. This will improve the production efficiency because draw-in is the most labour and time-consuming procedure throughout the whole fabric production process. Based on the specification listed in Table 4-2, all the specimens A1, A2, A3 and A4 can be woven into a continuous sheet of fabric with one draw-in. So it is the case for the specimens in group B, C and D. Fabric specimens with the size of 45 cm in width and 2 metres in length were produced for each type designed. Those specimens will later be used for mouldability study and as reinforcements for composites for their tensile and ballistic performance study.
Figure 4-10 Cross-sectional views of TTAI fabrics with yarns per weave repeat denoted: (a) Conventional 4-layer; (b) Wadded 4-layer; (c) Conventional 5-layer
Figure 4-11 The weave designs of TTAI fabrics: (a) Conventional 4-layer; (b) Wadded 4-layer; (c) Conventional 5-layer

4.3.3 Fabric analysis

The off-loom thickness and areal density of the TTAI fabrics produced were tested. The fabric specimens with the size of 20×20 cm were conditioned under the standard atmosphere with the temperature of 20 °C and humidity of 65% for 24 hours previous to the tests. Details of the testing procedures and results are presented as follows.
The device used for thickness measurement is a Messmer® micrometre. As is illustrated in Figure 4-12, the fabric specimen to be tested is kept on an anvil whose diameter being 60mm. A circular pressure foot whose diameter being 25mm is lowered onto the fabric samples until the pressure reaches 100KPa. This pressure value was set to simulate the standard atmospheric pressure (101KPa), which the fabrics underwent during vacuum bagging for the composite making. The readings on the screen indicate the thickness of fabric under the vacuum pressure, and also the thickness of fabrics in the composite made. Then, the above procedure is repeated to obtain the values of thickness at 5 different locations. A total of ten readings for each type of specimen is recorded and tabulated in Appendix Table 7. The conditioned fabrics are weighed by an electronic balance for their weight and normalised by their area in order to get their areal density, which is included in Appendix Table 8.
Figure 4-13 Results from fabric analyses: (a) Thickness of fabric specimens; (b) Areal density of fabric specimens

All of the fabric types specified in Table 4-2 are tested for their thickness and areal density according to the method described. The results are plotted in Figure 4-13. The horizontal axes of both plots were labelled based on the values of fabric weft tightness, as listed in Table 4-2. It is obvious from the testing results that both the thickness and the areal density of the TTAI fabric increase with the increase of their weft tightness. The value of weft tightness is positively related to the weft thread density, based on the calculation Equation (4-20). And the wadded structures are generally thicker and heavier than their conventional counterparts due to the existence of the additional sets of wadding warps.
4.4 Influences of wadding warp yarns on the tensile properties

4.4.1 FE analyses on wadded TTAI fabrics

4.4.1.1 Model description

In order to investigate the role of wadding yarns within a wadded TTAI structure, an FE model based on Specimen D2 is established. Specification of Specimen D2 was listed in Table 4-2. The geometric parameters defined in Section 4.2 based on the lenticular yarn cross-section are calculated to reflect the geometry of the TTAI fabric at its relaxed state. The model did not take the changes in cross-sectional shape into account during the analyses. The calculated geometric parameters of the three sets of yarns in D2 are listed in Table 4-3 and denoted in Figure 4-14.

Table 4-3 Geometric model for Specimen D2

<table>
<thead>
<tr>
<th>Set of yarn</th>
<th>Cross-section (mm)</th>
<th>Path (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Width</td>
<td>Height</td>
</tr>
<tr>
<td>Binding warp</td>
<td>0.870</td>
<td>0.122</td>
</tr>
<tr>
<td>Wadding warp</td>
<td>0.870</td>
<td>0.122</td>
</tr>
<tr>
<td>Weft</td>
<td>0.870</td>
<td>0.122</td>
</tr>
</tbody>
</table>

Figure 4-14 Denote of the geometric parameters of binding warp in FE model: (a) Binder path; (b) Lenticular cross-section; (c) Overview of the mesh on binding warp
Because the same type yarn 93tex Twaron® was used for all three sets of yarns, the cross-sectional geometry of binding warp, wadding warp and weft are considered as the same. In order to simulate the tight filament packing under vacuum pressure, a packing fraction $P_f$ of 91% is assumed for the filaments in these yarns.

Both the wadding warps and the wefts are assumed to be straight in the FE model as previously stated. Figure 4-15 is the face of D2 reinforced composite. It is seen that the light dots are the through-the-thickness binding warp yarns and the vertical threads being straight wadding warp yarns. The binding and wadding warps are found closely packed side-by-side. Hence, the width of the thread cross-sections $2a$ in the FE model was set to be the warp spacing. The height of cross-section $2h$ of all threads, the wavelength $p$ and thickness $H_w$ of the binder can be calculated according to Equation (4-10) to (4-14) and listed in Table 4-3.

The homogeneous isotropic material model was adopted for the yarn model [27, 167, 168]. The material properties of Twaron® yarns in the fabric FE model are included in Table 4-4. The density of yarn is calculated based on the 91% packing fraction. Discrete material orientation was assigned to the crimped binding warps along their paths. A total of 179514 solid C3D8R elements were created for a D2 fabric model at the size of 8×7.7 cm. The areal density of the constructed fabric is 501.62 g/cm², which is close to the areal density
measured in Figure 4-13. Hence, the geometric model established is considered valid to represent the wadded TTAI fabric, Specimen D2.

Table 4-4 Material properties for 93tex Twaron® [169]

<table>
<thead>
<tr>
<th>Properties</th>
<th>Density (kg/m$^3$)</th>
<th>Young’s modulus (GPa)</th>
<th>Poisson’s ratio</th>
<th>Failure strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>93tex Twaron®</td>
<td>1310.4</td>
<td>72</td>
<td>0.2</td>
<td>4.3</td>
</tr>
</tbody>
</table>

Figure 4-16 FE model for tensile test along warp direction

A constant displacement rate of 40 m/s was applied to one side of the fabric, with the opposite side being fixed, resulting in a tensile loading along the fabric warp direction. The displacement rate is optimised to avoid excessive distortions while saving calculation time. Displacement and the reaction force of the fabric were recorded. General contact between yarns with the coefficient of friction being 0.15 was defined. The established model is illustrated in Figure 4-16.

4.4.1.2 Result and discussion

The tensile force and displacement were recorded and the time history of tensile loadings on Specimen D2 is plotted in Figure 4-17. It is noticed that the slope of the curve gradually reduces as the fabric elongates until failure. This could be interpreted as the increase in fabric stress becomes more and more moderate as the fabric stretches.
The propagation of stress wave leads to the zero force at the beginning of the experiment. Because the tensile force is represented by the total reaction force of the fixed ends, it takes about 11µs for the fixed ends to react upon the tensile loadings initiated from the opposite end.

The stress distribution on one binding warp and the adjacent three wadding warps is extracted as shown in Figure 4-18. It is seen clearly that the straight wadding warps start to elongate upon the tensile loading directly. This explains the sharp increase in loading from

Figure 4-17 Time history of tensile loadings on Specimen D2 along warp direction

Figure 4-18 Stress distributions on binding and wadding warps: (a) at 0µs; (b) at 10µs; (c) at 20µs
11\(\mu\)s to 75\(\mu\)s. Whereas the crimped binding warp needs to be straightened prior to being stretched during the fabric elongation, and the force demanded to straighten a crimped yarn is much lower than that to stretch the yarn.

The increase in tensile loading slows down from 75\(\mu\)s till 135\(\mu\)s as the failure strain of the wadding warp is reached and the wadding warps start to fail. Followed by the failure of binding warps from 135\(\mu\)s onwards, the whole structure suffers from tensile failure in the end.

The tensile behaviour of the wadded TTAI along its warp direction implies that, unlike the wadded TTAI fabrics that have straight wadding warps to take the tensile loading from the beginning, the crimped binding warps need more time for straightening themselves in the conventional TTAI fabrics. When the tensile loadings are applied along the weft yarn direction, the straight weft yarns would demonstrate a similar tensile behaviour as the wadding warps in the previous case. Thus, the differences in the load-taking behaviours between the warp and weft direction will result in different tensile properties of the conventional TTAI reinforced composites.

The numerical model established allows direct visualisation of the stress distribution on yarns, particular the wadding and binding warps, providing direct evidence for the enhancement of the tensile properties along the warp direction of wadded TTAI. Also, the fabric model with detailed geometric information of wadded TTAI fabric helps the future establishment of yarn-level FE model. The model could help to investigate the role of different components within the composite structure against ballistic impact. In order to prove the predictions, experimental proofs were sought as presented in the following section.

**4.4.2 Experimental study on TTAI reinforced composites**

Previous studies by Han [170] on the tensile properties of the dry angle-interlock fabrics revealed that both the tensile strength and Young’s modulus experienced along the warp direction increases after adding wadding yarns into the conventional structures. Based on that, two types of composite panels reinforced by single-ply conventional and wadded TTAI respectively were produced and tested for their tensile properties. The reinforcing fabrics in both types of panels have the same warp tightness. The specifications of the two types of composites are listed in Table 4-5.
Table 4-5 Specimens for the comparison of tensile properties

<table>
<thead>
<tr>
<th>Specimen</th>
<th>TC</th>
<th>TW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reinforcement type</td>
<td>C2</td>
<td>D2</td>
</tr>
<tr>
<td>Fibre mass fraction (%)</td>
<td>61.37%</td>
<td>63.28%</td>
</tr>
</tbody>
</table>

The procedures of specimen preparation and tensile test follow the international test standard ASTM D3039 Tensile properties of polymer matrix composite material. Figure 4-19 is the drawing for the specimen preparation. The composites were firstly trimmed into the size of 250×25 mm. Four Aluminium tabs, whose dimension being 50×25×2 mm, are roughened before attached to both ends of the composite on both its sides by the Araldite® epoxy resin glue. A strain gauge whose sensors located at the highlighted blue areas in Figure 4-19 is also attached to the centre of the specimen. Figure 4-20(a) is the experimental setup for conducting the tensile tests. The tests were done on an Instron 5569 machine whose load cell being 50kN. A constant crosshead displacement rate of 2mm/min is employed for all specimens.
Three specimens with their length along the warp and weft directions respectively are prepared for the evaluation of composite tensile properties. The stress-strain relations are recorded during the tensile tests for the evaluation of the tensile properties of the composite specimens, as shown in Figure 4-21. The results are included in Table 4-6. Detailed results of the tensile properties along both the warp and weft directions of the specimens are tabulated in Appendix Table 9.

It is found from Table 4-6 that the Young’s modulus of the conventional TTAI reinforced composites along the weft direction is 4.48 times high than that of the warp direction. This results from the difference in the thread densities along both directions. In this case, the weft density is 30 picks/cm, whereas the warp density is only 11.5 ends/cm. As is illustrated in Figure 4-3, the weft picks could accommodate more threads by arranging themselves along both the fabric length and thickness directions. However, the warp density is restricted by the configurations of the through-the-thickness binding warps. It is known that the ballistic performance is closely related to the Young’s modulus of the target [171] because the high Young’s modulus would allow faster dispersion of the strain wave from the impact location. This highly unbalanced tensile behaviour of conventional TTAI reinforced composites would lead to a large variation in the ballistic performance across the composite plane, which is undesirable for armour design.
Table 4-6 Comparison of the tensile properties of conventional and wadded TTAI

<table>
<thead>
<tr>
<th>Specimen</th>
<th>TC</th>
<th>TW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s Modulus (MPa)</td>
<td>Warp direction</td>
<td>13402.56</td>
</tr>
<tr>
<td></td>
<td>Weft direction</td>
<td>60054.42</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td>Warp direction</td>
<td>222.10</td>
</tr>
<tr>
<td></td>
<td>Weft direction</td>
<td>519.99</td>
</tr>
<tr>
<td>Failure strain (%)</td>
<td>Warp direction</td>
<td>1.53</td>
</tr>
<tr>
<td></td>
<td>Weft direction</td>
<td>0.84</td>
</tr>
</tbody>
</table>

The introduction of straight wadding warps into the structure could be an effective solution to the issue. In this case, fabric specimen D2 has an overall warp density of 23 ends/cm, including both binding and wadding warps at the thread densities of 5.75 and 17.25 ends/cm respectively. Although the tightness of wadded TTAI D2 equals to that of the conventional TTAI C2, the warp density of D2 is twice that of C2. The Young’s moduli of wadded TTAI D2 reinforced composites along their warp direction experience a significant increase of 2.40 times from that of the conventional TTAI C2.

Meanwhile, the Young’s moduli along the weft direction of the wadded TTAI reinforced structure was 7.7% lower than that of the conventional TTAI reinforced composite. This agrees with the higher failure strain of TW found along its weft direction. Hence, it is indicated that the crimp level of wefts within a wadded TTAI reinforced structure being higher than that of the conventional TTAI reinforced one.

Figure 4-21 plots the stress-strain curve for the specimens of both the conventional and wadded TTAI reinforced composites, where ‘e’ and ’p’ denotes the tested material directions, which are the warp and weft yarns respectively. It is noticed that in Figure 4-21 (a) that the failure strain of TC along its warp direction is higher than that of TW. This results from the different crimp levels between the wadding and binding warps. The straightening of binder warps in the conventional TTAI structure will take place prior to the straining of fibres whereas the straight wadding warps in TW take the tensile loading directly before the binding warps are straightened. The process was simulated and presented in the previous section.
The wadded TTAI structure is considered as a solution for the improvement of the ballistic performance of TTAI reinforced composites. This is because the enhanced mechanical properties along the warp direction encourage an improved isotropy of the composite panel. The study on the effect of adding wadding yarns on the mouldability of wadded TTAI fabrics and ballistic performance of wadded TTAI fabric reinforced composites will further validate the use of this structure as continuous reinforcement for military helmets. Detailed analyses will be presented in the next chapter.

4.5 Summary

In addition, having the through-thickness binding warps as the conventional TTAI, the wadded TTAI is identified as a type of TTAI structure whose warp direction being
enhanced by an extra set of straight wadding warps. In this chapter, the 3D woven structure TTAI, especially the designed wadded TTAI have been analysed and manufactured.

The geometric parameters based on optical microscopy of their cross-sectional structures were characterised for establishing the geometrical model of TTAI structures. Furthermore, the structural parameters of TTAI fabrics including their representative yarn thickness and weave tightness were derived as the structural indexes for the performance evaluation in the future.

Based on the geometric and structural parameters of TTAI fabrics, a total of four groups of TTAI fabrics, whose tightness referred to their plain weave counterparts, were designed and fabricated on a dobby shuttle loom. The fabrication of 3D woven wadded TTAI fabrics requires an additional wadding warp beam in order to maintain the fabric tension. These fabric specimens will later be used for the evaluation of their mouldability and the ballistic performance of the composites they reinforced.

The FE model based on the aforementioned geometric model of the wadded TTAI fabric D2 was established. The tensile behaviours of the binding and wadding warp yarns in this wadded TTAI fabric model were found different. The straight wadding warps elongate upon tensile loading directly, whereas the crimped binding warps need to be straightened before stretches. The tensile tests of the conventional and wadded TTAI reinforced composites revealed that the wadded TTAI reinforced composites exhibited an improved in-plane isotropy by having a smaller difference between the Young’s modulus along the warp and weft directions when compared to that of the conventional TTAI reinforced composites. This is believed to be helpful for the improvement of the ballistic performance of the composites it reinforced.
Chapter 5 Optimisation of the continuous fabrics as reinforcements for military helmet shells

In the previous chapters, the continuously reinforced composites demonstrated their advantages in ballistic performance. The 3D woven angle-interlock fabric is believed to have good mouldability [7] and acceptable reinforcements for armour-grade composites [67, 78] based on the previous studies. The use of continuous conventional TTAI has been proved to be effective in reinforcing composite helmet shells for riot police use [10, 11]. The wadded TTAI fabric reinforced composites have also been proved to demonstrate improved in-plane isotropy, which is also helpful for enhancing the ballistic performance. However, the mouldability of wadded TTAI fabrics and the ballistic performance of the composites they reinforced require further evaluation.

The objective of this chapter is to optimise the design of the 3D woven TTAI fabrics, especially the wadded TTAI structures, for the required fabric mouldability and ballistic performance.

5.1 Mouldability studies on TTAI fabrics

The definition of fabric mouldability and the significance of predicting fabric mouldability have been reviewed in Section 2.3. In the present section, experimental investigations will be conducted to further understand the shear deformation mechanisms that dominating the moulding of fabric reinforcements. The definition of mouldability factor will be extended into predicting wadded TTAI structures, and the predicted results will be examined experimentally before used for the selection of continuous reinforcement for PASGT shaped helmet shapes.

5.1.1 Picture frame test for shear deformation behaviour of TTAI fabrics

The in-plane shearing of woven fabrics is a major fabric deformation mechanism before wrinkle formation during reinforcement moulding [86]. It is, therefore, useful to characterise the shear behaviour of the TTAI fabrics to form the theoretical basis of how the mouldability limit of the fabric is defined.

5.1.1.1 Picture frame test

An Instron 4411 machine whose load cell being 5KN was used for picture frame tests in the current study. The setup of the test is demonstrated in Figure 5-1. Because of the
restrictions from machine width, a picture frame with the length of its side being 160mm was designed and constructed accordingly, as illustrated in Figure 5-2. The initial gauge length, which is measured as the distance between top and bottom hinges at the square position, is set to be 226mm.

![Figure 5-1 Setup of the picture frame shear test](image)

The bottom of the frame is mounted on the machine base, while the top hinge is guided up at a constant movement rate of 20 mm/min, offering the fabric samples enough time to react to the loading. The fabric sample is clamped onto the frame, with its warps and wefts parallel to the frame sides. In this way, a fabric deformation field is created with its edges controlled along both the fabric warp and weft directions. All fabric samples are cut into square shapes with a size of 260x260mm, with four corners of the square removed by the size of 70x70mm each to prevent their hindrance to frame movement. Consequently, the fabric sample will be undergoing trellis movements together with the picture frame across the same plane during tests. Because the yarns within the fabric are aligned with the picture frame, the fabric angle, which is the angle between the warp and weft yarn, can be represented by the frame angle at the top and bottom of the frame. The angle at both top and bottom of the frame represents the angle between warps and wefts of the fabric sample. The load-displacement relationship is recorded dynamically during all tests. The fabric angle at a given amount of displacement can then be calculated according to the Equation (5-1).

\[
\beta = 2 \arccos \left( \frac{L_p + x}{\sqrt{2}L_p} \right), \beta \in [0, 90^\circ]
\] (5-1)
where $\beta$ is the fabric angle, the angle between warp and weft at yarn crossovers (deg); $L_p$ is the side length of the picture frame (mm) and $x$ is the displacement of the top hinge (mm).

![Figure 5-2 Dimensions of the picture frame](image)

![Figure 5-3 Principles for the calculation of fabric angle](image)

The load-displacement information was recorded for each test round. Each fabric sample went through three shearing cycles (from the initial position of fabric angle $90^\circ$ to a total displacement of 90mm).
5.1.1.2 Characterisation of shear deformation

Three types of specimens were subjected to the picture frame tests, namely, the conventional TTAI fabric C4, wadded TTAI fabric D4 and their plain weave reference Plain II, as specified in Table 4-2. All of them have the same fabric tightness. The fabric angles at various displacement points could be calculated according to Equation (5-1). The original load-displacement curves are interpreted into the load-fabric angle curves in Figure 5-4.

![Fabric Angle vs. Shear Force](image)

Figure 5-4 In-plane shear behaviour of fabric specimens

All three force-angle curves experienced three stages during the loading process. At first, only small forces were required for the frame to shut. In this region, the yarns adjusted their positions within the fabric structure until they were parallel to the frame sides. Meanwhile, the yarns rotated relatively at crossovers due to frictional resistance. As the frame angle decreased, the loading gradually built up and the yarn relative movements reached their extremes. This is the second stage where the force-angle meets its knee, beyond which no freedom for further in-plane yarn relative movement was left. Afterwards, the loading experienced a sharp increase. Pure compression and out-of-plane bending dominated the deformation. Yarns were distorted out of the original frame/fabric plane, led to wrinkles formed on fabrics.
Figure 5-4 shows that the forces required in shear Plain II are generally larger than that for C4 and D4, in order to reach the same fabric angle. In order to quantify the curves obtained in Figure 5-4, a bilinear approximation knee was used to represent the transition point of the curve moduli [172]. The fabric angle at the knee is related to the locking angle achieved during the in-plane shearing of fabric because they were both used to quantify the fabric angle at the limit of in-plane shearing. The knee was determined as the point of intersection of the two trendlines on the fabric angle-shear force curve, as is illustrated in Figure 5-5. The two linear trendlines both have the R-squared value of 0.95. Details of the trendlines and the fabric angles at knees are listed in Figure 5-5.

![Figure 5-5 Determination of the bilinear approximation knee](image)

Table 5-1 Quantification of the in-plane shear behaviour of fabric specimens

<table>
<thead>
<tr>
<th>Fabric Type</th>
<th>Trendline 1</th>
<th>Trendline 2</th>
<th>Fabric angle at knee (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plain II</td>
<td>$y=0.0003x+0.0317$</td>
<td>$y=-0.0124x+0.07849$</td>
<td>62.25</td>
</tr>
<tr>
<td>C4</td>
<td>$y=-0.0001x+0.0110$</td>
<td>$y=-0.0138x+0.4384$</td>
<td>31.20</td>
</tr>
<tr>
<td>D4</td>
<td>$y=-0.0001x+0.0117$</td>
<td>$y=-0.0108x+0.427$</td>
<td>38.81</td>
</tr>
</tbody>
</table>

The fabric angle at the knee of the Plain II curve is about twice those of the TTAI fabrics, specimen C4 and D4. This proved that the better mouldability of TTAI fabrics being better than the 2D woven plain fabrics. Meanwhile, although the wadded TTAI D4 and the conventional TTAI C4 have same weave tightness, the fabric angles at the knee of D4 is 2.4% larger than that of C4. This means that the in-plane shear limit of D4 was reached slightly earlier than that of C4. The differences in structures, including the increased yarn...
contact points within the wadded TTAI structure and increased fabric thickness, compared to the conventional C4, all attributed to this.

Knees on all three force-angle curves and the three regions distinguished by the knees on each curve indicate that all three fabric structures reacted to the picture-frame loading in a similar manner. Although both the conventional and wadded TTAI fabrics are three-dimensional woven structures, they both showed similar deformation behaviours when compared to the 2D plain weave. This similar in-plane shear deformation behaviour noticed in Figure 5-4 was also found in the previous studies by Prodromou et al. on plain and satin weaves [97]. Therefore, the use of locking angle method based on the pin-joint model for the characterisation of the shear deformation behaviour is feasible.

However, this picture frame shear test does have its limitations in determining the mouldability limit. Although an approximated knee can be calculated, the results were not obtained directly from the weave specifications of the woven structures. Therefore, more effective methods are necessary for locking angle determination.

5.1.2 Mouldability tester for fabric mouldability evaluation

5.1.2.1 Mouldability tester

The mouldability tester, demonstrated in Figure 5-6(a), is a piece of testing rig developed by Chen et al. and is proved to be valid for the assessment of fabric mouldability [7]. It takes into account of all the deformation mechanisms involved in fabric moulding, instead of only the in-plane shearing in the picture frame tests. The results should be more indicative to the mouldability evaluation, consequently.

During the test, fabric specimens at the size of 450×450mm are placed in between the top and base part of the rig. There is a probe mounted on the top part of the rig. Before the test, the groove from the bottom part and the ridge from the top part are engaged with the fabric specimen that being held in between. As the probe being pushed down, a pressing force is applied to the circular area with the diameter of 50mm at the centre of the fabric sample.
Figure 5-6 Mouldability tester: (a) An overview view [7]; (b) Illustration of the top view of the lower part (unit: mm)

Figure 5-6(b) indicates that the specimen sealed within the rig is partially subjected to pressing force and undergoing deformation. Also, because the edge of the specimen is gripped regardless of its yarn orientation in a relaxed state, a uniform deformation field is created consequently. The scale value of the probe is read as the deformation depth until wrinkles first appear on the fabric surface. Until then, the top part of the rig is lifted gently to allow the fabric be fed in whenever there is capacity for larger deformation. Therefore, the fabric deformation depth measured is used to quantify the mouldability of the fabric. The larger the deformation is, the more mouldable the fabric will be.

5.1.2.2 Mouldability evaluation experimentally

In order to experimentally quantify the mouldability of different fabrics, the deformation depths of various fabrics was measured by the mouldability tester. Ten specimens of each type of fabrics were tested for their deformation depths, and the results are listed in Table 5-2. More details of the test results are included in Appendix Table 10.
Table 5-2 Mouldability of designed TTAI specimens

<table>
<thead>
<tr>
<th>Fabric type</th>
<th>Deformation depth (cm)</th>
<th>Fabric type</th>
<th>Deformation depth (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A1)</td>
<td>12.54</td>
<td>(D1)</td>
<td>13.18</td>
</tr>
<tr>
<td>(A2)</td>
<td>12.20</td>
<td>(D2)</td>
<td>12.60</td>
</tr>
<tr>
<td>(A3)</td>
<td>11.54</td>
<td>(D3)</td>
<td>12.21</td>
</tr>
<tr>
<td>(B1)</td>
<td>12.32</td>
<td>(C1)</td>
<td>13.38</td>
</tr>
<tr>
<td>(B2)</td>
<td>12.06</td>
<td>(C2)</td>
<td>12.94</td>
</tr>
<tr>
<td>(B3)</td>
<td>11.48</td>
<td>(C3)</td>
<td>12.30</td>
</tr>
<tr>
<td>(B4)</td>
<td>11.13</td>
<td>(C4)</td>
<td>11.65</td>
</tr>
<tr>
<td>(Plain I)</td>
<td>3.64</td>
<td>(Plain II)</td>
<td>3.39</td>
</tr>
</tbody>
</table>

It is noticed that the deformation depths of both the conventional and wadded TTAI fabrics are around 3.5 times that of the plain weave fabrics in general. This explains the excellent mouldability of the 3D woven TTAI fabrics over the 2D plain weave fabrics.

Figure 5-7 Experimental results obtained from mouldability tester

Figure 5-7 outlined the deformation depths measured for different types of TTAI fabrics. The figures of specimen labels are in line with those listed in Table 5-2. Generally, the higher the weft density is, the smaller deformation depth will be. This is also the case for warp density, as indicated by comparing the specimens in Group A and B. In other words, the mouldability of TTAI fabrics decreases with the increase in fabric thread densities.

Apart from the thread density, the effect of wadding plan is also compared, as specimens in Group C and D are conventional and wadded TTAI fabrics respectively. Specimens with the same label share the same fabric tightness, but their deformation depths are found at different levels. The wadded structures show smaller deformation depths than their
conventional counterpart. This could result from the increased inter-thread friction introduced by at contact areas with the straight wadding yarns [96, 173].

Further to that, the influence of the TTAI fabric densities (warp and weft density respectively) and structures (conventional and wadded structures), parameters as yarn thickness and the number of straight weft layers are also influential to the TTAI mouldability factor values. However, the use of fabric tightness as an index for comparison normalised the influences from them and was not reflected from the experimental results.

5.1.3 Theoretical prediction of TTAI mouldability based on locking angle method

In order to theoretically predict the mouldability of both the conventional and wadded TTAI fabrics, a mathematical model based on the calculation of fabric locking angle will be described in this section.

Since yarn crossovers in TTAI fabrics only appear on the top and bottom layers, the shear deformation will be limited by these ‘pinned points’ on the outside layers. A unit cell is taken from the top layer, as the bottom layer shares identical property. In order to simplify the problem, a few assumptions were made based on the basis of the pin-joint model and the characteristics of materials used in high-performance applications. The assumptions are made as follows,

- a) Yarn crossovers at fabric surfaces considered as pin-joints;
- b) No slippage occurs;
- c) Yarns being inextensible and incompressible;
- d) The cross section of yarns idealised as constantly circular.

Although these assumptions could be arbitrary, it is necessary when complex fabric deformation mechanisms are involved during fabric moulding. The crimped binding warp yarns and the straight weft and wadding warp yarns in TTAI (as demonstrated in Figure 4-4) are of freedom to relative movements. The shear limits for TTAI fabrics will encounter with two different situations, namely the warp jamming and weft jamming. That is based on shearing along warp and weft axes, respectively. Figure 4-8 demonstrates the top view a 4-layer wadded TTAI fabric.

One unit cell of the wadded TTAI fabric is evaluated under the two jamming situations. In the illustration of the unit cell, the vertical and horizontal yarns are the warp and weft yarns, respectively. The colour code of each type of yarn is in line with that in Figure 4-3.
5.1.3.1 Warp jamming

Despite the differences in wadding plans, warp jamming of wadded TTAI fabrics always takes place when the binding warps and wadding warp yarns come into contact with each other. This is because the through-the-thickness binding warps are spaced out by the wadding warps in between them. Upon shear forces, the binding warps would eventually get in contact with wadding yarns, and that is when the warp jamming occurs.

![Diagram of warp jamming](image)

(a) Initial state  
(b) Warp jammed

Figure 5-8 A unit cell of wadded TTAI at warp jamming situation

As illustrated in Figure 5-8, a straight wadding warp was assumed to take its presence in between the top and second weft layer. Normally, the wadding warps and binding warps are arranged in intervals. ‘n-1’ ends of wadding warps are inserted between two adjacent binding warps, within an n-layer wadded TTAI structure. Although rarely seen, any additional wadding warps inserted tend to configure themselves in an overlapped manner, as one column from the projection view. Hence, one column of wadding warps would stop the shearing motion eventually. In this way, at warp shear limit, the warp locking angle is calculated by Equation (5-2).

\[ \alpha_{lock} = \arcsin \frac{d_1 + d_1'}{L_1} \]  

(5-2)
where, $\alpha_{1\text{lock}}$ is the locking-angle reached at warp jamming; $d_1$ is the thickness of binding warps; $d_1'$ is the representative thickness of wadding warps and $L_1$ is the warp spacing. The calculation of the representative thickness of yarn and the thread spacing refer to Equation (4-16) and (4-6) to (4-8) respectively explained in Section 4.2.

5.1.3.2 Weft jamming

For weft jamming, the existence of binding warps will prevent the contact between adjacent wefts at the same layer. This is because the binding warp yarn, which deflects through fabric thickness after the crossover, will separate the two adjacent weft yarns from the same layer with its thickness at weft shear limit.

As shown in Figure 5-9, the gap between the adjacent weft yarns shrinks with increasing shear forces and finally fills by the thickness of the binding warp yarn, which causes the unit cell to lock. Unlike warp jamming, the existence of wadding warps has no influence on weft jamming situation. This is because these wadding warps only exist in between the straight weft layers, which will not affect the relative movements between neighbouring weft yarns. Therefore, the locking angle $\alpha_{2\text{lock}}$ between binding warp and weft yarns when the weft yarns get locked first can be expressed as Equation (5-3).
where, $\alpha_{2lock}$ is the locking-angle reached warp jamming; $d_2$ is the representative thickness of the weft yarn and $L_2$ is the weft yarn spacing between adjacent wefts at the same layer.

Analyses made by Roedel [98] focused only on conventional TTAI fabrics, which can be regarded as a special occasion when the representative thickness of wadding warp is zero, i.e. $d'_1 = 0$ in Equation (5-2). Whereas the calculation of weft locking angles in both cases share the same calculation equations.

### 5.1.3.3 Mouldability factor

Whether it is warp jamming or weft jamming that dominates the overall shear limit is influenced by both the fabric thread density and the yarn representative thickness. The overall shear limit of TTAI is determined by whichever jamming situation with the larger locking angle because the fabric angle gradually shuts from $90^\circ$ upon in-plane shearing. Consequently, it is useful to find out which jamming situation reaches its locking angle first from fabric parameter point of view.

In general, for TTAI fabrics to have warp yarn jamming, it should satisfy $\alpha_{1lock} > \alpha_{2lock}$, which means $L_1 < \frac{d_1 + d'_1}{d_1 + d_2} \cdot L_2$. Conversely, for the TTAI fabric to have weft yarn jamming, which means $\alpha_{1lock} < \alpha_{2lock}$, then $L_1 > \frac{d_1 + d'_1}{d_1 + d_2} \cdot L_2$.

Normally, the same type of yarns (with same thickness $d_1 = d_2 = d'_1$) are used in fabric construction, so that we have:

- For conventional TTAI fabrics, where the thickness of wadding warp $d'_1 = 0$, if $L_1 < \frac{L_2}{2}$, it is warp jamming dominated; whereas when $L_1 > \frac{L_2}{2}$, it is weft jamming that is reached first.
- For wadded TTAI fabrics, if $L_1 < L_2$, then it is the warp jamming dominating; whereas when $L_1 > L_2$, it is weft jamming that is reached first.

In most of the cases, it is the weft jamming that is dominating for TTAI fabrics. The mouldability factor proposed by Roedel [98] is expressed as the larger locking angle between two jamming situations in Equation (5-4)
The smaller the mouldability factor, the more mouldable the fabric will be, and vice versa. From the calculation equations of locking angles for each jamming cases, it is obvious that TTAI fabrics with larger thread densities will exhibit larger mouldability factor, which indicates lower fabric mouldability. In a case where it is weft jamming dominated, the larger number of weft layer a TTAI has, the more mouldable it would be. This agrees with the conclusions by Chen et al. [7].

The mouldability factors of the TTAI fabrics designed and produced previously based on Table 4-2 are calculated according to Equations (5-4) and summarised in Table 5-3 as follows:

Table 5-3 Mouldability analyses for the designed TTAI fabric specimens

<table>
<thead>
<tr>
<th>Specimen type</th>
<th>Yarn representative thickness (mm)</th>
<th>Thread spacing (mm)</th>
<th>Locking angle (°)</th>
<th>Mouldability factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Warp spacing</td>
<td>Weft spacing</td>
<td>$\alpha_{1lock}$</td>
</tr>
<tr>
<td>(A1)</td>
<td>0.385</td>
<td>1.18</td>
<td>1.92</td>
<td>19.10</td>
</tr>
<tr>
<td>(A2)</td>
<td>0.385</td>
<td>1.18</td>
<td>1.79</td>
<td>19.10</td>
</tr>
<tr>
<td>(A3)</td>
<td>0.385</td>
<td>1.18</td>
<td>1.67</td>
<td>19.10</td>
</tr>
<tr>
<td>(A4)</td>
<td>0.385</td>
<td>1.18</td>
<td>1.56</td>
<td>19.10</td>
</tr>
<tr>
<td>(B1)</td>
<td>0.385</td>
<td>1.00</td>
<td>1.92</td>
<td>22.64</td>
</tr>
<tr>
<td>(B2)</td>
<td>0.385</td>
<td>1.00</td>
<td>1.79</td>
<td>22.64</td>
</tr>
<tr>
<td>(B3)</td>
<td>0.385</td>
<td>1.00</td>
<td>1.67</td>
<td>22.64</td>
</tr>
<tr>
<td>(B4)</td>
<td>0.385</td>
<td>1.00</td>
<td>1.56</td>
<td>22.64</td>
</tr>
<tr>
<td>(C1)</td>
<td>0.287</td>
<td>0.87</td>
<td>1.43</td>
<td>19.27</td>
</tr>
<tr>
<td>(C2)</td>
<td>0.287</td>
<td>0.87</td>
<td>1.33</td>
<td>19.27</td>
</tr>
<tr>
<td>(C3)</td>
<td>0.287</td>
<td>0.87</td>
<td>1.25</td>
<td>19.27</td>
</tr>
<tr>
<td>(C4)</td>
<td>0.287</td>
<td>0.87</td>
<td>1.18</td>
<td>19.27</td>
</tr>
<tr>
<td>(D1)</td>
<td>0.287</td>
<td>1.74</td>
<td>1.43</td>
<td>19.27</td>
</tr>
<tr>
<td>(D2)</td>
<td>0.287</td>
<td>1.74</td>
<td>1.33</td>
<td>19.27</td>
</tr>
<tr>
<td>(D3)</td>
<td>0.287</td>
<td>1.74</td>
<td>1.25</td>
<td>19.27</td>
</tr>
<tr>
<td>(D4)</td>
<td>0.287</td>
<td>1.74</td>
<td>1.18</td>
<td>19.27</td>
</tr>
</tbody>
</table>

It can be noticed that the weft jamming dominates the fabric jamming in all cases because the theoretically calculated weft locking angle $\alpha_{2lock}$ is always larger than the warp locking angle $\alpha_{1lock}$ for all the designed TTAI fabrics. This is the case for both the conventional and the wadded TTAI fabrics. Figure 5-10 presents the influence of weft tightness on the mouldability factor of TTAI fabrics. Based on the calculation Equation (4-20) for weft tightness, it is found that the weft tightness built up by increasing the weft densities in the TTAI structures. It is also noticed that the mouldability factor is positively correlated with...
the value of the tightness in all four groups of the TTAI structures. This is because the
calculation for the fabric tightness and locking angle are both related to the product of
‘representative thickness of the yarn’ and the ‘thread density’, according to Equation (5-2)
(5-3) (4-6) and (4-7).

Comparing the mouldability factors predicted to the deformation depths measured
previously in Figure 5-7, it can be noticed that fabric specimens with the same
mouldability factor, for example, specimen A1 and B1 exhibited different deformation
depths. The possible reason for this slight variation maybe because the locking angle
method is based on the pin-joint net model which only simulates the in-plan shearing
motion during fabric deformation process, whereas the mouldability test imitates the real
fabric moulding scenario which involves other deformation modes, such as out-of-plane
bending and compression. Other possible factors that could influence the bending,
compressing and even tensile motions including fabric thickness, yarn linear density,
weave pattern and so on. However, the locking angle method is still useful in the
quantification of TTAI mouldability.

Specimens in Group C and D are conventional and wadded TTAI fabrics respectively.
Despite the differences in wadding plan, the values of fabric tightness for those named
after the same numbering remain at the same level, as is listed in Table 4-2. This means
that the mouldability of wadded TTAI fabrics could be designed to be at the same level of
the conventional ones by referencing to the warp tightness of the fabrics. Taking Specimen
C1 and D1 as an example, both specimens have the same weft density of 28 picks/cm.
Therefore, the weft tightness and the weft locking angle remain the same. For the sake of

![Figure 5-10 Mouldability factor of TTAI fabrics dominated by weft jamming](image-url)
comparing the mouldability of the wadded and the conventional TTAI fabrics, the mouldability of C1’, and D1’ which are the wadded counterpart of C1 and the conventional counterpart of D1, are evaluated theoretically as listed in Table 5-4.

<table>
<thead>
<tr>
<th>Specimen type</th>
<th>TTAI Classification</th>
<th>Warp density (end/cm)</th>
<th>Warp tightness (%)</th>
<th>Warp locking angle (°)</th>
<th>Mouldability factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Binding warp</td>
<td>Wadding warp</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C1</td>
<td>Conventional</td>
<td>11.5</td>
<td>-</td>
<td>32.98</td>
<td>19.27</td>
</tr>
<tr>
<td>D1</td>
<td>Wadded</td>
<td>5.75</td>
<td>17.25</td>
<td>32.98</td>
<td>19.27</td>
</tr>
<tr>
<td>C1’</td>
<td>Wadded</td>
<td>11.5</td>
<td>34.5</td>
<td>63.94</td>
<td>41.31</td>
</tr>
<tr>
<td>D1’</td>
<td>Conventional</td>
<td>5.75</td>
<td>-</td>
<td>16.49</td>
<td>9.50</td>
</tr>
</tbody>
</table>

It can be found from Table 5-4 that, as long as the jamming is weft dominated, the adding of wadding yarns would not affect the mouldability of the TTAI fabric, which is the case for D1 and D1’. Once the warp locking angle becomes larger than that of the weft after adding the wadding warps, the mouldability of TTAI would be greatly restricted, as demonstrated between C1 and C1’.

The calculation of warp tightness provides a direct reference for the design of wadded TTAI fabrics. In this case, the wadded TTAI fabric D1, whose binding warp density being half that of C1 was designed to have the same level of warp tightness and mouldability as these of the conventional TTAI fabrics. This is because the wadding warps tend to arrange themselves into columns observed in Figure 4-4(a). Each column of wadding warp plays the same role as a binding warp in determining the warp tightness. Doubling up the binding warp spacing of C1 would provide space for the wadding warps to be inserted, and the warp tightness and warp locking angle resulted for the wadded structure D1 was the same as that of the C1. Consequently, the weft domination was kept for the wadded D1.

The use of circular cross-sections would simplify the problem, but the accuracy of the theoretical model could be influenced. Figure 5-11 demonstrates the changes in fabric angles during the in-plane shearing. Figure 5-11(a), (b) and (c) are the TTAI fabric D3 at its relaxed, right before jamming and jammed states. It is found that the widths of both the warp and weft yarns changed upon shearing. Further to that, a locking angle exists between the ranges of 26.8° to 28.6° was also identified. This agrees with the predicted 27.34° based on idealised circular cross-section. Hence, the use of circular yarn cross-section in the mathematical model for fabric mouldability prediction is valid. Future models should
consider the changes in yarn cross-sectional shapes for improved accuracy of the prediction.

Figure 5-11 TTAI D3 upon shearing: (a) Relaxed; (b) Right before jamming; (c) Jammed

5.1.4 Moulding of TTAI fabrics over a PASGT mould

Each doubly curved shape has a mouldability limit which quantifies the maximum mouldability factor of TTAI fabrics that are allowed as continuous reinforcement. In order to define the mouldability limit of a doubly curved shape, trial mouldings of the TTAI fabrics with a range of mouldability factors need to be conducted to identify the maximum mouldability factor. The defined mouldability limit would help reduce the time for trial-and-error during the selection process for continuous reinforcements.

Figure 5-12 Aluminium PASGT helmet mould: (a) Side view; (b) Top view; (c) Inside view
As referred to in the literature review Section 2.4.1, modern composite military helmets are originated and modified from the PASGT helmet shape. In order to gain a common recognition, the PASGT shell shape was chosen as the target shape for the present research. An aluminium mould with the shape of a PASGT shape is reproduced for the moulding of reinforcing fabrics, as is illustrated in Figure 5-12. The mould is also designed to enable the use as a mould for composite shell making based on the vacuum bagging method. It is composed of four parts, where the middle two parts are connected with the two side parts through bolting. In order to allow easy demoulding after resin infusion and curing processes, the middle parts could be removed first, making space for the removal of the two side parts afterwards.

Figure 5-13 Steps of reinforcement moulding over a helmet shape and the finished look [98]

The moulding of the TTAI fabrics follows the steps described by Roedel [98], as illustrated in Figure 5-13. First of all, gridlines at the size of 10×10 cm were drawn on the fabrics in line with the warp and weft directions. Afterwards, the fabric was draped onto the mould with one warp gridline and one weft gridline at the mid-sagittal line and the coronal line of the shell, respectively (refer to Figure 6-8). The mould surface was divided into four quarters, denoted by Fabric Area 1 to 4. The shearing of fabric starts from the left quarter of the mould outlined as Fabric Area 1. Maximum shear had to be applied to the fabric in order to accommodate the fabric to the decreasing mould surface towards the rim of the mould. The shearing motions were applied according to what Step 1 depicted. Metal pins were attached to the rim of mould for fixing the applied shear. The rest of the fabric was moulded to the shell surface following the numbering sequence, area by area. Wrinkles
would appear when the locking angle of the fabric was exceeded. The mouldability limit of
the PASGT shape was defined when there was no wrinkle identified on the mould surface
after moulding the four quarters according to the procedures described.

Through the moulding of all the TTAI samples listed in Table 4-2, the mouldability factor
limit was identified to be 25.54. Any TTAI fabrics with larger mouldability factors would
not be able to conform smoothly to the PASGT shell surface due to the wrinkles formed, as
in Figure 5-14(a), the red circle indicates the wrinkles formed on the shell surface. While
Figure 5-14(b) shows a perfectly conformed case where no wrinkles were found on the
shell.

![Moulded TTAI fabrics](image)

Figure 5-14 Moulded TTAI fabrics: (a) With wrinkles formed; (b) Conformed
continuously without wrinkles.

In this way, TTAI fabrics like specimens A1, A2, B1, B2, C1, C2, D1, D2 and all the
others with mouldability factor being smaller than or equal to 25.54 can be considered as
the continuous reinforcement for PASGT shaped helmet shells. The procedures described
can be utilised for selecting continuous TTAI fabric reinforcement for other doubly curved
shapes in the future.

5.2 Ballistic performance evaluation of TTAI reinforced composite

In order to provide an optimised reinforcing structure as the continuous reinforcement for
the military helmet shells, the ballistic performance of various TTAI fabric reinforced flat
composite panels were experimentally examined, including their energy absorption, planar
damage area and 3D damage volume. Experimental methods including shootings on the
ballistic range, ultrasonic C-scan and X-ray CT were employed as did for the study of the
effect of reinforcement continuity previously in Chapter 3 previously. The balance between
ballistic performance and mouldability is sought among the designed TTAI fabrics with required mouldability to reinforce military helmets continuously.

5.2.1 Influences of fabric thread density

According to the calculation equations (5-2) and (5-3), for weft jamming dominated TTAI fabrics, the smaller the weft density is, the more mouldable the TTAI fabric would be. It is useful to investigate the influences of thread density on the ballistic performance of the TTAI reinforced composites, as it is related to the mouldability of the TTAI fabrics. A group of composite panels reinforced with seven plies of TTAI fabrics with different weft densities were produced for tests as listed in Table 5-5. Details of the ballistic test results are listed in Appendix Table 11.

Table 5-5 Composite panels reinforced by TTAI fabrics with different thread densities

<table>
<thead>
<tr>
<th>Specimen type</th>
<th>Reinforcement type</th>
<th>Weft thread density (ppc)</th>
<th>Areal density (g/m²)</th>
<th>Fibre volume fraction (%)</th>
<th>Thickness (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P7B1</td>
<td>B1</td>
<td>26</td>
<td>7481</td>
<td>57.6</td>
<td>0.59</td>
</tr>
<tr>
<td>P7B2</td>
<td>B2</td>
<td>28</td>
<td>7662</td>
<td>59.2</td>
<td>0.67</td>
</tr>
<tr>
<td>P7B3</td>
<td>B3</td>
<td>30</td>
<td>7849</td>
<td>59.7</td>
<td>0.72</td>
</tr>
</tbody>
</table>

![Graph showing the relationship between impact and residual velocities for different thread densities.](image)

Figure 5-15 Impact-residual velocities of composite panels reinforced by TTAI fabrics with different weft thread densities

Ten specimens of each type of composite panels were tested on the ballistic range, and the impact and residual velocities of each shoot are recorded in Figure 5-15. The ballistic impact and residual velocities of each group are found distributed into three distinctive...
regions. The height of the region is related to the residual velocities resulted from the shooting. As is indicated in the plot, the residual velocities of composite panel P7B1, which is of the smallest weft thread density generally, locate in the top region. While the residual velocities of composite panel P7B3, who has the largest weft density among the three, locate in the bottom region. In another word, the smaller weft density of the reinforcing TTAI fabrics is, the less impact energy was absorbed by the composite panel it reinforced.

It is noticed that, even though the three types of composite panels reinforced by the same number of fabric plies, the areal densities of the resulted composites are different. As is measured and tabulated in Table 5-5, the panels reinforced by TTAI fabrics with higher weft density have larger areal density consequently. This means that more materials were used in resisting the ballistic impact. After normalising the impact energy by the areal density of the composite panel, the specified energy absorption (SEA) can be worked out to evaluate the ballistic performance and offset the influence brought by the variations in the areal density of the composite panels. The average and normalised energy absorption of the composite panels are summarised in Table 5-6.

<table>
<thead>
<tr>
<th>Specimen type</th>
<th>Energy absorption (J)</th>
<th>$V_{50e}$ (m/s)</th>
<th>SEA (J/kg·m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P7B1</td>
<td>75.92</td>
<td>389.62</td>
<td>10.15</td>
</tr>
<tr>
<td>P7B2</td>
<td>80.22</td>
<td>400.53</td>
<td>10.47</td>
</tr>
<tr>
<td>P7B3</td>
<td>81.10</td>
<td>402.71</td>
<td>10.33</td>
</tr>
</tbody>
</table>

The average energy absorption and estimated ballistic limit $V_{50e}$ both indicate that the higher the weft densities of the reinforcing TTAI fabrics are, the better the ballistic performance of the composite panels will be; while that is not quite the case when comparing the normalised SEA values. The $p$ values obtained from T-test between the energy absorption of panel P7B2 and P7B1, P7B3 and P7B1 are 0.0003 and 0.0001 respectively. This indicates significant differences between the ballistic performance of denser fabric reinforced composites (P7B2, P7B3) and that of the looser one (P7B1). The panels P7B2 and P7B3 still outperformed P7B1, but the advantages are insignificant. This may because of the little differences in the weft thread densities of the reinforcing fabric themselves. For example, if the areal density of the reinforcing TTAI fabric is big enough, an equivalent areal density of the composite panel could be achieved through fewer plies; and vice versa. Therefore, the impact damages introduced would be affected by these
changes and require further investigation. The selection of thread density should allow the reinforcement with enough mouldability in the first place.

5.2.2 Influences of panel construction

As aforementioned, the changes in the areal density of the single-ply TTAI fabrics would affect the arrangement of fabric plies within a composite panel. Composite panels of certain areal density could either be reinforced by fewer plies of fabrics with larger fabric areal density or more plies of fabrics with smaller areal density. TTAI fabrics with the same level of mouldability can be of various areal densities, due to the differences in thread densities, the number of straight weft layers as well as the thickness of yarns used during fabrication.

In this section, three types of composites, all with the panel areal density around 12kg/m² were designed, as tabulated in Table 5-7. All of the reinforcing fabrics used are of the mouldability factor around 25.54. But due to the differences in fabric specification, the resulted composite panels are of various panel constructions. To be more specific, panel P10B2 is reinforced by the least numbers of plies and the Twaron® yarn used is thicker (168tex); whereas P18C2 is of the most numbers of fabric plies and the Twaron® yarn used is thinner (93tex). The wadded TTAI reinforced panel P13D2 has fewer numbers of fabric plies when compared to the conventional TTAI reinforced P17C2, even though yarns of the same thickness were used for fabrication.

Table 5-7 Composite panels with different panel constructions

<table>
<thead>
<tr>
<th>Specimen type</th>
<th>Reinforcement type</th>
<th>Number of fabric plies</th>
<th>Areal density (kg/m²)</th>
<th>Fibre volume fraction (%)</th>
<th>Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P10B2</td>
<td>B2</td>
<td>10</td>
<td>11.95</td>
<td>54.15</td>
<td>8.89</td>
</tr>
<tr>
<td>P17C2</td>
<td>C2</td>
<td>17</td>
<td>12.02</td>
<td>56.37</td>
<td>8.91</td>
</tr>
<tr>
<td>P13D2</td>
<td>D2</td>
<td>13</td>
<td>11.93</td>
<td>55.87</td>
<td>9.55</td>
</tr>
</tbody>
</table>

Table 5-8 Ballistic performances of the composites with different panel constructions

<table>
<thead>
<tr>
<th>Specimen type</th>
<th>Impact energy (J)</th>
<th>Planar damage area (cm²)</th>
<th>3D damage volume (mm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P10B2</td>
<td>115.10</td>
<td>49.78</td>
<td>753.72</td>
</tr>
<tr>
<td>P17C2</td>
<td>113.84</td>
<td>74.96</td>
<td>1975.69</td>
</tr>
<tr>
<td>P13D2</td>
<td>116.91</td>
<td>36.87</td>
<td>126.46</td>
</tr>
</tbody>
</table>

All of the three specimens were subjected to ballistic tests and none of them were penetrated by the projectile. Details of the impact and the damage monitored are included in Table 5-8. The planar damage areas and the 3D damage volumes were measured by
ultrasonic C-scan and X-ray CT respectively, and will be discussed in the following sections.

5.2.2.1 Analyses of planar damage area

Figure 5-16 is the planar projected damage areas extracted from the ultrasonic C-scan detection. The experimental setup is exact the same as what was described in Section 3.3.1.2. Because all of the three panels were not perforated by the projectiles, an equivalent amount of impact energy was absorbed by them. Under similar ballistic threat level, the planar projected area of P13D2 is found to be the smallest among the three. Damages in P17C2 distributed into the largest areas and that in P13D2 being almost half of area, as indicated in Table 5-7.

Figure 5-16 Damage areas of panels with different structure parameters: (a) P10B2; (b) P17C2; (c) P13C2
The shape of the damaged area in P13D2 is near circular instead of being elliptical as the other two panels. All of the reinforcing fabrics were arranged in an aligned orientation (0/0)\(_n\) and the long axes of the ellipses are found along the warp direction of the reinforcing TTAI fabrics. The lengths of the maximum lengths of the long and short axis of the three damage areas are listed in Table 5-9. All of the measurements were taken from ImageJ [153].

<table>
<thead>
<tr>
<th>Specimen type</th>
<th>Length of long axis (cm)</th>
<th>Length of short axis (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P10B2</td>
<td>8.42</td>
<td>4.98</td>
</tr>
<tr>
<td>P17C2</td>
<td>10.85</td>
<td>5.62</td>
</tr>
<tr>
<td>P13D2</td>
<td>6.22</td>
<td>5.02</td>
</tr>
</tbody>
</table>

Table 5-9 Geometric information of the damaged areas

It is noticed that the damaged length in P17C2 along its warp direction is double the size of that along its weft direction. The differences in the shapes of damaged areas result from the differentiated crimp levels along the warp and weft directions of the fabrics. It is understood that the warp direction of the conventional TTAI fabrics like B2 and C2 are of smaller Young’s modulus and larger failure strain when compared to that of the weft direction, as indicated in Table 4-6. This is owing to the higher crimp level of the binding warps than that of the straight weft yarns.

While the tensile properties of the panels reinforced by wadded TTAI fabrics are expected to have a more balanced performance along both its warp and weft directions due to the existence of straight wadding warps, which are also with quite low crimp levels as witnessed in Figure 4-4(b). This implies the use of wadded structures over their conventional counterparts which have the same level of mouldability. Because the in-plane damage of the wadded TTAI reinforced composites would be more evenly distributed around the impact location and less severe than the conventional TTAI reinforced ones.

**5.2.2.2 Analyses on cross-sectional view at impact location**

The three composite panels were subjected to X-ray CT imaging, as described in Section 3.3.1.3. The machine settings used for scanning are listed in Table 5-10.
Table 5-10 Machine settings for scanning non-perforated composite panels

<table>
<thead>
<tr>
<th>Imaging parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerating voltage (kV)</td>
<td>225</td>
</tr>
<tr>
<td>Filament current (µA)</td>
<td>135</td>
</tr>
<tr>
<td>Filter</td>
<td>1mm Tin</td>
</tr>
<tr>
<td>Exposure time (ms)</td>
<td>708</td>
</tr>
<tr>
<td>Projections</td>
<td>3142</td>
</tr>
<tr>
<td>Voxel size (µm)</td>
<td>59.83</td>
</tr>
</tbody>
</table>

The 2D slice images of the three panels specified in Table 5-7 are reconstructed and examined for their damage morphology. Due to the differences in material composition between the steel projectile and the Twaron®/epoxy composite panels, the presence of steep edges of the projectile contour leads to dramatic changes in the amount of X-ray transmitted and absorbed around the projectile. Hence, streaking and aliasing artefacts appear around the edges of the projectile [148]. The streaking features and blurry boundaries were noticed on those slices with projectile presented, as highlighted in Figure 5-17. In order to minimise such negative effects, careful selections of the filter material and X-ray target materials were made, the contrast between composite and the background was also sacrificed.

![Figure 5-17 Scan artefacts on 2D slices with projectile presented (P13D2)](image-url)

![Figure 5-18 Top-view of the impacted composite plate with location of the 2D slices extracted from the reconstructed X-ray CT results marked](image-url)
Meanwhile, the slices before and after the appearance of the projectile were also used for the post-mortem examination at the impact locations. The locations of these slices are marked by red lines on Figure 5-18, which presents the top-view of the impacted composite plate. Slice (b) presents the slice image through the centre of the projectile, slice (a) and (c) present the first and last slices without the projectile around the impact location. These slice images of composite plates P10B2, P17C2, P13D2 are illustrated in Figure 5-19, Figure 5-20 and Figure 5-21, respectively.

Figure 5-19 2D slice images around the impact location of panel P10B2

Figure 5-20 2D slice images around the impact location of panel P17C2
A similar delamination distribution as that witnessed in Figure 3-13 can also be found on all three panels. The dishing delamination spreads wider and wider through the height of the projectile. The widest delamination always takes place at the reinforcement ply where the projectile stopped at, which is described as the last penetrated reinforcement ply.

Three distinctive regions of deformation across the thickness of the composite panel as are witnessed on all three panels at the impact location. The distribution of the three regions is schematically illustrated in Figure 5-22.

Section A is located on the first few plies near the entrance of the impacting projectile. The reinforcing fibres within the plies of Section A are found neatly cut by the projectile. There is no obvious deformation of fabric plies out of their original plane and the fibres are mainly broken due to transverse shearing. The fibres in Section B are found severely stretched and deformed out of their initial planes, lead to breakage and delamination. The reinforcing fabrics are not penetrated by the projectile in Section C, as the projectile
stopped at the exit of Section B. Cracking and bulging of the reinforcement plies are also noticed underneath the projectile. The rear plies of the panel may even break as witnessed in Figure 5-20(b). Detailed post-mortem analyses were conducted on the figures by ImageJ and summarised in Table 5-11.

Table 5-11 Analyses on the 2D slice images

<table>
<thead>
<tr>
<th>Specimen type</th>
<th>Projectile angle (°)</th>
<th>Number of penetrated plies</th>
<th>Penetration depth (mm)</th>
<th>Maximum thickness (mm)</th>
<th>Penetrated percentage (%)</th>
<th>Thickness increase (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P10B2</td>
<td>0.00</td>
<td>6</td>
<td>7.35</td>
<td>11.89</td>
<td>61.8</td>
<td>33.8</td>
</tr>
<tr>
<td>P17C2</td>
<td>-12.64</td>
<td>12</td>
<td>9.31</td>
<td>12.71</td>
<td>73.3</td>
<td>42.7</td>
</tr>
<tr>
<td>P13D2</td>
<td>2.16</td>
<td>7</td>
<td>6.63</td>
<td>11.98</td>
<td>55.3</td>
<td>25.5</td>
</tr>
</tbody>
</table>

The maximum thickness was measured by the thickness value of the thickest part of the impacted panel. The values quantify the backface deformation of the non-perforated panels. It is found that P17C2 was penetrated the severest with 12 plies and the penetration depth accounts for 73.3% of the maximum panel thickness measured along the central axis of the projectile. Whereas the wadded TTAI reinforced P13D2 was penetrated for 55.3% of its maximum thickness only, accounted for the least among the three. This can be interpreted as the largest amount of materials around the impact position of panel P17C2 was fractured to failure in order to resist the penetration of the projectile. Whereas, the fracture damages in P13D2 were less severe, which means the panel has a greater potential for resisting ballistic threats. Similarly, the thickness of P13D2 increased only 25.5% after impact along the projectile path, being the smallest among the three. The increase in panel thickness at impact location is critical to the success of a ballistic panel, especially for their applications as body armours, since large indentation could also hurt the armour wearers.

From the neat cuts on the entrance of the impacting projectile, it is inferred that the cylindrical projectiles were impacted on the panel perpendicularly. However, it is found that the projectile stopped in P17C2 inclined by an angle of 12.64° to the vertical position. Further to that, cracking of the reinforcing fabrics underneath the bottom left corner of the projectile is also noticed. The cracking was highlighted by blue dotted circles on Figure 5-20(b). Although it is technically difficult to catch the movement of the projectile as it proceeds inside the composite panel, the 2D cross-sectional slices reconstructed from X-ray CT only provides a look at the damage caused by it non-destructively. It could be assumed that the projectile actually proceeded further inside the panel before it was stopped by the fabric plies in Section C and bounced back to the current position. The resistance from the rear plies of the panel slowed down the projectile until the kinetic
energy of projectile was fully dissipated, and the projectile finds its final position to rest. Due to the cracks highlighted underneath the left corner of the projectile in Figure 5-20(b), the resisting force towards the projectile became weaker than that on the right-hand side. Although cracks in the rear plies of P10B2 were also highlighted in Figure 5-19, they located along the central line of the impact projectile, thus no inclination of the projectile was found. For P13D2, whose Section C is thicker and the delamination in Section B is mild compared to the other two panels, the projectile in it is also found straight.

5.2.2.3 Analyses on 3D damage volume

Previously, in Chapter 3, the use of 3D damage volume is proved to be an effect way of quantifying the severity of the delamination in the composite panel after the ballistic impact. The 3D damage volume of the three non-perforated composite panels was also segmented, as listed in Table 5-8. Panel P17C2 possesses the largest damage volume, which is 2.62 times and 15.62 times of that of P10B2 and P13D2, respectively. This means, given an equivalent amount of the impact energy being absorbed, more of the energy was dissipated through delamination of the reinforcing fabric plies for P17C2 than P10B2 and P13D2.

Compared to the other two panels, P17B2 has the most number of plies, and consequently the greater potential for delamination to develop. It was proposed by Boussu [60] that delamination should be encouraged before a multiply composite panel starts to absorb energy through the damage and deformation of fibres. However, the level of delamination should be carefully controlled, because it is closely related to the indentation depth of the composite panel after impact.

The inclination of the projectile noticed in Figure 5-20(b) implies that the delaminations generated in Section B could result from two different stages. The 3D damage volume segmented from the penetrated composite panels could be used directly to represent the delamination generated prior to the fibre rupture. Whereas the delamination damage obtained from the post mortem examination of the non-perforated panels took into account of the delamination caused by the slight bouncing back of the projectile along its penetration path before it finally stops in Section B. Therefore, the energy absorption should be considered more as a dynamic process, where the delamination introduced both before and after fibre fracture are accounted. Although the delamination resulted before and after the fibre ruptures are hard to be separated, an overall smaller delamination volume still indicates less impact energy have been absorbed through delamination damage.
This means the impact energy was dissipated more in other damage mechanisms, including fibre rupture and matrix cracking.

Apparently, the wadded TTAI reinforced panel P13D2 did better in utilising the fibres for energy absorption, not only because the smaller damage volume segmented, but also for the number of reinforcement plies penetrated and the smaller thickness increase than those of the conventional TTAI reinforced P10B2 and P17C2. Hence, under the same areal density of the composite panels, the use of reinforcements with greater ply areal density and fewer number of reinforcement plies would encourage less severe damage. At the same time, the wadded TTAI reinforced panel is proved to be more protective than its conventional TTAI reinforced counterparts.

The delamination damage between each reinforcement ply was also segmented, as presented in Figure 5-23, Figure 5-24 and Figure 5-25, respectively. The colour codes in each figure represent the delamination volume in different delaminated plies. The sequence of the colour code was arranged according to the delamination location from the impact face towards the back face, as was indicated in the bar chart under each figure. The projected 3D damage volume is found to coincide with the planar views obtained from ultrasonic C-scan, only the volume reflects the degree of damage more precisely throughout the panel thickness. The amount of volume for each delaminated ply is summarised in Figure 5-26.
Figure 5-23 Delamination volume of P10B2 at different positions: (a) View from impact face; (b) View from back face; (c) Cross-sectional view
Figure 5-24 Delamination volume of P17C2 at different positions: (a) View from impact face; (b) View from back face; (c) Cross-sectional view
Figure 5-25 Delamination volume of P13D2 at different positions: (a) View from impact face; (b) Cross-sectional view
Because of the differences in the total number of reinforcement plies in the three panels, the delaminated plies were compared in reference to the last penetrated plies of each panel. Hill-shaped distribution of delamination was noticed in Figure 5-26 for both of the conventional TTAI reinforced panels P10B2 and P17C2, with the peaks located right after the last penetrated reinforcement ply, which is also considered as the boundary between Section B and Section C. Whereas the delamination volume in Section B of the wadded TTAI reinforced panel P13D2 is evenly distributed before the last penetrated plies. This further supports the preference for the wadded TTAI fabrics as the reinforcement for ballistic composite panels over the conventional TTAI fabrics.

It is also worth mentioning that only three types of TTAI reinforcements were compared in the current study. Although the three types of TTAI were designed to have the same mouldability factor, the effect of each individual structural parameter on the ballistic performance of the composites still requires further investigation.

5.2.3 Comparison between wadded TTAI and plain weave reinforced composites

According to the findings and discussions in the previous sections, the 3D woven wadded TTAI fabrics was proved to be more effective than their conventional TTAI counterparts in terms of their use as reinforcements for ballistic applications. Due to the fact that the 2D plain weave fabric is still preferred reinforcing fabric structure for the making of the ballistic helmet in the current market, a comparison between ballistic performances of composite panels reinforced by wadded TTAI fabrics and plain weave fabrics becomes necessary. Details of the composite panels to compare are listed in Table 5-12.
Table 5-12 Composite panels reinforced by 2D and 3D woven fabrics

<table>
<thead>
<tr>
<th>Composite panel</th>
<th>Reinforcement type</th>
<th>Number of plies</th>
<th>Areal density (kg/m²)</th>
<th>Fibre volume fraction (%)</th>
<th>Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P27C</td>
<td>Plain 93tex</td>
<td>27</td>
<td>7.16</td>
<td>61.2</td>
<td>6.87</td>
</tr>
<tr>
<td>P8D2</td>
<td>D2</td>
<td>8</td>
<td>7.07</td>
<td>61.4</td>
<td>6.50</td>
</tr>
</tbody>
</table>

The wadded TTAI and plain weave fabrics used are of the same warp tightness and made from the same Twaron® yarns. The areal density of the two panels was controlled to be at the same level. Five specimens of each type of composites were tested for their ballistic performance on the shooting range and the results are listed in Table 5-13 (Details in Appendix Table 12 and Table 13).

Table 5-13 Ballistic performance of composite panels P27C and P8D2

<table>
<thead>
<tr>
<th>Composite type</th>
<th>Impact energy (J)</th>
<th>Energy absorption (J)</th>
<th>SEA (J/kg·m²)</th>
<th>V₅₀e (m/s)</th>
<th>3D damage volume (mm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P27C</td>
<td>113.24</td>
<td>95.95</td>
<td>13.40</td>
<td>438.05</td>
<td>1000.25</td>
</tr>
<tr>
<td>P8D2</td>
<td>113.67</td>
<td>99.11</td>
<td>14.02</td>
<td>445.22</td>
<td>347.382</td>
</tr>
</tbody>
</table>

The wadded TTAI fabric reinforced composite panel P8D2 outperforms the plain weave fabric reinforced P27C by showing a higher efficiency in energy absorption and a higher estimated ballistic limit. The p values obtained from T-tests are 0.0158 and 0.0162 for the obtained energy absorption and estimated ballistic limit results, respectively. This agrees with the findings from the previous researches [75, 174], where the 3D woven fabric reinforced composites possess higher ballistic limits than the 2D woven reinforced ones. Although the advantage is not significantly great, the use of wadded TTAI as a substitution for the conventional plain weave fabrics as a reinforcing structure for ballistic composite construction is proved to be valid. Especially when the discontinuous 2D woven reinforcement is required for the conforming into doubly-curved shapes, like the military helmets, the advantage of the 3D wadded TTAI fabrics as continuous reinforcements would be obvious. In the present research, wadded TTAI fabric D2 is regarded as the optimised continuous reinforcement for PASGT shaped helmet shells.

The cross-sectional 2D slice images around the impact location and 3D damage volume of specimen 4 of P27C and specimen 5 of P8C2, who had been impacted under similar impact energy, were also examined, as shown in Figure 5-27 and Figure 5-28.
Figure 5-27 2D slice images around the impact location of composite panels: (a) P27C; (b) P8D2

Figure 5-28 Comparison of the 3D damage volume: (a) P27C; (b) P8D2

It can be found from the 2D slice images that the penetration damages on the plain weave fabric reinforced P27C is similar to what was witnessed in Figure 3-15. The delamination between the reinforcement plies of P27C gradually spreads into wider radius in section B; while that in P8D2 are more evenly distributed between plies. The size of Section A in P27C is also found larger than that of P8D2.

Overall, the 3D delamination damage volume of P8D2 is only one-third to that of P27C. This means, for P8D2, more of the impact energy was dissipated through other forms. Due
to the existence of the non-crimp wadding warps and wefts, the in-plane continuity of fibres within 3D woven fabric reinforced P8D2 is better preserved than the plain weave reinforced P27C, in which the yarns within each fabric ply are highly crimped. The highly fibrillated failure morphology of P8D2 around the impact location indicates that more fibres in P8D2 were ruptured due to tensile failure rather than transverse shearing when compared to those in P27C [175, 176]. The shear strength of the aramid fibre is, at least, one magnitude smaller than its tensile strength [175]. Thus, more energy was absorbed through fibre tensile failure. Further research would be necessary in order to find out the mechanisms behind the superiority of the wadded TTAI over the plain weave against ballistic impacts.

All these facts indicate the preference over the 3D woven wadded TTAI fabric over its plain weave counterparts as reinforcements for doubly curved ballistic composites. From fabric production point of view, the only changes to make on the loom are the lift plans, additional warp beams and pick insertion rates, when considering a switch from plain weave to the 3D wadded TTAI. The 3D woven wadded TTAI fabrics can not only be of excellent predictable mouldability, but also of improved ballistic performance. This means, the time and labour consumption during reinforcement patterning could be reduced and standard protection will be achieved at lighter weights when compared to the conventional discontinuous reinforcing scheme.

**5.3 Summary**

In this chapter, the designed TTAI fabric reinforcements were subjected to studies about their mouldability and ballistic performance respectively, in order to find out the optimised continuous reinforcement for the PASGT-shaped helmet shell in particular.

First of all, the characterisation of the shear deformation testified the existence of locking angle and its role in defining the mouldability limit. The experimental evaluations on various designed TTAI fabrics demonstrated their excellent mouldability when compared to the conventional plain weave structures. Consequently, a further developed locking angle method, which taken into account of the wadded TTAI structure in addition to the conventional ones, was established for the mathematical prediction of the mouldability limits of TTAI fabrics with various specifications.

The mouldability limit of a PASGT-shaped military helmet shape was experimentally defined to be of the mouldability factor of 25.54, through actual moulding of TTAI fabrics onto the helmet surface. As a result, any TTAI structures with the mouldability factor no
larger than 25.54 could be engineered and considered as candidates for reinforcing the helmet shell continuously. This indicates the practical procedure of selecting the continuous TTAI reinforcements for future doubly curved composite applications.

Within the mouldability limit of a required shape, TTAI fabrics with highest possible thread density are found favourable in terms of the ballistic performance of the composite panels reinforced by them. Non-perforated test results indicated that, under the same level of fabric mouldability, panels reinforced by fewer fabric plies and heavier fabrics performed better. Also, the wadded TTAI fabric reinforced panel performed better than its conventional counterparts by exhibiting less penetrated plies and small thickness increase. An equivalent ballistic performance between the 3D wadded fabric and the 2D plain weave fabric reinforced panels was noticed, validated the superiority of using 3D wadded fabrics as continuous reinforcement against the discontinuous plain weave reinforcements for the construction of military helmet shells.

Both the ballistic test results and the post-mortem analyses indicated that the 3D woven wadded TTAI D2 with the mouldability factor of 25.54 being the optimised continuous reinforcement for the PASGT-shaped military helmet shells.
Chapter 6 Numerical study on the ballistic performance of the continuously reinforced helmet shells

6.1 Introduction

In the previous chapters, the 3D woven wadded TTAI fabrics are proved to be capable of being moulded into doubly curved military helmet shapes as the continuous reinforcements. The flat panels reinforced by the wadded TTAI fabrics were experimentally examined for their ballistic performance and damage morphology. Results indicate that improved ballistic performance can be expected when compared to their plain continuous and discontinuous counterparts. All these analyses were done on the basis of flat panels. In real situations, the composite panels are doubly curved for their use as reinforcements for helmet shells. The flat panels can be regarded as a special case when the curvature of every location across the surface being zero, or the radius of the curvature being infinite.

The ballistic performance of curved composites is regarded to be different from the flat ones, not only because of their geometric differences but also for the stretching and crimp of the fibres during the moulding of reinforcing materials [177]. Stargel [178] proved the existence of an optimal curvature of the target both numerically and experimentally. The ballistic resistance of composites increases as the radius of the curvature reduces until the reach of this optimal curvature, after which the ballistic limits decrease. Therefore, the determination of this optimal curvature is dependent on the material of the target and hard to predict.

Due to health and safety reasons, it is difficult for the currently available shooting range to accommodate a helmet shell. Hence, FE analyses are sought to be adopted for the validation of having wadded TTAI as continuous reinforcement for the construction of military helmet shells.

6.2 Brief introduction to ABAQUS/Explicit

ABAQUS/CAE is an up-to-date finite element analyser that integrated with result visualisation capabilities developed by Dassault Systems. An ABAQUS/CAE model database stores models and analysis jobs. Generally, there are two calculation algorithms for the nonlinear (the structure's stiffness changes as it deforms) finite element analyses in ABAQUS, namely the implicit ABAQUS/Standard and the explicit ABAQUS/Explicit [179]. The implicit finite element method in ABAQUS /Standard requires that a system of
equations is solved at the end of each solution increment. It is more efficient for solving smooth nonlinear problems. An ABAQUS/Explicit solution is advanced kinematically from one increment to the next. It is well-suited to solving high-speed dynamic events that require many small increments to obtain a high-resolution solution. In this way, ABAQUS/Explicit is the clear choice for a wave propagation analysis, which is the case for the ballistic response of the composites.

In ABAQUS/CAE, the model set-up, simulation, and post-processing are the three tasks to carry out a complete finite element analyse. First of all, objects including parts, materials and sections, assembly, sets and surfaces, steps, loads, boundary conditions and fields, interactions and their properties as well as meshes need to be specified or imported into ABAQUS/CAE in order to set up a model. The simulation solves the state of stress at each material point by adding strain every time increment. The calculation time is influenced by the model size, output accuracy, and computer power. Afterwards, the results of simulation could be visualised and extracted.

6.3 FE model for PASGT helmet shell

The PASGT-shaped helmet shell is chosen as the target shape for conducting the evaluation, as mentioned in Section 5.1.4. This section will describe the procedures to reconstruct the PASGT shape and the establishment of the FE model.

6.3.1 Generation of the geometric model of PASGT shell

The doubly-curved PASGT shell needs to be reconstructed for simulating the ballistic impact on the continuously reinforced composite shells. This reconstructed helmet shell should be able to precisely reflect the geometry of the shell and easy to be imported into ABAQUS® for further analyses.

6.3.1.1 Generation of the orthographic views

In order to determine the dimension of the shell in a 3D space, a replica of the PASGT-shaped helmet shell was scanned. A handheld laser scanner FARO ScanArm was employed for the task, as illustrated in Figure 6-1. It is capable of providing the point cloud information of complex parts and surfaces for reverse engineering.
Figure 6-1 Scanning of PASGT-shaped helmet replica: (a) FARO ScanArm; (b) Generating point-cloud

In order to interpret the point cloud information of the PASGT shell into a workable solid part for FE analyses, the top, side and front views of the scanned shell was generated at a scale of 1:2 by the computer-aided design (CAD) software Rhino3D ®[180]. The generated orthographic views are included in Figure 6-2.

Figure 6-2 Orthographic views of a half PASGT helmet shell: (a) Front view; (b) Side view; (c) Top view; (d) Perspective view
Measurements were taken from the three orthographic views of the shell before recreating the shape in SolidWorks® [181]. SolidWorks® is a solid modelling computer-aided design and engineering (CAD & CAE) software developed by Dassault Systèmes, which also developed the FE modelling software ABAQUS®. The solid geometrical model created in SolidWorks® could be imported into ABAQUS® without converting the file format. Detailed procedures to create the helmet geometry are stated and illustrated as follows.

6.3.1.2 Generation of the inner surface

First of all, the contour curves made up with the coordinates measured from the front and right views were recreated in a 3D space illustrated in Figure 6-3(a). A closed inner surface demonstrated in Figure 6-3(b) could then be generated by lofting the contour curves, ‘Loft’, is a command in SolidWorks® [181]. It allows the creation of surface by making transitions between profile curves.

![Figure 6-3 Generation of the inner surface: (a) Inner contour; (b) Lofted inner surface](image)

6.3.1.3 Generation of the ear convex

The ear convex is the convex located on both sides of the shell and is outside but joined with the inner surface of the shell just created. The inner surface of the convex was created by lofting three curves. The three curves are the projections of the convex shapes on the three orthographic views as indicated in Figure 6-4(a), (b) and (c), respectively.
Figure 6-4 Generation of the ear convex: (a) Top view of the curve; (b) Front view of the curve; (c) Inner surface of the ear convex

6.3.1.4 Generation of the solid shell

In order to create the exact helmet shape, the surfaces overlapped with the ear convex are removed and the edges of the shell were trimmed to form the brims in Figure 6-5(a). A standard thickness of 9mm was evenly added to the trimmed inner surface to form the solid shell.

Figure 6-5 Generation of the solid helmet shell: (a) Inner surface with ear convex and brim; (b) Adding thickness to the shell

The solid PASGT helmet shell generated is of smooth surfaces and exact the geometry of a standard PASGT shell shape, as illustrated in Figure 6-6. The shell geometry is exported as a ‘.STEP’ format file and imported into ABAQUS® for further analyses.
It is reviewed in Section 2.3.1 that the surface of PASGT helmet shell is of double curvature. This means that the curvature of each point on the shell surface is characterised by the curvatures of the two principal curves. As denoted in Figure 6-7, \( C_1 \) and \( C_2 \) are the curvatures of the two principal curves intersected at Point P. The radii \( R_1 \) and \( R_2 \) of the two principal curves, which equal to the multiplicative inverse of the curvature values respectively, can be calculated based on the Pythagoras theorem, which is expressed in Equation (6-1) [12].

\[
R = \frac{d}{2} + \frac{l^2}{8d} \tag{6-1}
\]

where \( d \) and \( l \) are the height and chord length of the arc.

**Figure 6-6** Solid geometry of PASGT helmet shell generated in SolidWorks®: (a) Front view; (b) Right view; (c) Top view; (d) Perspective view

**6.4 Evaluation of curvatures**

It is reviewed in Section 2.3.1 that the surface of PASGT helmet shell is of double curvature. This means that the curvature of each point on the shell surface is characterised by the curvatures of the two principal curves. As denoted in Figure 6-7, \( C_1 \) and \( C_2 \) are the curvatures of the two principal curves intersected at Point P. The radii \( R_1 \) and \( R_2 \) of the two principal curves, which equal to the multiplicative inverse of the curvature values respectively, can be calculated based on the Pythagoras theorem, which is expressed in Equation (6-1) [12].

\[
R = \frac{d}{2} + \frac{l^2}{8d} \tag{6-1}
\]

where \( d \) and \( l \) are the height and chord length of the arc.
In order to evaluate the curvature across the surface of the PASGT shell, five representative locations on the outer surface of the shell are chosen for curvature evaluations. The ballistic helmet testing standard NIJ 0106.01 provides a reference for the determination of the locations. Figure 6-8 illustrated the referencing planes [101]. Taken into consideration of the coverage of the PASGT shells, the level of the basic plane in current research is modified as the plane 60mm lower from the top position of the shell. Full descriptions of the locations of the five representative points are included in Table 6-1.
Table 6-1 Description of the locations of the five representative locations

<table>
<thead>
<tr>
<th>Representing</th>
<th>Description of location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top</td>
<td>Top of head, intersection of mid-sagittal and coronal planes</td>
</tr>
<tr>
<td>Back</td>
<td>Back of head, intersection of mid-sagittal and basic planes</td>
</tr>
<tr>
<td>Front</td>
<td>Front of head, intersection of mid-sagittal and basic planes</td>
</tr>
<tr>
<td>Upper side</td>
<td>Side of head, intersection of coronal and basic planes</td>
</tr>
<tr>
<td>Lower side</td>
<td>Side of head, intersection of coronal plane and the plane 70mm lower than basic plane</td>
</tr>
</tbody>
</table>

The radii of the two principal curvatures at five representative locations on the outer surface of PASGT shell was measured in ABAQUS® under a fixed chord length of 40mm. The corresponding curvatures are calculated and listed in Table 6-2.

Table 6-2 Curvatures at five representative locations

<table>
<thead>
<tr>
<th>Location</th>
<th>R₁ (mm)</th>
<th>R₂ (mm)</th>
<th>C₁ (mm⁻¹)</th>
<th>C₂ (mm⁻¹)</th>
<th>Mean curvature (mm⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top (P₁)</td>
<td>146.9893</td>
<td>118.0181</td>
<td>0.0068</td>
<td>0.0085</td>
<td>0.0076</td>
</tr>
<tr>
<td>Back (P₂)</td>
<td>94.8435</td>
<td>80.3164</td>
<td>0.0105</td>
<td>0.0125</td>
<td>0.0115</td>
</tr>
<tr>
<td>Front (P₃)</td>
<td>83.5863</td>
<td>114.5737</td>
<td>0.0120</td>
<td>0.0087</td>
<td>0.0103</td>
</tr>
<tr>
<td>Upper side (P₄)</td>
<td>114.1220</td>
<td>167.0356</td>
<td>0.0088</td>
<td>0.0060</td>
<td>0.0074</td>
</tr>
<tr>
<td>Lower side (P₅)</td>
<td>98.5986</td>
<td>225.8046</td>
<td>0.0101</td>
<td>0.0044</td>
<td>0.0073</td>
</tr>
</tbody>
</table>

The two principal curves used for determining the double curvature configure along three different axes in a 3D space. It is difficult to compare them under any two of the three axes. Therefore, the mean curvature of the two principal curves is employed for the characterisation of the curvature levels at different locations and displayed in Figure 6-9. It
is seen that the back of the shell has the largest mean curvature, followed by the front. The mean curvatures of the top and side of the shell are at an equivalent level. The differences in curvature could possibly lead to different ballistic performances, which would be investigated later.

### 6.5 FE model description

#### 6.5.1 Material properties

The Twaron®/Epoxy based wadded TTAI fabric D2 reinforced composites is assumed to be an orthotropic continuum. The tensile properties of the composite were tested and obtained previously in Section 4.4.1 and listed in Table 6-3.

<table>
<thead>
<tr>
<th>Density (kg/m³)</th>
<th>Young’s modulus (GPa)</th>
<th>Poisson’s ratio</th>
<th>Shear modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>E₁₁ E₂₂ E₃₃ Nu₁₂ Nu₁₃ Nu₂₃ G₁₂[182] G₁₃ G₂₃</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1249.21</td>
<td>55.76 32.20 3 0.26 0.26 0.3 1.38 9.47 9.47</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The orientations of the composite material along direction 1, 2 and 3 are defined as the warp, weft and through-the-thickness directions of the align-laid composite in the current model. The compressive stiffness of composite was found to be of the same magnitude to the stiffness of the matrix under high strain rate [103, 183, 184]. It is appropriate to use the modulus of the epoxy matrix to represent the transverse modulus of the composite. The Poisson’s ratio and out-of-plane shear moduli are calculated according to Equations (6-2) to (6-4).

\[
Nu_{12} = Nu_{13} = Nu_f \cdot F_f + Nu_m \cdot F_m \quad (6-2)
\]

\[
Nu_{23} = Nu_{12} \cdot \frac{1 - \frac{E_2}{E_1} \cdot Nu_{12}}{1 - Nu_{12}} \quad (6-3)
\]

\[
G_{23} = \frac{E_2}{2 \cdot (1 + Nu_{23})} \quad (6-4)
\]

where \(F_f\) and \(F_m\) are the fibre and matrix fraction of the composite, respectively.

The composite material exhibits different failure behaviour in different directions. Hill’s potential function can be used to model the anisotropic yield behaviour, which is a simple extension of the Mises function [179]. The stress ratios \(R_{ij}\) applied in Hill’s potential
function is expressed, in terms of the rectangular Cartesian stress components, as Equation (6-5).

\[ f(\sigma) = \sqrt{F(\sigma_{22} - \sigma_{33})^2 + G(\sigma_{33} - \sigma_{11})^2 + H(\sigma_{11} - \sigma_{22})^2 + 2L\sigma_{23}^2 + 2M\sigma_{31}^2 + 2N\sigma_{12}^2} \]  

(6-5)

where \( F, G, H, L, M, N \) are constants obtained from the results of tests carried out on the material, in various directions. They are defined as Equation (6-6) to (6-17).

\[ F = \frac{(\sigma^0)}{2} \left( \frac{1}{\sigma_{22}^{\sigma_0}} + \frac{1}{\sigma_{33}^{\sigma_0}} - \frac{1}{\sigma_{11}^{\sigma_0}} \right) = \frac{1}{2} \left( \frac{1}{R_{22}^{\sigma_0}} + \frac{1}{R_{33}^{\sigma_0}} - \frac{1}{R_{11}^{\sigma_0}} \right) \]  

(6-6)

\[ G = \frac{(\sigma^0)}{2} \left( \frac{1}{\sigma_{33}^{\sigma_0}} + \frac{1}{\sigma_{11}^{\sigma_0}} - \frac{1}{\sigma_{22}^{\sigma_0}} \right) = \frac{1}{2} \left( \frac{1}{R_{33}^{\sigma_0}} + \frac{1}{R_{11}^{\sigma_0}} - \frac{1}{R_{22}^{\sigma_0}} \right) \]  

(6-7)

\[ H = \frac{(\sigma^0)}{2} \left( \frac{1}{\sigma_{11}^{\sigma_0}} + \frac{1}{\sigma_{22}^{\sigma_0}} - \frac{1}{\sigma_{33}^{\sigma_0}} \right) = \frac{1}{2} \left( \frac{1}{R_{11}^{\sigma_0}} + \frac{1}{R_{22}^{\sigma_0}} - \frac{1}{R_{33}^{\sigma_0}} \right) \]  

(6-8)

\[ L = \frac{3}{2} \left( \frac{\tau}{\sigma_{23}} \right)^2 = \frac{3}{2R_{23}^{\sigma_0}} \]  

(6-9)

\[ M = \frac{3}{2} \left( \frac{\tau}{\sigma_{13}} \right)^2 = \frac{3}{2R_{13}^{\sigma_0}} \]  

(6-10)

\[ N = \frac{3}{2} \left( \frac{\tau}{\sigma_{12}} \right)^2 = \frac{3}{2R_{12}^{\sigma_0}} \]  

(6-11)

\[ R_{11} = \frac{\sigma_{11}}{\sigma_0} \]  

(6-12)

\[ R_{22} = \frac{\sigma_{22}}{\sigma_0} \]  

(6-13)

\[ R_{33} = \frac{\sigma_{33}}{\sigma_0} \]  

(6-14)

\[ R_{12} = \frac{\sigma_{12}}{\tau_0} \]  

(6-15)

\[ R_{13} = \frac{\sigma_{13}}{\tau_0} \]  

(6-16)

\[ R_{23} = \frac{\sigma_{23}}{\tau_0} \]  

(6-17)
where $\bar{\sigma}_y$ is the measured yield stress value; $R_0$ is the stress ratio defined with respect to a user-defined reference stress $\sigma^0$. The corresponding yield stress ($\bar{\sigma}_y$) is $R_0 \sigma^0$ and $\tau^0 = \sigma^0 / \sqrt{3}$.

Failure of the composite would be initiated when the equivalent plastic strain reaches the fracture strain of the material. According to the ABAQUS documentation \[179\], the uniaxial fracture strain of the composite along the referenced material direction is calculated as the difference between the tensile strain and yield strain. The weft direction was used as the reference direction in the current model. The yield strain of 0.86% along the reference direction corresponds to a yield stress of 479.55MPa. This yield stress was chosen to be the reference yield stress ($\sigma^0$). The tensile strength along the weft direction of the composites is 502.30MPa, corresponding to a tensile strain of 0.90%. In the current model, the fracture strain was calculated to be 0.04%. Table 6-4 lists the stress ratios used in the current model. The stress ratios related to shearing properties were taken from literature \[185\].

If the warp direction was taken as the reference direction, the stress ratio $R_{ij}$ would change relatively, as listed in Table 6-4 below. In this case, with the yield strain being 0.94%, the reference yield stress $\sigma^0$ would be 302.68MPa. The tensile strength 314.67MPa would result in a tensile strain of 0.98%, correspondingly. Therefore, the fracture strain would be 0.04% as well. The results obtained based on the material model with warp direction as its reference direction was proved to be exact the same as that with weft direction as the reference direction.

Table 6-4 Value of stress ratios $R_{ij}$ referred to material Direction 1 and 2

<table>
<thead>
<tr>
<th>Reference direction</th>
<th>$R_{11}$</th>
<th>$R_{22}$</th>
<th>$R_{33}$</th>
<th>$R_{12}$</th>
<th>$R_{13}$</th>
<th>$R_{23}$</th>
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<td>Direction 1</td>
<td>1</td>
<td>0.63</td>
<td>0.63</td>
<td>1.37</td>
<td>1.37</td>
<td>1.37</td>
</tr>
<tr>
<td>Direction 2</td>
<td>1.58</td>
<td>1</td>
<td>1</td>
<td>1.26</td>
<td>1.26</td>
<td>1.26</td>
</tr>
</tbody>
</table>

The density of the composite is measured as 1.249 g/cm$^3$, as indicated in Appendix Table 1. The projectile in the model is same as what was used in the experiments and regarded as a rigid body. Moulding of fabric reinforcements would result in structural changes in the reinforcement. Changes in yarn crimp and fibre orientation would lead to variations in the mechanical properties of the composite reinforced by the moulded fabrics, but the
influences are hard to be predicted. Therefore, all the material properties in the current model were obtained at their flat state, which did not account for the deformation of fabric reinforcements during moulding.

### 6.5.2 Mesh & assembly

In order to maintain the consistency and accuracy of the calculation, impacted areas with the size of 40*40mm through the thickness with the five representative locations as centres are partitioned. Solid C3D8R elements at the mesh size of 1.25*1.25*0.9mm³ are generated for the partitioned impact areas. Bottom-up meshes of the same type were assigned to the rest of the areas in order to retain the curved geometry of the shell while reducing the calculation time. A total of 68298 meshes were generated for the helmet shell. Figure 6-10 is an example of the meshing scheme for the projectile/assembly when impact at the top location.

![Figure 6-10 Mesh scheme for the projectile/helmet assembly: (a) Overall perspective view; (b) Close-up view](image)

A total number of 32312 solid C3D10M tetrahedron meshes was assigned to the projectile, whose height and diameter were both 5.5mm. The mesh and geometry of the projectile are illustrated in Figure 6-11.
The fixed boundary is assigned to the edges of the helmet. The contact friction between the projectile and the Twaron® reinforced composite is regarded as general at the coefficient of 0.18 [168, 186].

6.5.3 Model validation

Same material and meshing scheme are assigned to the flat panels to validate the helmet model established. The ballistic performance of the tested perforated model P8D2 and non-perforated model P13D2 are numerically investigated. The thickness values of the two panels in the model are 6.87 and 9.55 respectively, based on their actual thickness.

The simulation results for the perforated panel are included in Appendix Table 13. The comparison between the experimental and FE results are plotted in Figure 6-12. It can be found that the experimental and FE residual velocities under the same impact velocities are
at equivalent levels in each shooting. Further to that, the average energy absorption of panel P8D2 obtained from simulations is 99.66J, which are quite close to the experimental results 99.11J. The simulation of the projectile impacting P13D2 at the velocity of 480 m/s was found to be non-perforated as it was in the experimental shooting.

Both the perforated and non-perforated simulations revealed good agreement with the experimental results, and the FE model established is considered valid for the evaluation of the ballistic performance of the PASGT shell.

6.6 Influences of impact locations

It is known that the helmet shell is of various levels of curvature at different locations, as is demonstrated in Figure 6-9. In order to further validate the use of the continuously reinforced composite for the construction of doubly curved shells, the ballistic performance of the regenerated PASGT shell at different locations was numerically investigated.

6.6.1 On ballistic limit

The ballistic limits of the regenerated PASGT shell were evaluated at the five representative locations as well as for the flat panel with the same thickness. The highest impact velocity at which the projectile is stopped inside of the panel without complete penetration is defined as the ballistic limit of the composite based on the numerical model. The ballistic limit values were obtained based on trial-and-error.
Figure 6-13 demonstrates the projectile/helmet assembly when the helmet is impacted at the top location. Similarly, in the rest of the cases, the shells were impacted by the projectiles at incident angles normal to the shell curves at the specified location.

Figure 6-14 is the calculated ballistic limits of the PASGT shell at the five representative locations determined by NIJ standard 0106.01 [101]. The ballistic limit results indicate that the shell reacts to the impact differently at different locations. The front of the helmet shell appears to have the highest ballistic limit, followed by the back of the shell, which are both higher than that of their flat counterpart. Particularly, the ballistic limit of the front impact location is 5.4% higher than that of the flat panel. The ballistic limits of the top, the lower side and the upper side of the shell are found at an equivalent level, which is lower than that of the flat panel.

Figure 6-14 Ballistic limits of the PASGT shell at different locations

Figure 6-15 reveals the stress distribution on the top impact location at the impact velocity of 478 m/s. It is noticed that the damage was localised to the impact location while the shell itself did not go through severe deflection. Therefore, the differences in ballistic limits at different locations are closely related to the levels of curvature at the impact locations.
As indicated in Figure 6-9 the top, lower side and the upper side of the shell have similar mean curvatures around the value of 0.0075 mm\(^{-1}\), which are smaller than those of the front and back of the shell. This explains why their ballistic limits are at an equivalent level of the flat panels. Whereas the curvatures of front and back locations are at higher levels, and the ballistic limits are also found higher.

Research work by Stargel [178] proved that there is an optimal curvature of the panels under ballistic impacts. The present study agrees with that by revealing higher ballistic limits than the flat panels at the front and back locations, where the mean curvature values are around 0.011 mm\(^{-1}\). It is impractical to engineer helmets with various local curvatures at different locations because the shape of the helmet should go with the shape of the head in general. In order to improve the ballistic protection at the side and top of the head, it is
suggested to construct a global shell with the uniform curvature values across the head. The curvature values of the front could be considered in this case. The establishment of an FE model, which includes the changes in the mechanical properties of the reinforcement, would be more accurate in predicting the effects of curvature values on the ballistic performance of the composites.

6.6.2 On peak load

In order to further evaluate the effect of curvature on the ballistic performance of the helmet shell at different impact locations, the peak loads impacted on the helmet by the penetrating projectile was investigated numerically under the impact velocity of 480 m/s. The results are recorded in Figure 6-16.

![Figure 6-16 Peak loads of the PASGT shell at different impact locations](image)

It is noticed from Figure 6-16 that the front and back locations displayed smaller peak loads than that of the flat panel, where the peak load of front location is 7.6% lower than that of the flat panel. Meanwhile, the peak loads when impacted on the other three locations are found generally higher than that of the flat panel.

When looking at the peak loads in relate to the ballistic limits obtained previously shown in Figure 6-14, it is hard to ignore that the lower the peak load one impact received, the higher ballistic limit would result, and vice versa. The impact locations with larger curvatures, namely the front and back of the shell, did better in attenuating the impact loading by transmitting lower peak loads onto the composite shell.
The values of peak load would also reflect the peak accelerations the shell experienced based on Newton’s Second Law. Large accelerations would induce head accelerations, which are deadly harmful for the wearers as reviewed in Section 2.4.3.1. Therefore, it is indicative for the helmet designers to engineer the helmet geometry with considerations on the influence of the curvature.

### 6.7 Summary

One of the objectives of the present research is to numerically evaluate the ballistic performance of the continuous 3D woven fabric reinforced composite shells. In this chapter, an FE model based on the geometry of PASGT helmet shell was established and validated successfully for this purpose.

The curvature values of the doubly curved PASGT shell at five representative impact locations, namely the top, front, back, lower side and upper side were evaluated. Those five locations were specified by the NIJ standard 0106.01 and employed to evaluate the ballistic limit of helmets in practice. The shape of helmet shell follows the shape of head closely. Hence, the curvature values at those five impact locations are regarded as representative for providing guidance for future curvature designs. The calculated ballistic limits vary from location to location, with the back and front larger than the others.

The established FE model based on the material properties of the optimised wadded TTAI fabric D2 reinforced composite was validated against both the perforated and non-perforated experimental results. Good agreement was found in terms of residual velocities and energy absorption. Thus, the FE model is considered valid for the evaluation of the ballistic performance of the helmet shell continuously reinforced by the wadded TTAI fabric.

Although the ballistic limits varied from location to location, an equivalent ballistic limit of the helmet shell was noticed for the PASGT shell when compared to its flat counterparts. The values of shell curvature were found influential to the ballistic limits. The impacts on the front and back of the shell, which are with larger curvatures, were found better at attenuating the impact loading and offering higher impact resistance. It is suggested to construct a global shell with the uniform curvature values across the head. The curvature values of the front could be considered in this case.
Chapter 7 Conclusions and future work

7.1 Conclusions

The present study aims at engineering design composite military helmet shells with improved protection by reinforcing the composite shell with continuous 3D woven fabrics. The objectives set out for this PhD research include (1) to investigate the effect of reinforcement continuity on the ballistic performance of composites; (2) to identify the 3D woven fabric structure that could be moulded into military helmet shape; (3) to optimise the reinforcing scheme with the mouldable fabric as reinforcements for improved ballistic performance; (4) to numerically investigate the ballistic response of the designed continuously reinforced composite shell by impacting at different locations and provide guidance for the engineering of continuously reinforced composite military helmet shells.

The main achievements of the research could be concluded as follows:

a) Experimentally proved the preference over continuous fabric reinforcement than the discontinuous ones against ballistic impacts

A study on the effect of reinforcement continuity based on flat composite panel revealed that the continuously reinforced panels outperform the discontinuously reinforced ones. Up to 19.3% more of the kinetic energy carried by the projectile was absorbed by the continuously reinforced panels, leading to a 9.3% higher estimated ballistic limit than their discontinuous counterparts.

The post-mortem inspections through NDT tests including ultrasonic C-scan and X-ray CT found that the continuously reinforced composites were capable of distributing the delamination damage wider through the thickness. The 3D damage volume quantifies the damage resulted from the impacts and the continuously reinforced panels were found with larger damage volume, which explains the higher energy absorption. Furthermore, the discontinuously reinforced panels with longer overlapping lengths would lead to better ballistic performance.

All these findings pointed towards the use of continuous reinforcement for ballistic composite panel construction, which cannot be achieved in the case of military helmet shell with doubly-curved geometry by conventional plain or satin/ sateen woven fabrics.
b) Identified the 3D woven wadded TTAI fabrics as continuous reinforcement for military helmet shells

The 3D wadded TTAI fabrics enhanced the warp direction of the conventional TTAI fabrics by introducing an additional set of straight warp yarns into the structure. It is found from the tensile test result that the Young’s moduli of composites along the warp direction of wadded TTAI fabrics increased by 2.4 times from those reinforced by the conventional TTAI fabrics. The wadding yarns were found, through FE simulation, taking up the tensile loading directly upon tensile stretch along warp direction, whereas the crimped binding warps need to be straightened first. Consequently, improved in-plane isotropy of the composite panels could be achieved with the wadded TTAI fabrics as reinforcements.

The wadded TTAI fabric was found to deform similarly upon shearing to their conventional counterparts. Thus, the locking angle method was further developed for the prediction and evaluation of the mouldability of wadded TTAI fabrics. A mouldability limit of 25.54 was determined for PASGT helmet shape. Changes over the yarn linear density, thread density, number of weft layers and the wadding plan would convey various designs of TTAI fabrics that are with mouldability factor smaller than 25.54, which could be used as continuous reinforcements for PASGT helmet shells. This also provided model procedures for the selection of continuous reinforcement for doubly curved shapes.

c) Validated the protection of the continuously reinforced composite military helmet shells

Ballistic evaluations over the mouldable TTAI reinforced composites validated the use of them as reinforcements for ballistic applications based on flat panel. The reinforcements with higher thread density demonstrated better ballistic performance, as long as the mouldability factor of the TTAI fabric is under the mouldability limit.

Under the same level of fabric mouldability and composite areal density, panels reinforced with fewer plies of heavier fabrics exhibit better ballistic resistance. The wadded TTAI reinforced composite panels showed better ballistic resistance by giving smaller indentation and less penetration through panel thickness than the conventional TTAI reinforced ones. The delamination volume of wadded TTAI reinforced composites was found localised but evenly distributed through the penetrated plies.

An equivalent ballistic performance between the 3D wadded fabric and the 2D plain weave fabric reinforced panels was noticed. The 65.3% smaller delamination volume indicated
the better utilisation of the reinforcing fibres in energy absorption by the 3D woven wadded TTAI fabrics reinforced composites. This implies improvements in ballistic protection of the wadded TTAI continuously reinforced composites.

Numerical analyses of the curved shells reinforced by the wadded TTAI structure further validate their use for constructing the continuously reinforced military helmet shells. Although the ballistic limit varies from location to location, an equivalent ballistic limit of the helmet shell was noticed for the PASGT shell when compared to its flat counterparts. The impacts on the front and back of the shell, which are with larger curvatures, were found better at attenuating the impact loading and offering higher impact resistance. It is suggested to construct a global shell with the uniform curvature values across the head. The curvature values of the front could be considered in this case.

7.2 Recommendations for further research

Based on the work done in the present research, a number of projects are possible to be continued.

The resin transfer moulding (RTM) technique could be employed in the making of multiply continuously reinforced military helmet shells. Control over the viscosity of matrix and processing conditions would contribute to a high-quality thick composite shell.

Ballistic performance of continuously reinforced composite shell could be tested experimentally. The design of helmet curvature would optimise the protection level of helmets.

A systematic study of the failure mechanisms of the 3D woven fabric reinforced composites under ballistic impact would be helpful for understanding the superiority of them over the 2D woven fabric reinforced ones. A yarn-level FE model is considered to be a good approach in analysing the ballistic response of different component parts in resisting the impact.

The in-situ ultra-fast synchrotron radioscopic imaging provides a chance to investigate into the damage initiation and progression in composite panels upon ballistic impacts. Provided only post mortem scans were taken in current research, more information about the damage evolution could be revealed from the in-situ scans.
References


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### Appendix

#### Table 1 Density of composite panels

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Weight in air ($w_a$) (g)</th>
<th>Weight in water ($w_l$) (g)</th>
<th>Density (g/cm$^3$)</th>
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</tr>
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#### Table 2 Fibre volume fraction of composite panels

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<th>Specimen</th>
<th>Weight in air ($w_a$) (g)</th>
<th>Weight in water ($w_l$) (g)</th>
<th>Density (g/cm$^3$)</th>
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Table 3 Ballistic impact test results of 10ply plain weave fabric reinforced composites

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<th>Residual velocity (m/s)</th>
<th>Energy absorption (J)</th>
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Table 4 Ballistic impact test results of 20ply plain weave fabric reinforced composites

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Table 5 Ballistic impact test results of plain weave fabric with 20mm overlapping length discontinuously reinforced composites

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Table 6 Ballistic impact test results of plain weave fabric with 45mm overlapping length discontinuously reinforced composites

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<tr>
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<th>Residual velocity (m/s)</th>
<th>Energy absorption (J)</th>
<th>V_{50e} (m/s)</th>
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Table 7 Thickness of the TTAI specimens produced (Unit: mm)

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<td>0.718</td>
<td>0.781</td>
<td>0.763</td>
<td>0.817</td>
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<td>0.760</td>
<td>0.777</td>
<td>0.716</td>
<td>0.767</td>
<td>0.785</td>
<td>0.814</td>
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<td>0.763</td>
<td>0.778</td>
<td>0.814</td>
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<td>0.772</td>
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<th>C3</th>
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Table 8 Areal density of the TTAI specimens produced (Unit: g/m²)

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Table 9 Tensile properties of the conventional and wadded TTAI reinforced composites

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Table 10 Deformation depths measured using the mouldability tester (Unit: cm)

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Table 11 Ballistic performance of composite panels reinforced by TTAI fabric with different thread densities

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