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UHMWPE COMPOSITES FOR BALLISTIC IMPACT RESISTANT APPLICATIONS

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SCHOOL OF MATERIALS SCIENCE AND ENGINEERING

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Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research, is free of plagiarised materials, and has not been submitted for a higher degree to any other University or Institution.

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This thesis contains material from one paper published in the following peer-reviewed journal in which I am listed as a first author.

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The contributions of the co-authors are as follows:

- This research project was a collaboration between the School of Materials Science and Engineering, Nanyang Technological University and DSM Protective Materials.
- I prepared the manuscript drafts. The manuscript was revised by Dr Jan Stolk, Dr Ulrich Heisserer and Prof Hu Xiao.
- I designed, fabricated the test samples, and conducted the experiments at DSM Protective Materials Asia Pacific Pte Ltd.
- I fabricated the test samples at the School of Materials Science and Engineering.
- Dr Jan Stolk, and Dr Ulrich Heisserer assisted in the interpretation of the impact and ballistic results.
- Dr Alex Yong and Mr Li Zhi-Yi provided industrial supervision.
- Prof Hu Xiao provided research supervision and revised the manuscript.

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Abstract

Lightweight, high ballistic limit and low back-face signatures (BFS) upon impact are highly desirable performance measurements in the engineering of ballistic protection. On top of these characteristics, ballistic applications often need to be structurally sound with high stiffness and high yield strength. The complex and myriad performance demands of ballistic applications make selecting the proper materials challenging.

In the engineering of ballistic protective articles primarily using fibrous laminates, factors affecting ballistic limit and failure responses in the scope of intraply and interply hybridisation has not been studied extensively. Connected with this topic, the study on the effect of positioning of add-on materials in a ballistic article are still relevant.

This research work investigates the effects of material hybridisation of an ultrahigh molecular weight polyethylene (UHMWPE) fibre-based hard ballistic panel with carbon fibre, specifically for its low and high velocity impact responses. UHMWPE fibres possess unique mechanical properties such as high strength-to-weight ratio and high strain to fracture that make it a suitable candidate for use in ballistic applications. However, it is limited as a stand-alone material in structurally demanding environments due to its weak compressive and shear strength. A secondary material such as carbon fibre will be mainly used due to its highly synergistic properties such as its high strength and stiffness in tension and compression which will complement the UHMWPE fibre. Mechanical three-point bending, and ballistic tests will be used to provide a mechanistic understanding of the static and dynamic responses of the hybrid ballistic panel.

The relevance of this research topic was demonstrated through the utilisation of the principles of beam bending and fibrous responses to impact. This thesis investigates developing an innovative approach of intra- and interlayering hybridisation by unravelling key differences positioning of add-on materials make particularly upon impact. The reduction in back face deformation because of such hybridisation techniques thus aids in the development and design of ballistic articles to reduce fatal injuries to end users like

military and law enforcement personnel.

Through this research, unexpected effects simply by varying the positions of small amounts of carbon fibre layers within an UHMWPE panel through an only interlayer hybridisation technique were observed. Positive hybrid effects such as a 30% reduction in back-face signature (BFS) with a more than two times improvement in flexural properties were seen when homogeneous carbon fibre layers were added to the UHMWPE panel.

An intra- and interlayer dual hybridization type method also yielded positive outcomes when tested against falling dart test to simulate low velocity impact. The intralayer hybrid woven fabric consisting of UHMWPE and carbon fiber (PE-C) yielded interesting results in reducing BFS when added onto the UHMWPE panel. Front or back-facing PE-C hybrid had resulted in a substantial 25% reduction in BFS compared to neat UHMWPE panel. Adding PE-C hybrid fabric altered the impact failure mechanism. The added stiffness from the carbon fiber prevented excessive bending while the ductile UHMWPE fiber absorbed energy and prevented the layer from failing catastrophically. The combined effects of both materials proved to be beneficial in coping with impact events.

Interestingly, to design effective ballistic protective articles, its overall softness and stiffness play a crucial role in the outcome of its performance against impact. Too stiff and the material fails catastrophically; whilst too soft and the BFS becomes too great. Managing these two parameters remain an interesting engineering dilemma when it comes to fabricating ballistic resistive article. In addition, factors such as layer survivability play a crucial role in energy absorption and failure mechanism of the overall equipment and thus affect its performance. This thesis seeks to highlight the different responses of a hybrid panel of UHMWPE and carbon fibre as well as suggest design considerations in the engineering of ballistic resistive articles.

Lay Summary

In the design of personnel protective armour, features such as low weight, high resistance to projectile penetration and low back face deformation are important. Such armour need also to possess a certain degree of structural resistance such as in helmet applications. Thus, choosing the right kind of material is an important decision in ensuring effective ballistic resistive properties.

The evolution of choices in materials over time, moving from heavy metallic materials to lighter fibrous material opens new opportunities but also challenges. This thesis focuses on understanding responses to impact that arise from the hybridisation of fibres of ultrahigh molecular weight polyethylene (UHMWPE) and carbon fibre. In addition, it also looks thoroughly into the effects of position of the add-on carbon materials on an UHMWPE hard ballistic panel.

It was realised, through mechanical three point bending and ballistic testing, that interesting differences in failure mechanism between mixed UHMWPE-carbon and homogeneous carbon laminates were reasons for differences in mechanical and ballistic performances of the hybrid panels. The survivability of the add-on laminates through the different location it was placed were also great contributors for the reduction in the back face deformation.

The relevance of this research topic was demonstrated through the utilisation of the fundamental principles of beam bending and fibrous responses to impact uncovered in this thesis to design and engineer more effective hybrid protective armour.

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Abbreviations

BFS	Back Face Signature
C	Carbon
HE	High Elongation
LE	Low Elongation
NIJ	National Institute of Justice
PE	Polyethylene
UHMWPE	Ultrahigh Molecular Weight Polyethylene
V_{50}	Ballistic Limit Velocity

Chapter 1

Introduction

Lightweight, high ballistic limit and low back-face signature (BFS) upon impact are highly desirable performance measurements in the engineering of ballistic protective armour. On top of these characteristics, ballistic applications often need to be structurally sound with high stiffness and high yield strength. There are various material hybridisation techniques currently used to combat such challenges however, an intralayer and interlayer type of hybridisation specifically in fibrous based ballistic article are gaining traction. Enhancing the understanding of key factors that improve the impact responses of such hybrid articles is key in designing more effective armour. This chapter introduces the rationale, hypothesis, objectives, and scope of this thesis. The overview of various chapters within this thesis are included.

1.1 Background

The arms race of nations encourages the development of military technology. The ever-competitive defense industry is constantly searching for stronger, lighter, and tougher protective equipment to protect its military and law enforcement officers. Lightweight, high ballistic limit and low back-face signature (BFS) upon impact are highly desirable performance metrics in the engineering of ballistic protection. On top of these characteristics, ballistic applications often need to be structurally sound with high stiffness and high yield strength. The complex and myriad performance demands of ballistic applications make selecting the proper materials challenging.

The idea of material hybridisation to combat limitations in performance of a parent material is well accepted in the field of materials engineering, including for fibrous based material applications. Weaving of fibres in an intrayarn, intralayer and interlayer fashion are a few such methods. The outcome of such a hybridisation technique often yields surprising results. However, gaps in research to understand fundamental factors that affect impact responses are uncovered. These are often affected by the sensitivity of the samples to the impact testing environments selected by researchers as well as the complex nature of ballistic impact events.

Ballistic impact events are dynamic and complex in nature. Performances of ballistic articles are often measured by penetration limit velocity, energy absorption and attenuation capabilities and back face signature mitigation. While it would be easy to presume such a scientifically rich area of research would have been thoroughly investigated and thus the mechanisms well-established, on the contrary, unravelling the secrets of ballistic impact responses specifically of fibrous material often yield conflicting reports in the community.

This thesis aims to investigate the hybrid material engineering of an ultrahigh molecular weight polyethylene (UHMWPE) fibre based hard ballistic panel. Variables such as type, positioning and quantity of the add-on material (carbon fibre) will be assessed. Such work would further shed light and contribute significantly to the understanding of impact failure mechanisms of two-dimensional plate-like articles which would aid material designers. In addition, design considerations to develop more effective protective armour extending to three-dimensional articles, such as helmets, would be a possibility.

Understanding the failure mechanism of the various hybrid designs of UHMWPE-Carbon fibre ballistic panels upon low and high velocity impact would greatly contribute to the following:

I. The development of not only ballistically but structurally sound protective panels.
II. The identification of the ideal positioning of stiffer/tougher regions within a ballistic panel as an engineering design reference for protective equipment.

1.2 Hypothesis/Problem Statement

Problem Statement

UHMWPE fibre-based ballistic articles are characterized by high ballistic penetration limits, but also possess limitations in bending rigidity and back face signature. This may be contributed by the low compressive strength of PE fibres, as well as surface chemical inertness which limits interaction with a matrix. On the other hand, carbon fibres comparatively do not possess such deficits. Its high modulus and strength might make it ideal as a complementary material in a hybrid with PE fibres. Carbon fibre as a standalone is brittle and thus are naturally unsuited in high impact environments. This thesis explores the possibility of reducing deficits of PE articles through intra- and interply hybridisation with carbon fibres, without resulting in a loss of ballistic penetration limits.

UHMWPE fibre is indeed an interesting material to consider for use in ballistic applications [1]. One example is the HB26 Dyneema® prepreg material based on 0/90 unidirectional material. A study by Lässig et al. investigated its shock response behavior from impact situations like in ballistic impact events [2]. In addition, UHMWPE fibre possess unique mechanical properties that make it a suitable candidate for use in ballistic applications.

Firstly, they exhibit higher strength-to-weight ratio [3] and higher work to fracture properties as compared with aramid, carbon and glass fibres [4]. These intrinsic material properties of UHMWPE fibres make them suitable for use in high impact energy events prevalent in ballistics. In addition, they can also be used for applications that demand good low speed impact protection and damping properties [5, 6]. However, like many other materials, UHMWPE composites also possess their own set of property limitations. UHMWPE fibres are limited in compressive and shear strength [7]. Comparatively, its compressive strength is inferior to carbon fibres [4]. Furthermore, UHMWPE fibres are more surface inert than other structural fibres, which enhances their environmental stability but makes it challenging to obtain high fibre-matrix surface interactions [3]. The properties mentioned can limit its usage in structurally demanding applications as a stand-alone material. However, these structural limitations are also beneficial to the arrest of a projectile during a ballistic event by cross-ply UHMWPE cross-ply composites in compliant matrix. The high in-plane tensile modulus and strength of the UHMWPE fibres combined with its low interlaminar shear strength and compressive strength allows for effective energy absorption by blunting cracks [8], shearing and various other modes of delamination [9]. Although UHMWPE fibre-based ballistic panels possess a very high ballistic limit at a given weight [10], subsequent BFS of the article may be jeopardized by its lack in structural properties. One way to overcome these limitations is by introducing the concept of material hybridisation.

Hybridisation involves combining two constituent materials to achieve a new property [11-13]. The design outcome of the hybridisation may produce materials that inherit desirable properties from the parent material. Hybridisation can be done via interply hybridisation. This form of hybridizing materials involves stacking distinct layers of different materials one on top of the other prior to consolidation. Carbon fibre is an example of a highly synergetic material to be used in the hybridisation with UHMWPE fibre. Carbon fibres possess high specific strength and stiffness both in tension and in compression which would greatly compliment the low compressive and shear strengths of UHMWPE fibre. In addition, beneficial secondary effects of carbon fibres include their ease of use as a surface finish layer. Hence, it makes logical sense to attempt to hybridize UHMWPE ballistic materials with carbon fibre to get a structurally sound composite with a high ballistic limit and low BFS.

Hypothesis

The hypothesis of this thesis is that we can positively influence the back face signature and bending rigidity of UHMWPE ballistic articles by hybridizing with carbon fibres in an intraply and interply fashion. Strategic positioning of the carbon fibres in the composite panel will play a dominant role on the effect.

From this impact study, insights into the failure response of a hybrid UHMWPE fibre-based ballistic panel will facilitate the identification of key unique components that attribute to effective ballistic protection. In turn, this will allow for the development of future hybrid ballistic composite panels.

1.3 Objective and Scope

The present research is concerned with the design of UHMWPE fibre-based ballistic panels to enhance its ballistic performance via material hybridisation by providing a deeper understanding of its interaction with carbon fibre.

The objectives of this research are:

I. To study the ballistic performance of hybrids of UHMWPE and carbon fibre to provide leads to reduce the downsides of an UHMWPE fibre-based panels.

II. Provide insights into failure mechanism and responses of an UHMWPE fibre-based ballistic panel hybridized with carbon fibre against low and high impacts events, with the aim of providing material development leads.

III. To provide design guidelines in the engineering of an UHMWPE fibre-based ballistic protective article through understanding key performance factors when hybridized with carbon fibre.

The impact study was focused on understanding the responses of a hybrid panel consisting of UHMWPE and carbon fibre when subjected to low and high velocity impacts. The interactions between the different layers were evaluated for its ability to reduce back face deformation.

The role of UHMWPE fibre incorporated into homogeneous carbon laminate as well as the influence of the positioning of the add-on laminates during the ballistic impact will be investigated. To assess these effects, two tests namely mechanical three-point bending test as well as ballistic limit and BFS test will be conducted to understand the static and dynamic responses, respectively.

Insights into the best position to place the hybrid layer within the UHMWPE fibre-based ballistic panels would shed light on better designing future ballistic articles such as helmets. This study is expected to help in the future design of UHMWPE-based ballistic articles specifically for the Personal Protection business of DSM Protective Materials.

1.4 Dissertation Overview

The thesis addresses the lack of mechanistic insights related to the impact responses of an intralayer and interlayer type of fibrous laminates, of mainly UHMWPE and carbon fibre, for ballistic applications.

The thesis consists of seven chapters, which are summarized as follows.

Chapter 1 provides a rationale for the research and outlines the goals and scope.

Chapter 2 reviews the literature concerning fibre hybrid composites. This Chapter concludes with the thesis relevance in addressing the proposed knowledge gap.

Chapter 3 describes the experiments to be performed in line with the proposed research objective and scope. The material selection and experimental methodology was presented and rationalised in accordance with the intended observations. An overview of the various testing methods used in the thesis along with their corresponding underlying principles of operation is presented.

Chapter 4 forms the basis of the research by experimentally validating that UHMWPE and carbon fibre possess highly synergistic properties to elicit surprising ballistic impact performance. The hypothesis was validated as part of this study motivating further investigation to build mechanistic understanding.

Chapter 5 presents an investigation into the underlying mechanistic responses of the hybrid UHMWPE-carbon ballistic panels by evaluating forces and displacement responses set against low velocity impact and their subsequent effect in reducing back face signature.

Chapter 6 demonstrates the relevance of this research topic by exploring the possibility of an *intra*layer-*inter*layer type of hybridisation between UHMWPE and carbon fibre against high-speed ballistic impacts. This chapter suggests engineering considerations in the design of an effective protective armour that is structurally and ballistically sound.

Chapter 7 summarises the research findings and includes recommendations for further investigations.

1.5 Findings and Outcomes/Originality

This research led to several novel and impactful outcomes as follows:

1. Understanding of the failure mechanism of an intralayer-interlayer hybridisation of UHMWPE and carbon fibre subjected to low and high velocity impact.

2. Demonstrate that positioning of stiff/tougher regions of a ballistic article plays a significant role in reducing back face deformation for the safety of end-users.

3. Paved the path for the development of engineering guidelines for future protective articles that are ballistically and structurally sound.

4. Patent for Ballistic Molded Article WO2020/127187 A1. The use of carbon with Dyneema® fabric as a ballistic material.

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Chapter 2

Literature Review

In spite of the relatively mature research topic of hybrid composites, impact performance on those specifically concerning fibrous material composites is still not well understood. Conflicting research publications covering the different possible techniques of hybridisation and their effects on impact make this thesis topic a worthwhile study. This chapter will cover the review of ultrahigh molecular weight polyethylene fibre (UHMWPE) and carbon fibre, impact failure mechanism, types of fibrous hybridisation technique and other relevant literature to facilitate the identification of knowledge gap relevant to the topic of impact resistance of hybrid UHMWPE fibre based ballistic panels.

2.1 Brief review of high-performance fibres

High-performance fibres can be classified as fibres which possess ultra-strength and high modulus. They are often engineered for strength and stiffness and are used in aerospace, sports equipment, and ballistic resistance applications. Several common high-performance fibres are compared in Figure 2.1.

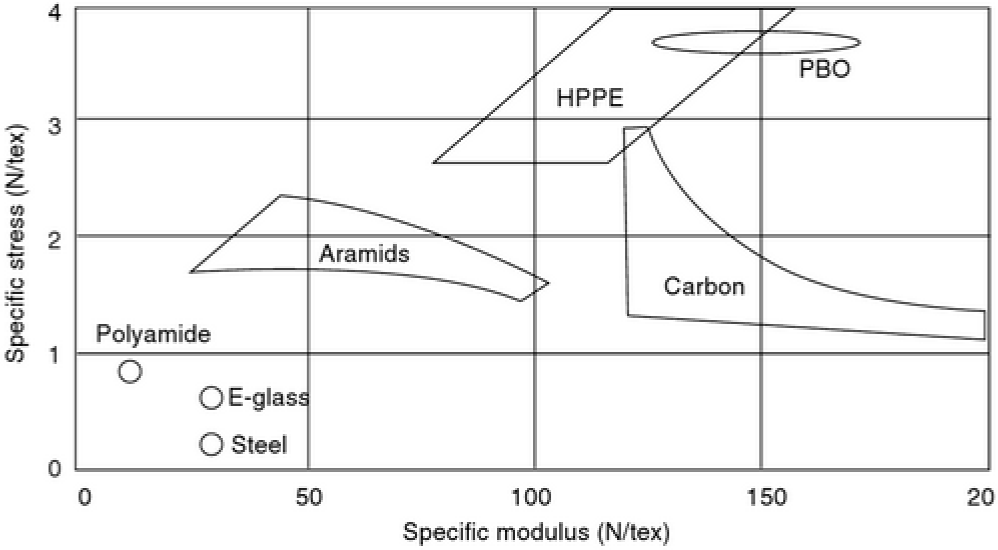
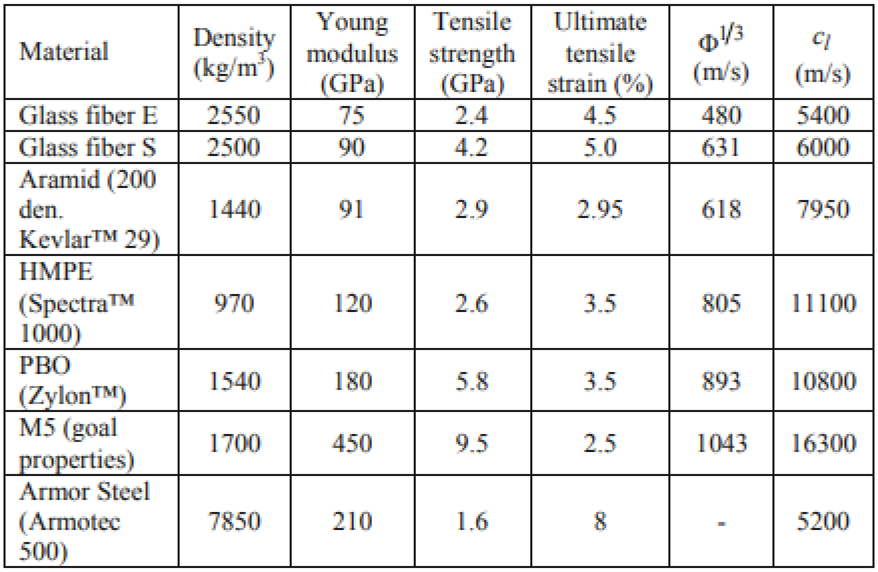


Figure 2.1. Specific strength versus specific modulus of various fibres [1].

Due to these properties, high-performance fibres are useful in the application areas where the specific strength and stiffness ratios are more competitive than conventional materials such as steel as seen in Figure 2.2.



Material	Density (kg/m^3)	Young modulus (GPa)	Tensile strength (GPa)	Ultimate tensile strain (%)	$\Phi^{1/3}$ (m/s)	c_l (m/s)
Glass fiber E	2550	75	2.4	4.5	480	5400
Glass fiber S	2500	90	4.2	5.0	631	6000
Aramid (200 den. Kevlar™ 29)	1440	91	2.9	2.95	618	7950
HMPE (Spectra™ 1000)	970	120	2.6	3.5	805	11100
PBO (Zylon™)	1540	180	5.8	3.5	893	10800
M5 (goal properties)	1700	450	9.5	2.5	1043	16300
Armor Steel (Armotec 500)	7850	210	1.6	8	-	5200

Figure 2.2. Mechanical properties of glass, aramid, HMPE, PBO and M5 fibres, compared to steel [2, 3].

The choice of fibres is a challenging task and depend greatly on the application intended for. In this thesis, impact and ballistic protection will be the main topic. Typically, in impact and ballistic events, arresting penetration of projectile, projectile deformation, decelerating and absorption of kinetic energy as well and spall shield capture are the main features that need to be addressed in the engineering of an effective protective armour [4].

Figure 2.3 plots the quasistatic tensile strength and Young's modulus of many high-performance fibres that can be exploited in a hybrid to design efficient ballistic resistant articles.

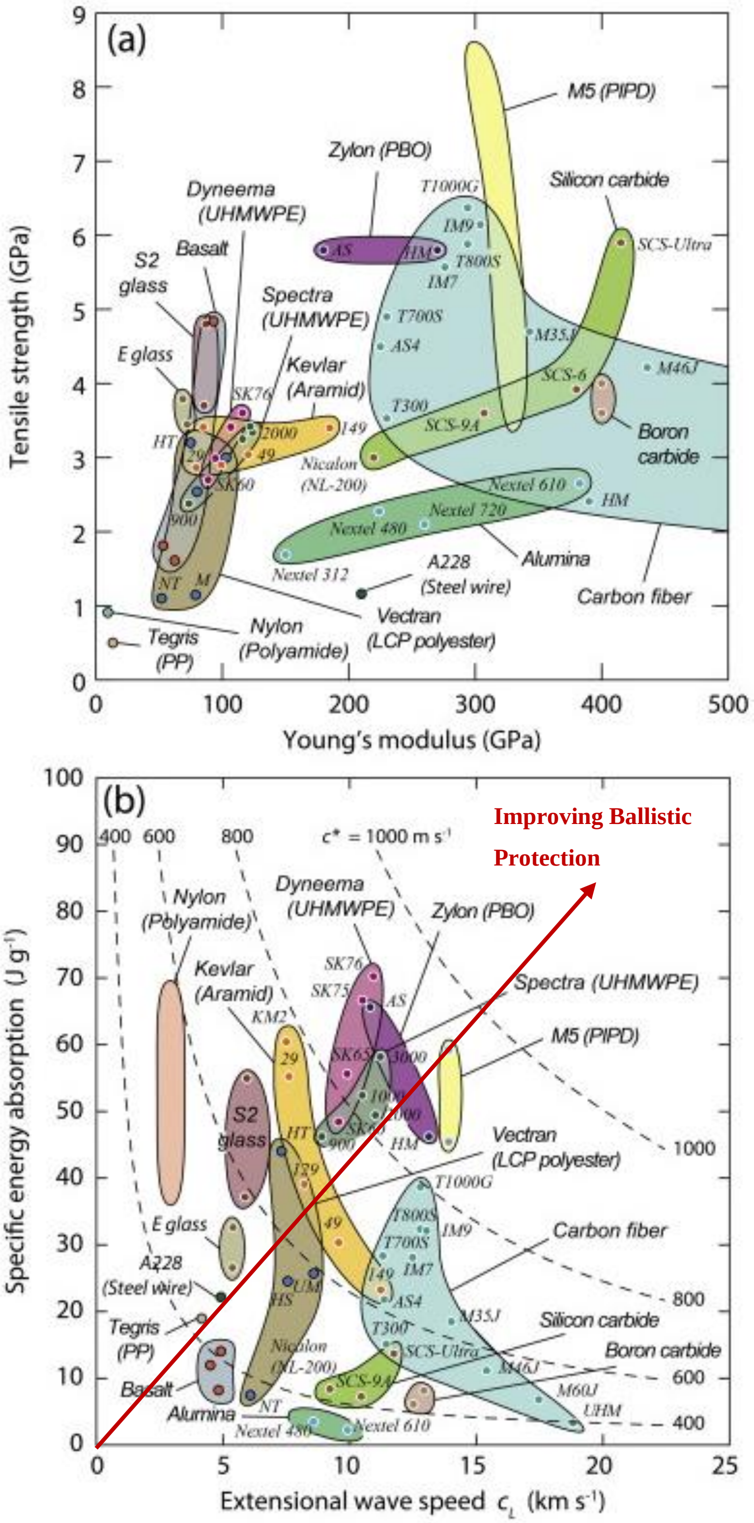


Figure 2.3. Material property charts comparing the (a) tensile strength and Young's modulus and (b) specific toughness and extensional wave speed, cL = (E/ρ)1/2 of high-performance fibres. Contours of the Cunniff velocity, c∗, are also plotted on (b) [4].

Cunniff [5] rationalised the choices of ballistic resistant fibres through scaling. Cunniff argued that the ballistic limit of fibre composites scales linearly with a material property index called Cunniff velocity c* of the fibre defined by:

$$c^* = \left(\frac{\sigma_f \varepsilon_f}{2p} \sqrt{\frac{E}{\rho}} \right)^{1/3} \qquad (1)$$

where σ_f and ε_f are the tensile failure strength and failure strain of the fibres respectively, E is the tensile modulus of the fibres and ρ their density. The two material properties that make up the definition of c* are the specific energy absorption $\sigma_f\varepsilon_f/(2\rho)$ and extensional wave speed of the fibres. A material property map with axes of these two properties is given in Figure 2.3(b), along with contours of the Cunniff velocity c*

It is interesting that a high tensile modulus like in carbon fibre is not enough. It is the combination of modulus and energy absorption that is vital in effective ballistic protection. In this thesis, hybrids of ultrahigh molecular weight polyethylene and carbon fibre were investigated for any synergistic ballistic resistant properties.

2.2 Fibre hybridisation

Material hybridisation involves combining two constituent materials to achieve a composite material with new properties. The design outcome of the hybridisation may produce materials that inherit desirable properties from the parent material. This strengthening strategy can also be extended to fibrous materials.

In fibre hybridisation, minimally two fibre types are brought together to complement the intrinsic property strengths and weaknesses of each individual fibre. The two fibre types typically formed in a composite can be categorised as low elongation (LE) and high elongation (HE) fibres. An excellent review paper by Swolfs et al aimed at summarising the various types of fibre hybridisation in polymer composites and the subsequent changes in mechanical properties through changes in failure mechanisms [6].

2.2.1 Fibre hybrid designs

The freedom to engineer and design fibre hybrid composites can come about through the choices in fibres and matrices as well as in choosing fibre orientations, plying sequence and preform types. The LE and HE fibres can be hybridised in many configurations. The three main hybrid configurations are captured in Figure 2.4.

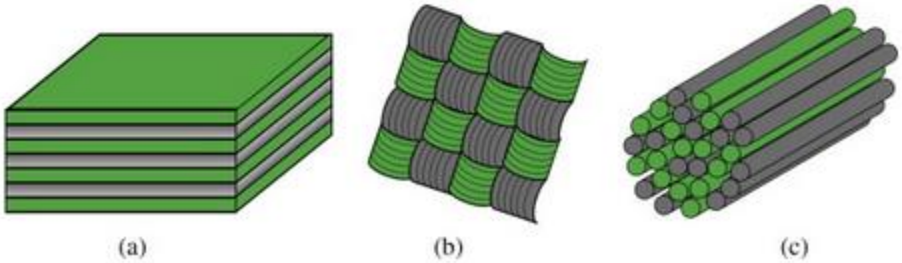


Figure 2.4. Three common types of fibre hybridization. (a) Interlayer, (b) intralayer, and (c) intrayarn [6].

Each configuration is designed to cater to the application in which the composite is intended for. The outcome in the mechanical properties of the composite is sensitive to the configuration sequences of the two constituent fibres. It is with such freedom in design strategies that allows fibre hybrid composite to be seen as an effective solution to mechanical and structural property limitations.

2.2.2 The hybrid effect

Many definitions of the term “Hybrid effect” exists due to complex differences that arise from hybridising materials together. However, Figure 2.5 captures the basic definition of the hybrid effect, which is the apparent failure strain improvement of the LE fibre in a hybrid composite compared to a non-hybrid composite [7].

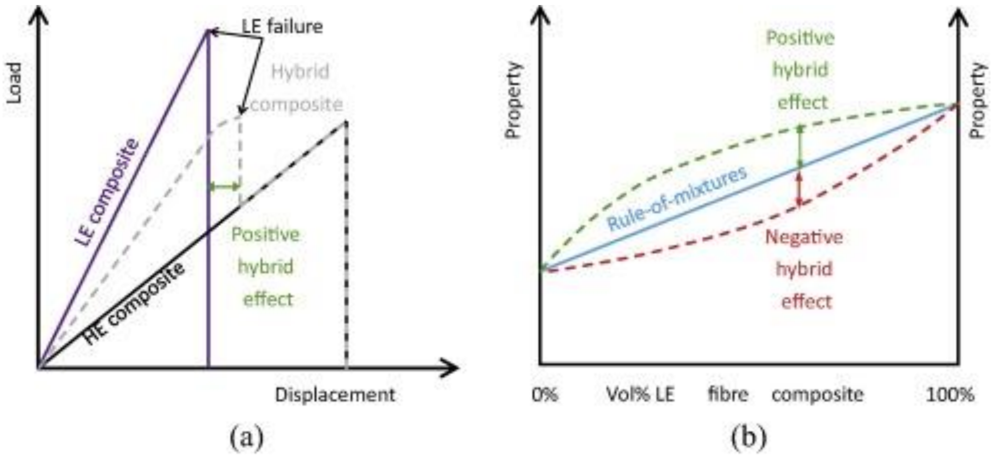


Figure 2.5. Illustrations of the definitions of the hybrid effect. (a) the apparent failure strain enhancement of the LE fibres, (at relative volume fraction of 50/50 and at twice the thickness of the reference) and (b) a deviation in properties from the rule of mixtures [7].

2.3 Hybridisation effects on impact resistance

A key mechanical property which remains as an interest of study is impact resistance. Impact resistance can be described as the ability of a material or structure to withstand a sudden load without catastrophic failure. It is, therefore, necessary to understand factors which govern failure caused by impact forces. In turn, better material hybridisation techniques can be adopted.

Impact resistance in fibrous hybrids have been extensively studied with various testing methods and performance measurements. Impact resistance are widely defined in three common ways; energy absorbed during penetration, damaged area after a non-penetration impact event and residual properties after impact. These parameters aim to measure changes in performance from hybridisation.

In this thesis, focus is placed on understanding the mechanical responses of fibre hybrid composites particularly in impact events, thus the following section describes experiments conducted by fellow researchers on this topic.

2.3.1 Fundamental parameters of impact resistance of composite materials

A review conducted by Cantwell and Morton [8] sought to summarise fundamental parameters which affect impact resistance of fibre-reinforce composites. Below are some key points mentioned in this review.

1. Strain energy absorbing capacity of the fibres. Fibres which possess a large area under the stress-strain curve were better at coping with impact forces. Several studies found that E-glass and Kevlar® failed in a more ductile and gradual manner as compared to carbon which failed catastrophically [9-12].
2. Strength of fibre/matrix interphase. It was found that weak interphases were better at stopping projectile impact by delamination and ease of fibre pull out failure mechanism which dissipates energy more effectively [13].
3. Impact velocity and strain rate. The differences in impactor speed and shape affects the local and global deformation response of the composite. Strain rate dependency is a key factor on the capacity of a composite to cope with impact forces [14-16].

2.3.2 Brief overview on the effects of positioning in an interlayer hybrid type

Several LE and HE high-performance fibres, were hybridised and tested against impact. The first comparison looks at the importance of material positioning within a panel. Layer positioning affects flexural stiffness and strength of the panel and thus alters the damage mechanism of the structure upon impact.

Symmetric hybridisation whereby LE fibres are positioned more towards the middle layers were tested by Enfedaque et al. [17] and Sevkat et al. [18]. They saw that externally placed glass fibres in a carbon/glass hybrid led to better penetration impact resistance. They both attributed this finding to the higher failure strain of glass fibre which delayed damage. However, Zulkifli et al. [19] found complete penetration when carbon was placed in the middle of an polyethylene/ carbon tested against a 9mm full metal jacket ammunition while other asymmetric layup, with the same areal density, showed significant improvements in impact resistance.

Asymmetric hybridisation types were tested by Sayer et al. [20] in an interlayer of carbon/glass fibres. A 30% improvement in the penetration impact resistance was found when carbon layers are placed on the impact side. Park and Jang [21] and White et al. [22] also tested an asymmetric hybrid of aramid/carbon fibre and found that a higher penetration impact resistance was obtained when carbon was placed on the impact side. They attributed this to the aramid layers being able to absorb energy on the tensile side. In addition, many other studies [23-25] also found advantageous effects when tough high performance polymer fibre layers were situated at the back and carbon layers on the strike face.

On the contrary, Jang et al. [26] who studied asymmetric aramid/carbon saw small improvements in impact performance regardless of the position of either fibres. However, when carbon was replaced with polyethylene (PE) fibres, it was found that placing the more ductile PE fibres on the impact side demonstrated an increased in impact resistance. These findings point to placing HE fibres on the impact side more beneficial.

The study of impact resistance still yields confusing and contradicting results possibly due to the challenge in defining and characterising the performance. Thus, the lack of a standardised testing method opens the impact experiments to minute differences which can totally throw the findings off-course. Sensitivity to the geometry of the impactor and clamping device are one such factor. Swolfs et al. [27] did an even recent review in 2019 and still found that impact resistance remains insufficiently understood.

Thus, this thesis aims to shed light on the idea of LE and HE hybridisation by focusing on hybrids of carbon and ultrahigh molecular weight polyethylene (UHMWPE) fibres.

2.4 Ultrahigh molecular weight polyethylene

A well-known fibre which fits into the category of high-performance fibre is the ultrahigh molecular weight polyethylene (UHMWPE) fibre. UHMWPE fibres are the strongest and lightest fibres available due to their high strength and low density.

The discovery and development of UHMWPE fibre were made in the DSM research laboratory in the 1960s through a novel gel-spinning process. DSM Dyneema's patented gel-spinning process, shown in Figure 2.6, involves dissolving polyethylene in a dilute solvent gel and the extrusion of the heated gel through a spinneret, forming fibres. The fibres are then drawn stepwise to build orientation and strength [28].

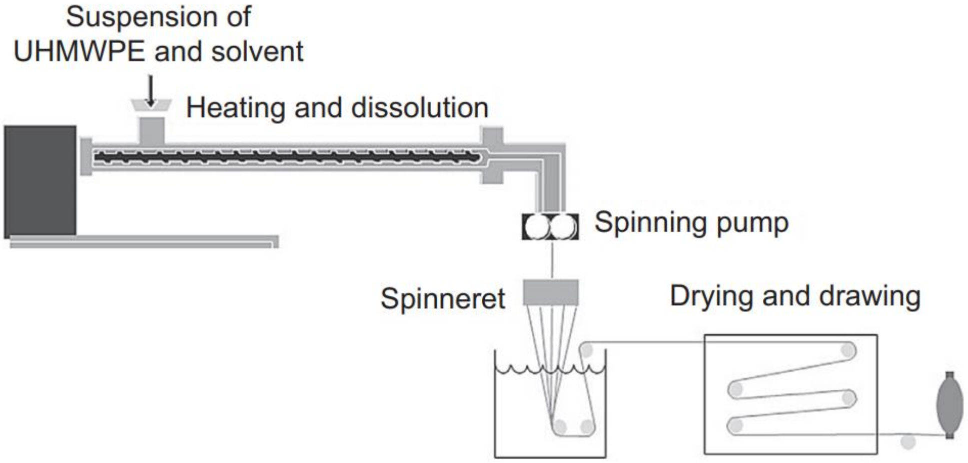


Figure 2.6. Gel-spinning process to produce Dyneema® fibres [28].

Dyneema®/ UHMWPE fibres are extremely long chains of the polyethylene monomer unit, as seen in Figure 2.7, with molecular weight in the range of millions. The longer chain means greater impact strength as there is a greater degree of intermolecular interactions along the polymer backbone by weak van-der Waals forces. This allows for an effective load dissipation along the chain.

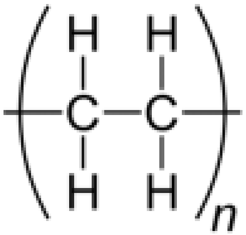


Figure 2.7. Polyethylene monomer units of UHMWPE.

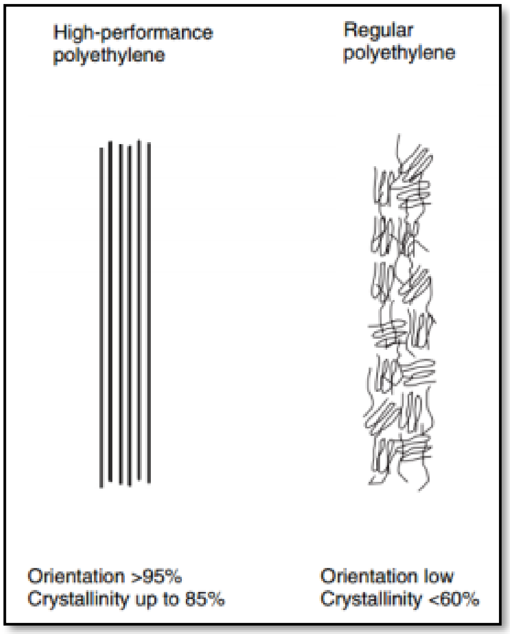
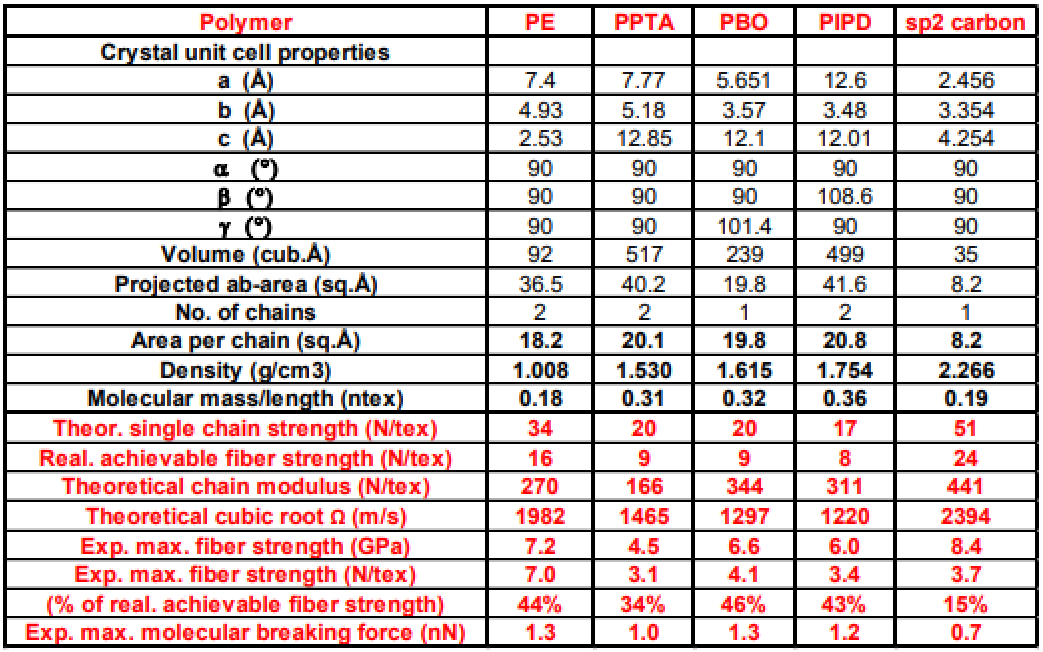


Figure 2.8. Difference between normal PE and UHMWPE (HPPE) [28].

The difference in the molecular orientations of UHMWPE fibre and to regular PE is its degree of entanglement as seen in Figure 2.8. Its high crystallinity aids in better load bearing capabilities in the axial direction thus attributing to its high strength property which is its key characteristic.

In addition, UHMWPE fibre has a density of 1.008 g/cm^3 which enables it to float in water. The exceptionally low density contributes to the high specific strength and stiffness of the fibre. This is nicely summarised by the investigative work by Harm et al., as seen in Figure 2.9, where the authors seek to compare and justify the inherent properties of UHMWPE fibre with other fibre types. It is interesting to note that theoretically, graphene is stronger than UHMWPE but its fibre strength in practice are never realised due to sensitivity to defects [29].



Polymer	PE	PPTA	PBO	PIPD	sp2 carbon
Crystal unit cell properties					
a (Å)	7.4	7.77	5.651	12.6	2.456
b (Å)	4.93	5.18	3.57	3.48	3.354
c (Å)	2.53	12.85	12.1	12.01	4.254
α (°)	90	90	90	90	90
β (°)	90	90	90	108.6	90
γ (°)	90	90	101.4	90	90
Volume (cub.Å)	92	517	239	499	35
Projected ab-area (sq.Å)	36.5	40.2	19.8	41.6	8.2
No. of chains	2	2	1	2	1
Area per chain (sq.Å)	18.2	20.1	19.8	20.8	8.2
Density (g/cm3)	1.008	1.530	1.615	1.754	2.266
Molecular mass/length (ntex)	0.18	0.31	0.32	0.36	0.19
Theor. single chain strength (N/tex)	34	20	20	17	51
Real. achievable fiber strength (N/tex)	16	9	9	8	24
Theoretical chain modulus (N/tex)	270	166	344	311	441
Theoretical cubic root Ω (m/s)	1982	1465	1297	1220	2394
Exp. max. fiber strength (GPa)	7.2	4.5	6.6	6.0	8.4
Exp. max. fiber strength (N/tex)	7.0	3.1	4.1	3.4	3.7
(% of real. achievable fiber strength)	44%	34%	46%	43%	15%
Exp. max. molecular breaking force (nN)	1.3	1.0	1.3	1.2	0.7

Figure 2.9. Comparison of maximum experimental and theoretical fibre strengths of ultrahigh molecular weight polyethylene (PE), para-aramids (PPTA), poly(p-phenylene benzobisoxazole) (PBO) PIPD and sp2 carbon [29].

In the UHMWPE ballistic composite created by DSM Protective Materials, unidirectional (UD) layers of fibres are impregnated with a thermoplastic matrix (typically 20 w% or less) and are stacked in a 0/90-degree arrangement as seen in Figure 2.10.

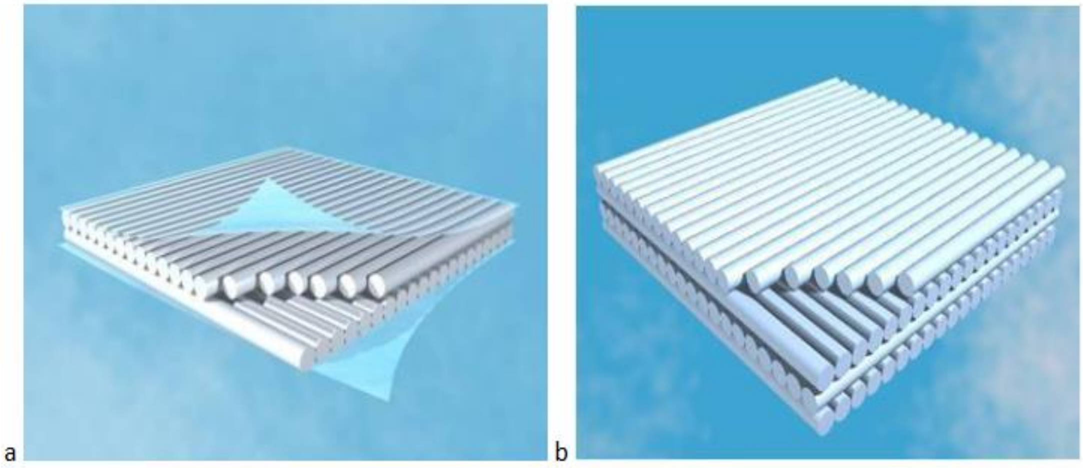
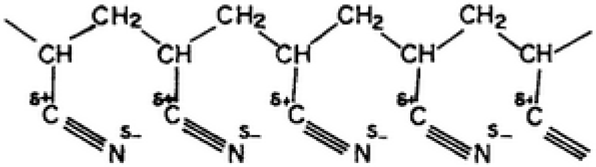


Figure 2.10. Schematic of the layup of an UHMWPE fibre composites intended for (a) flexible applications and (b) hard applications [28].

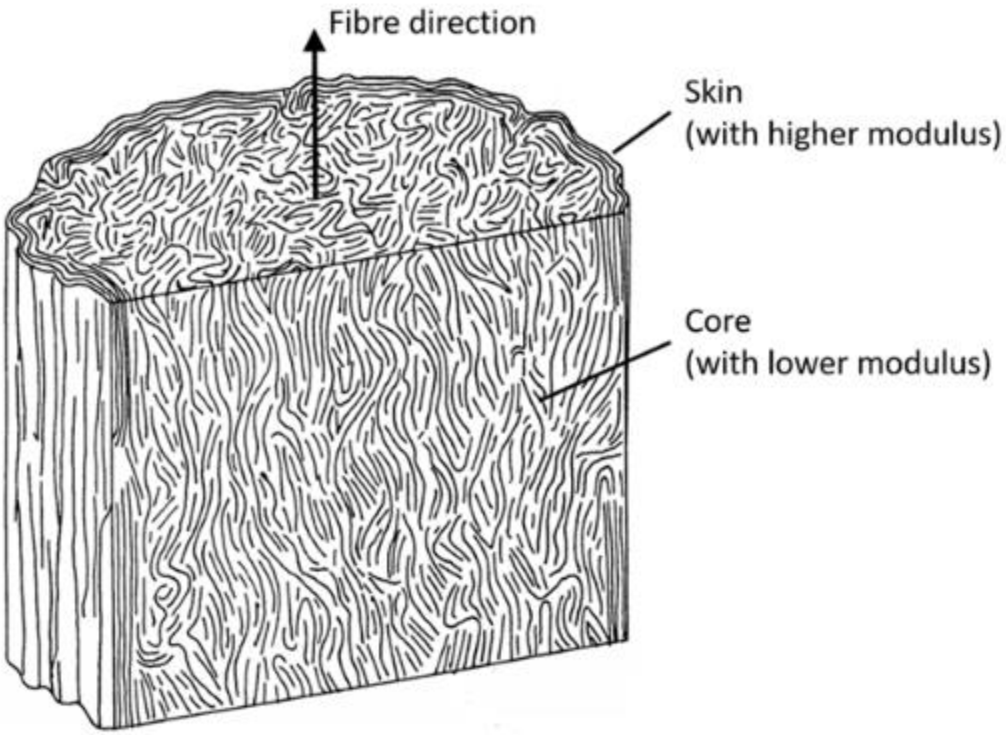
These prepregs can be moulded into different shapes (flat or curved) at high temperature and pressure depending on the intended application.

2.5 Carbon fibre

Carbon fibre is another type of high-performance fibre that is commonly used in applications which require high strength and modulus. Most commercial fibres are polyacrylonitrile (PAN)-based, in which carbon and nitrogen are the primary elements. PAN-based carbon fibres contain graphite planes that are oriented in the fibre direction and are also strongly folded. PAN-based carbon fibres possess a skin-core gradient with the skin having a higher modulus as seen in Figure 2.11. The high alignments of the graphitic planes make carbon fibres transversely isotropic.



(a)



(b)

Figure 2.11. (a) Structural formula of polyacrylonitrile (PAN) [30]. (b) Illustration of the microstructure of a PAN-based carbon fibre [31].

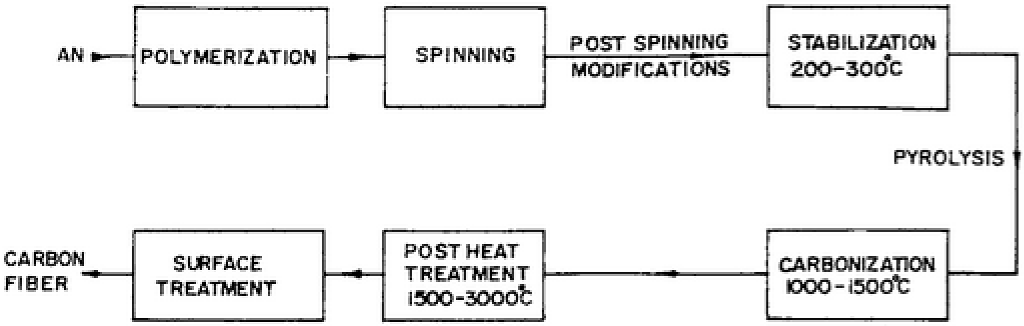


Figure 2.12. Fabrication steps of PAN-based carbon fibre [30].

The fabrication of PAN-based carbon fibre, as seen in Figure 2.12, can be summarized in the steps below.

1. Spinning: Polyacrylonitrile plastic is spun into fibres.

2. Stabilizing: Chemical alteration occurs by heating and oxygen in picked up by the fibre.
3. Carbonizing: Heat treatment expels non-carbon atoms which causes the formation of tightly bonded carbon crystals that are aligned.
4. Surface Treatment: Oxygen atoms are added onto the surface to provide better chemical and mechanical bonding properties.
5. Sizing: The surface treated fibres are finally coated with the compatible coating materials based on the adhesive used to form composite materials.

2.6 Overview of polyethylene and carbon fibre hybrids in impact resistance

In this section, a focused review on polyethylene and carbon fibre hybridisation is made which sets the background for the thesis in the later chapters. Different fibre hybridisation techniques involving polyethylene and carbon have been explored to understand synergistic properties that arise from these two types of fibres particularly in impact resistance, vibration dampening and structural properties.

Peijs et al. [32] investigated combining high performance polyethylene (HP-PE) with carbon fibres by intermingling them in an epoxy resin. The goal of this experiment was to observe changes in mechanical properties of the hybrid as compared to the pure fibre. The authors discovered possibilities of the hybrid HP-PE/carbon composites being used in structural applications with high damping and impact resistance. The hybrid HP-PE/carbon sample failed in a more ductile mode and retained its integrity after impact with enhanced structural property. This finding led the author to investigate further into impact resistant properties.

In his subsequent study, Peijs et al [33] extended the research onto understanding the effects of adding HP-PE fibre on the impact resistance behaviour of the HP-PE/carbon hybrid. The authors fabricated hybrid laminated structures by stacking prepreg plies of carbon and HP-PE fibre woven fabric in a (0,90) lay-up by placing different number of HP-PE plies on the non-impacted side of a six-ply carbon/epoxy laminate. Drop weight impact tests were used to probe the impact failure mechanics and damage evolution. The authors concluded that adding HP-PE plies to the non-impacted side of the carbon laminate had reduced the extent of damage to the composite. They attributed this finding to more efficient energy absorption mechanism in which the tough HP-PE fibres were able to absorb larger amounts of elastic energy thus minimising energy transfer to the carbon laminates. Additional energy was also dissipated by delamination at the interface. The addition of HP-PE fibres thus resulted in a composite with superior impact resistant properties than only-carbon laminate.

In the last of this series of impact investigations, Peijs et al. [34] investigated the influence of hybrid design of HP-PE and carbon fibre on impact strength. The authors fabricated samples that looked primarily into hybridising HP-PE and carbon in various interlayers and intrayarn. It was concluded that the impact performance of carbon-epoxy composites can be significantly improved by the addition of HP-PE fibres. Increased degree of hybridisation led to an increase in energy being absorbed due to high degrees of microstructural damage.

Such early works by Peijs et al. inspired future experiments that looked into fibrous hybrid composites for impact, including in ballistic resistant applications.

Bouwmeester et al. [35] investigated an intralaminar hybrid of carbon and ultrahigh molecular weight polyethylene on the impact resistance amongst other parameters. The authors observed that impact resistance increased due to the addition of a high failure strain fibre. It was noteworthy that carbon fibre and UHMWPE were found to be highly synergistic.

Jang and Moon [36] found that placing carbon at the impact side and UHMWPE fibre at the back showed better penetration limit. The authors owed this to the elastic and plastic deformation of UHMWPE fibre layers as the key to energy absorption during impact. It was also found that interfacial adhesion between carbon/UHMWPE fibre hybrid had a great influence on the impact behaviour.

2.7 Fibre hybrid composites in ballistic impact

Mankind has long sought ways to protect themselves from different kinds of threats for survival through ingenious ways of using materials from the environment. As we progress through the ages and with technological advancements, the use of non-conventional materials such as fibres are more commonly used as protective materials. As threats continue to become more deadly (ammunition), defensive techniques need also pick up.

The engineering of ballistic resistant armour is always confronted with two highly desirable design features, which are the effectiveness to arrest projectile and weight conservation. Protection from ballistic impact is still an interesting field of study especially in the use of fibre-reinforced composites. Fibres have the advantage of being much lighter as compared to conventional materials in protection such as metals.

The understanding of the ballistic impact event is crucial in the design of protective armour. During impact of the target, the kinetic energy of the projectile needs to be effectively dissipated through various damage and energy absorbing mechanisms [37]. There are a few common impact responses taking place.

1. Compressive forces on the target by the projectile. Compressive wave propagates in the thickness direction below the projectile resulting in compressive strain and transverse stress away from the impacted zone.
2. Tension in primary yarns resist penetration of projectile while deformation in the secondary yarns absorb excess energy.
3. Delamination and matrix cracking further absorbs energy through failure [38, 39].
4. Shear plugging [40].
5. Friction between projectile and target. Frictional forces aid in absorbing impact energy introduced by projectile [40].

2.7.1 Fundamental responses of yarn in ballistic impact

Yarns are made by twisting a set of fibres and they make up the basic component of ballistic protection material. Understanding the responses and failure at this level is important.

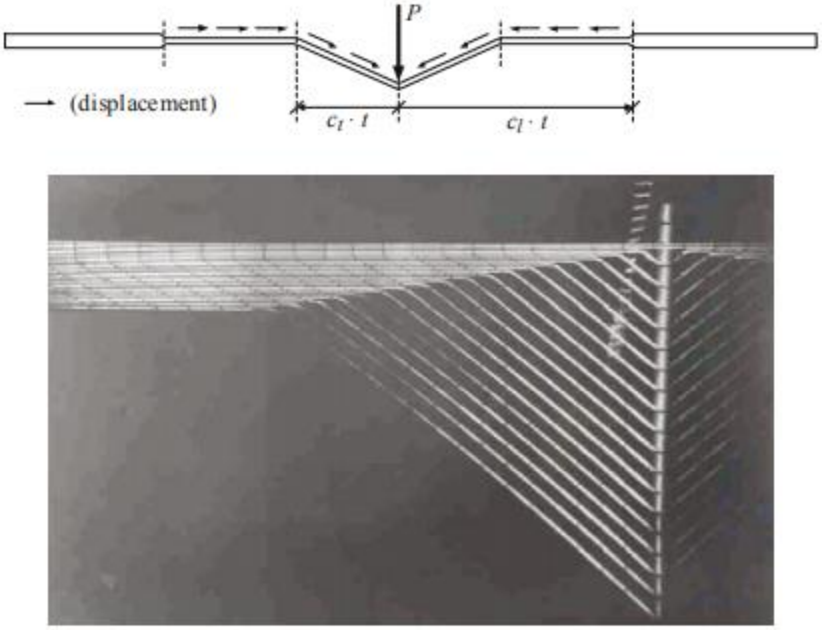


Figure 2.13. Top: Illustration of the deformation of a filament subjected to transverse impact. Bottom: Superposed and slightly displaced images of a polymeric fibre impacted by a projectile [41].

During impact, transverse and longitudinal deformation propagates away from the impact point as seen in Figure 2.13. Smith et al. [42] developed a theoretical model governing the motion of the filament.

$$c_l = \sqrt{\frac{1}{\rho}\left(\frac{d\sigma}{d\varepsilon}\right)_{\varepsilon=0}} \tag{2}$$

c_l represents the outermost longitudinal wave propagating at a constant velocity. ρ represents the mass density and the bracket term represents the Young’s modulus of the fibre.

$$c_p = \sqrt{\frac{1}{\rho}\left(\frac{d\sigma}{d\varepsilon}\right)_{\varepsilon=\varepsilon p}} \quad (3)$$

The longitudinal wave is followed by a plastic wave propagating at a slower velocity c_p.

$$U = \int_0^{\varepsilon_p} C(\varepsilon)\, dC = \int_0^{\varepsilon_p} \sqrt{\frac{1}{\rho}\left(\frac{d\sigma}{d\varepsilon}\right)}\, d\varepsilon \quad (4)$$

Material points on the fibre are accelerated towards the impact point at a velocity, U, that increases to the value at constant strain ε_p a transverse wave is formed in a shape of an inverted V with the impact point at the vertex [3].

$$c_t = \sqrt{\frac{1}{\rho}\frac{\sigma_p}{1+\varepsilon p}} \quad (5)$$

c_t represents the transverse wave velocity.

Abrate et al [3] reviewed the fundamental behaviour of yarns during ballistic impact and thus noted that the Young’s modulus of the fibre, its density and its tensile strength are the key properties to look out for in order to predict the ballistic performance of the yarn.

2.7.2 Ballistic failure mechanism of UHMWPE plates

Prior to hybridising UHMWPE fibres, it is essential to first look at the mechanism of penetration of laminates comprising of UHMWPE fibres in polymeric matrix. Attwood et al. [43] conducted a detailed study on the failure and revealed an interesting penetration mechanism upon ballistic impact of UHMWPE beams and plates.

Three penetration mechanism were previously proposed for the penetration of fibre composite. They are schematically highlighted in Figure 2.14.

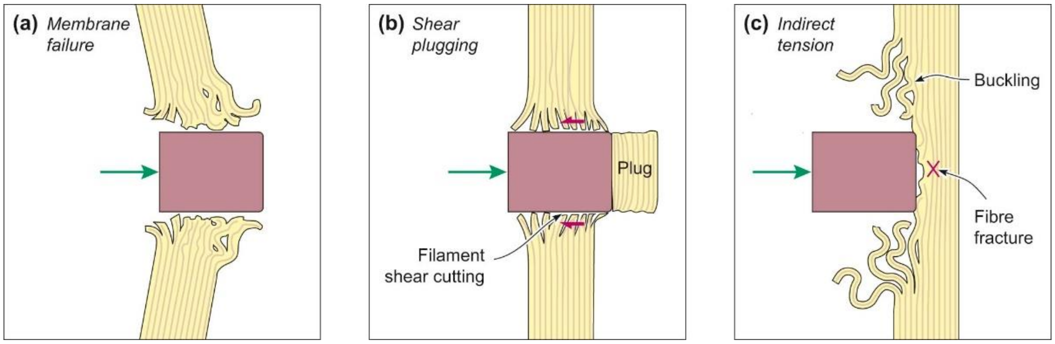


Figure 2.14. Illustration of three common penetration mechanisms observed in fibre composites (a) Failure by tensile stretching in a string-like mode [44] (b) shear-off at the edges of the projectile and the consequent formation of a shear plug [45]; and (c) progressive tensile ply failure by indirect tension developed due to the compressive stresses under the projectile [46, 47].

Attwood et al. considered these mechanisms but proposed their own findings for the failure specifically for a 0/90 UHMWPE composite beam upon ballistic impact. It was classified as the indirect tension mechanism as seen in Figure 2.15.

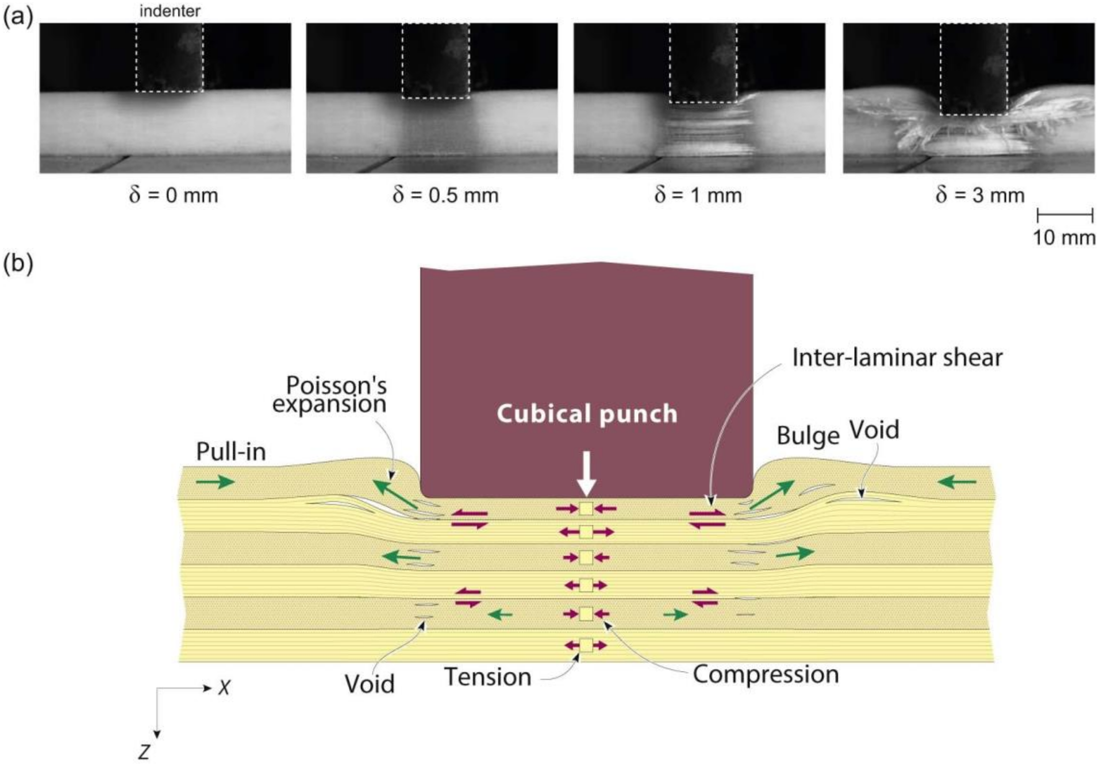


Figure 2.15. Schematics of the indirect tension mechanism [43].

The indirect tension mechanism as a failure mechanism describes how the plies in contact with the indenter experiences through-thickness compression and fail in in-plane tension.

2.8 Overview of polyethylene and carbon hybrids in ballistic impact

The use of carbon fibre composites in structurally demanding applications is well researched. The use of fibrous hybrids for the purpose of ballistic resistant and the engineering of lightweight armour is still of interest.

Larsson and Svensson [48] explored the idea of fibre hybridisation, particularly using carbon, PE and PBO fibres to look into achieving residual strength after ballistic impact. Samples were fabricated with differences in the positioning of various fibres. The authors found that carbon fibres placed at the impact site was advantageous for ballistic velocity limit and compression strength after impact. However, no clear explanation was drawn for the reported results.

The quantification of ballistic impact performance by looking at back face signature (BFS) is limited in literature. Particularly when it comes to (BFS) performance of ballistic panels, little has been published on the effects of hybridisation of UHMWPE based ballistic panels with small amounts of carbon fibre composite layers to improve this property [33, 48, 49]. One rare example is the book chapter of Folgar [50] that is focused on military helmet development and reports the use of a carbon-epoxy outer shell for an UHMWPE helmet.

2.8.1 Carbon – ultrahigh molecular weight polyethylene intralaminar hybrid

A recent hybridisation strategy of intralayering carbon and UHMWPE fibre has been gaining interest and traction within the fibre hybrid research field. Figure 2.16 displays the novel woven UHMWPE-carbon hybrid fabric which was developed by DSM primarily to enhance impact resistance and vibration dampening of homogeneous carbon fibre composite typically used in bicycles and leisure sport equipment [35, 51]

Figure 2.16. Novel woven fabric developed by DSM; an intralayer of carbon and ultrahigh molecular weight polyethylene fibre.

Now, the fibrous responses to impact, both by low velocity drop weight and high velocity ballistic impact are being studied by several groups. To elucidate on the impact response of this hybrid fabric, Zhao et al. [52] conducted two main tests namely the drop weight impact test and the ballistic test against a steel ball against fabricated panels consisting of only the hybrid composite and one with only carbon composite as reference. The two tests established that the hybrid carbon-UHMWPE fabric failed differently from the reference carbon fabric. The authors concluded that the UHMWPE inherent properties such as high toughness and failure strain prevented the splitting of the bottom surface of the laminate during impact thus improved its overall penetration limit. Figure 2.17 shows the observable difference of back face damage of the two types of fabric.

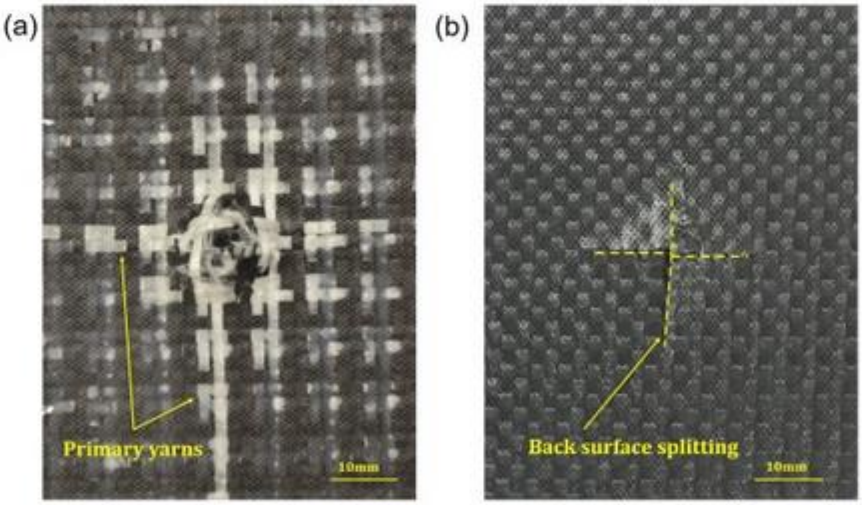


Figure 2.17. Visual observation of the back surfaces of hybrid specimen post impact by a steel ball at a speed of 100m/s (a) and (b) woven carbon specimen at a speed of 89m/s [52].

Zhao et al. [53] looked into the delamination behaviour of the carbon-UHMWPE hybrid composites via investigating the Mode I and Mode II fracture toughness. The group used a double cantilever beam (DCB) test and an end notched flexure (ENF) test. Several schemes of composites were selected. The authors concluded that the presence of UHMWPE fibres resulted in a 67% improvement in Mode I and more than 40% in Mode II interlaminar fracture toughness by attributing it to the larger UHMWPE yarns than carbon yarns on the interface creating epoxy resin rich areas.

Zhou et al. [54] took an even closer look at the Mode II interlaminar fracture behaviour of the hybrid woven carbon-UHMWPE epoxy composite by adopting similar ENF test. Several different composites with intralaminar and interlaminar hybridisation schemes were fabricated with non-stick Teflon inserted in the middle interface to initiate the fracture. The fracture growth and interfacial cracks were captured in Figure 2.18. The authors found that hybridisation with UHMWPE fibre greatly improved the Mode II fracture resistance to delamination due to extensive fibre bridging and relatively large fracture process zone.

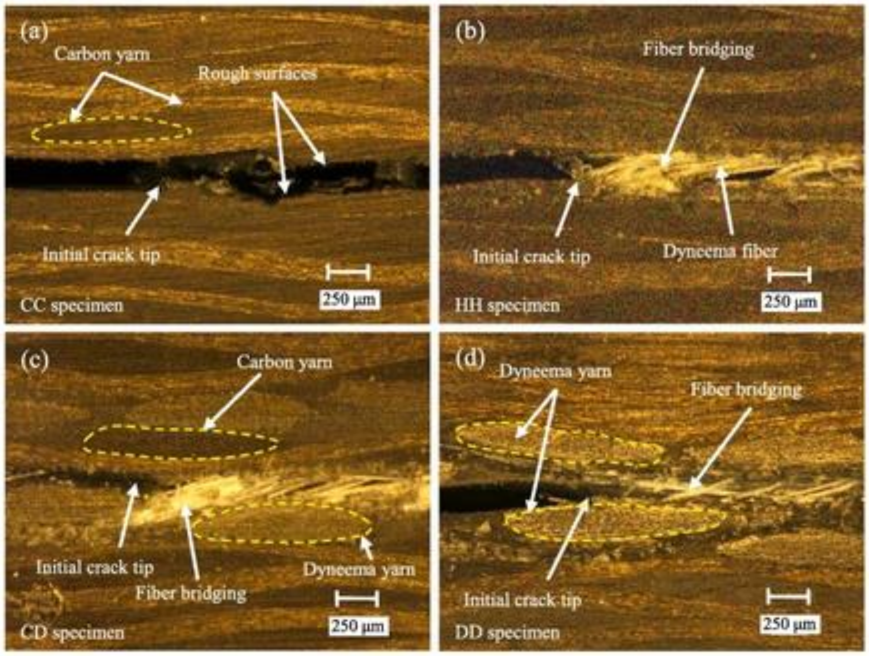


Figure 2.18. Edge photographs of ENF specimens (a) Carbon-carbon; (b) Hybrid-hybrid; (c) Carbon-UHMWPE; and (d) UHMWPE-UHMWPE specimen [54].

Cao et al. [55] simulated the in-plane mechanical behaviour of a twill 2,2 carbon-UHMWPE fabric reinforced epoxy composite by finite element (FE) model of a meso-scale representative volume element (RVE) to further understand the failure mechanism of such a composite.

Abtew et al. [56] wrote an excellent review paper on the ballistic impact mechanism on textiles and fibre-reinforced composites. In this review, it provided an overview of various works that enlisted the use of fibre and textiles in ballistic impact resistance. A highly relevant section mentioned in this review is the ply arrangement and sequence of the composite [57-59]. It was concluded that interply hybridisation [23, 60] and increased fibre angles [61] in the composite showed improve ballistic resistance by attributing it to significantly more effective energy absorbing mechanism [62].

2.9 Identified gaps in literature that will be addressed by this thesis

This literature review described the context of the research topic which is to look into fibre hybrid composites mainly on the impact resistance. Prior works related to fibre hybrid composites in low and high velocity impact are available in literature, however, newer, and novel hybridisation ideas are invented. Due to the challenging testing and various definition of impact resistance, this research area is still very much alive and gaining traction. There is still much work to achieve the goal of elucidating and understanding of key failure mechanism of fibrous hybrids upon impact [19].

This thesis will investigate an intra-interlayer type of dual fibre hybridisation on the impact and ballistic resistance performance. In addition, looks deeply into the back face signature reductions when tested against a projectile typically used in urban conflict. All in all, the thesis will serve to contribute to guidelines for the designing of a fibre-based ballistic resistant protective armour.

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Chapter 3

Experimental Methodology

The low and high velocity impact responses of a hybrid UHMWPE-carbon ballistic panel were investigated by static and dynamic loading. The static load test consists of understanding flexural properties through the use of a three-point bend test whilst the dynamic load test involves (a) the use of a drop weight impactor and (b) ballistic testing against a 9mm full metal jacket projectile to simulate actual impact events. The proposed methodology seeks to unravel fundamental differences in failure mechanism upon impact where positioning of carbon fibre containing layers affect the ability to reduce back face deformation in an UHMWPE fibre based ballistic panel. This chapter starts with the description of the materials used in this thesis and introduces the various tools and techniques that were employed to characterize the impact process.

3.1 Experimental Methodology

The study of fibrous material responses to impact loading is challenging due to the complex modes of energy transfer and failure mechanism. The priority of this study was to understand the fundamental factors positioning of carbon fibre in an ultrahigh molecular weight polyethylene ballistic panel play in enhancing structural rigidity and reducing back face deformation. As such, the design of the various hybrid sample panels is critical.

The experiments were organised to establish carbon fibre as a synergistic material to UHMWPE fibre capable of eliciting beneficial ballistic resistive properties. Following which, focus was placed on the effects of interply positioning towards being able to reduce back face deformation. The study finally looked into a novel intraply fabric of carbon and UHMWPE fibre in an intralayer-interlayer hybridisation type against ballistic impact.

The understanding of the different responses of the various hybrid panels to impact provides engineering design rules for ballistic applications where high penetration limit and structural robustness are of concern.

3.1.1 Mechanical characterisation of hybrid panels

The impact study will begin by the mechanical characterisation of the various hybrid samples. In this study, structural properties of the panels namely the flexural yield strength and flexural modulus will be obtained through a quasi-static three-point bend test using the ASTM D790 as a guide. This test was chosen to provide a first order mechanistic understanding of the bending of the ballistic panel which occurs during an actual ballistic impact, clearly realizing that the actual ballistic impact happens at much higher rates and consequently evokes additional mechanisms.

3.1.2 Unravelling the fibrous interactions of UHMWPE and carbon fibre upon impact

The correlation between the changes in the force-displacement curve, by low velocity drop weight impact test, of the various hybrid panel can be interpreted to obtain insights into the fibrous and interfacial interactions in the intraply-interlayering of the laminates. The differences in the failure mechanism between the mixed UHMWPE-carbon laminate versus the homogeneous carbon laminate will be documented to highlight key factors contributing to the reduction of back face deformation.

3.1.3 Simulating Ballistic Impact

9mm full metal jacket projectiles at various speeds were used to simulate actual ballistic impact events to establish the hypothesis that the pioneering use of an intraply-interlayer hybridisation of an UHMWPE fibre-based panel can yield positive ballistic resistive properties mainly to reduce back face deformation. Secondary effects such as projectile deformation difference may be interpreted to indicate advantages of positioning of stiffer materials within the ballistic panel.

3.2 Chemicals and reagents

In this experiment, the UHMWPE fibre based hard ballistic panels were fabricated using Dyneema® HB26 plies as the principal material. Dyneema® is DSM’s premium brand for UHMWPE fibre. HB26 prepreg is a 0/90/0/90 unidirectionally-assembled SK76 UHMWPE fibre impregnated with a polyurethane matrix having an areal density of 0.264kg/m^2 [1].

The novel intraply fabric consists of a 2/2 twill interwoven UHMWPE SK76 fibre + 3K carbon fibre having a fabric areal weight of 0.235kg/m^2 while the woven homogeneous Carbon fabrics had the same 2/2 twill-woven construction with a fabric areal weight of 0.200kg/m^2. The mixed UHMWPE-Carbon and Carbon dry fabrics were obtained from Cramer and Torayca respectively.

The matrix for the laminates were formed from a two-parts epoxy resin by the trade name EP62-1, which was supplied by Master Bond Inc. Parts A and B of the epoxy resin had densities of 1.17g/cm^3 and 0.98g/cm^3 respectively.

3.3 Sample Preparation

Hard ballistic panels of 400mm by 400mm dimensions were produced. To fabricate the hybrid hard panels, two or four layers of epoxy impregnated woven fabric were consolidated onto 12 plies of prepressed HB26 panel. The woven fabric composite layers were placed at two positions on the panels namely the front (strike face) and back. Figure 3.1 is a schematic diagram to show the lay-up sequence of each layer within the composite.

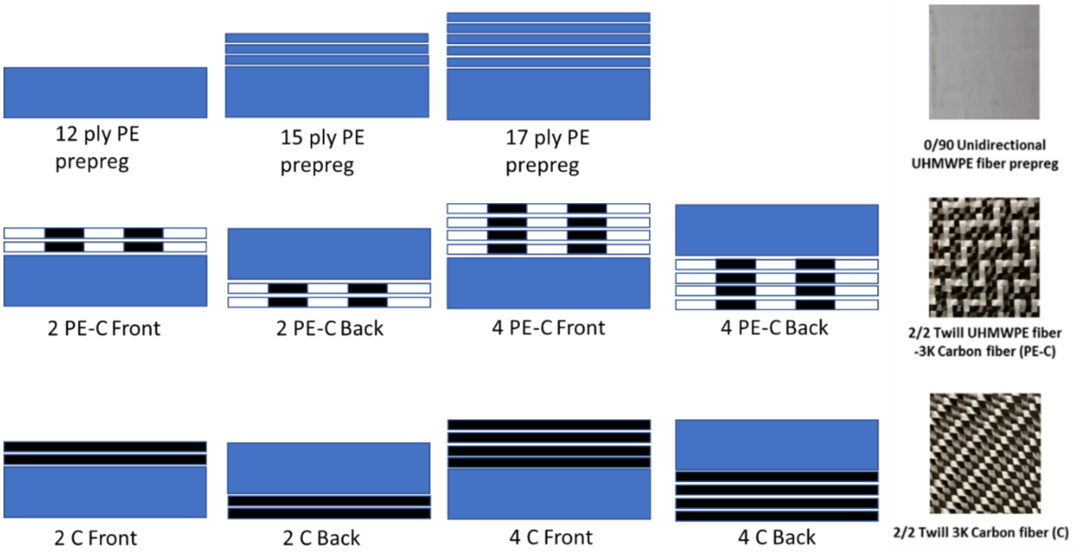

Figure 3.1. Schematic diagram representing the number and lay-up sequence of each material within the hard panel test samples. Hybrid panel consists of 12 ply PE prepregs interply hybridized with two- or four-layers of 2/2 Twill-woven PE-C or C fabric.

3.3.1 Fabric impregnation

Hand layup technique was used in the impregnation of the dry PE-C or C fabrics. A fibre to matrix weight ratio of approximately 60:40 was chosen for each twill fabric layer. The required amounts of part A and part B epoxy were first mixed using a centrifuge mixer for 30 seconds and was then manually spread over each dry woven fabric layer.

To complete the impregnation process and subsequent curing, the fabric stack is later pressed uniaxially using a hydraulic hot press machine together with the prepressed PE panel.

3.3.2 Hydraulic hot-pressing cycles

A hydraulic hot press was used in a two-stage pressing cycle. To allow for ease of removal of the panels from the hot platens of the press machine, silicone release films were placed on the top and bottom of the stack before the pressing cycle.

The first stage of pressing involves only HB26 PE prepreg plies. The plies are first subjected to a constant temperature of 125°C at a pressure of 20 bars for the first 20 minutes of the cycle followed by 165 bars of pressure for 45 minutes and subsequently the sample was cooled at 25°C for 10 minutes. Pressure consolidation recommendations were obtained from a work by Lässig et al. [2].

The second stage of pressing involves curing the epoxy impregnated fabrics that had been laid onto the prepressed PE panel (as explained above). While the epoxy resin is still viscous, the composite panel is subjected to a temperature of 80°C and a pressure of 20 bars for 30 minutes and subsequently cooled at 25°C for 10 minutes thus hardening and completing the epoxy curing process. The 400mm by 400mm panels were then cut into 200mm by 200mm samples by bandsaw.

3.3.3 Summary table of the various 200mm by 200mm panels fabricated.

Table 1. Summary of the stacking sequence and areal densities of the various ballistic panel fabricated.

Sample	**Stacking Sequence**	**Areal Density (kg/m^2)**
12 ply PE	[PE prepreg]$_{12}$	3.17
15 ply PE	[PE prepreg]$_{15}$	3.96
17 ply PE	[PE prepreg]$_{17}$	4.48
2-Front	[PE-C]$_2$ / [PE prepreg]$_{12}$	3.89
	[C]$_2$ / [PE prepreg]$_{12}$	3.82
4-Front	[PE-C]$_4$ / [PE prepreg]$_{12}$	4.61
	[C]$_4$/ [PE prepreg]$_{12}$	4.47
2-Back	[PE prepreg]$_{12}$/ [PE-C]$_2$	3.89
	[PE prepreg]$_{12}$/ [C]$_2$	3.82
4-Back	[PE prepreg]$_{12}$/ [PE-C]$_4$	4.61
	[PE prepreg]$_{12}$/ [C]$_4$	4.47

notes:
PE prepreg denotes Dyneema® HB26 prepreg ply used.
PE-C denotes epoxy impregnated 2/2 Twill-woven, mixed UHMWPE with Carbon fibre fabric layer.
C denotes epoxy impregnated 2/2 Twill-woven, homogeneous 3K Carbon fibre fabric layer.

3.4 Experimental Methods

3.4.1 Three-point bending

To study the flexural strength of each panel concept, ASTM D790 standard for three-point bending test was adopted. Five beam samples having beam length, width, and height of 150mm, 13mm and nominally 4mm respectively were pre-cut from the various ballistic hard panels. For the three-point bending test, an Instron 5567 mechanical test bench with 500N load cell was used. A span length of 128mm was chosen. The upper loading and lower support anvils measure 5mm in diameter. The loading nose was displaced vertically by 20mm at a test speed of 5mm/min.

3.4.2 Drop-weight impact test

Drop-weight impact tests were performed according to ASTM D7137/ D7136M. Figure 3.2 shows the drop weight impact test set up as well as the top and bottom in-built circular clamps of 40mm diameter. A hemispherical impactor of 20mm by diameter can be attached to an adjustable drop mass. The impact force was measured by a force sensor connected to the impactor. Each 100mm by 100mm sample was placed on top of a circular impact frame of 40mm diameter. Clamps in-built within the drop-weight impact tester machine automatically engage prior to impact ensuring the samples are securely fastened with 3kN force to the impact frame. In this study, three impact energies were selected namely 12.5J, 25J and 50J. The drop mass and height were adjusted accordingly to ensure the desired impact energy subjected to each specimen. The average data of three samples were taken per lay-up design. The results obtained from this test were highly reproducible with coefficient of variation in key values evaluated in this study below 0.1 making the observed differences significant.

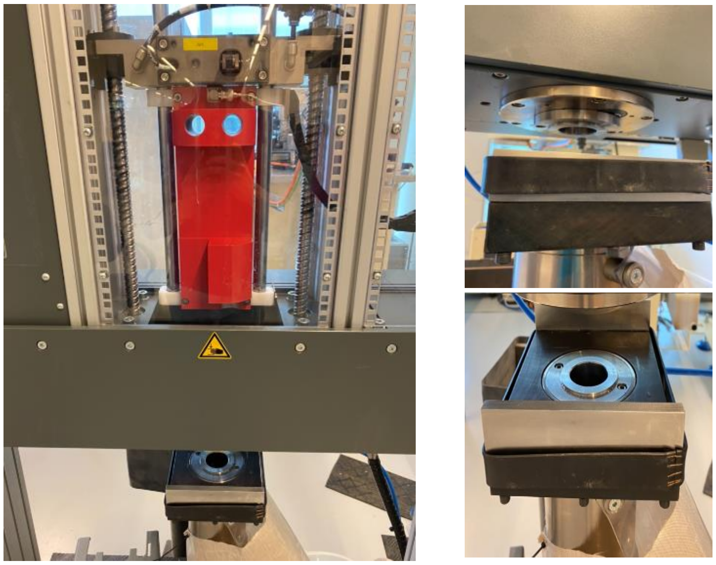

Figure 3.2. A Zwick/Roell HIT230F drop-weight impact tester displaying the top and bottom clamping plates.

3.4.3 Ballistic performance

High velocity impact tests were performed using an automatic projectile system developed in the shooting range of DSM Protective Materials Asia Pacific Technical Centre. The ballistic test set up is presented in Figure 3.3. Each 200mm by 200mm target panel was placed five meters from the tip of the gun nozzle where it was strapped firmly against Roma Plastilina clay backing OR in the presence of a Teflon spacer, with a 12.5mm thickness, (detailed dimensions described in chapter 7). The Roma Plastilina Clay was conditioned according to the requirements set out in the NIJ standard [3]. In this thesis, all panels were tested against the 9mm Full-Metal Jacket (FMJ) projectile of 8-gram mass. A light screen box, which measures the speed of the impacting projectile by measuring the precise time of entry and exit, was placed three metres from the gun nozzle.

Figure 3.3. Ballistic test set up; Light screen for projectile velocity determination was placed 3 metres away from the gun nozzle and the target sample was placed 5 metres from the gun nozzle.

The ballistic impact tests were designed to investigate the damage evolution and failure mechanism differences in a mixed UHMWPE-carbon or homogeneous Carbon composite panel. To evaluate the ballistic performance of the composite panels, two performance measurements namely the V_{50} ballistic limit value and the back-face signature (BFS) data were collected and compared.

3.4.3.1 V_{50} ballistic limit test

The ballistic limit velocity, denoted by V_{50}, is the threshold velocity at which statistically 50% of the projectiles penetrate, and 50% are arrested within the bounds of the sample. In our experimental design, eight-shot data, one shot per 200mm by 200mm panel, were obtained for each panel lay-up to ensure repeatability in performance and sufficient shot-to-edge distance. The projectiles were precisely laser-guided to the middle of each sample panel. To evaluate the V_{50}, the impact velocity of four shots of penetration and four shots of stops were considered.

The speeds of the projectiles are set by the amount of gun powder loaded into the cartridge case. The following describes the methodology followed during the shooting test of eight shots.

- The speed of each subsequent shot is increased by 20m/s if the projectile is stopped by the panel.
- The speed of each subsequent shot is decreased by 20m/s if the projectile penetrates the panel.
- The overall speed range (lowest and highest) of the 9mm FMJ projectile used in calculating the V_{50} performance should not exceed 40m/s to ensure reliable results.

To ensure the precision of the V_{50} value, a pair of values consisting of the highest and lowest projectile speeds are removed. The arithmetic mean value of the remaining three penetrations and three stop speeds are considered in the V_{50} calculation as seen in the formula below.

$$V_{50}(\text{m/s}) = \text{Sum of lowest speed penetrations and highest speed stops} \, / \, \text{Number of shots} \, (=6)$$

3.4.3.2 Back face signature

To evaluate the deformation of the panels after shooting, the back-face signature (BFS) of non-penetrating shots were taken by measuring the deepest point of imprint on the conditioned Roma Plastilina clay as seen in Figure 3.4, following NIJ 0101.06 standard requirements [3]. For comparison purposes, the 9mm FMJ projectile velocity of nominally 200m/s or 360m/s was chosen for ballistic evaluation.

Figure 3.4. A vernier calliper was used to measure the back face signature which corresponds to the deepest point made on the Roma Plastilina clay backing post-impact.

3.5 Sources of experimental errors

Practically it is difficult to maintain a constant projectile velocity, most of the data collected were of shots that were in the range +/- 40m/s. Due to the complex nature of ballistic tests, such as the slight variations in clay consistency and projectile speeds, the BFS values typically show some spread. This source of error was mitigated by obtaining several data and averaging the readings.

Systemic errors were minimised by ensuring the instruments were calibrated and zeroing was performed before conducting of the experiments.

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Chapter 4

Interlayering Effects of Carbon Fibre on an UHMWPE Ballistic Panel

In this chapter, the effects of inter-ply stacking sequences on the ballistic and structural performance of ultra-high molecular weight polyethylene (UHMWPE) fibre/Carbon fibre hybrid composite hard ballistic panels have been studied. Effects of positioning on small amounts of carbon layer on the mechanical and ballistic performance of the hybrid panels are discussed. Ballistic testing against 9mm full-metal jacket (FMJ) ammunition and mechanical three point bending tests were carried out. A mechanistic understanding of the ballistic impact behaviour and failure mechanism are described. The strategic positioning of carbon layers to boost structural and ballistic performance are explained.

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4.1. Introduction

Lightweight, high ballistic limit and low back-face signatures (BFS) upon impact are highly desirable performance measurements in the engineering of ballistic protection. On top of these characteristics, ballistic applications often need to be structurally sound with high stiffness and high yield strength. One example is in military helmets whereby ear-to-ear stiffness is an important feature. The complex and myriad performance demands of ballistic applications make selecting the proper materials challenging.

Earlier studies also delved into the idea of hybridizing UHMWPE layer with carbon composite layer. Li et al saw that adding a moderate amount of carbon fibre into UHMW-Polyethylene/epoxy composite led to a great improvement in both compressive and flexural properties [1]. But due to the brittle matrix, such composites are not suitable for ballistic applications. The work by Larsson and Svensson showed that adding organic fibres to carbon fibres was advantageous for ballistic performance [2]. They investigated the residual compressive strength after ballistic impact and the ballistic limit velocity of the hybrid material only. They did not investigate the hybrid effects on the BFS and out-of-plane flexural properties. Furthermore, they mostly considered high fractions of carbon with a relatively small amount of UHMWPE, leading to structurally sound composites at the expense of weight and ballistic performance. For ballistic applications it is more interesting to study the opposite whereby UHMWPE fibre composite is the principal material and the carbon fibre composite layer is the minority add-on material. The matrices they used in their study, in which the polyethylene fibres were embedded, were either a relatively stiff epoxy or a very soft elastomeric matrix. More recent hard ballistic UHMWPE composites based on polyurethane matrices have an intermediate stiffness. The study of Cwik et al. [3] screened many inter-hybrid panel concepts for their ballistic performance under very high velocity impact with a 20mm copper FSP projectile of 60.25g. The reference of a monolithic 23mm thick HB26 panel (dimension 250mm x 250mm, areal density of 23.5 kg/m², ballistic limit against the investigated threat approx. 700m/s) is compared to hybrids where a certain areal density fraction (>13%) of the strike face is replaced by alternative materials. As the focus of their work is on ballistic performance and not on structural rigidity and it is known that *un*cured carbon fibre laminates have a higher ballistic limit than their cured counterparts [4] the authors apply dry carbon fabric (among other materials) together with a second alternative material (PP, bulk UHMWPE or Tegris®) to replace 35% or 28% of the strike face areal density.

Contrary to the reported studies we want to investigate if an UHMWPE cross-ply composite with an intermediate stiffness matrix can actually be hybridized with *small* amounts of carbon fibre epoxy laminate, and still provide high ballistic protection, combined with low BFS and good structural performance at minimal weight.

Particularly when it comes to BFS performance of ballistic panels, little has been published on the effects of hybridisation of UHMWPE based ballistic panels with small amounts of carbon fibre composite layers to improve this property [2, 3, 5]. One rare example is the book chapter of Folgar [6] that is focused on military helmet development and reports the use of a carbon-epoxy outer shell for an UHMWPE helmet.

Thus, in this chapter, the objective was to investigate if low amounts of pure carbon fibre/epoxy composite layers, placed in various positions, within the UHMWPE-based hard ballistic panels can improve the BFS as well as structural behaviour, without affecting its ballistic limit performance. These findings provide guidance for designing an optimal hybrid stacking sequence for applications that need to be structurally stable without compromising on its ballistic properties.

4.2 Experimental procedure for ballistic impact study on interlayer hybridisation

The goal in this chapter was to establish that carbon fibre, in woven form, could be used as a synergistic material with UHMWPE fibre specifically for ballistic resistant applications. It was also of interest to understand plying position on the effects on ballistic as well as in reducing back face deformation. Chapter 4 represents the first trial studies on the idea of strategic positioning of stiff add-on regions in an UHMWPE fibre-based panel. The add-on carbon-epoxy laminates were added in the front, middle, back, and front-back. The sample preparation techniques of the various hybrid ballistic panel consisting of the interlayer laminates of homogeneous carbon-epoxy and UHMWPE-polyurethane were described previously in Chapter 3. The table below summarises the samples fabricated in this first trial look.

Table 2. Summary of panel concepts fabricated.

Sample	Material Configuration	# of layers used per material respectively
a	HB26	12
b	C/HB26	2/12
c	HB26/C/HB26	6/2/6
d	HB26/C	12/2
e	C/HB26/C	2/12/2

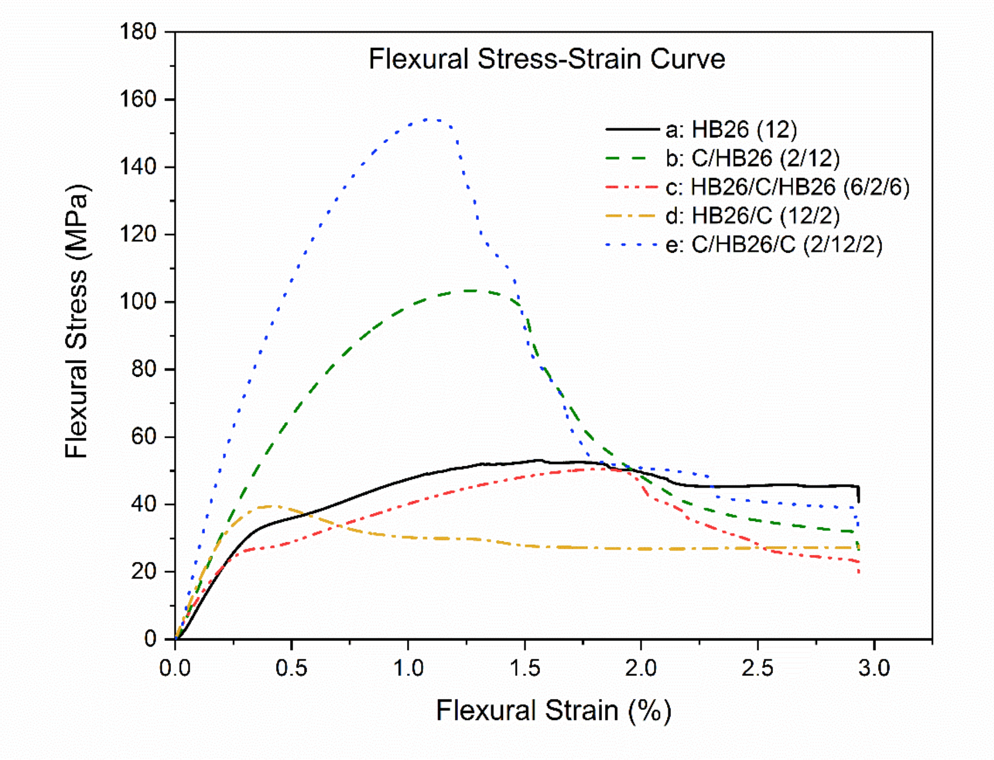
notes:
HB26 denotes the grade of Dyneema® prepreg ply used.
C denotes epoxy impregnated 2/2 Twill-woven, 3K Carbon fibre fabric layer.

Mechanical characterisation via the three-point bending test was conducted to obtain flexural properties of the various hybrid panels designed. Ballistic testing against 9mm full metal jacket projectile was conducted to obtain penetration limit (V_{50}) as well as back face signature. The unexpected ballistic resistive properties and failure mechanism of the different hybrid panels are compared in this chapter.

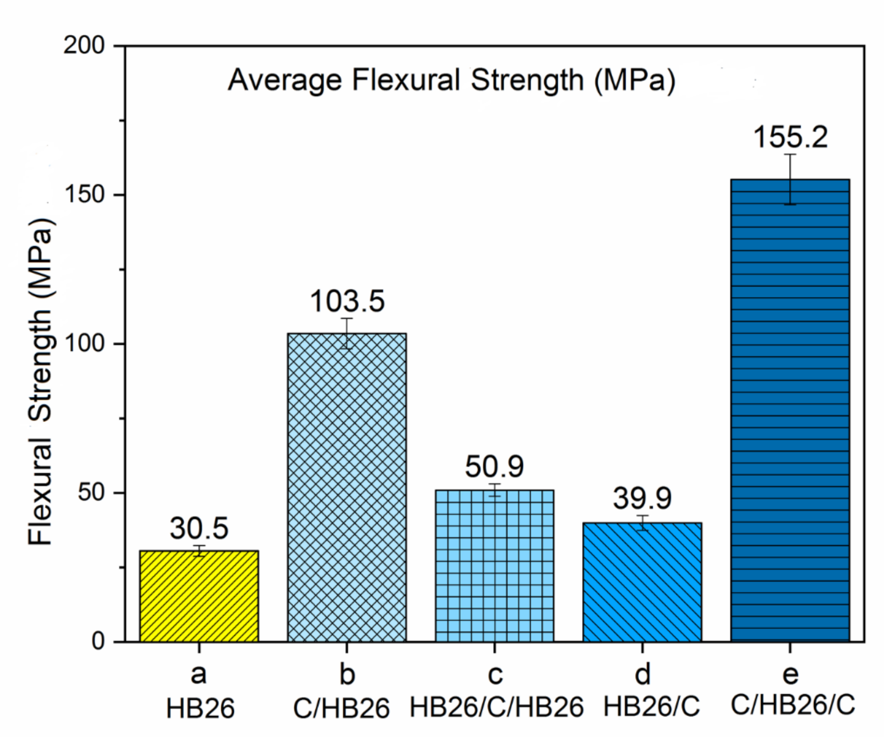
The quasi-static three-point bending test and dynamic ballistic test of the concepts are discussed together to develop a mechanistic understanding of the impact event. In a ballistic non-perforation impact the target panels display bending of the back-face. This happens at a range of strain rates and by complex mechanisms, however, to support understanding it is illustrative to compare the investigated configurations also in a quasi-static bending test on a beam. In addition, the three-point bending test gives a good indication on the structural rigidity of a product. This is important for ballistic application that have a structural requirement next to ballistic ones, such as for vehicle armour in military helmet applications where the ear-to-ear compression stiffness is an important feature. For further reference refer to [7].

4.3. Static test: Flexural Strength and Flexural Modulus

The quasi-static test responses of the hybrid panels subjected to three-point bending testing according to ASTM D790 were noted. Structural properties such as flexural strength and modulus were collected. The results are presented in Figure 4.1 below. The values of the flexural properties are obtained from the average of five samples per hybrid concept. The apparent flexural strain and flexural stress is calculated as described in ASTM D790 from the force vs. midpoint deflection data and known sample geometry. That evaluation assumes linear beam theory that is not fully applicable to HB26 as the compressive stiffness of that material is lower than the tensile stiffness causing a shift of the neutral axis and other nonlinear effects, thus the calculated values should be treated as apparent properties. This imbalance manifests itself from the fact that the C-front-faced HB26 where the carbon layer that is stiff in compression is on the compressive side shows a higher flexural strength than the reverse concept where the HB26 is on the compressive side without support of carbon. Flexural strength is determined at the point of maximum force while the flexural modulus is obtained from the initial slope of the flexural stress-flexural strain curve.


Flexural Stress-Strain Curve
a: HB26 (12)
b: C/HB26 (2/12)
c: HB26/C/HB26 (6/2/6)
d: HB26/C (12/2)
e: C/HB26/C (2/12/2)
Flexural Stress (MPa)
0
20
40
60
80
100
120
140
160
180
Flexural Strain (%)
0.0
0.5
1.0
1.5
2.0
2.5
3.0

(A)


Average Flexural Strength (MPa)
Flexural Strength (MPa)
0
50
100
150
200
30.5
103.5
50.9
39.9
155.2
a
HB26
b
C/HB26
c
HB26/C/HB26
d
HB26/C
e
C/HB26/C

(B)

(C)

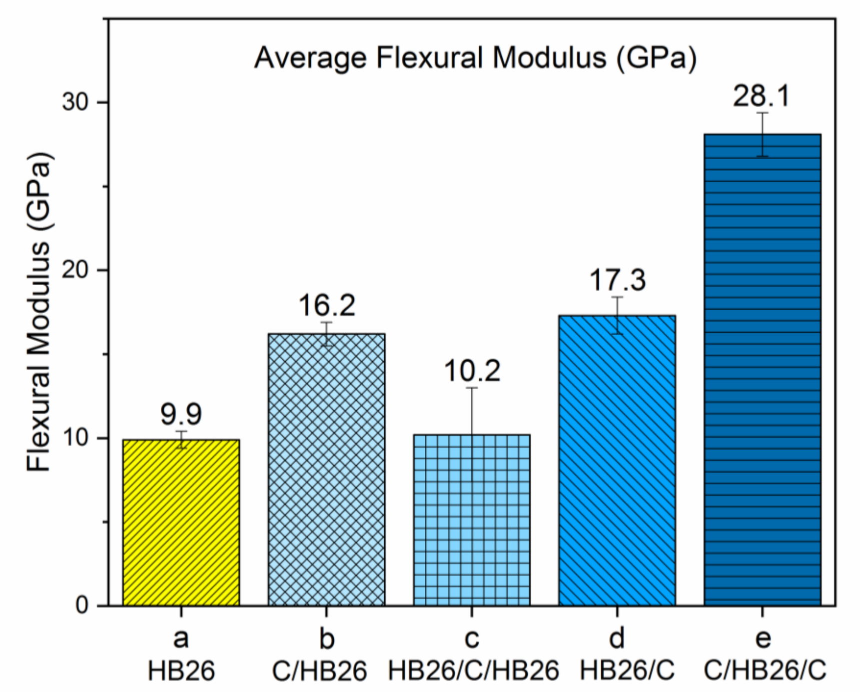


Figure 4.1. (A) The flexural stress-strain curves of the various hybrid panel concepts. (B) A comparison of average flexural strength of the various hybrid panel concepts. (C) A comparison of average flexural modulus of the various hybrid panel concepts. (a) Neat HB26, (b) Front-faced carbon fibre composite layer hybrid, (c) Middle carbon fibre composite layer hybrid, (d) Back-faced carbon fibre layer composite hybrid and (e) Front-back carbon fibre layer composite hybrid.

As seen from the flexural strength results in Figure 4.1(B), when compared against the neat HB26 panel concept, the addition of two carbon fibre composite layers results in a dramatic improvement in its flexural strength especially for the front and front-back hybrid configuration by approx. 240% and 410% respectively. Noteworthy improvements were also observed for the middle and back hybrid configurations by 67% and 31% respectively. The flexural strength improvement can be explained by the asymmetry of the strength of UHMWPE in compression and tension [8]. During bending, the neutral axis of the neat HB26 concept shifts towards the bottom tensile side due to the low compressive strength of the UHMWPE fibres. This means that a larger proportion of the beam height experiences compression than tension upon bending, hence its low yield strength. Thus, the addition of a stiffer (in compression) and rigid carbon composite layer at the front, which is the compressive side of the beam, restores the compressive stiffness of the top compressive side causing the stark increase in the flexural yield strength.

Differences were also observed for the flexural modulus performance of the hybrid panels. As seen from the results in Figure 4.1(C), the addition of carbon composite layers in the front, back and front-back hybrid concepts had shown a significant improvement in the overall flexural modulus, when compared against the neat HB26 panel, by approximately 64%, 75% and 184% respectively. However, no significant improvements were observed for the middle hybrid concept. These results demonstrate that the inclusion of the carbon fibre composite layers at the right location enhances structural properties like bending rigidity.

Improvements in the flexural modulus for the front and back hybrid configuration are the result of a stiffer overall beam due to the addition of the carbon-epoxy layer. The asymmetry of the modulus of UHMWPE panel in compression and tension is not as noticeable as for the yield strength. The reason is that while the yield strength is evaluated at the maximum load further down the test, the flexural modulus is evaluated right at the start of the test where the UHMWPE fibres still contribute to the compressive modulus [8]. The middle hybrid configuration had not much improvement when compared to neat HB26 as the stiff carbon layer is positioned close to the neutral axis and thus provides no significant contribution to the bending rigidity.

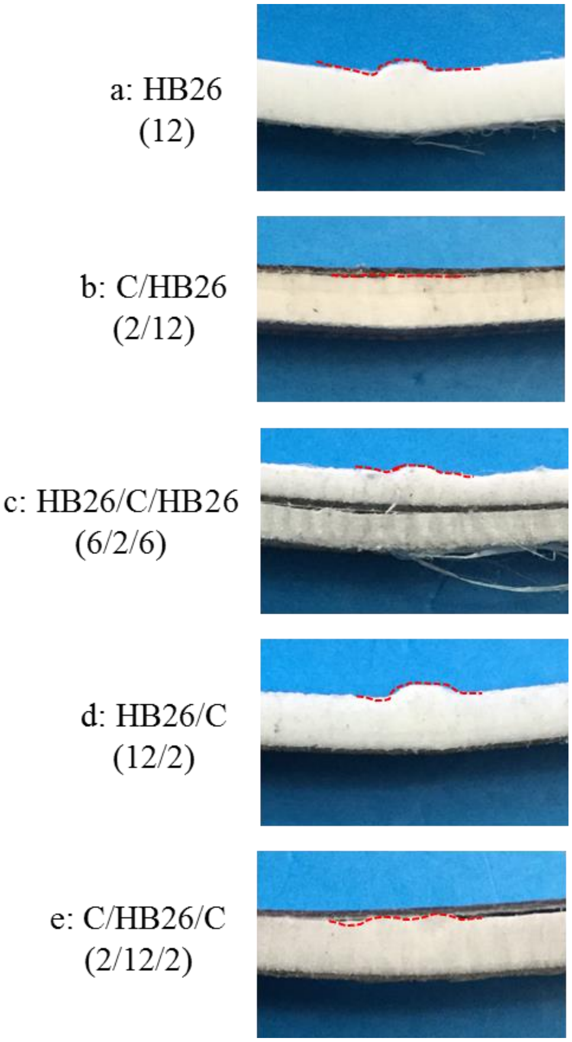


Figure 4.2. Observable differences in the extent of buckling of the 12 plies of UHMWPE component in the hybrid beams subjected to the three-point bending test of (a) Neat HB26, (b) Front-faced carbon fibre composite layer hybrid, (c) Middle carbon fibre composite layer hybrid. The red dashed line highlights the deformed configuration of the upper HB26 edge.

In addition to flexural force response, an interesting observation was made in the different extent of buckling of the UHMWPE component of the hybrid beams after the three-point bending test between the different hybrid concepts. As seen in Figure 4.2, significant differences were observed in the degree of buckling, most notably, when comparing (a) neat UHMWPE beams with hybrid beams containing carbon fibre composite layer at the front face namely in concepts (b) and (e). For concepts (b) and (e) there is significant suppression of the bump seen. In the buckling some small-scale delamination between the HB26 layers is seen.

Buckling in the hard panels is caused by the easy interlaminar shearing of the HB26 layers relative to each other combined with the poor intrinsic compression strength of UHMWPE fibres [8-10]. Small scale delamination plays a role. If the material locally delaminates, the critical buckling stress reduces, causing buckling of plies on the compressive side. Clear differences in the extent of buckling post three-point bending were observed with the greatest suppression seen for the front and front-back carbon hybrid beams. The presence of the stiffer carbon composite layer has physically suppressed the buckling. These observations could lead to further research work on the possibility of enhancing structural properties of UHMWPE based applications.

4.4. Dynamic test: Ballistic properties

4.4.1. V_{50} ballistic limit

The V_{50} ballistic value of the various hybrid panels, were systematically compared with each other to highlight the differences in performance. The average result of six shots data per sample type are represented in Figure 4.3 below. All projectiles used in this study were 9mm FMJ (DM41).

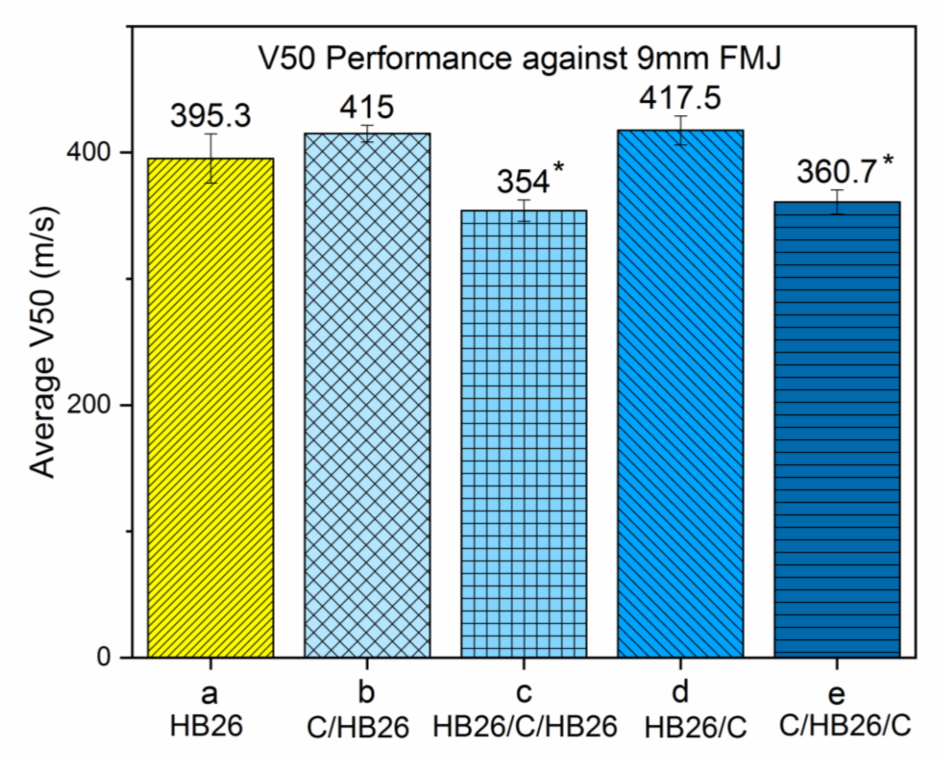


Figure 4.3. A comparison in V50 ballistic limit performance of (a) Neat HB26, (b) Front-faced carbon fibre composite layer hybrid, (c) Middle carbon fibre composite layer hybrid, (d) Back-faced carbon fibre composite layer hybrid and (e) Front-back carbon fibre composite layer hybrid.

As seen in Figure 4.3, when compared against neat HB26 panel, the addition of two carbon composite layers at the front, middle, back, and front-back of the hybrid panel had resulted in different V_{50} performance. The hybrid front and back facing panels showed a 5% improvement in the V_{50} performance. Although the improvement is relatively small, it is good to note that the ballistic limit performance had not been compromised by this addition. On the other hand, a statistically significant drop (marked with an asterisk) of 12% and 10% in V_{50} performance was observed for the middle and front-back hybrid concept respectively when compared against neat HB26 panel.

The slight improvement in V_{50} ballistic limit performance for the front and back facing carbon hybrid panel may be attributed to an overall stiffer panel which increases the decelerating force the projectile encounters as witnessed by the change in projectile shape as seen in Figure 4.5(B) below. Although the brittle carbon fibres do little to improve the ballistic limit, a more deformed ('mushroomed') projectile nonetheless increases the contact surface area to the impacted panel for effective energy dissipation by the UHMWPE fibres. Pure carbon is an inferior ballistic material than UHMWPE of same areal density as shown in a study by Karthikeyan et al where the ballistic limit of a cured carbon-epoxy plate was only a quarter of a HB26 plate of the same areal density [11]. Similar observations are reported by Cwik et al. [4]. The middle hybrid concept was the worst performer probably due to the thin UHMWPE laminate at the front that is hindered to deform in membrane mode by the middle carbon barrierlike discussed by O'Masta et al. [12]. As for the front-back concept, the membrane deflection of the UHMWPE layers were greatly inhibited by the rigid carbon composite sandwich structure. These led to an overall reduction in the mechanism of energy absorption of the UHMWPE fibre [13-15].

4.4.2. Back face signature (BFS)

A second performance metric, the back-face signature was evaluated using the average of a six shots data per sample type. The measurements of the back-face signature are presented in Figure 4.4.

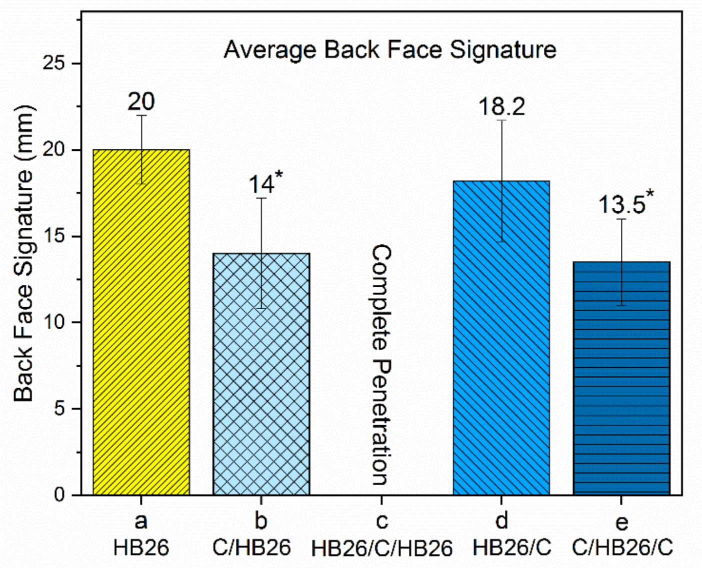


Figure 4.4. A comparison of the average back-face signature caused by the impact of the 9mm DM41 projectile nominally at 360 m/s (a) Neat HB26, (b) Front-faced carbon fibre composite layer hybrid panel, (c) Middle carbon fibre composite layer hybrid panel, (d) Back-faced carbon

fibre composite layer hybrid panel and (e) Front-back carbon fibre composite layer hybrid panel. No BFS data could be obtained for the (c) middle carbon hybrid panel as full perforation of the panel occurred at the selected testing velocity.

Interestingly, statistically significant reduction (marked with an asterisk) in BFS were observed for the front-faced and front-back facing hybrid panels of approximately 30% and 33% respectively when compared against neat HB26 panels whilst only a 9% reduction is seen for the back-faced hybrid panel despite the similarity in V_{50} performance of the front-faced and back-faced hybrid panels. No BFS data could be determined for the middle hybrid panel configuration as it was completely penetrated at the testing velocity of 360 m/s.

Figure 4.5 depicts the cross-sectional view of panels post ballistic testing against 9mm FMJ bullet together with a sketch highlighting relevant features.

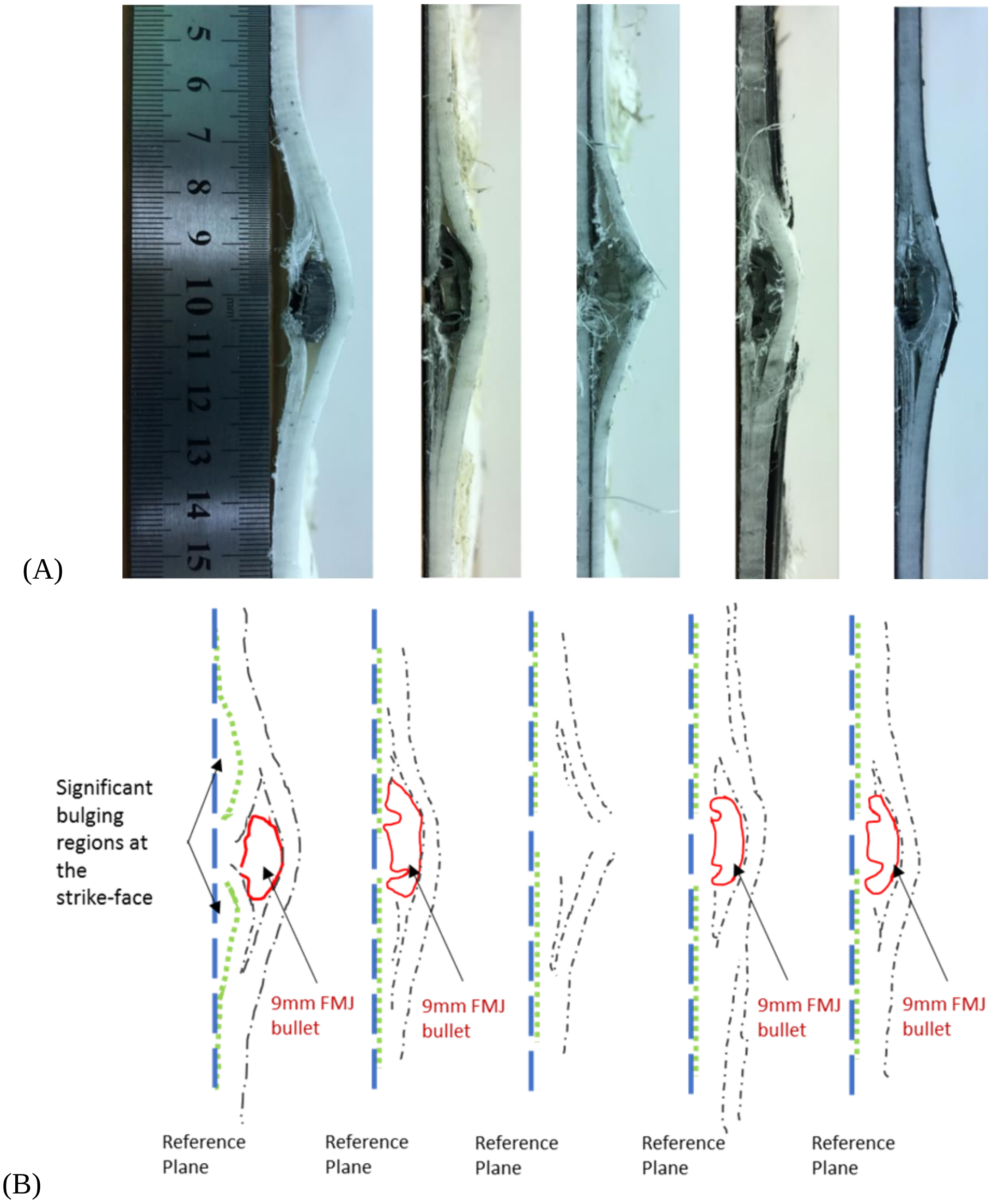


Figure 4.5. (A) Cross-sectional view of the panel after shot with 9mm FMJ projectile arrested (B) Outline of the arrested projectile and damage post impact within the (a) Neat HB26 panel, (b) Front-faced carbon fibre composite layer hybrid panel, (c) Middle carbon fibre composite layer hybrid panel (complete penetration), (d) Back-faced carbon fibre composite layer hybrid panel, and (e) Front-Back carbon fibre composite layer panel.

From Figure 4.5, we can see that in the absence of a carbon composite layer for the neat HB26 concept, the greatest bulging at the strike face of the panel is observed (as seen in the green dotted line from the reference plane) thus translating in the greatest BFS measured of all the panels. The significant reduction of BFS for the front-facing carbon configuration is related to the suppression of the bulging effect away from the point of entry of the projectile. The front facing carbon layer thus changes the global deformation mode, by suppressing local bending away from the impact location even though it was locally penetrated. This is a consequence of the increase in bending stiffness and yield strength of the panel, as well as that the well adhering carbon laminate prevents drawing-in of the fibres in the in-plane direction that would generate extra length for BFS. For the back-faced carbon composite layer hybrid panel we notice that despite the absence of bulging on the strike face, the carbon composite layer at the back was still severely damaged. As the flexural stress-strain curve of this concept suggests, Figure 4.1(A) this is due to the bulging of the tensile side exceeding the flexural strain that the brittle carbon laminate can withstand, causing the carbon composite layer to fracture and lose its supporting properties. Concerning the middle configuration, the thin UHMWPE laminate at the front and back had failed to provide sufficient material to absorb local impact energy and thus resulted in a failure to arrest the projectile altogether. The greatest reduction was seen for the front-back hybrid configuration. This could be due to the combined effects seen in the front-faced and back-faced hybrid panel. However, a lower V_{50} ballistic limit performance was observed for the front-back hybrid panel when the panel becomes too rigid. This shows that the right balance of stiffness and flexibility is necessary in designing an optimized hybrid panel.

In summary, the presence of a well-adhered stiff carbon composite layer at the front face has reduced the bending compliance of the UHMWPE component of the panel thus assisting in withstanding the bulging. This suppresses the global bulging deformation mode of the UHMWPE layers, thus reducing the BFS. This is similarly observed in the flexural bending test as seen in Figure 4.2, where the UHMWPE layer buckling was suppressed as the panel becomes structurally stiffer. Another interesting observation is that the perforated but elsewhere overall well-adhered carbon-epoxy layer at the front, notably for the front facing carbon hybrid panel, could have assisted in preventing the drawing-in of the immediate UHMEPW layers, thus assisting in the reduction of the bulging of the panel. Our results suggest that the greatest positive effect in improving structural performance whilst maintaining ballistic limit performance is to place carbon (stiff in in-plane compression) at the front (impact) side of the UHMWPE hard ballistic panels. In structural applications on the side that encounters compression under bending loads.

4.5 Effects of interfacial adhesion

From our experiment, we saw how a stiffer and resistive panel to bending and buckling had a great effect on its static (flexural test) and dynamic (ballistic test) performances. Key factors to improving its performance is the ability of the panels to suppress buckling and bending of the UHMWPE component of the hybrid panel. In order to do so, it is essential that the carbon layer adheres well to the UHMWPE composite layers. In our experiments this was the case. Generally, one may consider improving interfacial adhesion between the UHWMPE and carbon composite layers. An improvement in this could further enhance the resistive force to buckling and bending.

4.6 Overall design considerations

All in all, from the results of our experiment, indeed adding the carbon composite layers onto UHMWPE fibre panels would yield desirable structural properties without the loss in ballistic performance. One may argue that replacing the same weight of carbon composite material with UHMWPE fibre would yield a greater V_{50} ballistic limit velocity due to the increase in the amount of high tensile strength fibre to absorb energy. However, the gain in supplementary benefits in BFS and flexural performance would be greatly reduced. Hence if one considers next to the ballistic limit velocity the structural performance *and* BFS as key criteria, it is better to add a small amount of carbon fibre layer to the UHMWPE-based application at the right position.

4.7. Conclusion

In this chapter, a significant positive hybrid effect is observed when carbon is added onto an UHMWPE hard ballistic panel in both ballistics as well as structural performance. Most notable effects were seen in differences with regard to BFS as well as flexural strength and modulus. The presence of a stiffer carbon fibre composite layer on the UHMWPE hard ballistic panel on the outside had improved the bending rigidity of the panel.

Through a front facing carbon hybrid configuration, a significant reduction in BFS as well as a dramatic improvement in flexural strength could be obtained. Hence during designing of panels involving UHMWPE fibre in ballistically and structurally demanding environments, one may choose to add a few layers of carbon composite in the outer layers of a hard-ballistic panel.

Future research should investigate the reasons as to why middle carbon configuration performed the poorest. One possible mechanism to consider are through-thickness shock waves that are reflected as tensile waves at a low impedance boundary but as compressive wave at a high impedance layer causing additional pressure on the UHMWPE enhancing failure by the indirect tension mechanism [16] and their interaction with the projectile in the light of Nguyen [17].

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Chapter 5

Low Velocity Impact of Intra- and Interlayers of UHMWPE/Carbon laminates

In this chapter, the effects of hybridizing hard ballistic unidirectional cross-ply Ultra-High Molecular Weight Polyethylene (UHMWPE) fibre ballistic panels with composite layers of woven mixed PE-Carbon (PE-C) fibre fabric on low velocity impact performance, with a particular focus on back face deformation were studied. Mechanical falling dart impact test were employed to provide mechanistic understanding of the typical bulging event during ballistic impact of hard panels. Forces and displacements during the impact event were analyzed, showing the unique responses of these hybrid hard ballistic composite panels. The differences in the performance of these add-on laminates were discussed in terms of survivability and energy absorption.

5.1. Introduction

Fibrous materials have long been promising in the designing of lightweight and ballistic resistant armor. Fiber-hybrid composites consist of two or more fiber types typically embedded in a matrix. The lack of desirable inherent material property of a primary fiber can be overcome by combining it with a secondary fiber to produce composites that have properties with a better compromise than the individual fibers themselves. The material of interest in this study is the Ultrahigh Molecular Weight Polyethylene (UMHWPE) fiber. UHMWPE fiber are an excellent candidate for impact resistive applications [1, 2]. Classified as a high-performance material, UHMWPE fiber possesses higher strength-to-weight ratio and higher work to fracture properties as compared to other high-performance fibers such as aramid, carbon, and glass fibers [3, 4]. These properties allow it to absorb energy effectively. However, UHMWPE fiber possess its own limitation such as its low compressive strength [5, 6]. This is where the concept of material hybridization can be adopted to improve the overall property of the composite. One such synergistic material that was considered in this study is carbon fiber. Carbon fibers possess high specific strength and stiffness both in tension and compression [4] which compliments the shortfall in properties of UHMWPE fiber. There are several ways in which fibers can be configured within a composite such as by interlayering, intralayering and intrayarning [7, 8] to elicit beneficial mechanical properties. Reinforcements in the form of interweaving stiff carbon fibers and UHMWPE show interesting effects when it comes to reducing BFS during impact events.

Low back-face signatures (BFS) upon impact of ballistic panels are highly desirable outcome in the engineering of ballistic protective armor. For example, for body armor, a maximum BFS guide value of 44mm is defined in the NIJ 0101.06 standard [9] to avoid substantial injury to the user. In order to avoid exceeding this value, ballistic engineers are still developing and tapping onto the idea of material composites. The complex performance demands of ballistic applications make selecting the proper materials challenging. Fiber hybridization for low-velocity impact resistant applications continue to be of interest to many researchers [10-18]. These researchers explore the effects on impact resistance by hybridizing low elongation (LE) and high elongation (HE) fibers in a composite while others played on the idea of interplying sequences [19-28] of a composite. However, low-velocity impact studies on intraply hybrid composites are few and are gaining recent interest [29-32]. A recent novel woven polyethylene-carbon (PE-C) hybrid fabric has been developed by DSM [33-35] primarily targeted at enhancing the impact resistance and vibration dampening of pure carbon fiber composite commonly used in the applications of bicycles and leisure sport equipment. Zhao et al. [36] studied the low-velocity impact under drop-weight as well as the ballistic potential of such a fabric against steel ball. The presence of a tough HE fiber such as UHMWPE fiber altered the failure mechanism of brittle LE fiber such as the carbon fiber [37] by absorbing energy more efficiently translating to a greater area of delamination. Thorough research has also been done concerning the mode I and II [38, 39] interlaminar fracture toughness of this novel PE-C fiber composite.

Previously, our team have studied the mechanical and ballistic performance of UHMWPE hard-ballistic panel hybridized with carbon fiber-epoxy composite as an add-on layer [40]. Counter-intuitively, the addition of stiff carbon fiber at the impact face had beneficial effects in reducing the back-face signature upon ballistic impact. As a follow up investigation, we propose to rationalize the substitution of the carbon fiber intralayer by PE-C hybrid woven intralayer. At current, no work has been repeated at looking into using the novel PE-C fabric as supplementary add-on material in a hard-ballistic panel for impact and ballistic applications.

In this paper, our focus was to understand the low-velocity impact performance when an intralayer fiber hybrid composite was simply added onto an UHMWPE ballistic panel in an interlayer fashion. These panels were specifically fabricated by the addition of a mixed PE-C fabric with epoxy onto an UHMWPE fiber-based ballistic panel. Force-displacement and back face signature (BFS) damage mechanism comparison of a UHMWPE fiber based hard panel hybridized with the novel mixed PE-C fabric or the carbon-only fabric, placed at two positions of the panel, were investigated experimentally through drop-weight impact tests.

5.2 Experimental procedure for low velocity impact study

The objective of this chapter was to understand fundamental fibrous interactions between carbon fibre and UHMWPE fibre through a small-scale low velocity impact study. The failure differences of the add-on laminates are of key concern. A novel intraply fabric of carbon and UHMWPE fibre produced by DSM is introduced in this study to investigate for potential ballistic resistive properties.

The sample preparation techniques of the various hybrid ballistic panel consisting of the interlayer laminates of homogeneous carbon-epoxy and UHMWPE-polyurethane were described previously in Chapter 3 as seen in Figure 3.1. The data obtained were based on the average of three samples per sample type.

Low velocity impact test, as described in chapter 3, was conducted to evaluate, and compare differences in back face deformation reduction and to identify key factors which result in them. This test allows fundamental understanding of failure mechanism of each type of hybrid panel in an actual ballistic test by small scaling the impact event.

5.3 Evaluation of back face deformation resistance

Responses of the hybrid panels subjected to drop-weight impact test were captured by force-displacement graphs. Each curve drawn in Figure 5.1 is the average of three impact tests done per sample type. These curves provide indications of the fibrous interaction of the various hybrid composite lay-up design. Deflection measurements in this study correspond to the punch displacement value at half of the maximum force (Fmax) on the unloading part of the curve. Back face deformation (BFD) of the specimen were compared post impact.

5.3.1 Comparison of force-displacement curves between ballistic panels with PE-C and C

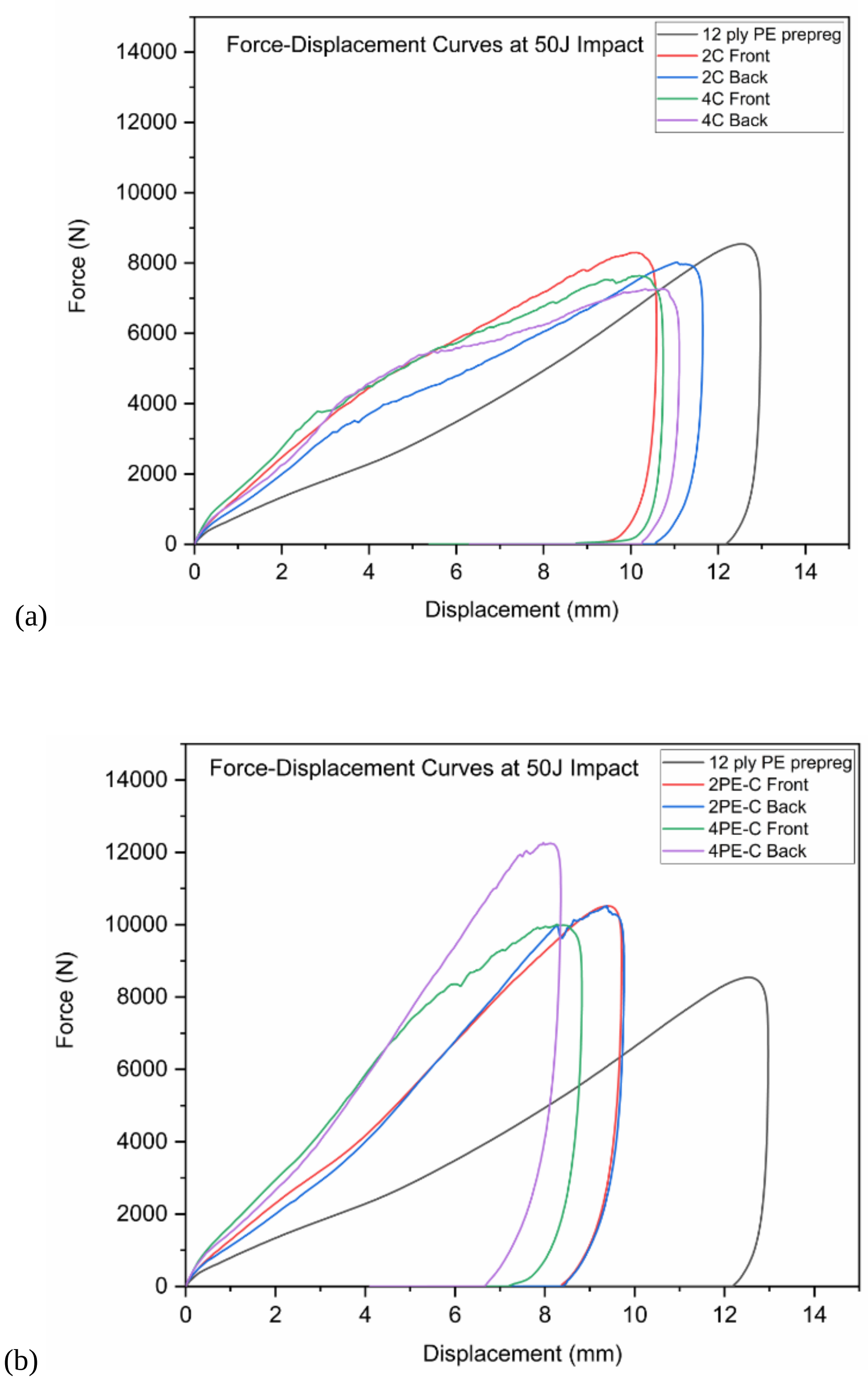


Figure 5.1. Force-displacement curves at 50J impact: (a)(b) C and PE-C composite panels against 20mm impactor respectively.

Figure 5.1 shows the force-displacement curves of the various hybrid composites as well as the reference neat 12 ply PE panel subjected to 50J impact energy with a 20mm diameter impactor. The curves capture and illuminate the unique responses of the composite in the presence and absence of UHMWPE fiber upon drop-weight impact.

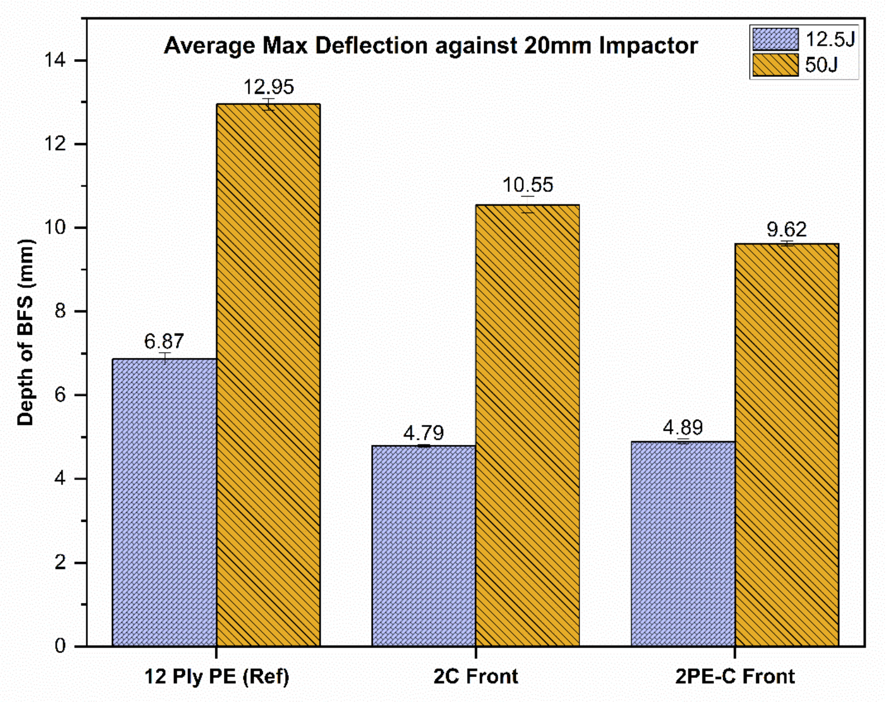
Firstly, as the samples are not penetrated, the work done (area under the curve) are found to be the same although the rate of work done differ between the various composite panels as seen by the difference in steepness of the curve. Secondly, the PE-C panels exhibited a greater peak force when compared against the C or neat sample. This shows its ability to withstand greater amounts of forces without failing prematurely like the C samples. This also suggests that different failure and propagation mechanism do exist for each panel. Comparing the PE-C and the C sample, the instances of jagged dips on the curves are greater in the C curve which are very representative of a higher degree of brittle carbon fiber fracture having taken place.

Overall, when compared to the neat 12 plied PE panel sample, the simple addition of PE-C and C layers successfully show that BFS can be reduced as seen by the smaller displacement of the sample.

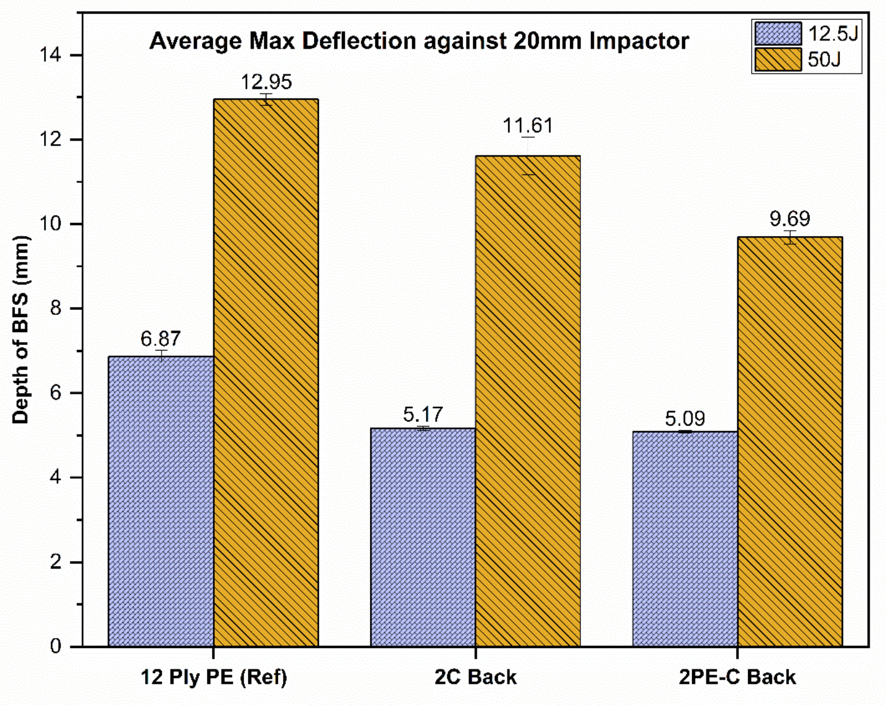
The results obtained highlight the advantages of having UHMWPE fiber interwoven into a carbon fabric. Force displacement curves showed that the addition of UHMWPE fiber had resulted in the smallest vertical displacement of the sample as compared to the neat and only-carbon fiber samples and thus a smaller depth of BFS.

5.3.2 Comparison of deflection between PE-C and C hybrid

The average maximum deflection of the various composite panels is presented in Figure 5.2. When compared to neat 12 ply PE panel, it was evident that the addition of the PE-C and C layers at the front and back made a positive effect in improving the overall resistance to deflection of the hybrid panels in the drop-weight impact test at the various impact energies. Interestingly however, the degree at which the improvements were observed varied for front versus back locations for the C systems while the PE-C systems displayed very similar values.



(a)



(b)

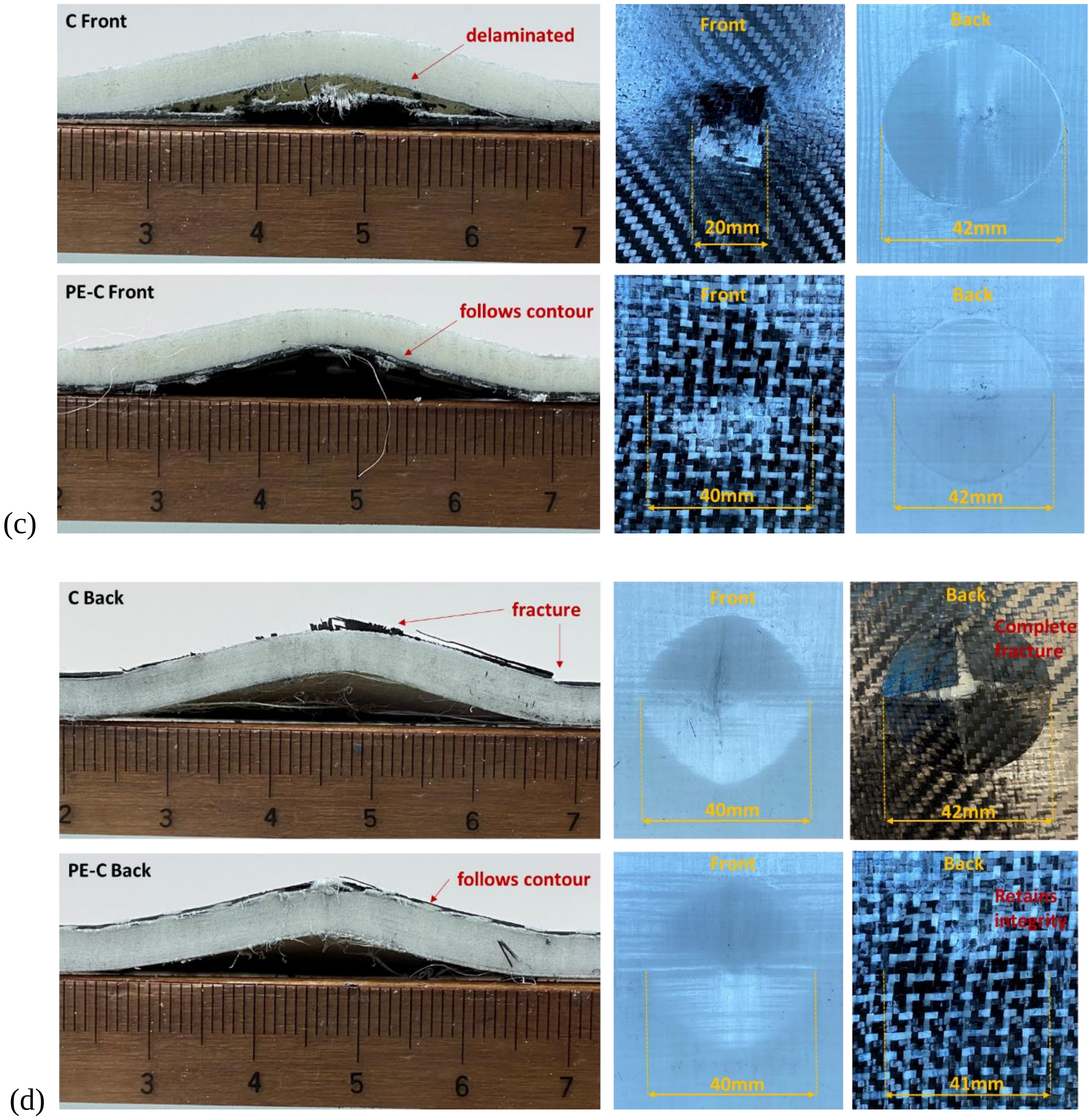


Figure 5.2. Comparison of the average deflection of (a) Front and (b) Back 2C and 2PE-C hybrid panels at 12.5J and 50J. Cross-sectional, front and back images of (c) Front and (d) Back 2C and 2PE-C hybrid panels at 50J against a 20mm impactor.

Figure 5.2 (a) and (b) represents the deflection results of both the C and PE-C front and back hybrid samples subjected to drop-weight impact testing against a 20mm diameter impactor. The greatest difference can be seen at the higher impact energy of 50J. A reduction in deflection of approximately 26-29% was seen for both the front and back PE-

C composite panel whilst a 19% and 10% reduction in deflection were observed for C composite panel, respectively. The PE-C samples showed an overall consistent performance at both impact energies regardless of the positioning of the hybrid layer whereas a greater deviation of performance was observed for the C samples.

As seen in Figure 5.2 (c), the type of localized failure mechanism of C and PE-C layers when placed at the front were very different with PE-C showing a greater area of damage as compared to C. The PE-C layer remained intact, did not fail in a brittle manner and was even ductile enough to be able to follow the contours of the bulging of the remaining 12 plies of UHMWPE prepreg material. On the other hand, the C layers failed catastrophically. The premature fracture of the C layer reduced the effectiveness of absorbing energy early in the impact event. The loss of the benefit of the layer translated to a greater displacement of the sample and thus a greater BFS.

On the other hand, Figure 5.2 (d) sheds light on the damage on the back face of the panel. Similarly, the PE-C layer retains its fabric integrity while the C layer showed catastrophic brittle fracture as seen by the cross-like crack propagation. Zhao et al. [28] attributes the suppression of the splitting of the PE-C layers to the Dyneema® yarns having a higher strain to failure and fracture toughness in tension as compared to carbon yarns resulting in a greater area of bulging and thus more effective energy absorption of the PE-C composite panel.

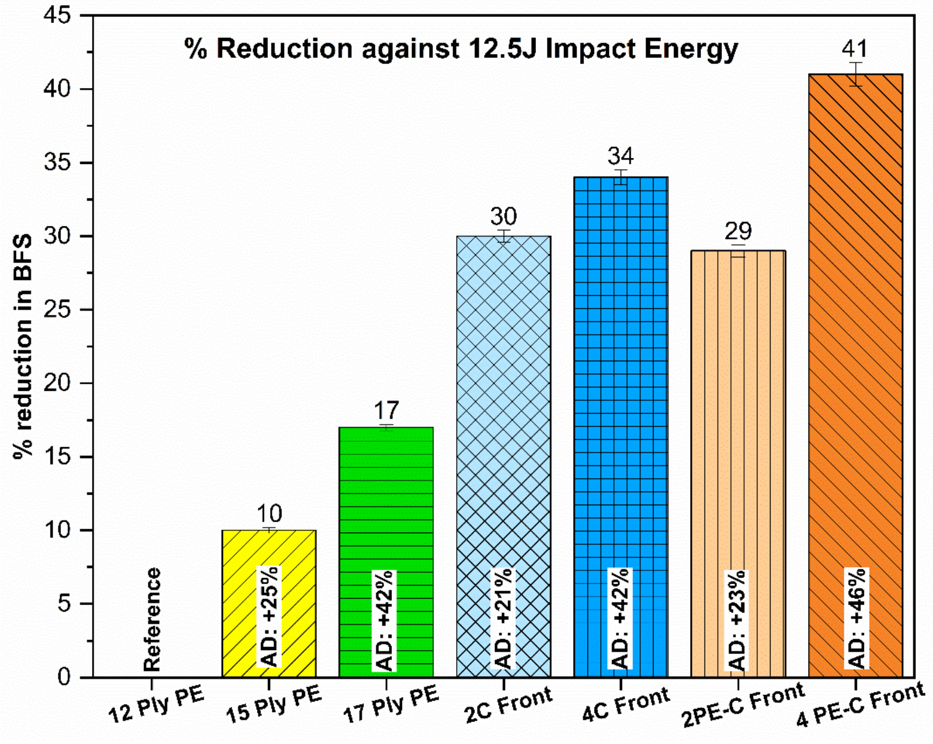
5.3.3 Comparison of post-deflection when doubling PE-C or C hybrid layers

In our experiment we also investigated the effects of doubling the hybrid layers within the composite panel on deflection. Figure 5.3 below provides clarity on the overall percentage change in the deflection, as seen in Table 3, and highlights some interesting observations.

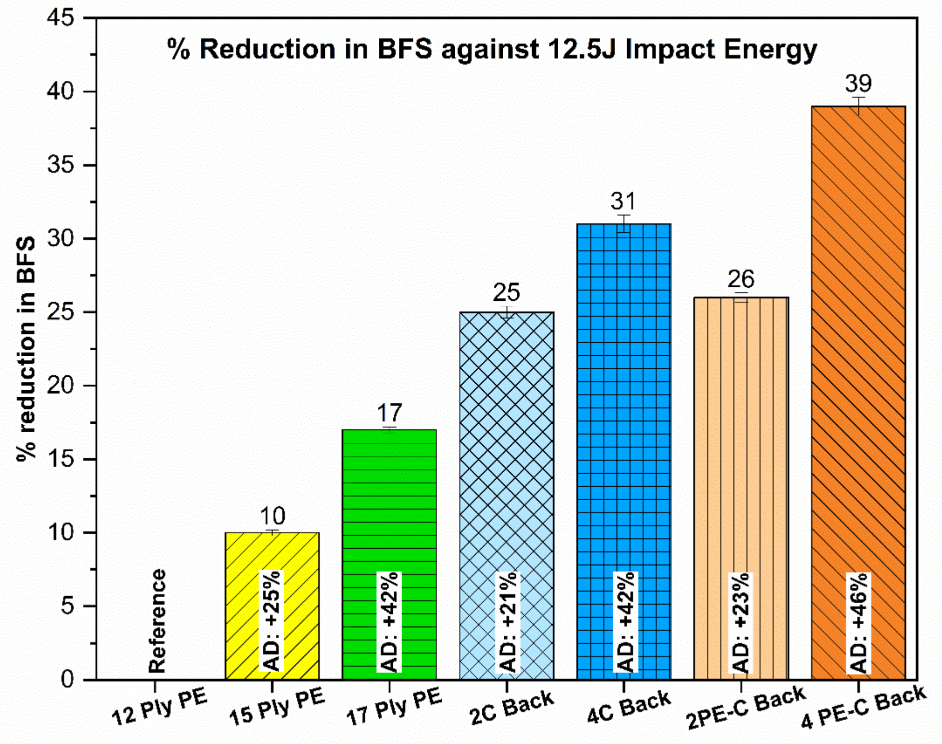
Table 3. Overall comparison of the change in deflection of all neat and hybrid composite samples when impacted at 12.5J and 50J against a 20mm impactor.

Samples	AD (kg/m2)	BFS (mm) / [% Change in Deflection]	
		12.5J Impact	50J Impact
12 Ply PE (Reference)	3.17	6.87 (+/- 0.14)	12.95 (+/- 0.14)
15 Ply PE	3.96	6.20 (+/- 0.10) [-10% +/- 0.2%]	11.74 (+/- 0.06) [-9% +/- 0.1%]
17 Ply PE	4.49	5.67 (+/- 0.03) [-17% +/- 0.2%]	11.09 (+/- 0.01) [-14% +/- 0.1%]
2C Front	3.82	4.79 (+/- 0.03) [-30% +/- 0.4%]	10.55 (+/- 0.20) [-19% +/- 0.3%]
2C Back	3.82	5.17 (+/- 0.05) [-25% +/- 0.4%]	11.61 (+/- 0.45) [-10% +/- 0.3%]
4C Front	4.47	4.56 (+/- 0.04) [-34% +/- 0.5%]	10.72 (+/- 0.12) [-17% +/- 0.2%]
4C Back	4.47	4.76 (+/- 0.09) [-31% +/- 0.6%]	11.16 (+/- 0.19) [-13% +/- 0.2%]
2PE-C Front	3.89	4.89 (+/- 0.06) [-29% +/- 0.4%]	9.62 (+/- 0.06) [-26% +/- 0.2%]
2PE-C Back	3.89	5.09 (+/- 0.03) [-26% +/- 0.3%]	9.69 (+/- 0.16) [-25% +/- 0.3%]
4PE-C Front	4.61	4.05 (+/- 0.07) [-41% +/- 0.8%]	8.74 (+/- 0.05) [-33% +/- 0.3%]
4PE-C Back	4.61	4.17 (+/- 0.04) [-39% +/- 0.6%]	8.21 (+/- 0.08) [-36% +/- 0.4%]

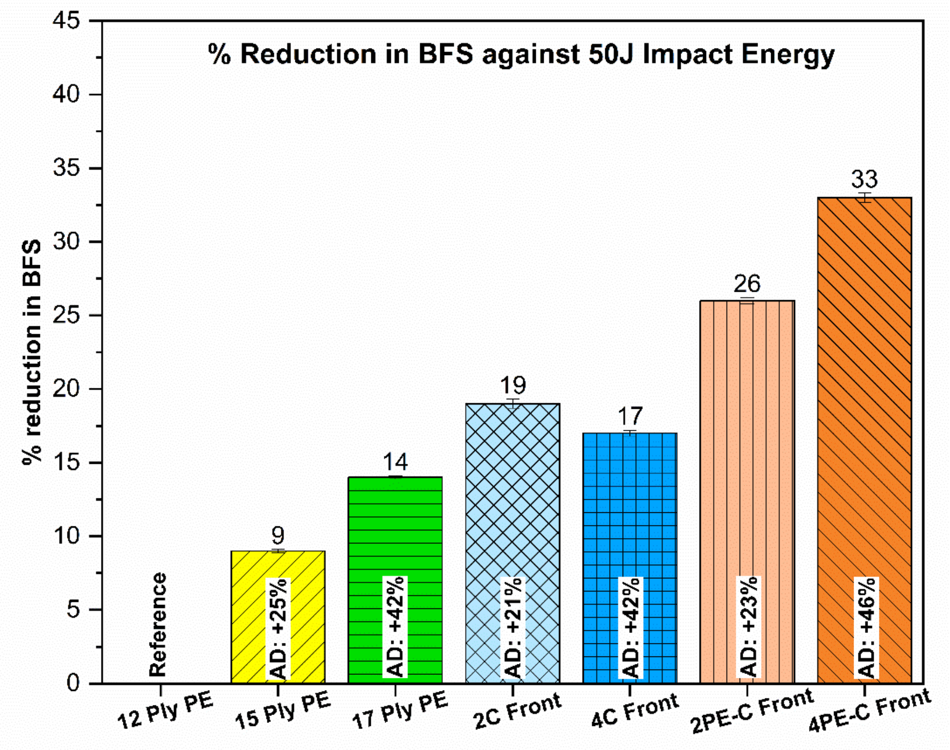
*(-) represents a decrease in BFS.



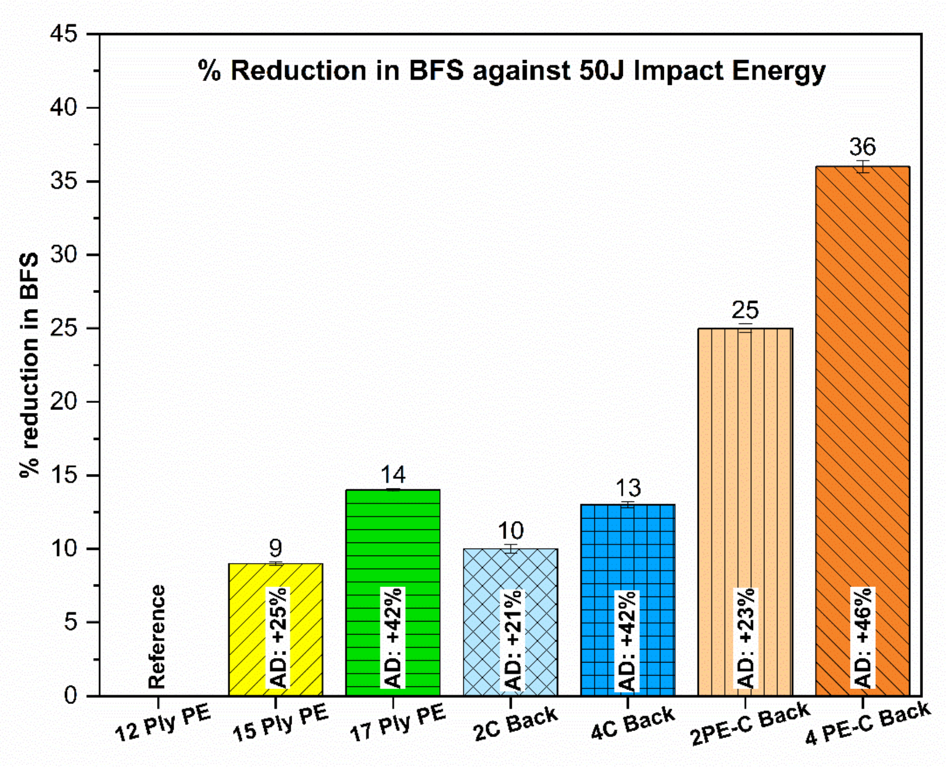
(a)


% Reduction in BFS against 12.5J Impact Energy
% reduction in BFS
0
5
10
15
20
25
30
35
40
45
Reference
10
17
25
31
26
39
AD: +25%
AD: +42%
AD: +21%
AD: +42%
AD: +23%
AD: +46%
12 Ply PE
15 Ply PE
17 Ply PE
2C Back
4C Back
2PE-C Back
4 PE-C Back

(b)


% Reduction in BFS against 50J Impact Energy
% reduction in BFS
0
5
10
15
20
25
30
35
40
45
Reference
9
14
19
17
26
33
AD: +25%
AD: +42%
AD: +21%
AD: +42%
AD: +23%
AD: +46%
12 Ply PE
15 Ply PE
17 Ply PE
2C Front
4C Front
2PE-C Front
4PE-C Front

(c)



(d)

Figure 5.3. Overview of the back-face signature reduction of the different samples in terms of percentage change at 12.5J (a,b) and 50J (c,d).

Firstly at 12.5J, as seen in Figure 5.3 (a) and (b), the percentage reductions in BFS for the front and back systems are very similar indicating that the threshold for catastrophic failure of both the C and PE-C layers have not been exceeded. Thus, the impact energy was subsequently increased to 50J. At 50J impact energy, as seen in Figure 5.3 (c) and (d), significant differences in the performance between PE-C and C layers began to surface. It was consistently clear that PE-C outperformed C hybrid samples in reducing BFS regardless of positioning. As explained previously, the presence of PE fibres resulted in the survivability of the layer and better coping towards impact.

Secondly, results of doubling the add-on layers as seen in Figure 5.3 (c) and (d), proved to have showed no appreciable advantage when it comes to the C hybrid. On the contrary, adding more layer of PE-C resulted in further improvements to the reduction of BFS. It is noteworthy that the improvement in reduction was not as significant as going from zero to two add-on layers. It was observed that the reduction in BFS, going from two to four layers of PE-C, only improved by 7% and 11% for the front and back designs respectively. The improvements found were disproportionate to the increase in areal density and thus overall weight addition to the design. Hence, there is little benefit to double the add-on layers as the weight addition had note resulted in a linear reduction of BFS. Thus, it is recommended to add only two layers for a good compromise on performance and weight.

In addition, when comparing the same areal density, thus the neat 15 and 17 ply PE samples respectively, the addition of PE-C layers had tremendously improved the BFS reduction capabilities whilst for the C samples, only small improvements were seen for the front and no improvements for the back design. This shows that it is advantageous to replace some layers of PE for the hybrid PE-C fabric to reduce BFS.

5.5 Conclusion

In this chapter, the impact behaviour of the novel woven UHMWPE-Carbon (PE-C) fiber hybridized onto a panel of UHMWPE-fiber based ballistic panel in a dual intra-interlayer hybridization have been investigated through the comparison of the results against pure carbon fabric by drop-weight impact tests and showed promising results. The force-displacement response and damage mechanism of the front and back composite panels were discussed. The results showed interesting unique synergies arising from the hybridization of UHMWPE-fiber based ballistic panel with PE-C or C layers prove effective in reducing back face signature.

The novel PE-C hybrid layers outperformed C layers due to its ability to survive the impact event when the high toughness and failure strain of UHMWPE yarns prevent the premature failure of brittle carbon yarns and even after the carbon fiber has failed the UHMWPE yarns ensured the fabric's integrity. Thus, being more effective in overall energy absorption. However, adding stiffness alone to reduce the depth of BFS was not the most ideal solution. A combination of stiffness and ductility seem to be the best option in mitigating BFS.

Our results evidently highlight that the position of the add-on carbon-containing layer plays a huge role in affecting deflection resistance. One must consider the survivability of the carbon-containing layer at low velocity impact events. Increased local stresses resulting from greater impact pressure affect the behaviour of the hybrid layers. This pushes brittle carbon yarns to maximum strain much quicker resulting in its premature failure in the absence of UHMWPE yarns. A good compromise of performance and weight is to add two layers of PE-C at the front.

This work provides a glimpse of the possible behaviour of the PE-C and C hybrid layers in impact applications and paves the way in guiding the engineering of future personal protective armour. Further work is needed to verify if the results for this impact tests holds true in a ballistic impact event. A continuation of our previous work described in [40] will be conducted to explore the full potential of material hybridisation in composites for impact applications.

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Chapter 6

High Velocity Ballistic Impact of UHMWPE/Carbon Hybrid Panels

In this chapter, focus was placed in testing the ballistic resistive properties of a novel hybrid fabric consisting of UHMWPE and carbon fibre as an add-on laminate to an UHMWPE fibre based hard panel. High velocity impact tests were conducted using a 9mm full-metal jacket (FMJ) projectile to test the limits of the hybrid fabric. Mechanical characterisation such as flexural properties using a three-point bending test provided insights into understanding property-application relations. Differences in failure mechanism in the ballistic test were compared to the results in the previous chapter on low velocity impact to draw synergies in this scale-up. Observable differences in projectile deformation were reported to understand secondary effects of such a hybridisation. In this test, spacer offsets were added to simulate air gaps typically found in protective helmets and the results obtained were found to be positively unexpected.

6.1 Introduction

In the engineering of ballistic protective applications, properties such as light weight, high penetration limit velocity as well as low back-face deformation are required. Over time, personal protective equipment evolved from the use of metallic materials, that tend to be denser and heavier to fibrous materials that are light and are able to provide the same protection levels [1]. Efforts to develop impact resistant articles using fibres are gaining traction.

Carbon fibre is an example of a widely used high performance material to reinforce advanced composite materials. Its high specific tensile strength and high modulus make it a great candidate in designing light but strong composites [2, 3]. However, as a standalone material, its brittle nature limits its application in impact demanding environments. To combat this, fibre hybridisation techniques such as intrayarning, intralayering or interlayering are adopted [4]. A marriage of high elongation (HE) and low elongation (LE) fibres reveal beneficial impact-resistive properties. Research investigating hybridizing carbon fibre with HE fibres such as aramid or glass fibres has shown interesting synergies in terms of impact properties [5-10].

A more recent HE fibre used in an intraply method of fibre hybridisation is the Ultra High Molecular Weight Polyethylene (UHMWPE) fibre. A novel woven UHMWPE-carbon hybrid fabric was developed [11, 12] primarily targeted at enhancing the impact resistance and vibration dampening of homogeneous carbon fibre composite commonly used in the applications of bicycles and leisure sport equipment. Our research contributes to unravel unexpected ballistic application possibilities with the use of such a fabric. Behaviours of the hybrid fabric against drop weight and low velocity impact were studied [13-15]. The results obtained largely attributed the improvement in absorption of impact energy to the differences in failure mechanism of the fabric when compared to conventional carbon fabric. Hence, it will be interesting to see if there will be actual ballistic resistant properties.

UHMWPE fibre is well known for its use capability to arrest projectiles and for its ballistic resistance. Unique properties such as exhibiting high strength-to-weight ratio and high fracture strain make it an excellent material in ballistic applications [16-18]. As with most materials, there are some drawbacks. UHMWPE fibres are poor in compression and shear strength [19] as compared to carbon fibre [20]. Hence, the interweaving of UHMWPE fibre and carbon fibre could potentially unlock unexpected synergies.

In this paper we sought to understand the differences in the ballistic impact reactions against a 9mm FMJ projectile, primarily on the back face signature (BFS) reduction of two ballistic panels. They consist of an UHMWPE based flat panel laminated with either an epoxy impregnated woven fabric consisting of an intralyer of UHMWPE and carbon fibre or homogeneous carbon fibre. These add-on layers were plied at different positions on the UHMWPE based panel to highlight position dependency factors. The trade-offs in ballistic limit and BFS are discussed. Small-scale mechanical three-point bending tests were conducted to provide an understanding on the flexural properties of the different composite panels and secondary effects on projectile blunting are highlighted in this paper as well.

6.2 Experimental procedure for high velocity impact study

The objective of this chapter was to understand fundamental fibrous interactions between carbon fibre and UHMWPE fibre through a ballistic impact test against a 9mm full metal jacket projectile. The sample preparation techniques of the various hybrid ballistic panel consisting of the interlayer laminates of homogeneous carbon-epoxy and UHMWPE-polyurethane were described previously in Chapter 3. The table below summarises the samples fabricated that are investigated in this chapter.

Table 4. Summary table of the various 200mm by 200mm panels fabricated.

Sample	Stacking Sequence	Areal Density (kg/m^2)
12 ply PE	[PE prepreg]$_{12}$	3.17
15 ply PE	[PE prepreg]$_{15}$	3.96
17 ply PE	[PE prepreg]$_{17}$	4.48
2-Front	[PE-C]$_2$ / [PE prepreg]$_{12}$	3.89
	[C]$_2$ / [PE prepreg]$_{12}$	3.82
4-Front	[PE-C]$_4$ / [PE prepreg]$_{12}$	4.61
	[C]$_4$/ [PE prepreg]$_{12}$	4.47
2-Back	[PE prepreg]$_{12}$/ [PE-C]$_2$	3.89
	[PE prepreg]$_{12}$/ [C]$_2$	3.82
4-Back	[PE prepreg]$_{12}$/ [PE-C]$_4$	4.61
	[PE prepreg]$_{12}$/ [C]$_4$	4.47

In this chapter, Teflon spacer, with a 12.5mm thickness, (detailed dimensions described in Figure 6.1) against Roma Plastilina Clay backing was introduced to provide preliminary data on the effects of air gaps typically found in ballistic applications such as military helmets. Any differences in V_{50} performance due to the spacer was not established in this chapter as it would deviate from the main thesis.

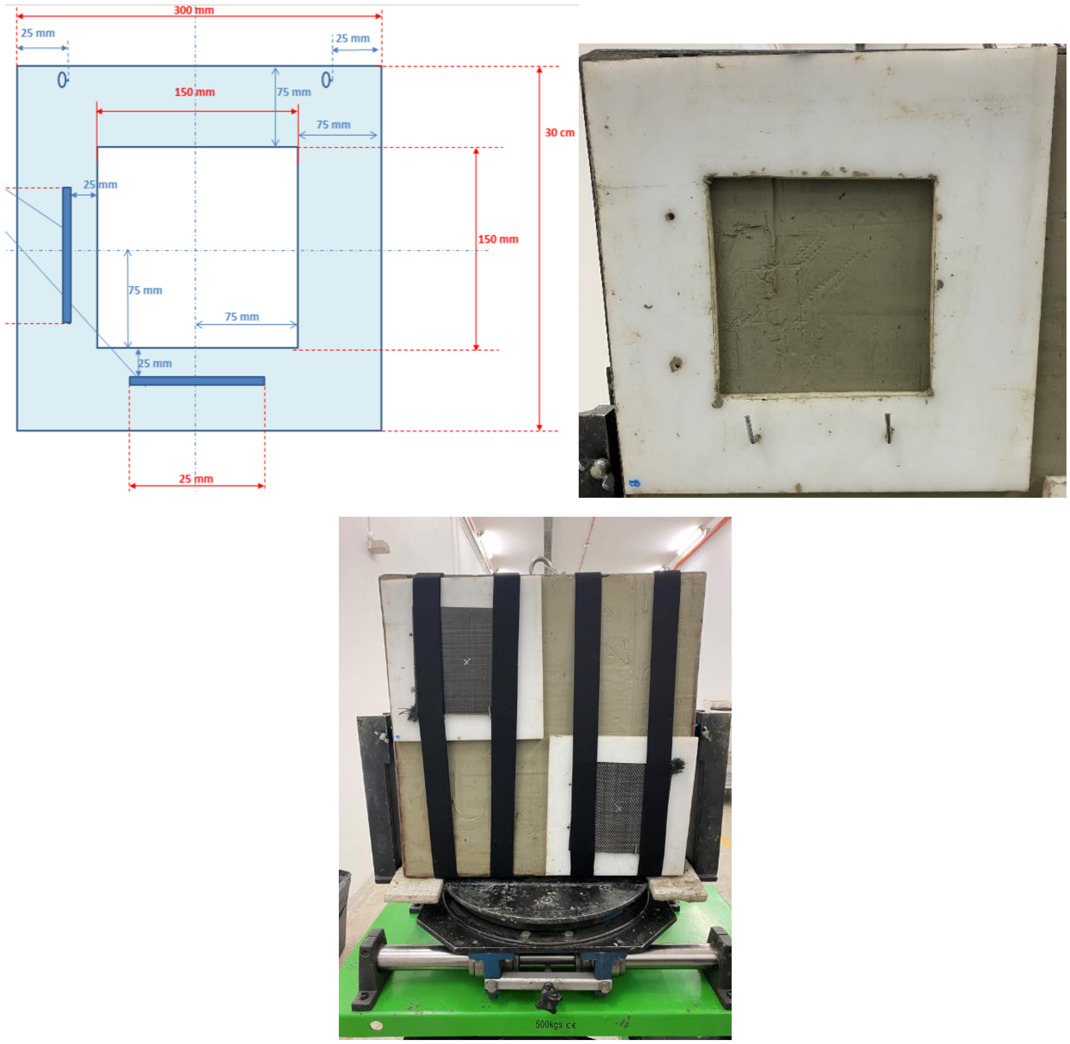


Figure 6.1. (Top) Teflon Spacers used on top of a Roma Plastilina Clay backing. (Bottom) 200mm by 200mm samples secured onto the spacer and clay backing.

6.3 Results

In this investigation, and similarly reported in our previous work but with a different focus, (refer to Chapter 4), quasi-static three-point bending, and dynamic ballistic tests were experimentally carried out to shed insights on the mechanistic response when a projectile impacts the composite panels as designed in methodology (section 3.1). The three-point bending test reveals the flexural properties of the composite panel and thus provide an indication of the potential of the add-on layers of either the mixed PE-C or homogeneous C in enhancing structural properties that can be useful in certain protective equipment like in military helmets where mechanical rigidity is a design feature. The conducted ballistic test models the actual situation during projectile impact and aids in discerning the key differences in damage evolution and failure mechanism between the mixed PE-C and homogeneous C and its outcome on the BFS.

6.3.1 Mechanical characterization: Flexural strength and modulus of the composite panel

The flexural characteristics of the composite panels are evaluated via the three-point bending test guided by the ASTM D790 standards. Two main data namely the flexural strength and flexural modulus were obtained. The values of the flexural properties are obtained from the average of five samples per hybrid concept. Flexural strength is determined at the point of maximum force while the flexural modulus is obtained from the initial slope of the flexural stress-flexural strain curve.

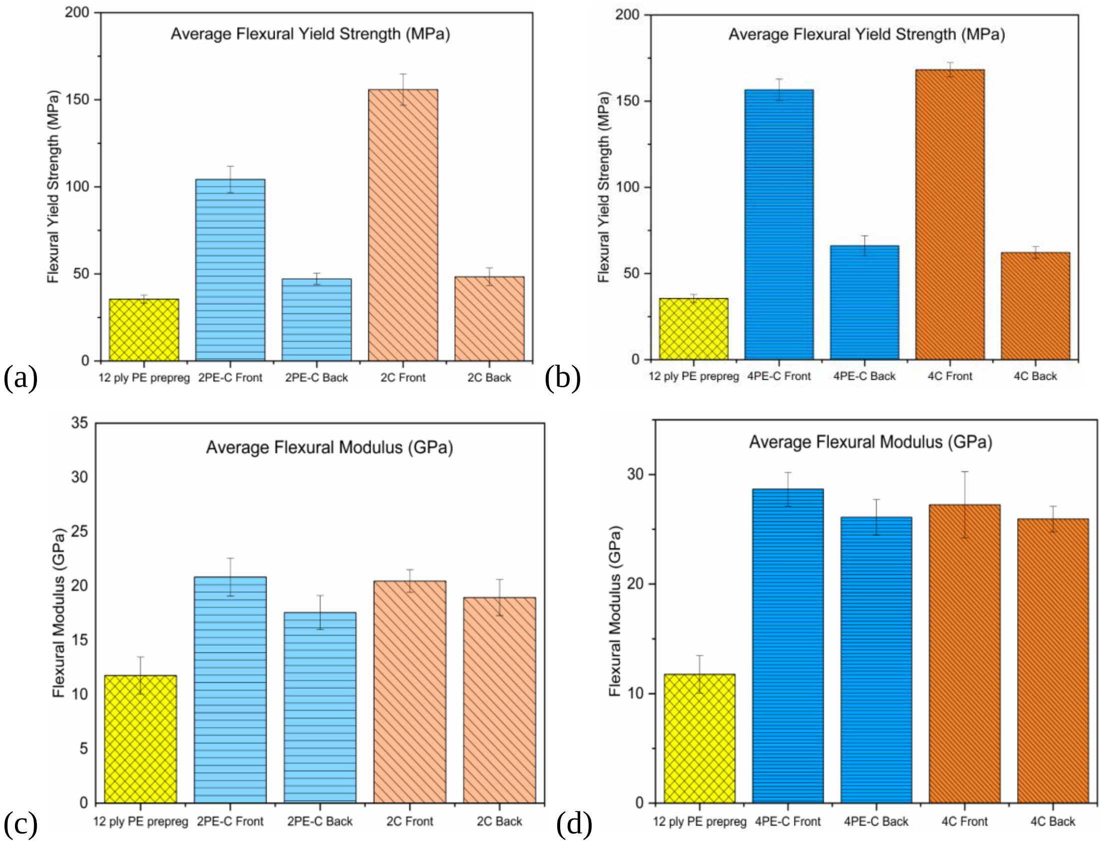


Figure 6.2. The flexural characteristics of the various composite panels. (a) & (b) Comparison of the average flexural strength of the various composite panels. (c) & (d) Comparison of the average flexural modulus of the various composite panels.

As seen in Figure 6.2(a), a substantial improvement of 190% and 330% in flexural strength were obtained simply by adding 2PE-C and 2C layers at the front of a neat 12 ply PE panel, respectively. For the mechanistic understanding, consult [15]. As seen in Figure 6.2(b), the addition of two more layers of PE-C at the front continued improving the flexural strength of the composite panel however, only a slight additional benefit was noticed for the 4C front panel. The true flexural strength could not be captured because of ply delamination on the interface between the PE prepreg and the epoxy impregnated 4C fabric layer. The weak adhesion between the different layers became the limiting factor in the test. Nevertheless, the data reveals that positioning of the add-on layer greatly affects flexural yield strength where placing them at the top (front) yields greater improvement. The continued improvement in flexural yield strength for the PE-C composite panel going from two to four layers signal the overall relative flexure softness of a PE-C layer as compared to the stiff C layer.

As seen in Figure 6.2(c) and 6.2(d), the apparent flexural modulus of both the PE-C and C panels improved by the same factor. This attributed to the fact that the modulus of a material is measured at the beginning slope of the stress-strain curve where the UHMWPE fibres are still capable of contributing to the compressive modulus [15].

6.3.2 Dynamic test: Ballistic performance

6.3.2.1. V_{50} ballistic limit

The V_{50} ballistic limit of the various composite panels were experimentally obtained and the average of three samples per sample type are represented in Figure 6.3 below. All projectiles used in this study were 9mm FMJ.

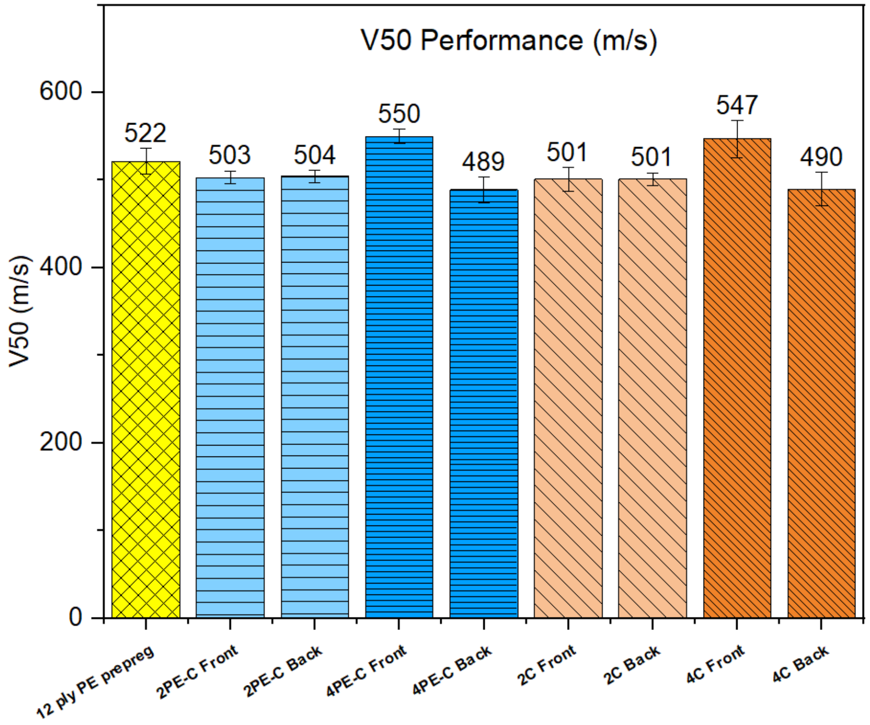


Figure 6.3. A comparison in V50 ballistic limit performance of the various composite panels tested against 9mm FMJ in the presence of a spacer of 12.5mm thickness.

The results in Figure 6.3 show a positive outcome of such a hybrid design. When comparing against the 12 ply PE prepreg, the addition of two layers of PE-C or C layers at the front or back showed only a slight drop in the V50 performance, indications that no adverse effects would be introduced by such an addition that increase the structure rigidity as investigated in section 4.1.

Interestingly, the positioning and material makeup of the add-on layers did not matter much in the V_{50} ballistic limit test. This is because at such high projectile energies, the 2PE-C and 2C layers at the front could not survive the initial local impact whilst for the addition of 4PE-C or 4C layers at the front showed a slight improvement of 9% compared to the two layers in ballistic performance. The added stiffness at the front could have benefitted the panel by slowing and blunting the projectile earlier-on.

However, the addition of either two or four PE-C and C layers at the back could not fully contribute to the panel as a whole as the limitation becomes the weak bonding of the add-on epoxy layers and the PE prepreg plies at the back becomes the limiting factor. The delamination and eventual dislodge of the add-on layers at the back could have occurred at the time where the initial high impact pressure wave travelling through the panel from the front to the back. Thus, rendering the back add-on layers useless in this case.

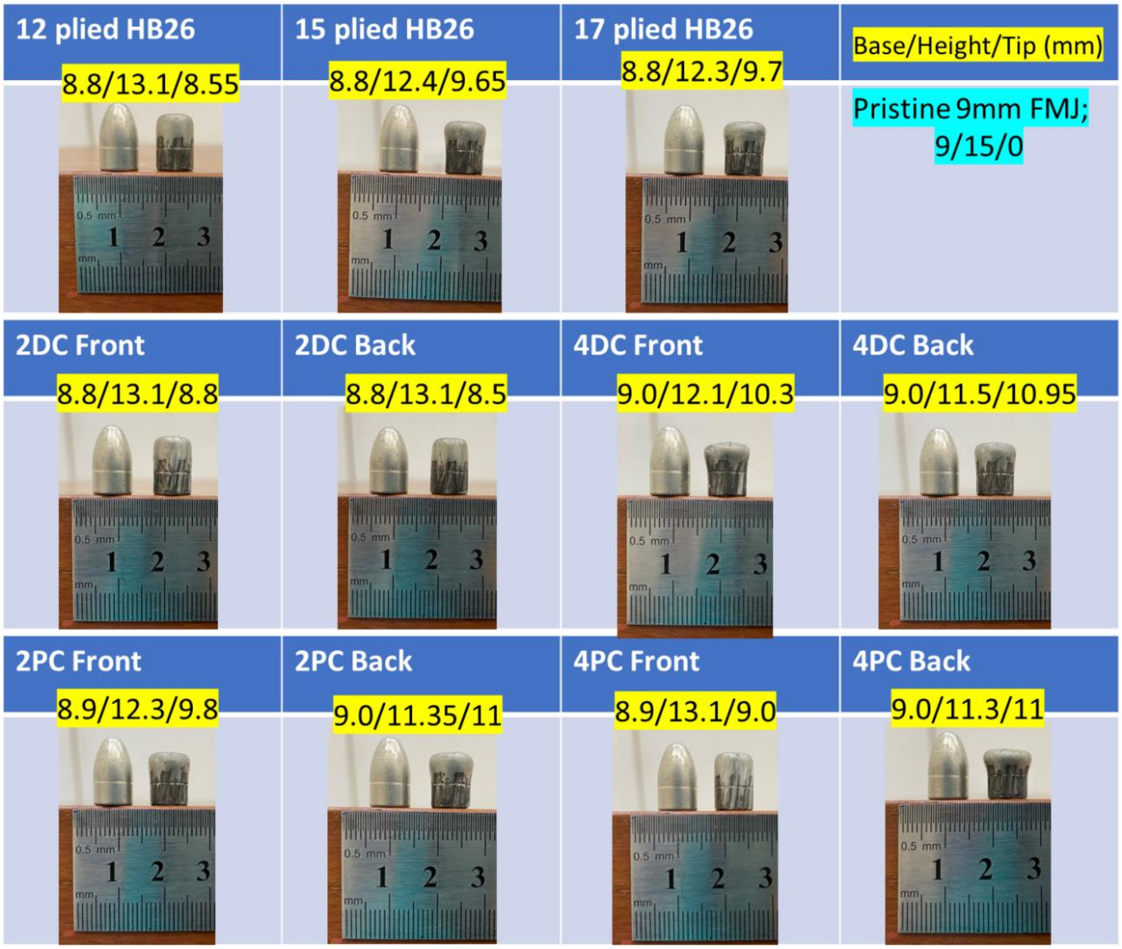
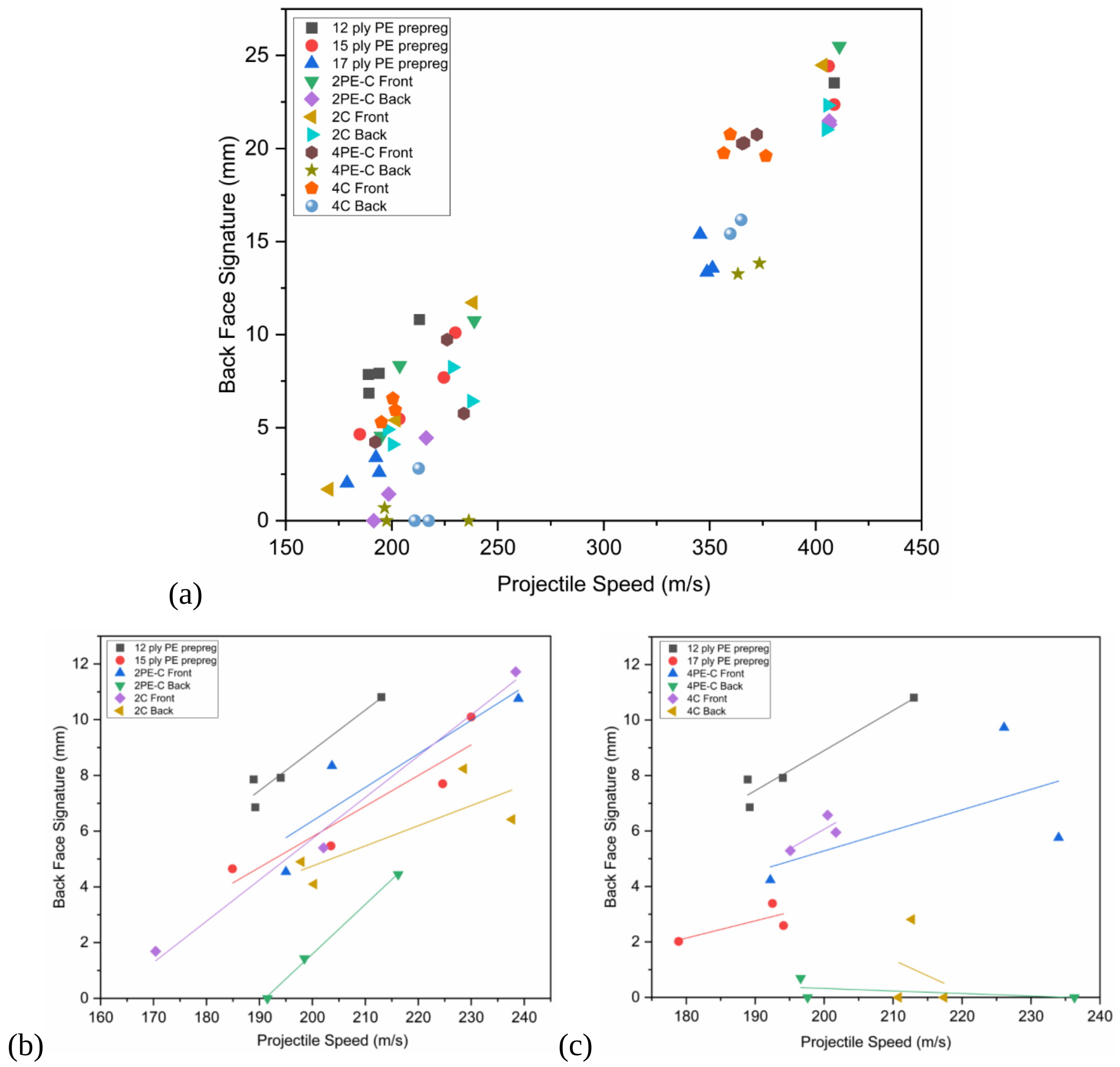


Figure 6.4. Comparison of the base, height and tip changes post-impact of a 9mm FMJ projectile on the various composite panels.

Figure 6.4 shows images of the deformed 9mm FMJ projectile after impact and we can clearly see that projectile blunting had occurred by measuring changes in the base, height and tip. Mushrooming or blunting of a projectile is desirable as it could hasten energy absorption by increasing the frontal surface area of the projectile thus allowing a greater area of contact to absorb energy effectively.

6.3.2.2. Back Face Signature (BFS)

The back-face signature reported in Figure 6.5 corresponds to the deepest point made on the clay backing, ignoring the 12.5mm spacer thickness used to simulate the air gap in a ballistic helmet. The BFS result showed in Figure 6.5 could inspire the potential benefits of incorporating UHMWPE fibre into homogeneous carbon fabric to support the idea of hybrid material composites in helmet development competence.



(d)

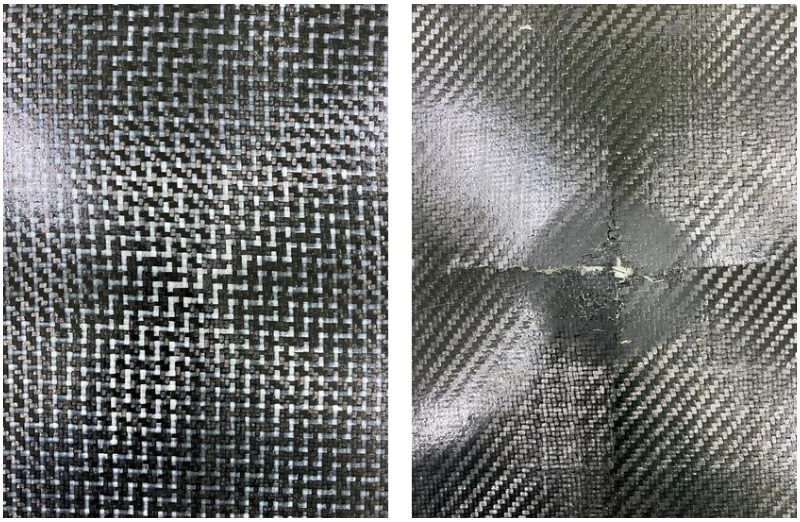


Figure 6.5. (a) An overview of all BFS data obtained at different projectile speed regions. Single-shot on 200mm by 200mm panel with a 12.5mm offset from the clay. (b) & (c) A comparison of the back-face signature of the various composite panel post-impact by a 9mm FMJ projectile at mean speed of 200m/s. Lines are linear fits as guide to the eye. (d) Typical visual failure differences between the back 2PE-C (right) and 2C (left) post impact (~200m/s).

In this section, the ability of the composite panels to reduce BFS will be discussed by looking at the cluster of data for each type of composite panel.

Figure 6.5(a) provides an overview of the various shots conducted at two projectile speed regions. Dissecting the graph, one can see that within each speed regions, the composite panels that had the either the mixed PE-C or homogeneous C add-on layers at the back proved to had better been able to reduce BFS as compared to the front design. Moreover, the PE-C panels had an even lower BFS as compared to the C panels. The results had confirmed that the incorporation of UHMWPE fibres into homogeneous woven carbon fabric were indeed beneficial.

The data in the 200m/s region showed a greater variation in BFS performance for the two add-on layer panels as compared to the 350m/s region probably due to the limitation of the add on layers to cope with the higher impact energies. Hence, we decided to focus our study on the data in the 200m/s speed region.

Fig 6.5(b) compares the BFS for the composite panels having an areal density (AD) of approximately 3.8kg/m^2. Several observations can be made. Firstly, when compared against the neat 12 ply PE prepreg panel, the addition of the either PE-C and C layers at the front and back had shown to have reduced BFS. Secondly, when compared against the same AD, with reference to the 15 ply PE prepreg, the performance of the front 2PE-C and 2C panel were similar; however, the back 2PE-C and 2C showed even lower BFS clusters. Lastly, the composite panel with the mixed PE-C layers at the back consistently exhibited the lowest BFS.

A similar comparison, as seen in Figure 6.5(c), was made for the composite panels having an AD of approximately 4.5kg/m^2. The ranking in BFS reduction for the 4PE-C and 4C composite panels were consistent to those with the 2PE-C and 2C composite panels however, the reduction in BFS was expected to be greater.

6.4. Discussion

The experimental findings highlight the benefits of material hybridisation of an UHMWPE fibre-based panel in enhancing structural and ballistic performance. The idea of an intralayer-interlayer material hybrid of UHMWPE fibre and carbon fibre proved to have synergistic benefits.

The significant increase in flexural properties of the composite panels from the simple addition of an epoxy-PE-C and C layer to a neat PE prepreg panel are explained in the results and discussion section of [15]. As seen in Figure 6.2, it is noteworthy that the flexural strength for the PE-C panels were not greatly compromised, considering that stiffer carbon yarns are replaced with low compressive strength UHMWPE yarns. This finding is encouraging if one wanted to consider interweaving UHMWPE fibre onto conventional homogeneous woven carbon fabric for the use of structural and ballistic applications.

V_{50} ballistic limit performance for the neat 12 ply PE prepreg, PE-C and C composite panels were the same as seen in Figure 6.3. This may be due to the V_{50} limit being greatly influenced by the stiffness of the panel, which corresponds to the modulus of the panel. It was indeed found that they were all similar. An increase in V_{50} limit for the front 4PE-C and 4C design can partly be attributed to a significantly stiffer impact front, thus not only being able to slow but also to blunt the projectile. Overall, the addition of the PE-C and C layers had not compromised on the penetration limit of the panel whilst benefitting from the substantial increase in structural properties.

Despite having similar ballistic limit and mechanical properties, interestingly the BFS results were different. These findings correspond to an observable difference in the impact response and fracture mechanism between the PE-C and C layers when placed at the front or back.

Firstly, as seen in Figure 6.5, the position of the PE-C and C layers on the PE panel influenced the reduction of BFS. Placing the add-on layers at the back showed consistently a lower BFS. The survivability of the add-on layers is crucial to elicit beneficial BFS reduction abilities of the overall composite panel. The add-on layers for the front panel designs were completely penetrated rendering them useless early in the impact. However, the back add-on layers did not receive the full localised impact from the projectile allowing these stiff layers to contribute to absorbing and dissipating energy. Thus, translating to a smaller BFS.

Upon closer visual inspection, there were clear differences between the failure mechanism of the PE-C laminates and the C laminates at the back as shown in Figure 6.5(d). For the PE-C laminate, the presence of a more ductile UHMWPE fibre prevented the brittle fracture of the carbon fibre. Having a greater strain to failure and fracture toughness, the UHMWPE fibres prevented the splitting of the interwoven fabric resulting in a greater area of bulging and more effective energy absorption [14]. This was similarly noted in our previous work on low-velocity impact tests for the same composite panels [15].

6.4.1 Design considerations

Our findings highlight the unexpected benefits of incorporating PE-C laminates to the back of a 12 ply PE prepreg panel. In designing a ballistic article, where areal density is of key concern, one may consider adding two layers of epoxy PE-C laminate at the back instead of three more plies of PE prepreg in order to maximise BFS reduction as well as to greatly enhance structural properties.

6.5. Conclusion

In this chapter, the mechanical characterisation and ballistic performance of introducing UHMWPE fibre through the use of the novel woven UHMWPE-carbon (PE-C) fibre fabric, developed by DSM, were investigated with a woven homogeneous carbon (C) fibre used as a reference. The effects on back face signature reduction upon ballistic impact by a 9mm FMJ projectile were discussed. The results showed that weaving in UHMWPE fibre into only-carbon fabric had shown to be effective in reducing BFS. In addition to the low-velocity performance [20] it was now found that these new materials also demonstrate great properties under ballistic conditions. It was found to be beneficial to combine the two fibre types to produce a woven fabric having the best of both properties: the high fracture strain and toughness from UHMWPE fibre and the high compressive strength and stiffness of carbon fibre.

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Chapter 7

Conclusions and Recommendations

This final chapter serves to summarise the various work performed throughout the thesis and provide an overview of the progress made so far on the topic of ballistic impact of an UHMWPE-based ballistic panel. A brief discussion on the degree of validation achieved for the presented hypothesis and the corresponding novelty and research impact of the various work undertaken is included. Recommendations for future studies to clarify any ambiguity and for further topical development are proposed.

7.1 Summary

There were three main objectives proposed for the ballistic impact study of hybrid UHMWPE-Carbon ballistic panel, and they were accomplished sequentially leading to the completion of this thesis.

a) To evaluate synergistic ballistic resistive properties between carbon and UHMWPE through interply hybridising homogeneous carbon laminate onto UHMWPE fibre-based ballistic panels.

The ballistic impact performance of interply hybrid of UHMWPE-carbon fibre ballistic panels were investigated by a combined static (three-point beam bending) and dynamic (ballistic projectile impact) testing approach. The feasibility of using carbon fibre with UHMWPE fibre was established through a combined understanding of bending behaviour as well as ballistic response against a 9mm full metal jacket projectile (FMJ). The studies revealed unexpected positive synergistic outcomes such as improved structural rigidity of the overall panel without a loss in penetration limit performance through the addition of small amounts of add-on carbon laminate. The hybridisation of these two fibre types addressed key factors necessary for good impact energy absorption, which is sufficient stiffness, contributed largely by carbon-epoxy laminate, and relative flexibility and softness, contributed largely by UHMWPE-polyurethane laminate.

b) To evaluate the low and high velocity impact responses of an intraply hybrid fabric of UHMWPE and carbon fibre in terms of its ballistic limit and back-face signature differences.

In this study, the understanding of fundamental responses of fibrous hybrids constituting of UHMWPE and carbon fibre of a ballistic impact event were addressed through low and high velocity impact. Falling dart test was used to simulate low velocity impact responses. Unique force-displacement responses of the various hybrid panels were unraveled which led to the understanding of small-scale failure mechanism and significant energy absorption differences. Subtle changes in material type and positions within the composite panel led to unexpectedly great differences in back face deformation reductions. These findings were later validated by the high velocity impact ballistic test. These two studies revealed the importance of the survivability of the add-on laminates in reducing back face deformation.

c) Explain key failure mechanisms and suggest design considerations in the engineering of ballistic protective equipment through the understanding of material positioning within a composite panel.

This study primarily focused on the understanding of hybrid ply positioning and inter-fibre interactions of UHMWPE and carbon fibre during ballistic impact. Two key factors that affected the various hybrid panels' ability to reduce back face deformation are (a) positioning of the add-on materials as well as (b) differences in failure mechanism of the laminate which led to different energy absorption responses. The failure modes were identified in post-impact visual analysis. Local impact stresses tested the survivability of the add-on laminates, where the mixed UHMWPE-carbon (PE-C) laminate showed superior resilience to failure as compared to the homogeneous carbon (C) laminate. The presence of UHMWPE fibre in the PE-C laminate was largely responsible for differences in fracture mechanism which prevented the premature catastrophic failure of the layer. This intraply woven hybrid layer proved to have enhanced the impact energy absorption and thus led to a smaller back face deformation.

d) Patent creation: Patent for Ballistic Molded Article W02020/127187 A1

The patent describes the use of carbon with Dyneema® fabric in a ballistic-resistant molded article comprising of a consolidated stack of layers and a process for producing a ballistic resistant molded article.

7.2 Discussion of the Hypothesis

The hypothesis of this thesis is that we can positively influence the back-face signature and bending rigitiy of UHMWPE ballistic articles by hybridizing with carbon fibres in an interply and intraply fashion. Strategic positioning of the carbon fibres in the composite panel will play a dominant role in the effect.

The aim of the thesis was to understand the low and high velocity impact responses of a hybrid UHMWPE-carbon fibre ballistic panel to suggest a more effective engineering of ballistic protective equipment that are also structurally sound. The key hypothesis of this thesis proposes the possibility of utilising an intraply and interlayer hybridisation technique consisting of UHMWPE and carbon fibre to identify ballistic resistive properties. The hypothesis has been partly tested in Chapter 4 where it was proven that interlayering small amounts of carbon fibre laminate have shown to be able to mitigate back face deformation without the loss in penetration limit although the specific failure mechanisms needed to be further looked into.

Thus, as documented in Chapter 5, low velocity impact via falling dart testing was conducted to elucidate on the fibrous responses to impact loading. Key insights onto the force and displacement responses of the various hybrid panel design led to the mechanistic understanding of the panel failures.

In Chapter 6, the work was expanded to validate if the findings found in the previous chapters held true in an actual high velocity ballistic impact event. It was found that the results indeed held true. Intraply hybridisation by the incorporation of UHMWPE fibre onto homogeneous carbon fabric had shown surprising improvements in reducing back face deformation. The role of UHMWPE fibre in reducing back face deformation were explained. The novel fabric had shown to be superior to conventional only-carbon fabric. Studies on the failure mechanism of such a hybrid intraply fabric is limited in literature but are gaining traction in the ballistic composite materials research.

Key insights regarding the failure mechanics of an intraply and interlayer type of hybridisation obtained by these impact studies confirms the hypothesis. Based on the fibrous responses to low and high velocity impact leading to improved performances in back face reduction and structural rigidity of the panels identified in this thesis, the engineering of future UHMWPE fibre-based article can be extended to three dimensional articles.

7.3 Novelty and research impact

Throughout the thesis, several novel and impactful research works was started as follows:

Understanding the failure responses of an intra-interply hybridisation of UHMWPE and carbon fibre towards low and high velocity impact.

Few prior works on the ballistic impact behaviour of an intra- and interply dual hybridisation type consisting of UHMWPE fibre and carbon fibre are available in literature. In this research, a new intraply fabric of UHMWPE-carbon fibre showed greater improvements in being able to reduce back face deformation against a 9mm full metal jacket projectile (also novel) as compared to a homogeneous carbon laminate. Comparative failure mechanisms were highlighted.

Demonstrate that positioning of stiff/tougher regions in the thickness of a ballistic article plays a significant role in reducing back face deformation for the safety of end-users.

Our published work, described in Chapter 4, communicated the influence of stiff/ tougher as well as softer/ductile regions within an UHMWPE fibre based ballistic panel against a 9mm FMJ projectile. In this project, stiff carbon fibres were beneficial to be placed on the impact front, to deform the projectile early, whilst ductile PE fibres absorbed energy by freely bulging at the back. The consequences of material placement towards the effectiveness of a ballistic panel to mitigate back face signature and retain structural integrity was highlighted.

Possible development and engineering of future protective articles that are ballistically and structurally sound.

The competitive defence technology sector constantly seeks ways into engineering ballistic protective armour that are lightweight and strong. This thesis highlights the possibility of hybridizing ballistic panels constituting of UHMWPE and carbon fibre in an intra- and interply hybrid which revealed significant synergistic ballistic properties. In addition, it recommends ways one may choose to design protective armours that are not only ballistically better but structurally sound as well.

7.4 Recommendation for future work

The scope of this thesis was purposefully limited to the study of low and high velocity impact of a hybrid UHMWPE fibre based ballistic panel to support the composite knowledge of the personal protection business of DSM Protective Materials. The thesis established the use of carbon fibre as the only add-on material in two forms, an intraply woven fabric and an interlayer laminate, to highlight synergistic ballistic resistive properties. However, more supplementary work can be done to improve the overall understanding of hybridization between UHMWPE and carbon fibre.

7.4.1 Study on the effects of modulating interlaminar fracture toughness (ILFT)

This thesis showed how a stiffer and resistive panel to bending and buckling had a great effect on its static (flexural test) and dynamic (ballistic test) performances. Key factors to improving its performance is the ability of the panels to suppress buckling and bending of the UHMWPE component of the hybrid panel. In order to do so, it is essential that the carbon laminates adhere well to the UHMWPE layers. It will be interesting to consider modulating interlaminar fracture toughness between the two interface layers of the UHMWPE-polyurethane and carbon-epoxy. An improvement in this could further enhance the resistive force to buckling and bending. The effects of changing the ILFT properties can be studied with regards to the effects they have on the ballistic performance.

7.4.2 Numerical modelling of ballistic impact

In this thesis, experimental findings particularly in predicting the strategic placement of stiff fibres such as carbon on relatively compliant UHMWPE fibre based ballistic panels, were conducted. Experimental findings point to key mechanistic insights where best to include regions which are stiff as well as regions to avoid. In *Chapter 4*, symmetric designs yielded poor ballistic limit performance (ie middle and sandwich structure). Placing stiff carbon fibre in the middle degraded the ballistic resistive property of the panel by disrupting the overall penetrating ability of UHMWPE panel when the cured single laminate is separated into two. Secondly, considering Nguyen's simulation work [1], the carbon fibre regions were well inside the penetration zone rendering brittle carbon fibers useless in arresting the high energy projectile. In addition, placing carbon fibre on the exterior in a sandwich layout led to a highly stiff panel which resulted in a lower ballistic resistance.

To complement the existing experimental efforts laid out in this thesis, the impact events can be modelled via explicit finite element simulations to estimate the ballistic performance and to understand the failure mechanisms. Based on the parametric studies, empirical relations can be developed for ballistic limit velocity. Attempts to simulate complex ballistic events may give rise to further clarity and understanding key insights such as interface dwell, interaction between the projectile and hybrid composite laminates, damage size estimation etc. Other benefits may include being able to determine the optimum composition for the hybrid fabric (vol% of UHMWPE and carbon fibre) to balance stiffness and flexibility; to be able to virtually design components by predicting key regions to induce stiffness or flexibility bearing in mind the intended purpose and application; as well as greatly reducing resources in terms of time and materials to conduct experiments leading to increased productivity in fabricating and manufacturing ballistic panels.

References

1. NGUYEN, L.H., S. RYAN, and A.C. ORIFICI. *A numerical investigation on the response of thick ultra-high molecular weight polyethylene composite to ballistic impact*. in *29th International Symposium on Ballistics*. 2016.