UNIVERSITI PUTRA MALAYSIA

KENAF-ARAMID FIBRE-REINFORCED POLYVINYL BUTYRAL HYBRID COMPOSITES FOR MILITARY HELMET

SUHAD DAWOOD SALMAN

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By

SUHAD DAWOOD SALMAN

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

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DEDICATIONS

To you who faced with me the Good and evil time,

Who battle with me the difficult Days,

Who shared with me the stress and effort,

Who always support me…stood with me,

My helper on Life's path,

My Lover,
My husband Hasan

To my Beloved…My Mother and Father

To my wonderful Sisters...Rafah and Tawheed

To my life Sons...Ameer and Ahmad

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the Degree of Doctor of Philosophy

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January 2017

Chairman : Zulkiflle Leman, PhD
Faculty : Engineering

Traditionally, the helmet shell has been used to provide protection against ballistic threats to reduce head injuries and fatalities. Owing to the high cost of aramid fibres and the necessity for environmentally friendly alternatives, a portion of aramid was replaced by plain woven kenaf fibre, with different arrangements and thicknesses, without jeopardising the stringent requirements demanded by military helmet specifications. Furthermore, novel helmets have been produced and tested with a specific threat level (National Institute of Justice standards, NIJ), in order to reduce the dependency on the ballistic resistance components. Experiments were conducted with more focus on the estimation the NIJ level, ballistic limit (V_{50}), maximum energy absorption, hybrid failure mechanism and trauma depth. The NIJ results showed that the laminated hybrids with kenaf fibres passed the 4th level (III-A) up to four layers, using 9 mm FMJ ammunition. While laminated hybrid shell with six kenaf layers and above passed the 3th level (II). Hybrid with 16 aramid/3 kenaf laminated composite recorded the highest V_{50} among other hybrids composite, 633.7 m/s. The arrangement of fibre layers was also found to affect the ballistic performance of the hybrid composites significantly, placing woven kenaf alternate with aramid fabric layers provided a lower ballistic limit velocity than placing woven kenaf together and aramid layers separately for the same hybrid volume and thickness. The laminated composites were subjected to physical, tensile, flexural, drop weight impact and quasi-static penetration tests. The laminates composed of 19 layers and were fabricated using different number and configurations of plain woven kenaf and aramid layers reinforced Polyvinyl Butyral (PVB) film, by the hot press technique. The experimental results demonstrated that the overall mechanical properties of the kenaf/aramid hybrid were dependent on the kenaf fibre content. Hybrid with 17 aramid/2 kenaf layers exhibited the best mechanical properties compared to other hybrid composites. Generally, the results suggested that stacking sequence, thickness and kenaf fibre content significantly influenced the mechanical and ballistic performance. It can be concluded from the research that it is possible to reduce the amount of aramid fibres in conventional PASGT (Personal Armour System Ground Troops) shell by 21% by hybridizing aramid with kenaf fibre, thus providing a lower cost alternative that is environmentally friendly.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Doktor Falsafah

KOMPOSIT POLIVINIL BUTIRAL HIBRID BERTETULANG GENTIAN KENAF-ARAMID UNTUK TOPI KELEDAR TENTERA

Oleh

SUHAD DAWOOD SALMAN

Januari 2017

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Topi keledar digunakan untuk memberi perlindungan terhadap ancaman balistik dan mengurangkan kecederaan di kepala serta kematian. Sebahagian gentian aramid telah digantikan dengan gentian kenaf biasa yang ditenun, dengan menggunakan aturan lapisan komposit berbeza dan ketebalan yang berbeza. Gentian kenaf biasa lebih murah dan lebih bersifat mesra alam tanpa menjejaskan keperluan ketat yang dituntut oleh spesifikasi topi keledar tentera. Tambahan pula, topi keledar yang bersifat baharu ini telah dihasilkan dan diuji dengan tahap ancaman tertentu (National Institute of Justice standards, NIJ), dalam usaha untuk mengurangkan kebergantungan kepada komponen rintangan balistik. Eksperimen telah dijalankan dengan memberikan tumpuan lebih kepada anggaran tahap NIJ, had balistik (V_{50}), penyerapan tenaga maksimum, mekanisme kegagalan hibrid dan kedalaman trauma. Keputusan NIJ menunjukkan bahawa dengan menggunakan 9 mm FMJ peluru, kacukan berlapis dengan gentian kenaf telah lulus tahap ke-4 (III-A) sehingga empat lapisan. Hibrid berlamina dengan enam lapisan kenaf dan ke atas telah lulus tahap ke-3 (II). Hibrid dengan shell16 aramid/3 kenaf komposit berlapis merekodkan hadlaju V_{50} , yang tertinggi di kalangan hibrid komposit yang lain iaitu sebanyak 633.7 m/s. Selain itu, susunan lapisan serat juga didapati memberi kesan ketara kepada prestasi balistik komposit hibrid, dengan meletakkan tenunan kenaf ganti dengan lapisan fabrik aramid memberikan halaju had balistik yang lebih rendah daripada meletakkan kenaf ditenun bersama-sama dan lapisan aramid berasingan bagi jumlah hibrid dan ketebalan yang sama. Komposit berlapis diuji dengan menggunakan ujian fizikal, tegangan, lenturan, ujian berat jatuh dan ujian penembusan kuasi-statik. Hibrid berlamina terdiri daripada 19 lapisan dan telah direka menggunakan nombor yang berbeza dan konfigurasi dataran kenaf dan aramid lapisan tenunan. Hibrid berlamina ini diperkukuhkan dengan penggunaan polivinil butiral (PVB) filem dan menggunakan teknik tekanan panas. Keputusan eksperimen menunjukkan bahawa sifat-sifat mekanik

keseluruhan hibrid kenaf / aramid bergantung kepada kandungan gentian kenaf. Hibrid dengan 17 lapisan aramid/2 lapisan kenaf mempamerkan sifat-sifat mekanik terbaik berbanding komposit hibrid lain. Secara umumnya, keputusan eksperimen mencadangkan bahawa penyusunan urutan, ketebalan dan kandungan serat kenaf sangat mempengaruhi dalam prestasi mekanikal dan balistik. Kesimpulannya, hasil kajian menunjukkan bahawa jumlah gentian aramid dalam PASGT konvensional (*Personal Armour System Ground Troops*) mungkin boleh dikurangkan sebanyak 21% dengan menghibridkan gentian aramid dengan serat kenaf, sebagai langkah alternatif untuk kos yang lebih rendah dan bersifat lebih mesra alam.

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I certify that a Thesis Examination Committee has met on 31 January 2017 to conduct the final examination of Suhad Dawood Salman on her thesis entitled "Kenaf-Aramid Fibre-Reinforced Polyvinyl Butyral Hybrid Composites for Military Helmet" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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LIST OF ABBREVIATIONS

ASTM	American Standard of Testing Materials
ACH	Advanced Combat Helmet
AHP	Analytical Hierarchy Process
CP	Complete penetration
E_{abc}	Energy Absorption
E_b	Modulus of Elasticity in Bending
E_d	Impact Energy
FMJ	Full metal jacket
FRPS	Fibre reinforced polymers
FSPs	Fragment simulating projectiles
IEDs	Improvised explosive devices
LWH	Lightweight helmet
NIJ	National Institute of Justice
PASGT	Personnel Armor System Ground Troops
PD	Penetration depth
PP	Partial penetration
PVB	Polyvinyl Butyral
SPR	Span to punch ratio
STRIDE	Science and Technology Research Institute for Defence, Malaysian Ministry of Defense
US	United States
vol	Volume fraction
V_r	Residual Velocity
V_s	Striking Velocity

CHAPTER ONE

INTRODUCTION

1.1 Background

Protecting the head from injury is critical to the function and survivability. Traditionally, helmets have been utilized to provide protection against shrapnel and ballistic threats, which have reduced head injuries and fatalities. However, home-made bombs or improvised explosive devices (IEDs) have been increasingly used in the theatre of operations (Samil and David, 2012). There is an urgent need to develop head protection helmet in the way such that it becomes less both costly and environmentally harmful. To the military and civilian people who are exposed to different threats require adequate protective gears to safeguard themselves. From this scenario, the demands for helmet armours are driving the protective equipment industry to create solutions in order to provide lightweight and reliable protection from a variety of ballistic threats and most importantly, helmet armours that are marketable to wide a range of consumers.

Composite materials are continually becoming a more attractive choice of material in various industrial applications as a result of their high strength-to-weight and high stiffness-to-weight ratios. While composite materials offer significant gains in performance as a result of their unique ability to be tailored towards a specific application, they can also offer a means of incorporating biobased materials into a product. This is through the use of natural fibres as ballistic protective fibres. Recently, environmental regulations, costs and lightweight encourage researchers to develop new reliable materials (Kline and Company Inc., 2000). Natural fibre reinforced polymer composites have been a viable option in replacing traditional materials due to their availability (Amar, Manjusri, Lawrence, Susan, Bruce and Georg, 2005; Richardson, Madera-Santana and Hague, 1998). Currently, there is a need to understand their behavior in order to be safely and economically driven into the ground (Cheeseman and Bogetti, 2003).

From ancient times, natural textiles have been used as compliant laminates, not only for clothing and protection against the elements but also for bodily protection. From the use of leather on Grecian shields, layered silk in ancient Japan, to chain mail and suits of armour in the Middle Ages, personal protection has sought to protect its wearer from the corresponding advances in armaments. However, the advent of firearms relegated these forms of protection obsolete until the development of high-strength, high-modulus fibers in the 1960s. These materials ushered in a newer of body armour that offered protection against small arms munitions. To achieve advancements in armour performance levels at a reduced weight, further investigations are required in materials to develop innovative designs.

Natural fibers, when compared to their synthetic or mineral-based counterparts, generally have lower mechanical properties. These low mechanical properties are a major inhibitory when trying to develop high-performance products. One method for increasing their level of mechanical performance is to hybridize natural fibers with synthetic fibres. The benefit of using hybrid composites is that the advantages of one type of fibre can overcome the disadvantages of the other type of fibre. A viable compromise between the higher material properties of synthetic fibres and the environmental benefits of natural fibres is found by utilizing both synthetic and natural fibres to create a hybrid fibre reinforced composite system. Material properties are also improved by the efficient arrangement of the structural members. The use of hybrid natural/synthetic fibre reinforced composites for structural applications has been shown to be a feasible alternative to traditional synthetic building materials (Musch, 2008). As a result, a balance in cost, performance, and sustainability could be achieved through proper composite material design.

A considerable amount of published work which utilized natural fibre material such as sisal, kenaf, and ramie as hybrid composite reinforcements with the synthetic fibres, have been highlighted (Saba, Paridah and Jawaid, 2015). However, woven natural fabric as compacted reinforcement in composite materials subjected to impact loadings is scarce. This work provides an investigative study of the helmet shell materials based on a comprehensive review of existing hybrid studies. Owing to the high cost of aramid fibre and the necessity for environmentally friendly alternatives, a portion of aramid fibre was replaced by kenaf fibre based Polyvinyl Butyral film (PVB) in the hybrid laminated composite. The hybridization has been characterized ballistically and structurally. The focus of the present work is to identify materials and design opportunities that could be used to engineer a lighter helmet shell that meets prescribed baseline performance specifications from hybridization of kenaf and aramid fibres. In addition, aramid/PVB-Phenolic and kenaf/PVB composites were fabricated with specified mechanical and ballistic characteristics.

To design a functional helmet, it is important to analyze the structure of helmets. The main helmet components are the foam liner (integral skin) and the shell (composite). Basically, the function of the foam is to absorb most of the impact energy, while the function of the shell is to resist penetration of any foreign object from touching the head and resulting in direct skull damage, and to distribute the impact load on a wider foam (Carey, Herz, Corner, McEntire, Malabarba, Paquette and Sampson, 2000). Usually, manufacturers design their helmet based on experimental verification. During the experimental verification, the helmet must absorb the energy of the impact and resist penetration (Walsh, Scott and Spagnuolo, 2005). This penetration test is the main criteria for shell thickness determination. If a thicker shell is chosen, the strength will increase, as well as cost and weight, therefore an alternative material should be considered (Aare and Kleiven, 2007).

By the 1970s, a company called DuPont had developed a fabric called Kevlar with bullet resistant properties, and National Institute of Justice (NIJ) began testing the fabric in the armour applications. Since that time, ballistic field test results found the Kevlar ballistic vests to be a successful method to use in the protection field (Chua and Chena, 2010). The general method for characterizing a material's ballistic performance is to conduct a V_{50} ballistic test. A V_{50} is defined as the velocity at which there is an equal probability of a partial or a complete perforation for the given armour and threat. Security classification becomes critical when both the threat and armour are discussed or presented simultaneously, especially if the mass efficiency of the armour is significant. In addition, transient deformation, which is a direct result of the kinetic energy, is concomitant with the ballistic impact and it plays a very significant role in determining the design and materials selection of a helmet system (Czechowski, Jankowski and Kubiak, 2012). In the static and dynamic structural performance, practical durability is a necessary trait for any article used in combat (Faur-Csukat, 2006). Helmets must also pass static structural tests as well. The other considerations which are the comfort, cost, weight distribution, and a host of other factors, also influence design and material selection of a typical helmet. Many of these factors are weighted evaluations through models and experimental testing to reveal possible issues or concerns with the helmet system (Cunniff, 1992).

1.2 Problem Statement

It is a proven fact that hybrid composite materials play an important part in ballistic protection and many published works have been done to highlight its ballistic capabilities (Velmurugan, Sikarwar and Gupta, 2010). Among the top performance is the Kevlar fibre composite, which possesses one of the highest specific modulus. The specific strength and stiffness are significantly greater than monolithic materials such as steel and aluminum, which make them attractive for numerous weight critical applications. However, cost and weight consideration play an important role in helmet application requirements (Torki, Stojanović, Živković, Marinković, Škapin, Uskoković and Aleksić, 2012). Hence a suitable and lightweight solution should be explored by developing new materials. Composite armour provides an excellent solution in terms of strength over weight ratio, but is expensive due to the high demands for its raw materials (carbon, aramid, etc.) to a non-armour application. Thus an alternative material is required to reduce the dependency towards ballistic resistance component, so further understanding of its impact and mechanical properties should be taken into considerations. Therefore, to develop innovative designs of hybrid kenaf/aramid fibre reinforced composites for sustainable construction may be possible to create a material with the combined advantages (Davoodi, Sapuan, Ahmad, Ali, Khalina and Jonoobi, 2010). Sustainability is defined as the ability to balance performance and environmental constraints.

The ballistic testing apparatus is crucial tools in order to identify key parameters defining the perforation and damage phenomenon and also to provide engineering reference data of the armour materials. Hybridization of woven kenaf with aramid fibres to use in the helmet shell application is a really challenging subject and deserves a sophisticated research study, to achieve balance in cost and performance.

1.3 Aim of this Study

The use of natural fibres in the industrial application provides challenges for researchers to improve suitable techniques which can be used for structural applications such as automotive, protective helmet, household and construction industry. The primary aim of this study is to develop a hard helmet shell by combining plain woven kenaf fibres with aramid fabric reinforced Polyvinyl Butyral (PVB) film to form a hybrid composite and engineer a lighter helmet shell that meets prescribed baseline performance specifications and replace or reduce utilization of aramid fibres. The structural performance was controlled by changing the distribution of laminated designs to achieve the most beneficial arrangement of kenaf/aramid layers for helmet shell design while balancing performance and environmental constraints. This approach is expected to develop a helmet shell armour which is less cost and environmental friendly compared with the conventional helmet shell without jeopardizing the ballistic-resistant capabilities.

1.4 Research Objectives

With the background in mind, it is clear that a better knowledge of the ballistic properties of structural fibre reinforced polymers (FRPs) would make it possible to manufacture the ballistic protection of the helmet shell. Therefore, the research objectives are:

1. To determine physical properties of kenaf fibre and the influence of fibre content on tensile, flexural and morphological properties of woven kenaf/ Polyvinyl Butyral (PVB) composites.
2. To determine the effect of stacking sequences of laminates on tensile, flexural, low velocity impact behavior and quasi-static loading of plain woven kenaf and aramid fabric reinforced PVB based composites.
3. To evaluate the impact characteristics and penetration resistance capabilities (V_{50} and impact resistance level NIJ and blunt trauma depth) of woven kenaf and aramid fibres reinforced PVB based composites when subjected to actual ballistic impact tests under different projectile speeds.
4. To fabricate a helmet shell from the best composite combination and perform military actual ballistic tests.

1.5 Scope of the Study

The Personnel Armor System Ground Troops (PASGT) is investigated as the type of ballistic helmet. Presently, there are two types of ballistic threats: (i) the penetration of handgun bullets (NIJ test) and (ii) piercing of fragmented shells (V_{50} test).

The scope of this research is limited to provide tensile, flexural, quasi-static penetration, drop weight impact and ballistic resistance results for multi layers of woven kenaf/aramid reinforced Polyvinyl Butyral composite, as well as physical and mechanical of kenaf fibre. The woven kenaf fibres were used without any treatment, naturally. In addition, the target struck by two types of projectiles; 9 mm, 8.0 g full metal jacket (FMJ) bullets to investigate the NIJ levels and .22 calibre (diameter of 7.62 mm) fragment simulating projectiles (FSPs) to determine the V_{50} ballistic limit.

Apart from that, this research emphasizes on the structural integrity of the ballistic helmet shell when impacted at high velocity. Furthermore, the plain weave style was used in this work because it was reported that it has high strength to the impact test. From previous work, it was indicated that the plain weave style has had significant effects on the final results of using natural fibres.

1.6 Thesis Layout

This thesis consists of five chapters where all the contents are summarized at the end of each chapter. Chapter 1 introduces the reader to the context of this study and the objectives which were derived from the problem statement. Chapter 2 overviews the development of helmet armour research by previous work, the development in helmet armour protection, helmet design and material considerations and static and dynamic structural performance and stability that have been developed by other researchers.

Chapter 3 describes the materials and methodology used for this study, a specific approach in designing and planning the course of study, several experimental test procedures and setups incorporated into this research. Chapter 4 presents the results of physical and mechanical properties of the kenaf fibre, plain woven kenaf/PVB, aramid/PVB-Phenolic and kenaf/aramid hybrid composites. In addition, the effects of kenaf volume fraction on the tensile, flexural and drop weight properties were discussed. The morphological properties of the fracture surface of the hybrid composites were also analyzed. Furthermore, this chapter encompasses the quasi-static penetration and ballistic impact properties results of the hybrid composite materials. The effect of layering sequence, trauma injury and failure modes of hybrid composite laminates were also discussed. Finally, Chapter 5 presents the summary of the findings outlines specific conclusions drawn from the current study and recommendations for future work.

1.7 Contributions of Work

In this present study, the research contributions are as follows:

(a) Experimental procedures for fabrication kenaf/aramid reinforced PVB film using hot press technique.
(b) Examine the possibility to use kenaf fibres in the military helmet shell.
(c) Comparison of volume fraction and thickness for the different kenaf fibre layers in terms of tensile, flexural, impact load, impact energy and penetration resistance applications in the military helmet industry.

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