**UNIVERSITI PUTRA MALAYSIA**

***MECHANICAL AND BALLISTIC PROPERTIES OF NATURAL FIBREARAMID HYBRID LAMINATED COMPOSITES***

**RIDWAN BIN YAHAYA**

# MECHANICAL AND BALLISTIC PROPERTIES OF NATURAL FIBRE-ARAMID HYBRID LAMINATED COMPOSITES

By

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

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**Chairman** :**Professor Mohd Sapuan Salit, PhD**
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The advantages of using natural fibres in a wide range of applications, together with environmental concerns, have led researchers to explore natural/synthetic fibre hybrid composites. In this study, a natural/synthetic hybrid composite was prepared using the hand lay-up method in a laminate configuration. Natural fibres were systematically chosen for hybridisation with the high-performance synthetic fibre, Kevlar (aramid fibre). This selection was conducted using the analytical hierarchy process (AHP), in which the cost, availability and mechanical properties were considered. The result indicates that kenaf fibres are the most potential fibres for hybridisation with Kevlar. Hand lay-up method was adopted to fabricate the kenaf/Kevlar hybrid composites. It's followed by mechanical and ballistic test which conducted with reference to international standards. Based on this study, it was found that post-curing temperature, kenaf content and resin-hardener mixing ratio gives significant effects on the mechanical properties of kenaf-Kevlar hybrid composites. Experimental works on the effects of kenaf contents and fibre orientation indicate that woven and unidirectional kenaf fibres reinforced composites display better tensile and flexural properties as compared to the non-woven mat. It is also noticed that increasing volume fraction of kenaf fibre in hybrid composites reduces tensile and flexural properties. Based on SEM micrographs the hybrid composites failed by the typical splitting process and interfacial shear fracture. Composite with kenaf mat contains the high void in laminates and poor interfacial bonding. The research revealed that hybrid composite with Kevlar as the outer layers display a better mechanical property as compared to other hybrid composites. Hybrid composites with treated kenaf fibres resulted in higher mechanical properties than the non-treated hybrid composites. However, hybrid composites with high kenaf content show low density (0.88g/m$^3$) and contains a high content of the voids (25.67%). After the water absorption test, the impact strength was decreased about 45.38 to 78.52%. The mechanical properties of kenaf-Kevlar hybrid composites are a function of fibre content. The hybrid composites with Kevlar-kenaf (78/22) ratio exhibited better mechanical properties compared to other hybrid composites. Ballistic measurement tests of

hybrid composites were carried out by using fragment simulating projectiles at different impact and residual velocities. The highest V50 was observed in sample 14B (452 m/s), with a thickness of 12.7 mm, which exceeded that of sample 14A (295 m/s), with a thickness of 10.43 mm, by 34%. Sample 8B, with a thickness of 9.7 mm, exhibited a $V_{50}$ of 393 m/s, while sample 8A, with a thickness of 8.08 mm, had a V50 of 295 m/s. In terms of the specific energy absorption, sample 8A absorbed 40.09% less than 8 Kevlar, while sample 8B absorbed 37.71% less than 8 Kevlar. The results indicate a significant decrease in energy absorption due to the addition of kenaf layers in hybrid type B. It was observed that ballistic properties increase with the thickness and areal density of the composites. Interlayer delamination was observed as the modes of failure in kenaf-Kevlar hybrid composites. Overall, the experimental results demonstrate the potential of kenaf-Kevlar hybrid composites for ballistic impact applications.

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

**SIFAT MEKANIK AND BALISTIK KOMPOSIT HIBRID BERLAMINASI SERAT ASLI –ARAMID**

Oleh

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Kelebihan menggunakan gentian asli dalam pelbagai aplikasi, disamping kebimbangan kemusnahan alam sekitar, telah membawa penyelidik untuk meneroka komposit hybrid asli/serat. Dalam kajian ini, komposit hibrid serat asli/sintetik telah disediakan dengan menggunakan tangan kaedah hand lay-up dalam konfigurasi lamina. Gentian asli telah dipilih secara sistematik untuk penghibridan dengan serat sintetik berprestasi tinggi, Kevlar (gentian aramid). Pemilihan ini dijalankan dengan menggunakan proses analisis hierarki (AHP), di mana factor kos, ketersediaan dan sifat-sifat mekanik dipertimbangkan. Hasil kajian telah menunjukkan bahawa serat Kenaf adalah serat paling berpotensi untuk penghibridan dengan Kevlar. Kaedah 'hand lay-up' telah digunakan untuk menghasilkan composite hybrid kenaf/Kevlar. Ia diikuti oleh ujian mekanikal dan balistik yang dijalankan merujuk kepada standard antarabangsa. Berdasarkan kajian ini, didapati bahawa suhu selepas perawatan kimia, kandungan kenaf dan nisbah campuran resin-pengeras memberikan kesan yang besar ke atas sifat-sifat mekanikal komposit hybrid kenaf-Kevlar Kajian eksperimen menunjukkan kandungan kenaf dan orientasi gentian menunjukkan bahawa komposit dengan serat tenunan dan serat satu arah memaparkan sifat tegangan dan lenturan yang lebih baik berbanding dengan serat bukan tenunan. Juga didapati bahawa peningkatan pecahan isipadu gentian kenaf dalam hibrid komposit mengurangkan tegangan dan sifat-sifat lenturan. Berdasarkan mikrograf SEM komposit hibrid gagal melalui proses pembahagian khas dan patah ricih antara muka. Komposit dengan kenaf bukan tenun mengandungi lompang yang tinggi dalam laminat dan ikatan antara muka yang lemah. Kajian ini mendedahkan bahawa komposit hibrid dengan Kevlar sebagai lapisan luar memaparkan sifat mekanikal yang lebih baik berbanding komposit hibrid lain. Komposit hibrid dengan gentian kenaf terawat menyebabkan sifat-sifat mekanik lebih tinggi daripada komposit hibrid kenaf tidak dirawat. Walau bagaimanapun, komposit hibrid dengan kenaf menunjukkan kandungan ketumpatan rendah (0.88g / $m^3$) dan mengandungi kandungan yang tinggi lompang (25.67%). Selepas ujian penyerapan air,

kekuatan hentaman telah menurun kira-kira 45.38-78.52%. Sifat-sifat mekanik kenaf-Kevlar komposit hibrid adalah bergantung kepada kandungan serat. Komposit hibrid dengan Kevlar / kenaf nisbah (78/22) dipamerkan sifat-sifat mekanikal yang lebih baik berbanding komposit hibrid lain. Ujian balistik terhadapat komposit hibrid telah dijalankan dengan menggunakan serpihan simulasi projectiles pada kelajuan hentaman dan residual yang berbeza.. Nilai $V_{50}$ tertinggi di rekodkan pada sampel 14B (452 m/s), dengan ketebalan 12.7 mm, melebihi nilai bagi sampel 14A (295 m/s), dengan ketebalan 10.43 mm, sebanyak 34%. Sampel 8B, dengan ketebalan 9.7 mm, menunjukkan $V_{50}$ pada 393 m/s, manakala sampel 8A, dengan ketebalan 8.08 mm, mempunyai $V_{50}$ =295 m/s. Dari segi penyerapan tenaga spesifik sampel 8A menyerap 40.09% kurang daripada sample 8 Kevlar, manakala sampel 8B menyerap 37.71% kurang daripada sample 8 Kevlar. Keputusan menunjukkan penurunan ketara dalam penyerapan tenaga disebabkan oleh penambahan lapisan kenaf dalam jenis hibrid B. Didapati bahawa sifat-sifat balistik meningkat dengan ketebalan dan ketumpatan luas bagi komposit. Deliminasi anatara lapisan dilihat sebagai mod kegagalan dalam kenaf-Kevlar komposit hibrid. Secara keseluruhan, keputusan eksperimen menunjukkan potensi kenaf-Kevlar komposit hibrid untuk aplikasi kesan balistik.

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## LIST OF ABBREVIATIONS

| | |
|---|---|
| ABS | Acrylonitrile-Butadiene-Styrene |
| AEW | Amine equivalent weight |
| AFV | Armoured fighting vehicles |
| AHP | Analytical hierarchy process |
| *APC* | Armoured personnel carrier |
| APS | Aminopropyl Triethoxy Siloxane |
| ASTM | American Society for Testing and Materials |
| AV | Armoured vehicle |
| CR | Consistency index |
| DGEBA | Diglycidyl Ether of Bisphenol A |
| DOE | Design of experiment |
| EEW | Epoxy equivalent weight |
| EFB | Oil palm empty fruit bunch |
| Esp | Specific energy absorption |
| FRC | Fibre reinforced composites |
| FRP | Fibre reinforced polymers |
| GFRP | Glass fibre reinforced polymer |
| GMT | Glass mat thermoplastic |
| HDPE | high-density polyethylene |
| IFWIT | Instrumented falling weight impact testing |
| KBFB | Kenaf bast fibers bundle |
| KF | Kenaf bast fibre |
| KG | Kenaf-glass |
| K-HDPE | Kenaf bast fibre reinforced high density polyethylene |
| LNR | Liquid natural rubber |
| MAPP | Maleic Anhydride Grafted Polypropylene |
| MCDM | Multi-criteria decision making |
| MMT | Montmorillonite |
| N | Newton |
| NaOH | Sodium hydroxide |
| NKTB | National Kenaf and Tobacco Board |
| PBT | Polybutylene terephthalate |
| PET | Polyethylene terephthalate |
| PLA | Poly (lactic acid) |
| PLLA | Poly-l-lactic acid |
| pMDI | Polymeric Methylene Diphenyl Diisocyanate |
| POM | Polyoxymethylene |
| PPTA | Poly-Para-Phenylene Terephtalamide |
| PU | Polyurethane |
| RHA | Rolled homogeneous armour |
| SEM | Scanning electron microscopy |
| SMC | Sheet moulding compound |
| TPNR | Thermoplastic polypropylene natural rubber |
| UHMWPE | Ultra-High Molecular Weight Polyethylene |
| UPE | Unsaturated polyester resin |
| $V_{50}$ | Ballistic velocity limit |

# CHAPTER 1

# INTRODUCTION

## 1.1 Background

Composite materials containing synthetic fibres were introduced in the 1960s due to the limitations of metals, such as their weight, strength and low relative stiffness. The primary advantages of these materials are related to their high strength and high specific stiffness. Nylon with high toughness was first evaluated for ballistic protection. It was then found that toughness is not the only criterion for ballistic protection [1]. High-performance aramid fibres are widely used in ballistic protection due to their properties such as high strength, high modulus and good tenacity [2]. These fibres are used in a wide range of structural and impact-resistant applications that require high performance and low weight [3]. Ballistic protection involves both personal and structural protection. Aramid fibre-reinforced polymer composites are used for protecting personnel in military assets, such as military vehicle spall liners [4][5].

In this study, the term 'ballistic-resistant composites' will be used to describe composites developed with the aim of providing protection against ballistic impacts. Ballistic-resistant composites are used to fabricate hard plates for body armour and portable ballistic shields such as ballistic clipboards used by police officers, to provide ballistic protection for fixed structures such as critical control rooms or guard stations, and provide ballistic protection for the occupants of vehicles. Ballistic impact events include situations in which a projectile is fired from a gun at a speed greater than 244 m/s [6]. As researchers aim to develop green composite materials, more research has focused on natural fibres as a replacement for synthetic fibres. The use of natural fibres has been further encouraged by the 'end-of-life' regulation for the automotive industry in Europe and Asia [7]. Research on natural fibre composites has been rapidly growing. Kenaf (*Hibiscus cannabinus, L. family Malvaceae*), an herbaceous annual plant, has been used since ancient times for various purposes, for example, as rope, canvas, or sacking. There are numerous advantages for using this natural lignocellulose fibre to reinforce a matrix, including economic and ecological advantages, low density, non-abrasiveness during processing, high specific mechanical properties, and biodegradability. A more environmentally suitable option with a fully biodegradable end-of-life can be achieved by incorporating biodegradable resins [8]. These plant fibres grow naturally, are renewable and require less energy to manufacture than synthetic fibres [9]. Natural fibres are low cost, low density, non-abrasive and less harmful during handling and have desirable specific properties [9].

The potential of natural fibres combined with environmental concerns has led to innovative studies of natural fibres for ballistic impact applications [10]. Natural fibre composites alone are inadequate to withstand high-velocity impacts, but the hybridisation of natural and synthetic fibres provides an alternative to achieve this purpose. Hybridisation usually involves two different types of fibres that are combined together to form an interply or laminate hybrid, an intraply or tow-by-tow hybrid, an intimately mixed hybrid or some type of mixture [11]. The properties of a hybrid composite depend on factors such as fibre content, fibre length, fibre orientation, the extent of fibre intermingling, the fibre-to-matrix interface, the layering patterns of both fibres and the failure strain of individual fibres [12]. The main advantages of hybrid composites lie in the ability to combine the properties of their constituents [13]. Moreover, costs can be reduced by supplementing a cheaper type of fibre to reduce the amount of more expensive fibre (for example, by combining a low-cost natural fibre with a higher-cost synthetic fibre) in producing hybrid laminates to gain comparable mechanical strength and chemical properties in comparison to laminates obtained from the expensive fibres alone.

In this study, the potential of introducing natural fibre as a partial replacement of synthetic fibres by the hybridisation of natural fibres and aramid (Kevlar) fibre-reinforced epoxy composites are explored, with the aim of developing ballistic-resistant composites or, specifically, vehicle spall-liners. The primary research is concentrated on the selection of a natural fibre using the analytical hierarchy process (AHP), the fabrication of a hybrid composite, and an investigation of the composite properties (physical, mechanical and ballistic). Through this research, a natural-synthetic fibre hybrid composite was developed with specified mechanical and ballistic properties.

## 1.2 Problem Statements

Synthetic fibre-reinforced composite materials, such as Kevlar fibre-reinforced polymer composites, are increasingly being used in high-velocity impact applications. Composites offer a number of distinct advantages over more conventional engineering materials such as aluminium or steel, including higher specific strength and stiffness, superior corrosion resistance and improved fatigue properties. High-performance synthetic fibre-reinforced polymer composites are widely used in ballistic-resistant composites for body armour plates and vehicle spall-liners. Composite structures offers the opportunity for significant weight savings over metallic structures through buckling, interlaminar failure, fibre–matrix debonding, fibre pull-out, matrix deformation/cracking, friction and fibre breakage [14]. However, there is a consensus that the performance must be tempered by financial concerns [15], and the use of synthetic fibre involves high processing costs [9]. In addition, most fibres are manufactured using petroleum-based resources. Environmental awareness and the depletion of petroleum resources have motivated researchers to explore the potential of natural fibre as an alternative composite material. Currently, natural fibre composites are generally employed in non-structural applications, such as interior linings for automotive components [7][16], packaging materials [17], insulation [18][19][20][21], acoustic absorption panels [22][23] and building materials [24][25].

Interestingly, ballistic-resistant composites differ from structural laminates. In ballistic laminates, a higher matrix volume content and high adhesion give poor ballistic behaviour, whereas in structural laminates, these characteristics are necessary to utilise the full strength of the material. The properties of ballistic laminates include a high fibre content, poor fibre impregnation, moderate adhesion and the presence of bubbles (voids) [26]. Unlike traditional structural composites, compliant laminates, also known as armour-grade composites, have a 20% weight fraction matrix and are designed to readily delaminate [27].

The potential applications of natural fibre in ballistic composites have been explored [10]. Natural fibre composites represent an environmentally sustainable alternative to conventional synthetic fibre composites. Fibres derived from plants are renewable and have low levels of embodied energy compared to synthetic fibres. Natural fibres are also low cost, low density, non-abrasive and less harmful during handling and have superior specific properties [8]. The advantages of using natural fibre in terms of economic and environmental aspects have motivated numerous studies on natural fibre for ballistic composites [10]. Composites for ballistic applications require high strength and stiffness, light weight, crack resistance, fatigue resistance, and high impact resistance. Natural fibres are known to exhibit high moisture absorption and poor fibre/matrix adhesion, thus displaying poor mechanical properties. Therefore, the hybridisation of natural fibres with synthetic fibres to form a hybrid composite may allow one to produce a material with a combination of advantages. Due to their properties, such as being low-cost, biodegradable, renewable and highly available, natural fibres have potential as a partial replacement of currently used synthetic fibres for ballistic-resistant composites. This research was conducted to develop a natural fibre kenaf-aramid (Kevlar) hybrid composite using the low-cost hand lay-up method, and the mechanical and ballistic properties of the composite were analysed.

## 1.3 Research Objectives

The main objective of this study is to explore the possibility of using natural fibre as a partial replacement for man-made synthetic fibres in the form of a hybrid composite. The specific research objectives are as follows:

i) To select natural fibres for hybrid composite using the analytical hierarchy process (AHP)
ii) To investigate the factors affecting the properties of natural fibre-aramid hybrid composites
iii) To determine the mechanical properties of natural fibre-aramid hybrid composites
iv) To examine the ballistic properties of natural fibre-aramid hybrid composites

## 1.4 Significance of this Study

In recent years, researchers have attempted to decrease our dependence on petroleum-based materials and products due to increased environmental concerns. This aim has encouraged researchers to investigate suitable materials that are both environmentally friendly and sustainable for replacing existing synthetic materials. A total replacement of synthetic fibre in ballistic-resistant composites is not possible due to limitations in the mechanical properties of natural fibres. As an alternative, natural fibre can be used via hybridisation with synthetic fibres in polymer composites. As an environmentally friendly alternative, a combination of natural and synthetic fibre and epoxy resin in the form of a hybrid laminate is an interesting material. It is expected that the findings of this study may initiate a new step in the application of natural fibre composites.

## 1.5 Scopes and Limitations of this Study

The scope of the present research is limited to experimental evaluations of the physical, mechanical and ballistic properties of natural-synthetic fibre hybrid composites for ballistic impact applications. Prior to the experiment works, the selection of materials was conducted using analytical hierarchy process. The materials used are limited to kenaf fibres, aramid (Kevlar) and epoxy matrix. The hand lay-up fabrication method was utilised in this research. To further evaluate the hybrid composites, the factors affecting their properties were also studied.

## 1.6 Thesis Organisation

This study is divided into four parts. The first part is a preliminary study, which consists of the selection of a natural fibre for hybrid composite fabrication. Based on the objectives, the next steps involve a determination of the factors affecting the mechanical and ballistic properties of natural fibre hybrid composites. The physical, mechanical and ballistic properties of the hybrid composites were also studied. This thesis is structured into nine chapters. Chapter 1 provides the readers with an overview of this study and the objectives derived from the problem statements. Chapter 2 presents a comprehensive literature review on relevant areas associated with the topics in this research. Next, Chapter 3 presents the overall research methodology applied in this research. Chapter 4 to Chapter 7 are presented in the form of research publications, including published articles and manuscripts under review, which form the major contribution of this study. Chapter 4 encompasses the first article, entitled "Selection of natural fibres for kenaf-aramid hybrid laminated spall liners". This article reports the use of the analytical hierarchy process method together with a sensitivity analysis to determine the best natural fibre for use in hybrid composites based on the product design specifications. Chapter 5 presents three articles, which discussed on the factors affecting the properties of kenaf-aramid hybrid composites. Chapter 6 consists of two articles which discussed on the physical and mechanical properties of kenaf-aramid hybrid composites. This chapter discusses the effect of kenaf volume content and fibre orientation on the tensile and flexural properties of kenaf/aramid hybrid composites. The composite morphology was also examined. Next, Chapter 7 presents the fifth article, entitled "Measuremnt of ballistic impact performance of woven kenaf-aramid hybrid laminated composites". This article investigates the energy absorption and ballistic limit of kenaf-Kevlar hybrid composites. The effect of the layering sequence is also discussed. The following chapters (Chapter 8) consist of general discussion of the articles in previous chapters. Additional information about the articles was elaborated in this chapter. Chapter 9 stated the conclusions as well as recommendations for future works are presented.

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