



UNIVERSITI PUTRA MALAYSIA

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

SUHAD DAWOOD SALMAN

FK 2017 22



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

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**

January 2017

COPYRIGHT

All material contained within the thesis, including without limitation text, logos, icons, photographs and all other artwork, is copyright material of Universiti Putra Malaysia unless otherwise stated. Use may be made of any material contained within the thesis for non-commercial purposes from the copyright holder. Commercial use of material may only be made with the express, prior, written permission of Universiti Putra Malaysia.

Copyright © Universiti Putra Malaysia



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

KENAF ARAMID FIBRE REINFORCED POLYVINYL BUTYRAL HYBRID COMPOSITES FOR MILITARY HELMET

By

SUHAD DAWOOD SALMAN

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

Pengerusi : Zulkiflle Bin Leman, PhD
Fakulti : Kejuruteraan

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.



ACKNOWLEDGEMENTS

First of all, I would like to praise to Allah SWT for giving me the time, patience, physical and mental strength, to have finally completed this research.

I would like to express my deeply indebted and gratitude to the chairman of the supervisory committee, Associate Professor Dr. Zulkiflle Leman for his continuous support and advice throughout this research. Deepest appreciation is also extended to the members of the supervisory committee, Dr. Mohamed Thariq Bin Hameed Sultan, Dr. Mohamad Ridzwan Bin Ishak and Dr. Francisco Cardona, for their valuable comments and suggestions during the study. Special thanks to Mr. John van Hoboken, Mrs. Rayne Ramliza Bt Raybayi, Dr. Ridwan Yahaya, Mr. Mohd Fauzy B. Mohd Nor and to everyone who has helped me in completing this research project.

I am indebted to all the wonderful people at the Department of Mechanical and Manufacturing Engineering for their help during the experimental testings. I am also thankful for the help rendered by the staff at the Science Technology Research Institute for Defence, Malaysian Ministry of Defence (STRIDE). Thanks are also due to the staff at the Brazen Composites Malaysia Company for their assistance on the works.

Lastly, I would like to extend my greatest appreciation to my family, for their overwhelming support and blessing. Also, thanks to all my friends and colleagues for their constant support and encouragement that have directly or indirectly contributed to the completion of this study.

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

Zulkiflle Leman, PhD

Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Mohamed Thariq bin Hameed Sultan, PhD, P.Eng

Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Mohamad Ridzwan bin Ishak, PhD

Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Francisco Cardona, PhD

Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Member)

ROBIAH BINTI YUNUS, PhD

Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

Signature: _____
Name of
Chairman of
Supervisory
Committee: Assoc. Prof. Dr. Zulkiflle Leman

Signature: _____
Name of
Member of
Supervisory
Committee: Ir. Dr. Mohamed Thariq bin Hameed Sultan

Signature: _____
Name of
Member of
Supervisory
Committee: Dr. Mohamad Ridzwan bin Ishak

Signature: _____
Name of
Member
Supervisory
Committee: Dr. Francisco Cardona

TABLE OF CONTENTS

	Page
ABSTRACT	i
ABSTRAK	iii
ACKNOWLEDGEMENTS	v
APPROVAL	vi
DECLARATION	viii
LIST OF TABLES	xiii
LIST OF FIGURES	xiv
LIST OF ABBREVIATIONS	xix
 CHAPTER	
1 INTRODUCTION	1
1.1 Background	1
1.2 Problem Statement	3
1.3 Aim of this Study	4
1.4 Research Objectives	4
1.5 Scope of the study	5
1.6 Thesis Layout	5
1.7 Contribution of Work	6
 2 LITERATURE REVIEW	 7
2.1 Introduction	7
2.2 Development in Helmet Protection	7
2.3 Helmet Design and Material Considerations	8
2.3.1 Conventional Material Systems	8
2.3.2 Modern Material Systems	9
2.4 Impact Tests	9
2.5 Mechanisms Influencing Impact Performance	12
2.5.1 Material Properties	12
2.5.2 Fabric Structure	13
2.5.3 Projectile Geometry	13
2.5.4 Impact Velocity	14
2.5.5 Multiple Plies	14
2.6 Hybrid Composite Materials	15
2.6.1 Aramid Fibres	16
2.6.2 Kenaf Fibres	16
2.6.3 Matrix	18
2.7 Static Structural Performance of aramid and Kenaf Composites	19
2.8 Dynamic Structural Performance of Kevlar and Kenaf Composites	23
2.9 Performance Measures of Military Helmets	25
2.10 Ballistic Standard for Helmet	26
2.11 Summary	26

3	MATERIALS AND METHODS	27
3.1	Introduction	27
3.2	General Method of Approach	27
3.3	Materials and Tools	29
3.3.1	Aramid Fibres	30
3.3.2	Kenaf Fibres	31
3.3.3	Polyvinyl Butyral (PVB) Resin	31
3.4	Hybrid Composites Preparation	32
3.4.1	Composite Specimen Fabrication for Mechanical Tests	35
3.4.2	Composite Specimen and Helmet Shell Fabrication for High Impact Tests	37
3.5	Experimental Procedure	40
3.5.1	Kenaf Fibre Characterization	40
3.5.2	Density, Weight Fraction, Volume Fraction and Voids Content	41
3.5.3	Tensile Test	43
3.5.4	Flexural Test	44
3.5.5	Drop Weight Impact Test	45
3.5.6	Quasi-Static Penetration Test	47
3.5.7	Ballistic Impact Test	49
3.6	Hybrid Failure Mechanism	54
3.7	Summary	54
4	RESULTS AND DISCUSSION	55
4.1	Introduction	55
4.2	Kenaf Fibres Characterization	55
4.3	Density, Weight Fraction, Volume Fraction and Voids Content Measurement	56
4.4	Mechanical Properties of Kenaf/Aramid Reinforced PVB Composites	60
4.4.1	Tensile Properties of Kenaf/Aramid Composites	60
4.4.2	Flexural Properties of Kenaf/Aramid Composites	66
4.4.3	Drop Weight Impact Properties of Kenaf/Aramid Composites	70
4.4.4	Quasi-Static Penetration Properties	82
4.5	Ballistic Impact Properties	89
4.5.1	NIJ Results	89
4.5.2	Trauma Injury Results	90
4.5.3	V ₅₀ Results	93
4.5.4	Energy Absorption	96
4.6	Hybrid Failure Mechanism	101
4.6.1	Tensile Damage Assessment	101
4.6.2	Flexural Damage Assessment	103
4.6.3	Drop Weight Impact Damage Assessment	103
4.6.4	Hybrid Damage Mechanisms under Quasi-Static Penetration Tests	104

4.6.5	Hybrid Damage Mechanisms under Ballistic Tests	106
4.7	Design Cost Estimation	110
4.8	Summary	111
5	SUMMARY, CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH	112
5.1	Conclusions	112
5.2	Recommendations	113
	REFERENCES	114
	APPENDICES	
	BIO DATA OF STUDENT	
	LIST OF PUBLICATIONS	



LIST OF TABLES

Table	Page
3.1 Physical and mechanical properties of Heracron® aramid fabric	31
3.2 Physical and mechanical properties of PVB film	32
3.3 Specifications of the laminated hybrid composites	36
3.4 Specifications of the laminated hybrid composites for ballistic tests	39
4.1 Properties of kenaf yarns	56
4.2 Properties of plain weave kenaf fabric	56
4.3 Calculated composite densities, void contents and corresponding fiber volume fractions	59
4.4 Energy absorption and maximum load of quasi static tested samples	86
4.5 NIJ levels results	89
4.6 The penetration depth (PD) for each laminated hybrid	90
4.7 Ballistic resistance results	94
4.8 Energy absorption of ballistic resistance result	96
4.10 The expected cost	110

LIST OF FIGURES

Figure	Page
2.1 Historical perspective of U.S. Army helmet design and materials from World War I to the latest headgear system	8
2.2 Schematic demonstrating the three principal damage mechanisms for low velocity impact: a) matrix cracking, b) shear delamination, c) tensile fibre failure	10
2.3 Projectile impact into fabric armour	11
2.4 Sphere impacting single ply of fabric (a) side view, (b) top view of z displacement contours and (c) bottom view showing principal yarns under high stress	12
2.5 The kinds of projectile	13
2.6 Description of the penetration process of compliant laminates with (a) compaction and (b) spring-back	15
3.1 Flow chart describing the outline plan to carry out the research work.	28
3.2 Flow chart describing the composite fabrication process	29
3.3 Plain woven (a) aramid fibres, (b) kenaf fibres and (c) PVB film	30
3.4 The hybrid composite panels preparation process	33
3.5 Hybrids H5 and H5A stacking sequence	34
3.6 Compression moulding hot press and temperature profile	34
3.7 Composite panels produced from mould after cured and cut by grinding machine	37
3.8 Ballistic hybrid laminate fabrication processes	38
3.9 Plain woven kenaf: top view and cross section view	41
3.10 Tensile test specimens and sample setup being implemented on the tensile strength testing machine	43
3.11 Flexural test specimens and sample setup being implemented on the flexural strength testing machine	45

3.12	Overall view of the drop weight impact machine with impactor load cell and support fixture.	47
3.13	The quasi-static test setup showing the clamping apparatus	48
3.14	Actual set-up for ballistic impact test	49
3.15	Actual set-up for flat panels and helmet shells for ballistic tests	50
3.16	9 mm projectile for NIJ tests	51
3.17	Clay-backed ballistic testing and trauma depth	52
3.18	Fragment simulating projectiles for V_{50} tests	53
4.1	Change in composite density based on fiber volume fractions	60
4.2	Tensile stress-strain curves of kenaf, aramid composites and their hybrids	61
4.3	Tensile stress-strain curves of the alternative laminated hybrids of kenaf/aramid fibers.	62
4.4	Tensile stress-strain curves of each hybrid and its alternative laminate	64
4.5	Tensile properties of all laminated composites	65
4.6	Flexural stress-strain curves of kenaf, aramid composites and their hybrids	66
4.7	Flexural stress-strain curves of the alternative laminated hybrids of kenaf/aramid fibers	67
4.8	Flexural stress-strain curves of each hybrid and its alternative laminate	68
4.9	Flexural properties of all laminated composites	69
4.10	Hysteresis cycles for drop weight impact force-displacement curves of kenaf, aramid composites and their hybrids at 50 J	71
4.11	Hysteresis cycles for drop weight impact force-displacement curves of alternative layers of kenaf, aramid composites at 50 J	71

4.12	Hysteresis cycles for drop weight impact force-displacement curves of each hybrid and its alternative laminate at 50 J	73
4.13	Drop weight impact parameters of all hybrid laminates, peak impact force and absorbed energy at 50 J	74
4.14	Hysteresis cycles for drop weight impact force-displacement curves of kenaf, aramid composites and their hybrids at 75 J	75
4.15	Hysteresis cycles for drop weight impact force-displacement curves of alternative layers of kenaf, aramid composites at 75 J	76
4.16	Hysteresis cycles for drop weight impact force-displacement curves of each hybrid and its alternative laminate at 75 J	77
4.17	Drop weight impact parameters of all hybrid laminates, peak impact force and absorbed energy at 75 J	78
4.18	Hysteresis cycles for drop weight impact force-displacement curves of kenaf, aramid composites and their hybrids at 100 J	79
4.19	Hysteresis cycles for drop weight impact force-displacement curves of alternative layers of kenaf, aramid composites at 100 J	79
4.20	Hysteresis cycles for drop weight impact force-displacement curves of each hybrid and its alternative laminate at 100 J	81
4.21	Drop weight impact parameters of all hybrid laminates, peak impact force and absorbed energy at 100 J	82
4.22	Penetration force-displacement curves of kenaf, aramid composites and their hybrids	83
4.23	Penetration force-displacement curves of the alternative laminated hybrids of kenaf/aramid fibers	83
4.24	Penetration force-displacement curves of each hybrid and its alternative laminate	84
4.25	Maximum penetration load of all hybrid composites	85
4.26	Penetration energy of all hybrid composites	86

4.27	Specific energy absorption and energy density of all hybrid composites	87
4.28	Energy-fibre volume fraction curves of kenaf and aramid hybrid composites	88
4.29	Percentage changes in energy and maximum load of hybrid composites	88
4.30	Penetration depths and impact velocity for all hybrid laminated composites	91
4.31	The effect of different composite configurations on penetration depth of all hybrid composites	92
4.32	Penetration depth-volume fraction curves of kenaf and aramid hybrid composites	93
4.33	Residual velocities as a function of impact velocities	94
4.34	Ballistic limit (V_{50}) of all composites	95
4.35	Ballistic limit (V_{50})-fibre volume fraction curves of kenaf and aramid hybrid composites	95
4.36	Residual energy versus striking energy of the projectile	97
4.37	Energy absorption of all hybrid composites during ballistic tests	98
4.38	Energy absorption-volume fraction curves of kenaf and aramid hybrid composites	98
4.39	Energy absorption-Striking velocity of the hybrid composites	99
4.40	Specific energy absorption and energy density of all hybrid composites.	100
4.41	Percentage changes in energy absorption of hybrid composites	101
4.42	Optical pictures of damaged surface of hybrid composite laminates after tensile test (a) aramid composite Ar, (b) hybrid of placing kenaf layers and aramid layers separately H5, (c) hybrid of placing kenaf layers alternate with aramid layers H5A, (d) kenaf composite Kf	102
4.43	Optical pictures of damaged surface of hybrid composite laminates after flexural test (a) aramid composite Ar, (b) hybrid of placing kenaf layers and aramid layers separately	103

	H5, (c) hybrid of placing kenaf layers alternate with aramid layers H5A, (d) kenaf composite Kf	
4.44	Optical pictures of damaged surface of hybrid composite laminates after drop-weight impact test at 100 J (a) aramid composite Ar and (b) kenaf composite Kf	104
4.45	Optical pictures of damaged surface of hybrid composite laminates after quasi static test, cross-sectional surface, rear surface and impacted surface, (a) aramid composite Ar, (b) hybrid of placing kenaf layers and aramid layers separately H5, (c) hybrid of placing kenaf layers alternate with aramid layers H5A, (d) kenaf composite Kf	105
4.46	Optical pictures of ballistic failure modes of hybrid composite laminates, cross-sectional surface, impacted surface and rear surface, (a) aramid composite Ar, (b) hybrid of placing kenaf layers and aramid layers separately H3, (c) hybrid of placing kenaf layers alternate with aramid layers H3A, (d) kenaf composite Kf	107
4.47	(a) Exterior helmet shell impacted, (b) Interior helmet shell impacted (c) Impact depth using Roma Plastilina clay, at different velocities	106
4.48	Optical pictures of ballistic failure modes of hybrid composite laminates, cross-sectional surface, impacted surface and rear surface(a) aramid composite Ar, (b) hybrid of placing kenaf layers and aramid layers separately H1, (c) hybrid of placing kenaf layers alternate with aramid layers H1A, (d) kenaf composite Kf	109

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.

REFERENCES

- Aare, M., & Kleiven, S. (2007). Evaluation of head response to ballistic helmet impacts using the finite element method. *International Journal of Impact Engineering*, 34(3): 596-608.
- Abrate, S. (1991). Impact on Laminated Composite Materials. *Applied Mechanics Reviews*, 44(4): 155-190.
- Afdzaluddin, A., Maleque, M. A., & Iqbal, M. (2013). Synergistic Effect on Flexural Properties of Kenaf-Glass Hybrid Composite. *Advanced Materials Research*, 626: 989-992.
- Agarwal, B. D., Broutman, L. J., & Chandrashekhara, K. (2006). *Analysis and performance of fiber composites* (3rd ed.). New York: John Wiley & Sons.
- Agbo, S. (2009). *Modelling of Mechanical Properties of a Natural and Synthetic Fiber-Reinforced Cashew Nut Shell Resin Composites*. M. Sc. Thesis, University of Nigeria, Nigeria.
- Ahmed, K. S., & Vijayarangan, S. (2008). Tensile, flexural and interlaminar shear properties of woven jute and jute-glass fabric reinforced polyester composites. *Journal of Materials Processing Technology*, 207(1–3): 330-335.
- Aji, I., Sapuan, S., Zainudin, E., & Abdan, K. (2009). Kenaf fibres as reinforcement for polymeric composites: a review. *International Journal of Mechanical and Materials Engineering*, 4(3): 239-248.
- Aji, I. S., Zainudin, E. S., Khalina, A., Sapuan, S., & Khairul, M. (2011). Studying the effect of fiber size and fiber loading on the mechanical properties of hybridized kenaf/PALF-reinforced HDPE composite. *Journal of Reinforced Plastics and Composites*, 30(6): 546-553.
- Akil, H. M., Cheng, L. W., Ishak, Z. M., Abu Bakar, A., & Abd Rahman, M. (2009). Water absorption study on pultruded jute fibre reinforced unsaturated polyester composites. *Composites Science and Technology*, 69(11–12): 1942-1948.
- Akil, H. M., De Rosa, I. M., Santulli, C., & Sarasini, F. (2010). Flexural behaviour of pultruded jute/glass and kenaf/glass hybrid composites monitored using acoustic emission. *Materials Science and Engineering: A*, 527(12): 2942-2950.
- Akil, H. M., Omar, M. F., Mazuki, A. A. M., Safiee, S., Ishak, Z. A. M., & Abu Bakar, A. (2011). Kenaf fiber reinforced composites: A review. *Materials & Design*, 32(8–9): 4107-4121.

- Al-Kinani, R., Najim, F., & de Moura, M. (2014). The effect of hybridization on the GFRP behavior under quasi-static penetration. *Mechanics of Advanced Materials and Structures*, 21(2): 81-87.
- Ali, A., Shaker, Z., Khalina, A., & Sapuan, S. (2011). Development of Anti-Ballistic Board from Ramie Fiber. *Polymer-Plastics Technology and Engineering*, 50(6): 622-634.
- Ali, M. E., Yong, C. K., Ching, Y. C., Chuah, C. H., & Liou, N.-S. (2014). Effect of Single and Double Stage Chemically Treated Kenaf Fibers on Mechanical Properties of Polyvinyl Alcohol Film. *BioResources*, 10(1): 822-838.
- Almeida Jr, J. H. S., Amico, S. C., Botelho, E. C., & Amado, F. D. R. (2013). Hybridization effect on the mechanical properties of curaua/glass fiber composites. *Composites Part B: Engineering*, 55: 492-497.
- Amar, K. M., Manjusri, M., Lawrence, T. D., Susan, E. S., Bruce, R. H., & Georg, H. (2005). *Natural Fibers, Biopolymers, and Biocomposites*. Boca Raton, FL, USA: CRC Press.
- Anuar, H., Ahmad, S., Rasid, R., Ahmad, A., & Busu, W. (2008). Mechanical properties and dynamic mechanical analysis of thermoplastic-natural-rubber-reinforced short carbon fiber and kenaf fiber hybrid composites. *Journal of Applied Polymer Science*, 107(6): 4043-4052.
- Ashori, A. (2010). Hybrid composites from waste materials. *Journal of Polymers and the Environment*, 18(1): 65-70.
- Ashori, A., Harun, J., Raverty, W. D., & Yusoff, M. N. M. (2006). Chemical and morphological characteristics of Malaysian cultivated kenaf (*Hibiscus cannabinus*) fiber. *Polymer-Plastics Technology and Engineering*, 45(1): 131-134.
- ASTM D 3379-75R89E01, (1989). Standard Test Method for Tensile Strength and Young's Modulus for High-Modulus Single-Filament Materials. ASTM International, West Conshohocken, PA
- ASTM D 6264-98, (1998). Standard Test Method for Measuring the Damage Resistance of a Fiber-Reinforced Polymer-Matrix Composite to a Concentrated Quasi-Static Indentation Force. ASTM International, West Conshohocken, PA.
- ASTM D 3039/D 3039M-08, (2008a). Standard test method for tensile properties of polymer matrix composite materials. ASTM International, West Conshohocken, PA.
- ASTM D2260-03R09, (2009a). Standard Tables of Conversion Factors and Equivalent Yarn Numbers Measured in Various Numbering Systems. ASTM International, West Conshohocken, PA

- ASTM D 2734-09, (2009b). Standard Test Methods for Void Content of Reinforced Plastics. ASTM International, West Conshohocken, PA.
- ASTM D 1895-96R10E01, (2010b). Standard Test Methods for Apparent Density, Bulk Factor, and Pourability of Plastic Materials. ASTM International, West Conshohocken, PA
- ASTM D 790-10, (2010c). Standard test methods for flexural properties of unreinforced and reinforced plastics and electrical insulating materials. ASTM International, West Conshohocken, PA.
- ASTM D 7136/D 7136M-15, (2015). Standard Test Method for Measuring the Damage Resistance of a Fiber-Reinforced Polymer Matrix Composite to a Drop-Weight Impact Event. ASTM International, West Conshohocken, PA
- Athijayamani, A., Thiruchitrambalam, M., Natarajan, U., & Pazhanivel, B. (2009). Effect of moisture absorption on the mechanical properties of randomly oriented natural fibers/polyester hybrid composite. *Materials Science and Engineering: A*, 517(1–2): 344-353.
- Atiqah, A., Maleque, M. A., Jawaid, M., & Iqbal, M. (2014). Development of kenaf-glass reinforced unsaturated polyester hybrid composite for structural applications. *Composites Part B: Engineering*, 56: 68-73.
- Azwa, Z. N., & Yousif, B. F. (2013). Characteristics of kenaf fibre/epoxy composites subjected to thermal degradation. *Polymer Degradation and Stability*, 98(12): 2752-2759.
- Azwa, Z. N., Yousif, B. F., Manalo, A. C., & Karunasena, W. (2013). A review on the degradability of polymeric composites based on natural fibres. *Materials & Design*, 47: 424-442.
- Babu, M. G., Velmurugan, R., & Gupta, N. (2006). Energy absorption and ballistic limit of targets struck by heavy projectile. *Latin American Journal of Solids and Structures, an ABCM Journal*, 3(1): 21-39.
- Bada, B. S., & Raji, K. A. (2010). Phytoremediation potential of kenaf (*Hibiscus cannabinus* L.) grown in different soil textures and cadmium concentrations. *African Journal of Environmental Science and Technology*, 4(5): 250-255.
- Bagheri, Z. S., El Sawi, I., Bougherara, H., & Zdero, R. (2014). Biomechanical fatigue analysis of an advanced new carbon fiber/flax/epoxy plate for bone fracture repair using conventional fatigue tests and thermography. *Journal of the Mechanical Behavior of Biomedical Materials*, 35: 27-38.
- Bakar, M. A. A., Ahmad, S., Kuntjoro, W., & Kasolang, S. (2013). Effect of Carbon Fibre Ratio to the Impact Properties of Hybrid Kenaf/Carbon Fibre Reinforced Epoxy Composites. *Applied Mechanics and Materials*, 393: 136-139.

- Bakar, N. H., Mei Hyie, K., Ramlan, A. S., Hassan, M. K., & Jumahat, A. (2014). Mechanical Properties of Kevlar Reinforcement in Kenaf Composites. *Applied Mechanics and Materials*, 465: 847-851.
- Bandaru, A. K., Patel, S., Sachan, Y., Alagirusamy, R., Bhatnagar, N., & Ahmad, S. (2016). Low velocity impact response of 3D angle-interlock Kevlar/basalt reinforced polypropylene composites. *Materials & Design*, 105: 323-332.
- Barauskas, R., & Abraitienė, A. (2007). Computational analysis of impact of a bullet against the multilayer fabrics in LS-DYNA. *International Journal of Impact Engineering*, 34(7): 1286-1305.
- Bazhenov, S. (1997). Dissipation of energy by bulletproof aramid fabric. *Journal of Materials Science*, 32(15): 4167-4173.
- Becker, E. B. (1998). Helmet development and standards. In N. Yoganandan, F. A. Pintar & Larson, Sanford J. (Eds.), *Frontiers in Head and Neck Trauma: Clinical and Biomedical*, OHMSHA: IOS Press.
- Beg, M. D. H., & Pickering, K. L. (2008). Accelerated weathering of unbleached and bleached Kraft wood fibre reinforced polypropylene composites. *Polymer Degradation and Stability*, 93(10): 1939-1946.
- Begum, K., & Islam, M. (2013). Natural fiber as a substitute to synthetic fiber in polymer composites: a review. *Research Journal of Engineering Sciences*, 2(3): 46-53.
- Benevolenski, O., Karger-Kocsis, J., Mieck, K.-P., & Reubmann, T. (2000). Instrumented perforation impact response of polypropylene composites with hybrid reinforcement flax/glass and flax/cellulose fibers. *Journal of Thermoplastic Composite Materials*, 13(6): 481-496.
- Bessadok, A., Langevin, D., Gouanvé, F., Chappey, C., Roudesli, S., & Marais, S. (2009). Study of water sorption on modified Agave fibres. *Carbohydrate Polymers*, 76(1): 74-85.
- Bhatnagar, A. (2006). *Lightweight ballistic composites: military and law-enforcement applications*. Cambridge, UK: Woodhead Publishing.
- Bilisik, A. K., & Turhan, Y. (2009). Multidirectional stitched layered aramid woven fabric structures and their experimental characterization of ballistic performance. *Textile Research Journal*, 79(4): 1331–1343.
- Blackwood, W., Anderson, T., Bennett, C., Corson, J., Endsley, M., Hancock, P., Hochberg, J., Hoffman, J., & Kruk, R. (1997). *Tactical displays for soldiers: Human factors considerations*. Washington, DC: National Academy Press.
- Bledzki, A., & Gassan, J. (1997). Natural fiber reinforced plastics. *Handbook of engineering polymeric materials*: 787-810.

- Bledzki, A. K., & Gassan, J. (1999). Composites reinforced with cellulose based fibres. *Progress in Polymer Science*, 24(2): 221-274.
- Boccaccini, A., Atiq, S., Boccaccini, D., Dlouhy, I., & Kaya, C. (2005). Fracture behaviour of mullite fibre reinforced–mullite matrix composites under quasi-static and ballistic impact loading. *Composites Science and Technology*, 65(2): 325-333.
- Bonnia, N., Ahmad, S., Zainol, I., Mamun, A., Beg, M., & Bledzki, A. (2010). Mechanical properties and environmental stress cracking resistance of rubber toughened polyester/kenaf composite. *Express Polym. Lett*, 4: 55-61.
- Brown, J. R., & Egglestone, G. T. (1989). *Ballistic properties of composite materials for personnel protection*. (Technical Report No. MRL-TR-89-6), Materials Research Laboratory Cordite Avenae: Maribyrnong, Australia.
- Burgueño, R., Quagliata, M. J., Mohanty, A. K., Mehta, G., Drzal, L. T., & Misra, M. (2005). Hybrid biofiber-based composites for structural cellular plates. *Composites Part A: Applied Science and Manufacturing*, 36(5): 581-593.
- Calamari, T. A., Tao, W., & Goynes, W. R. (1997). A preliminary study of kenaf fiber bundles and their composite cells. *Tappi journal*, 80(8): 149-153.
- Campbell, D. T., & Cramer, D. R. (2008). Hybrid thermoplastic composite ballistic helmet fabrication study. *Advancement of Materials & Process Engineering*.
- Campbell, S. (2009). PASGT Helmet Test: An Example of Effective Intra-Government Testing Collaboration: DTIC Document.
- Cannon, L. (2001). Behind armour blunt trauma-an emerging problem. *Journal of the Royal Army Medical Corps*, 147(1): 87-96.
- Cantwell, W. J., & Morton, J. (1991). The impact resistance of composite materials — a review. *Composites*, 22(5): 347-362.
- Carey, M. E., Herz, M., Corner, B., McEntire, J., Malabarba, D., Paquette, S., & Sampson, J. B. (2000). Ballistic helmets and aspects of their design. *Neurosurgery*, 47(3): 678-689.
- Carr, D. (1999). Failure mechanisms of yarns subjected to ballistic impact. *Journal of materials science letters*, 18(7): 585-588.
- Cay, A., Atrav, R., & Duran, K. (2007). Effects of warp-weft density variation and fabric porosity of the cotton fabrics on their colour in reactive dyeing. *Fibres & Textiles in Eastern Europe*, 15(1): 91-94.
- Cernak, I., & Noble-Haeusslein, L. J. (2010). Traumatic brain injury: an overview of pathobiology with emphasis on military populations. *Journal of Cerebral Blood Flow & Metabolism*, 30(2): 255-266.

- Cheeseman, B. A., & Bogetti, T. A. (2003). Ballistic impact into fabric and compliant composite laminates. *Composite Structures*, 61(1–2): 161-173.
- Cheung, H.-y., Ho, M.-p., Lau, K.-t., Cardona, F., & Hui, D. (2009). Natural fibre-reinforced composites for bioengineering and environmental engineering applications. *Composites Part B: Engineering*, 40(7): 655-663.
- Choi, H. Y., Wu, H.-Y. T., & Chang, F.-K. (1991). A new approach toward understanding damage mechanisms and mechanics of laminated composites due to low-velocity impact: Part II—analysis. *Journal of Composite Materials*, 25(8): 1012-1038.
- Chow, P., Lambert, R. J., Bowers, C., & McKenzie, N. (2000). Physical and mechanical properties of composite panels made from kenaf plant fibers and plastics. In: *Proceedings of the 2000 International Kenaf Symposium*, Yasuura, Hiroshima, Japan, (pp. 139-143).
- Chua, C.-K., & Chena, Y.-L. (2010). Ballistic-proof Effects of Various Woven Constructions. *Fibres & Textiles in Eastern Europe*, 18(6): 83.
- Cicala, G., Cristaldi, G., Recca, G., Ziegmann, G., El-Sabbagh, A., & Dickert, M. (2009). Properties and performances of various hybrid glass/natural fibre composites for curved pipes. *Materials & Design*, 30(7): 2538-2542.
- Colakoglu, M., Soykasap, O., & Özek, T. (2007). Experimental and Numerical Investigations on the Ballistic Performance of Polymer Matrix Composites Used in Armor Design. *Applied Composite Materials*, 14(1): 47-58.
- Corbière-Nicollier, T., Laban, B. G., Lundquist, L., Leterrier, Y., Månson, J. A. E., & Jolliet, O. (2001). Life cycle assessment of biofibres replacing glass fibres as reinforcement in plastics. *Resources, Conservation and Recycling*, 33(4): 267-287.
- Cui, X. D., Zeng, T., & Fang, D. N. (2006). Study on ballistic energy absorption of laminated and sandwich composites. *Key Engineering Materials*, 306-308: 739-744.
- Cunniff, P. M. (1992). An analysis of the system effects in woven fabrics under ballistic impact. *Textile Research Journal*, 62(9): 495-509.
- Cunniff, P. M. (1999). The V50 performance of body armor under oblique impact. In: *Proceedings of the 18th International Symposium on Ballistics*, Antonio, TX, (pp. 814-821).
- Czechowski, L., Jankowski, J., & Kubiak, T. (2012). Experimental tests of a property of composite material assigned for ballistic products. *Fibres & Textiles in Eastern Europe*, 20(3): 61-66.

- Da Silva, R. V., Aquino, E. M. F., Rodrigues, L. P. S., & Barros, A. R. F. (2008). Development of a hybrid composite with synthetic and natural fibers. *Matéria (Rio de Janeiro)*, 13(1): 154-161.
- David, N., Gao, X.-L., & Zheng, J. (2009). Ballistic resistant body armor: contemporary and prospective materials and related protection mechanisms. *Applied Mechanics Reviews*, 62(5): 050802.
- Davoodi, M. M., Sapuan, S. M., Ahmad, D., Aidy, A., Khalina, A., & Jonoobi, M. (2011). Concept selection of car bumper beam with developed hybrid bio-composite material. *Materials & Design*, 32(10): 4857-4865.
- Davoodi, M. M., Sapuan, S. M., Ahmad, D., Aidy, A., Khalina, A., & Jonoobi, M. (2012). Effect of polybutylene terephthalate (PBT) on impact property improvement of hybrid kenaf/glass epoxy composite. *Materials Letters*, 67(1): 5-7.
- Davoodi, M. M., Sapuan, S. M., Ahmad, D., Ali, A., Khalina, A., & Jonoobi, M. (2010). Mechanical properties of hybrid kenaf/glass reinforced epoxy composite for passenger car bumper beam. *Materials & Design*, 31(10): 4927-4932.
- De Albuquerque, A., Joseph, K., de Carvalho, L. H., & d'Almeida, J. R. M. (2000). Effect of wettability and ageing conditions on the physical and mechanical properties of uniaxially oriented jute-roving-reinforced polyester composites. *Composites Science and Technology*, 60(6): 833-844.
- de Lange, P. J., Akker, P. G., Mäder, E., Gao, S.-L., Prasithphol, W., & Young, R. J. (2007). Controlled interfacial adhesion of Twaron® aramid fibres in composites by the finish formulation. *Composites Science and Technology*, 67(10): 2027-2035.
- De Rosa, I. M., Santulli, C., Sarasini, F., & Valente, M. (2009). Post-impact damage characterization of hybrid configurations of jute/glass polyester laminates using acoustic emission and IR thermography. *Composites Science and Technology*, 69(7-8): 1142-1150.
- Dehury, J. (2014). *Processing & characterization of jute/glass fiber reinforced epoxy based hybrid composites*. (PhD Thesis), National institute of technology, Rourkela, India.
- Deka, L. (2008). *Quasi-static and multi-site high velocity impact response of composite structures*. (PhD Thesis), University of Alabama, Birmingham, Alabama.
- Dhakal, H., Zhang, Z., Bennett, N., & Reis, P. (2012). Low-velocity impact response of non-woven hemp fibre reinforced unsaturated polyester composites: Influence of impactor geometry and impact velocity. *Composite Structures*, 94(9): 2756-2763.

- Dhakal, H. N., Zhang, Z. Y., Guthrie, R., MacMullen, J., & Bennett, N. (2013). Development of flax/carbon fibre hybrid composites for enhanced properties. *Carbohydrate Polymers*, 96(1): 1-8.
- Dhakal, H. N., Zhang, Z. Y., & Richardson, M. O. W. (2007). Effect of water absorption on the mechanical properties of hemp fibre reinforced unsaturated polyester composites. *Composites Science and Technology*, 67(7–8): 1674-1683.
- Dhakal, H. N., Zhang, Z. Y., Richardson, M. O. W., & Errajhi, O. A. Z. (2007). The low velocity impact response of non-woven hemp fibre reinforced unsaturated polyester composites. *Composite Structures*, 81(4): 559-567.
- Dipa, R., & Jogeswari, R. (2005). Thermoset Biocomposites. In A. K. Mohanty, M. Misra & L. T. Drzal (Eds.), *Natural Fibers, Biopolymers, and Biocomposites*. CRC Press.
- Dittenber, D. B. (2013). *Natural Kenaf Fiber Reinforced Composites as Engineered Structural Materials*. (PhD. Thesis), West Virginia University, Morgantown, USA.
- Dittenber, D. B., & GangaRao, H. V. S. (2012). Critical review of recent publications on use of natural composites in infrastructure. *Composites Part A: Applied Science and Manufacturing*, 43(8): 1419-1429.
- Duan, Y., Keefe, M., Bogetti, T., & Cheeseman, B. (2002). Modeling the impact behavior of high-strength fabric structures. In: *Fiber Society Annual Technical Conference*, Natick, Massachusetts, (pp. 16-18).
- El-Tayeb, N. S. M. (2009). Development and characterisation of low-cost polymeric composite materials. *Materials & Design*, 30(4): 1151-1160.
- Endruweit, A., Gommer, F., & Long, A. (2013). Stochastic analysis of fibre volume fraction and permeability in fibre bundles with random filament arrangement. *Composites Part A: Applied Science and Manufacturing*, 49: 109-118.
- Erkendirci, Ö. F., & Haque, B. Z. G. (2012). Quasi-static penetration resistance behavior of glass fiber reinforced thermoplastic composites. *Composites Part B: Engineering*, 43(8): 3391-3405.
- Fairuz, A., Sapuan, S., Zainudin, E., & Jaafar, C. (2014). Polymer composite manufacturing using a pultrusion process: a review. *American Journal of Applied Sciences*, 11(10): 1798.
- Faruk, O., Bledzki, A. K., Fink, H.-P., & Sain, M. (2012). Biocomposites reinforced with natural fibers: 2000–2010. *Progress in Polymer Science*, 37(11): 1552-1596.
- Faur-Csukat, G. (2006). A study on the ballistic performance of composites. *Macromolecular symposia*, 239(1): 217-226.

- Fifield, L. S., & Simmons, K. L. (2010). Compression molded, bio-fiber reinforced, high performance thermoset composites for structural and semi-structural applications. In: *10th Annual Automotive Composites Conference & Exhibition, 15–16 September, Michigan, USA*.
- Fink, B. K. (2000). Performance metrics for composite integral armor. *Journal of Thermoplastic Composite Materials*, 13(5): 417-431.
- Flynn, J. M. (2013). *Characterization of mechanical properties in hybridized flax and carbon fiber composites*. (PhD. Thesis), North dakota state university, Fargo, North Dakota, USA.
- Fulton, I. T. (2011). *The effect of layup and pressure on mechanical properties of fiberglass and kenaf fiber composites*. (M. Sc. Thesis), Mississippi State University, Oktibbeha County, Mississippi, USA.
- Gama, B. A., Islam, S. W., Rahman, M. M., Gillespie Jr, J., Bogetti, T. A., Cheeseman, B. A., Yen, C. F., & Hoppel, C. P. (2005). Punch shear behavior of thick-section composites under quasi-static, low velocity, and ballistic impact loading. *SAMPE Journal Jul/Aug*, 41(4): 6-13.
- Ganpule, S., Gu, L., Alai, A., & Chandra, N. (2012). Role of helmet in the mechanics of shock wave propagation under blast loading conditions. *Computer methods in biomechanics and biomedical engineering*, 15(11): 1233-1244.
- Gellert, E., Cimpoeu, S., & Woodward, R. (2000). A study of the effect of target thickness on the ballistic perforation of glass-fibre-reinforced plastic composites. *International Journal of Impact Engineering*, 24(5): 445-456.
- Ghani, M. A. A., Salleh, Z., Hyie, K. M., Berhan, M. N., Taib, Y. M. D., & Bakri, M. A. I. (2012). Mechanical Properties of Kenaf/Fiberglass Polyester Hybrid Composite. *Procedia Engineering*, 41(0): 1654-1659.
- Gibson, R. F. (2010). A review of recent research on mechanics of multifunctional composite materials and structures. *Composite Structures*, 92(12): 2793-2810.
- Gogineni, S., Gao, X.-L., David, N., & Zheng, J. (2012). Ballistic impact of Twaron CT709® plain weave fabrics. *Mechanics of Advanced Materials and Structures*, 19(6): 441-452.
- Gopinath, G., Zheng, J. Q., & Batra, R. C. (2012). Effect of matrix on ballistic performance of soft body armor. *Composite Structures*, 94(9): 2690-2696.
- Gower, H. L., Cronin, D. S., & Plumtree, A. (2008). Ballistic impact response of laminated composite panels. *International Journal of Impact Engineering*, 35(9): 1000-1008.
- Greenhalgh, E. S., Bloodworth, V. M., Iannucci, L., & Pope, D. (2013). Fractographic observations on Dyneema® composites under ballistic

- impact. *Composites Part A: Applied Science and Manufacturing*, 44: 51-62.
- Gross, R. A., & Kalra, B. (2002). Biodegradable polymers for the environment. *Science*, 297(5582): 803-807.
- Guoqi, Z., Goldsmith, W., & Dharan, C. (1992). Penetration of laminated Kevlar by projectiles—I. Experimental investigation. *International Journal of Solids and Structures*, 29(4): 399-420.
- Gururaja, M. N., & Hari Rao, A. N. (2012). A review on recent applications and future prospectus of hybrid composites. *International Journal of Soft Computing and Engineering (IJSCE)*, 1(6): 352-355.
- Hancox, N. L. (2000). An overview of the impact behaviour of fibre-reinforced composites. In S. R. Reid & G. Zhou (Eds.), *Impact Behaviour of Fibre-Reinforced Composite Materials and Structures* (pp. 1-32), Cambridge, UK: Woodhead Publishing Ltd.
- Hani, A. A., Roslan, A., Jaafar, M., Roslan, M., & Ariffin, S. (2011). Mechanical properties evaluation of woven coir and kevlar reinforced epoxy composites. *Advanced Materials Research*, 277: 36-42.
- Hani, A. A., Shaari, M., Radzuan, N. M., Hashim, M., Ahmad, R., & Mariatti, M. (2013). Analysis of woven natural fiber fabrics prepared using self-designed handloom. *International Journal of Automotive & Mechanical Engineering*, 8: 1197-1206.
- Hariharan, A. B. A., & Khalil, H. P. S. A. (2005). Lignocellulose-based Hybrid Bilayer Laminate Composite: Part I - Studies on Tensile and Impact Behavior of Oil Palm Fiber-Glass Fiber-reinforced Epoxy Resin. *Journal of Composite Materials*, 39(8): 663-684.
- Hetherington, J. (1992). The optimization of two component composite armours. *International Journal of Impact Engineering*, 12(3): 409-414.
- Hetherington, J., & Rajagopalan, B. (1991). An investigation into the energy absorbed during ballistic perforation of composite armours. *International Journal of Impact Engineering*, 11(1): 33-40.
- Hill, C., & Hughes, M. (2010). Natural Fibre Reinforced Composites Opportunities and Challenges. *Journal of Biobased Materials and Bioenergy*, 4(2): 148-158.
- Holbery, J., & Houston, D. (2006). Natural-fiber-reinforced polymer composites in automotive applications. *Jom*, 58(11): 80-86.
- Huber, T., Bickerton, S., Müssig, J., Pang, S., & Staiger, M. P. (2013). Flexural and impact properties of all-cellulose composite laminates. *Composites Science and Technology*, 88(0): 92-98.
- Huda, M. S., Drzal, L. T., Mohanty, A. K., & Misra, M. (2008). Effect of fiber surface-treatments on the properties of laminated biocomposites from

poly(lactic acid) (PLA) and kenaf fibers. *Composites Science and Technology*, 68(2): 424-432.

- Husman, G. E., Whitney, J. M., & Halpin, J. C. (1975). Residual strength characterization of laminated composites subjected to impact loading, Foreign object impact damage to composites, ASTM STP 568 (pp. 92-113).
- Ibrahim, T., & Hafeez, T. M. (2014). *A study of crashworthiness characteristic of woven kenaf fabric reinforced composites tube*. (M. Sc. Thesis), Universiti Tun Hussein Onn Malaysia, Johor, Malaysia.
- Iremonger, M., & Went, A. (1996). Ballistic impact of fibre composite armours by fragment-simulating projectiles. *Composites Part A: Applied Science and Manufacturing*, 27(7): 575-581.
- Ishak, M. R., Leman, Z., Sapuan, S. M., Edeerozey, A. M. M., & Othman, I. S. (2010). Mechanical properties of kenaf bast and core fibre reinforced unsaturated polyester composites. *IOP Conference Series: Materials Science and Engineering*, 11(1): 012006.
- Ismail, H., Omar, N. F., & Othman, N. (2011). The effect of kenaf fibre loading on curing characteristics and mechanical properties of waste tyre dust/kenaf fibre hybrid filler filled natural rubber compounds. *BioResources*, 6(4): 3742-3756.
- Jawaid, M., & Abdul Khalil, H. P. S. (2011). Cellulosic/synthetic fibre reinforced polymer hybrid composites: A review. *Carbohydrate Polymers*, 86(1): 1-18.
- Jawaid, M., Khalil, H. A., Khanam, P. N., & Bakar, A. A. (2011). Hybrid composites made from oil palm empty fruit bunches/jute fibres: Water absorption, thickness swelling and density behaviours. *Journal of Polymers and the Environment*, 19(1): 106-109.
- Jeyanthi, S., & Rani, J. J. (2012). Improving mechanical properties by kenaf natural long fiber reinforced composite for automotive structures. *J. Appl. Sci. Eng*, 15(3): 275-280.
- Joseph, P. V., Rabello, M. S., Mattoso, L. H. C., Joseph, K., & Thomas, S. (2002). Environmental effects on the degradation behaviour of sisal fibre reinforced polypropylene composites. *Composites Science and Technology*, 62(10-11): 1357-1372.
- Joshi, S. V., Drzal, L. T., Mohanty, A. K., & Arora, S. (2004). Are natural fiber composites environmentally superior to glass fiber reinforced composites? *Composites Part A: Applied Science and Manufacturing*, 35(3): 371-376.
- Kamardin, N. K., Taib, Y. M., & Kalam, A. (2013). Impact Toughness of Kenaf Powder, Polypropylene and Kevlar. *Applied Mechanics and Materials*, 393: 152-155.

- Kang, T. J., & Lee, S. H. (1994). Effect of stitching on the mechanical and impact properties of woven laminate composite. *Journal of Composite Materials*, 28(16): 1574-1587.
- Kasano, H., Kamoshida, H., Abe, K., & Kubokawa, H. (2012). Ballistic Impact Behavior and Properties of Double-Ply Woven Fabrics. In: *ECCM15-15th European conference on composite material 24-28 June, Venice, Italy*.
- Khalil, H. A., Jawaid, M., & Bakar, A. A. (2011). Woven hybrid composites: water absorption and thickness swelling behaviours. *BioResources*, 6(2): 1043-1052.
- Khalil, H. A., Kang, C., Khairul, A., Ridzuan, R., & Adawi, T. (2009). The Effect of Different Laminations on Mechanical and Physical Properties of Hybrid Composites. *Journal of Reinforced Plastics and Composites*, 28(9): 1123-1137.
- Kim, H. J., & Seo, D. W. (2006). Effect of water absorption fatigue on mechanical properties of sisal textile-reinforced composites. *International Journal of Fatigue*, 28(10): 1307-1314.
- Kim, J.-K., & Sham, M.-L. (2000). Impact and delamination failure of woven-fabric composites. *Composites Science and Technology*, 60(5): 745-761.
- Kim, W., Argento, A., Lee, E., Flanigan, C., Houston, D., Harris, A., & Mielewski, D. F. (2012). High strain-rate behavior of natural fiber-reinforced polymer composites. *Journal of Composite Materials*, 46(9): 1051-1065.
- Kline, & Company Inc. (2000). Opportunities for natural fibers in plastic composites. In: *Proceedings of progress in wood Fiber-plastic composites Conference 25 May, Toronto, Canada*.
- Kong, K., Hejda, M., Young, R. J., & Eichhorn, S. J. (2009). Deformation micromechanics of a model cellulose/glass fibre hybrid composite. *Composites Science and Technology*, 69(13): 2218-2224.
- Kulkarni, S., Gao, X.-L., Horner, S., Zheng, J., & David, N. (2013). Ballistic helmets—their design, materials, and performance against traumatic brain injury. *Composite Structures*, 101: 313-331.
- Larsson, F., & Svensson, L. (2002). Carbon, polyethylene and PBO hybrid fibre composites for structural lightweight armour. *Composites Part A: Applied Science and Manufacturing*, 33(2): 221-231.
- Larsson, M. P., & Ahmad, M. M. (2006). Improved polymer–glass adhesion through micro-mechanical interlocking. *Journal of Micromechanics and Microengineering*, 16(6): S161.

- Lee, B., Walsh, T., Won, S., Patts, H., Song, J., & Mayer, A. (2001). Penetration failure mechanisms of armor-grade fiber composites under impact. *Journal of Composite Materials*, 35(18): 1605-1633.
- Leman, Z., Sapuan, S. M., Azwan, M., Ahmad, M. M. H. M., & Maleque, M. (2008). The effect of environmental treatments on fiber surface properties and tensile strength of sugar palm fiber-reinforced epoxy composites. *Polymer-Plastics Technology and Engineering*, 47(6): 606-612.
- Leman, Z., Sapuan, S. M., Saifol, A. M., Maleque, M. A., & Ahmad, M. M. H. M. (2008). Moisture absorption behavior of sugar palm fiber reinforced epoxy composites. *Materials & Design*, 29(8): 1666-1670.
- Lim, C., Tan, V., & Cheong, C. (2002). Perforation of high-strength double-ply fabric system by varying shaped projectiles. *International Journal of Impact Engineering*, 27(6): 577-591.
- Lim, J. S. (2013). Ballistic Behavior of Heracron®-Based Composites: Effect of the Number Multifilaments on High-Speed Projectiles. *Modeling and Numerical Simulation of Material Science*, 3(3): 84-89.
- Lim, J. S., & Kim, J. H. (2014). Ballistic behavior of Heracron®-based composites: effect of fiber density and fabrication method. *Composite Interfaces*, 21(6): 543-552.
- Lim, J. S., Lee, B. H., Lee, C. B., & Han, I. S. (2012). Effect of the Weaving Density of Aramid Fabrics on Their Resistance to Ballistic Impacts. *Engineering*, 4(12A): 944-949.
- Lin, C., & Fatt, M. S. H. (2006). Perforation of composite plates and sandwich panels under quasi-static and projectile loading. *Journal of Composite Materials*, 40(20): 1801-1840.
- Madsen, B., Hoffmeyer, P., & Lilholt, H. (2007). Hemp yarn reinforced composites – II. Tensile properties. *Composites Part A: Applied Science and Manufacturing*, 38(10): 2204-2215.
- Madsen, B., Thygesen, A., & Lilholt, H. (2009). Plant fibre composites – porosity and stiffness. *Composites Science and Technology*, 69(7–8): 1057-1069.
- Maleque, M. A., Afdzaluddin, A., & Iqbal, M. (2012). Flexural and Impact Properties of Kenaf-Glass Hybrid Composite. *Advanced Materials Research*, 576: 471-474.
- Mall, S., & Gao, X. (2000). A two dimensional rule-of-mixtures micromechanics model for woven fabric composites. *Journal of Composites, Technology and Research*, 22(2): 60-70.
- Mansor, M. R., Sapuan, S. M., Zainudin, E. S., Nuraini, A. A., & Hambali, A. (2013). Hybrid natural and glass fibers reinforced polymer composites

- material selection using Analytical Hierarchy Process for automotive brake lever design. *Materials & Design*, 51(0): 484-492.
- Mathur, V. K. (2006). Composite materials from local resources. *Construction and Building Materials*, 20(7): 470-477.
- McEntire, B. J., & Whitley, P. (2005). *Blunt impact performance characteristics of the Advanced Combat Helmet and the Paratrooper and Infantry Personnel Armor System for ground troops helmet*. (No. 2005-12), U.S. Army Aeromedical Research Laboratory: Virginia, USA.
- McManus, L. R., Durand, P. E., & Claus Jr, W. D. (1976). *Development of a one piece infantry helmet*. (No. 76-30-CEMEL), Natick, Massachusetts: U.S. Army Natick Research and Development Command.
- Merdas, I., ThomINETTE, F., Tcharkhtchi, A., & Verdu, J. (2002). Factors governing water absorption by composite matrices. *Composites Science and Technology*, 62(4): 487-492.
- Methacanon, P., Weerawatsophon, U., Sumransin, N., Prahsarn, C., & Bergado, D. T. (2010). Properties and potential application of the selected natural fibers as limited life geotextiles. *Carbohydrate Polymers*, 82(4): 1090-1096.
- Military Standard MIL-H-44099A, (December 1986). Military Specification Helmet, Ground Troops And Parachutists. *U.S. Army Natick Research, Development, and Engineering Center*, Natick, MA.
- MIL-STD-662F, (1997 December). V₅₀ Ballistic Test For Armor. Department Of Defence Test Method Standard.
- Milanese, A. C., Cioffi, M. O. H., & Voorwald, H. J. C. (2011). Mechanical behavior of natural fiber composites. *Procedia Engineering*, 10(0): 2022-2027.
- Mines, R. A. W., Roach, A. M., & Jones, N. (1999). High velocity perforation behaviour of polymer composite laminates. *International Journal of Impact Engineering*, 22(6): 561-588.
- Mohanty, A., Misra, M., & Drzal, L. (2002). Sustainable bio-composites from renewable resources: opportunities and challenges in the green materials world. *Journal of Polymers and the Environment*, 10(1-2): 19-26.
- Mohanty, A., Misra, M., & Hinrichsen, G. (2000). Biofibres, biodegradable polymers and biocomposites: an overview. *Macromolecular Materials and Engineering*, 276(1): 1-24.
- Mohanty, A. K., Misra, M., & Drzal, L. T. (2001). Surface modifications of natural fibers and performance of the resulting biocomposites: An overview. *Composite Interfaces*, 8(5): 313-343.

- Morin, B., Adams, B., Follo, B., & Salem, D. (2009). Weight reduction and cost savings using hybrid composites containing high modulus polypropylene fiber. *COMPOSITES and POLYCON*: 15-17.
- Muhi, R., Najim, F., & De Moura, M. (2009). The effect of hybridization on the GFRP behavior under high velocity impact. *Composites Part B: Engineering*, 40(8): 798-803.
- Murali Mohan Rao, K., Mohana Rao, K., & Ratna Prasad, A. V. (2010). Fabrication and testing of natural fibre composites: Vakka, sisal, bamboo and banana. *Materials & Design*, 31(1): 508-513.
- Musch, J. C. R. (2008). *Design Optimization of Sustainable Panel Systems Using Hybrid Natural/synthetic Fiber Reinforced Polymer Composites*. (M. Sc. Thesis), Michigan state university, East Lansing, Michigan, United States.
- Naik, N., & Doshi, A. (2008). Ballistic impact behaviour of thick composites: Parametric studies. *Composite Structures*, 82(3): 447-464.
- Naik, N., & Shrirao, P. (2004). Composite structures under ballistic impact. *Composite Structures*, 66(1): 579-590.
- Naik, N., Shrirao, P., & Reddy, B. (2006). Ballistic impact behaviour of woven fabric composites: Formulation. *International Journal of Impact Engineering*, 32(9): 1521-1552.
- Naik, N. K., & Doshi, A. V. (2005). Ballistic impact behavior of thick composites: analytical formulation. *AIAA journal*, 43(7): 1525-1536.
- Navarro, C. (1997). Simplified Modelling of the Ballistic Behaviour of Fabrics and Fibre-Reinforced Polymetric Matrix Composites. In: *Key Engineering Materials*, (pp. 383-402).
- NIJ Standard-0106.01, (December 1981). Ballistic helmets. National Institute of Justice, U.S. Department of Justice, Washington, DC 20531.
- NIJ Standard-0108.01, (September 1985). Ballistic Resistant Protective Materials. National Institute of Justice, U.S. Department of Justice, Washington, DC 20531.
- NIJ Standard-0101.04, (September 2000). Ballistic Resistance of Personal Body Armor. National Institute of Justice, U.S. Department of Justice, Washington, DC 20531.
- Nilakantan, G., Keefe, M., Wetzal, E. D., Bogetti, T. A., & Gillespie, J. W. (2011). Computational modeling of the probabilistic impact response of flexible fabrics. *Composite Structures*, 93(12): 3163-3174.
- Nunna, S., Chandra, P. R., Shrivastava, S., & Jalan, A. K. (2012). A review on mechanical behavior of natural fiber based hybrid composites. *Journal of Reinforced Plastics and Composites*, 31(11): 759-769.

- Ochi, S. (2008). Mechanical properties of kenaf fibers and kenaf/PLA composites. *Mechanics of Materials*, 40(4–5): 446-452.
- Ou, R., Zhao, H., Sui, S., Song, Y., & Wang, Q. (2010). Reinforcing effects of Kevlar fiber on the mechanical properties of wood-flour/high-density-polyethylene composites. *Composites Part A: Applied Science and Manufacturing*, 41(9): 1272-1278.
- Paine, J. S., & Rogers, C. A. (1995). Observations of the drop-weight impact response of composites with surface bonded nitinol layers. In: *Proc. ASME Materials Division: Presented at the 1995 ASME Int. Mechanical Engineering Congr. and Exposition (Nov. 1995)*.
- Pandey, J. K., Ahn, S. H., Lee, C. S., Mohanty, A. K., & Misra, M. (2010). Recent Advances in the Application of Natural Fiber Based Composites. *Macromolecular Materials and Engineering*, 295(11): 975-989.
- Pandya, K., Kumar, C. V. S., Nair, N., Patil, P., & Naik, N. (2015). Analytical and experimental studies on ballistic impact behavior of 2D woven fabric composites. *International Journal of Damage Mechanics*, 24(4): 471-511.
- Pandya, K. S., Pothnis, J. R., Ravikumar, G., & Naik, N. (2013). Ballistic impact behavior of hybrid composites. *Materials & Design*, 44: 128-135.
- Pandya, K. S., Veeraj, C., & Naik, N. (2011). Hybrid composites made of carbon and glass woven fabrics under quasi-static loading. *Materials & Design*, 32(7): 4094-4099.
- Parikh, D., Calamari, T., Sawhney, A., & Warnock, M. (2002). Refining of Kenaf Fibers for Processing into Automotive Nonwovens. In: *Proceedings of the Beltwide Cotton Conferences. 11-12 January, Atlanta, GA*.
- Park, J. L., Chi, Y.-S., & Kang, T. J. (2013). Ballistic performance of hybrid panels composed of unidirectional/woven fabrics. *Textile Research Journal*, 83(5): 471-486.
- Park, R., & Jang, J. (1998). Stacking sequence effect of aramid-UHMPE hybrid composites by flexural test method: MATERIAL PROPERTIES. *Polymer Testing*, 16(6): 549-562.
- Petrucchi, R., Santulli, C., Puglia, D., Sarasini, F., Torre, L., & Kenny, J. M. (2013). Mechanical characterisation of hybrid composite laminates based on basalt fibres in combination with flax, hemp and glass fibres manufactured by vacuum infusion. *Materials & Design*, 49: 728-735.
- Prat, N., Rongieras, F., Sarron, J.-C., Miras, A., & Voiglio, E. (2012). Contemporary body armor: technical data, injuries, and limits. *European journal of trauma and emergency surgery*, 38(2): 95-105.

- Qatu, M. S. (2011). Application of kenaf-based natural fiber composites in the automotive industry. In: *SAE 2011 World Congress & Exhibition, Technical Paper 2011-01-0215*, Mississippi State University, Mississippi, USA.
- Radif, Z. S., Ali, A., & Abdan, K. (2011). Development of a green combat armour from rame-kevlar-polyester composite. *Pertanika Journal of Science and Technology*, 19(2): 339-348.
- Ramaswamy, G. N., Sellers, T., Tao, W., & Crook, L. G. (2003). Kenaf nonwovens as substrates for laminations. *Industrial Crops and Products*, 17(1): 1-8.
- Ramnath, B. V., Kokan, S. J., Raja, R. N., Sathyanarayanan, R., Elanchezhian, C., Prasad, A. R., & Manickavasagam, V. (2013). Evaluation of mechanical properties of abaca-jute-glass fibre reinforced epoxy composite. *Materials & Design*, 51: 357-366.
- Rao, H. R., Kumar, M. A., & Reddy, G. R. (2011). Hybrid composites: Effect of fibers on mechanical properties. *International Journal of Macromolecular Science*, 1(1): 9-14.
- Rao, Y., Waddon, A. J., & Farris, R. J. (2001). The evolution of structure and properties in poly(p-phenylene terephthalamide) fibers. *Polymer*, 42(13): 5925-5935.
- Rashid, A., & Hani, A. (2013). Analysis of woven natural fiber fabrics prepared using self-designed handloom. *International Journal of Automotive and Mechanical Engineering*, 8: 1197-1206.
- Rassmann, S., Paskaramoorthy, R., & Reid, R. G. (2011). Effect of resin system on the mechanical properties and water absorption of kenaf fibre reinforced laminates. *Materials & Design*, 32(3): 1399-1406.
- Ray, B. C., & Rathore, D. (2014). Durability and integrity studies of environmentally conditioned interfaces in fibrous polymeric composites: Critical concepts and comments. *Advances in Colloid and Interface Science*, 209: 68-83.
- Razali, N., Sultan, M., & Aminanda, Y. (2014). The study of impact behaviour of two types of glass fibre reinforced polymer (GFRP) subjected to low velocity impact. *Advanced Materials Research*, 1044-1045: 153-157.
- Razali, N., Sultan, M., Mustapha, F., Yidris, N., & Ishak, M. (2014). Impact damage on composite structures—a review. *The International Journal Of Engineering And Science*, 3(7): 8-20.
- Rebouillat, S., & Hearle, J. (2001). *High Performance Fibers* (pp. 23-61), Cambridge, UK: Woodhead Publishing
- Reis, P. N. B., Ferreira, J. A. M., Antunes, F. V., & Costa, J. D. M. (2007). Flexural behaviour of hybrid laminated composites. *Composites Part A: Applied Science and Manufacturing*, 38(6): 1612-1620.

- Richardson, M. O., Madera-Santana, T. J., & Hague, J. (1998). Natural fibre composites. The potential for the Asian markets. *Progress in rubber and plastics technology*, 14(3): 174-188.
- Risby, M. S., Wong, S. V., Hamouda, A. M. S., Khairul, A. R., & Elsadig, M. (2008). Ballistic Performance of Coconut Shell Powder/Twaron Fabric against Non-armour Piercing Projectiles. *Defence Science Journal*, 58(2): 248-263.
- Risdall, J. E., & Menon, D. K. (2011). Traumatic brain injury. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, 366(1562): 241-250.
- Rustemeyer, J., Kranz, V., & Bremerich, A. (2007). Injuries in combat from 1982–2005 with particular reference to those to the head and neck: a review. *British journal of oral and maxillofacial surgery*, 45(7): 556-560.
- Saba, N., Paridah, M. T., & Jawaid, M. (2015). Mechanical properties of kenaf fibre reinforced polymer composite: A review. *Construction and Building Materials*, 76: 87-96.
- Sabet, A. R., Beheshty, M. H., & Rahimi, H. (2009). Experimental study of sharp-tipped projectile perforation of GFRP plates containing sand filler under high velocity impact and quasi - static loadings. *Polymer Composites*, 30(10): 1497-1509.
- Saheb, D. N., & Jog, J. P. (1999). Natural fiber polymer composites: A review. *Advances in Polymer Technology*, 18(4): 351-363.
- Salleh, F. M., Hassan, A., Yahya, R., & Azzahari, A. D. (2014). Effects of extrusion temperature on the rheological, dynamic mechanical and tensile properties of kenaf fiber/HDPE composites. *Composites Part B: Engineering*, 58: 259-266.
- Salleh, Z., Berhan, M. N., Hyie, K. M., & Isaac, D. H. (2012a). Cold-pressed Kenaf and Fibreglass Hybrid Composites Laminates: Effect of Fibre Types. *World Academy of Science, Engineering and Technology, International Science Index* 71, 6(11): 740 - 744.
- Salleh, Z., Hyie, K. M., Berhan, M. N., Taib, Y. M., Hassan, M., & Isaac, D. (2013). Effect of Low Impact Energy on Kenaf Composite and Kenaf/Fiberglass Hybrid Composite Laminates. *Applied Mechanics and Materials*, 393: 228-233.
- Salleh, Z., Taib, Y. M., Hyie, K. M., Mihat, M., Berhan, M. N., & Ghani, M. A. (2012b). Fracture Toughness Investigation on Long Kenaf/Woven Glass Hybrid Composite Due To Water Absorption Effect. *Procedia Engineering*, 41: 1667-1673.
- Samil, F., & David, N. (2012). An Ergonomic Study of a Conventional Ballistic Helmet. *Procedia Engineering*, 41: 1660-1666.

- Santulli, C. (2007). Impact properties of glass/plant fibre hybrid laminates. *Journal of Materials Science*, 42(11): 3699-3707.
- Santulli, C., Janssen, M., & Jeronimidis, G. (2005). Partial replacement of E-glass fibers with flax fibers in composites and effect on falling weight impact performance. *Journal of Materials Science*, 40(13): 3581-3585.
- Sarasini, F., Tirillò, J., Ferrante, L., Valente, M., Valente, T., Lampani, L., Gaudenzi, P., Cioffi, S., Iannace, S., & Sorrentino, L. (2014). Drop-weight impact behaviour of woven hybrid basalt-carbon/epoxy composites. *Composites Part B: Engineering*, 59: 204-220.
- Sarasini, F., Tirillò, J., Valente, M., Ferrante, L., Cioffi, S., Iannace, S., & Sorrentino, L. (2013a). Hybrid composites based on aramid and basalt woven fabrics: Impact damage modes and residual flexural properties. *Materials & Design*, 49: 290-302.
- Sarasini, F., Tirillò, J., Valente, M., Valente, T., Cioffi, S., Iannace, S., & Sorrentino, L. (2013b). Effect of basalt fiber hybridization on the impact behavior under low impact velocity of glass/basalt woven fabric/epoxy resin composites. *Composites Part A: Applied Science and Manufacturing*, 47: 109-123.
- Saravana Bavan, D., & Mohan Kumar, G. C. (2010). Potential use of natural fiber composite materials in India. *Journal of Reinforced Plastics and Composites*, 29(24): 3600-3613.
- Sarron, J.-C., Caillou, J.-P., Da Cunha, J., Allain, J.-C., & Trameçon, A. (2000). Consequences of nonpenetrating projectile impact on a protected head: study of rear effects of protections. *Journal of Trauma and Acute Care Surgery*, 49(5): 923-929.
- Schwinghamer, R., & Whitaker, A. (1993). U. S. Patent No. MFS-28523. NASA Tech Briefs: A. NASA Marshall Space Flight Center; Huntsville, United States.
- Scott, B. (1999). The penetration of compliant laminates by compact projectiles. In: *Proceedings of the 18th International Symposium of Ballistic*, San Antonio, Texas, (pp. 1181-1191).
- Scott, R., Lee, S., Poon, C., & Gaudert, P. (1991). Impact and compression response of composite materials containing fortifiers. *Polymer Engineering & Science*, 31(18): 1310-1315.
- Scott, R. A. (2005). *Textiles for protection*. Cambridge, UK: Woodhead Publishing.
- Sethi, S., & Ray, B. C. (2015). Environmental effects on fibre reinforced polymeric composites: Evolving reasons and remarks on interfacial strength and stability. *Advances in Colloid and Interface Science*, 217: 43-67.

- Sharba, M. J., Leman, Z., Sultan, M. T., Ishak, M. R., & Hanim, M. A. A. (2015). Effects of kenaf fiber orientation on mechanical properties and fatigue life of glass/kenaf hybrid composites. *BioResources*, 11(1): 1448-1465.
- Sharifah, H., Martin, P., Simon, T., & Simon, R. (2005). Modified polyester resins for natural fiber composites. *Compos. Sci. Technol*, 65(3-4): 525-535.
- Sheikh, A. H., Bull, P. H., & Kepler, J. A. (2009). Behaviour of multiple composite plates subjected to ballistic impact. *Composites Science and Technology*, 69(6): 704-710.
- Shim, V., Tan, V., & Tay, T. (1995). Modelling deformation and damage characteristics of woven fabric under small projectile impact. *International Journal of Impact Engineering*, 16(4): 585-605.
- Sreekala, M. S., George, J., Kumaran, M. G., & Thomas, S. (2002). The mechanical performance of hybrid phenol-formaldehyde-based composites reinforced with glass and oil palm fibres. *Composites Science and Technology*, 62(3): 339-353.
- Sukumaran, K., Satyanarayana, K., Pillai, S., & Ravikumar, K. (2001). Structure, physical and mechanical properties of plant fibers of Kerala. *Metals Materials and Processes*, 13(2-4): 121-136.
- Sultan, M. T. H., Basri, S., Rafie, A. S. M., Mustapha, F., Majid, D. L., & Ajir, M. R. (2012). High velocity impact damage analysis for glass epoxy-Laminated plates. *Advanced Materials Research*, 399: 2318-2328.
- Sultan, M. T. H., Worden, K., Staszewski, W. J., & Hodzic, A. (2012). Impact damage characterisation of composite laminates using a statistical approach. *Composites Science and Technology*, 72(10): 1108-1120.
- Tan, P. (2013). Finite element simulation of the behaviours of laminated armour systems against blast wave and projectile dynamic impacts. *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials Design and Applications*, 227(1): 2-15.
- Tan, P. (2014). Numerical simulation of the ballistic protection performance of a laminated armor system with pre-existing debonding/delamination. *Composites Part B: Engineering*, 59: 50-59.
- Tan, V., Lim, C., & Cheong, C. (2003). Perforation of high-strength fabric by projectiles of different geometry. *International Journal of Impact Engineering*, 28(2): 207-222.
- Tan, V. B. C., & Khoo, K. J. L. (2005). Perforation of flexible laminates by projectiles of different geometry. *International Journal of Impact Engineering*, 31(7): 793-810.
- Tehrani Dehkordi, M., Nosrati, H., Shokrieh, M. M., Minak, G., & Ghelli, D. (2013). The influence of hybridization on impact damage behavior and

residual compression strength of intraply basalt/nylon hybrid composites. *Materials & Design*, 43: 283-290.

- Tham, C., Tan, V., & Lee, H. (2008). Ballistic impact of a KEVLAR® helmet: Experiment and simulations. *International Journal of Impact Engineering*, 35(5): 304-318.
- Thwe, M. M., & Liao, K. (2002). Effects of environmental aging on the mechanical properties of bamboo–glass fiber reinforced polymer matrix hybrid composites. *Composites Part A: Applied Science and Manufacturing*, 33(1): 43-52.
- Tita, V., de Carvalho, J., & Vandepitte, D. (2008). Failure analysis of low velocity impact on thin composite laminates: Experimental and numerical approaches. *Composite Structures*, 83(4): 413-428.
- Torki, A. M., Stojanović, D. B., Živković, I. D., Marinković, A., Škapin, S. D., Uskoković, P. S., & Aleksić, R. R. (2012). The viscoelastic properties of modified thermoplastic impregnated multiaxial aramid fabrics. *Polymer Composites*, 33(1): 158-168.
- Tudu, P. (2009). *Processing and characterization of natural fiber reinforced polymer composites*. (Bachelor's Thesis), National Institute of Technology, Rourkela.
- Underwood, J. (December 1981). *Technology Assessment Program NIJ Standard for Ballistic Helmets*. National Institute of Justice, U.S. Department of Justice, Washington, DC 20402.
- Utracki, L. A. (2010). *Rigid ballistic composites (Review of literature)*. (Technical Report no. 53838), NRC Institute for Research in Construction: NRC Industrial Materials Institute; National Research Council Canada
- Varma, I. K., Anantha Krishnan, S. R., & Krishnamoorthy, S. (1989). Composites of glass/modified jute fabric and unsaturated polyester resin. *Composites*, 20(4): 383-388.
- Vasquez, K. B., Logsdon, K. P., Dorman, D. B., & Chancey, V. C. (2011). Combat Helmet-Headform Coupling Characterized From Blunt Impact Events. In: *ASME 2011 International Mechanical Engineering Congress and Exposition*, Denver, Colorado, USA, (pp. 41-49).
- Velmurugan, R., Sikarwar, R., & Gupta, N. (2010). Analytical modeling for ballistic perforation of angle-ply and hybrid composite laminates. In: *Proceedings of the IMPLAST 2010 conference*, Rhode Island, USA.
- Wahab, A., & Hafizah, N. (2007). *Development of Multi-Layered Kenaf (Hibiscus Cannabinus L.) Board Using Core and Bast Fibres*. (M. Sc.Thesis), Universiti Putra Malaysia.
- Walsh, S. M., Scott, B. R., & Spagnuolo, D. M. (December 2005). *The development of a hybrid thermoplastic ballistic material with application*

to helmets. (Report No. ARL-TR-3700), U.S. Army Research Labs, Aberdeen, Maryland.

- Walsh, S. M., Scott, B. R., Spagnuolo, D. M., & Wolbert, J. P. (2006). Composite helmet fabrication using semi-deformable tooling. In: *Society for Manufacturing Processing Engineering International Symposium*, Long Beach, CA.
- Walters, W., & Scott, B. (1990). High velocity penetration of a Kevlar reinforced laminate. In: *International SAMPE Technical Conference, 22 nd*, Boston, MA, (pp. 1078-1091).
- Wambua, P., Ivens, J., & Verpoest, I. (2003). Natural fibres: can they replace glass in fibre reinforced plastics. *Composites Science and Technology*, 63(9): 1259-1264.
- Wambua, P., Vangrimde, B., Lomov, S., & Verpoest, I. (2007). The response of natural fibre composites to ballistic impact by fragment simulating projectiles. *Composite Structures*, 77(2): 232-240.
- Wan Busu, W. N., Anuar, H., Ahmad, S. H., Rasid, R., & Jamal, N. A. (2010). The Mechanical and Physical Properties of Thermoplastic Natural Rubber Hybrid Composites Reinforced with Hibiscus cannabinus, L and Short Glass Fiber. *Polymer-Plastics Technology and Engineering*, 49(13): 1315-1322.
- Wang, C., & Jang, B. (1991). Deformation and fracture mechanisms of advanced polymer composites under impact loading. *Journal of Thermoplastic Composite Materials*, 4(2): 140-172.
- Wang, W., Sain, M., & Cooper, P. A. (2006). Study of moisture absorption in natural fiber plastic composites. *Composites Science and Technology*, 66(3-4): 379-386.
- Wang, X., Hu, B., Feng, Y., Liang, F., Mo, J., Xiong, J., & Qiu, Y. (2008). Low velocity impact properties of 3D woven basalt/aramid hybrid composites. *Composites Science and Technology*, 68(2): 444-450.
- Wang, Y., Li, J., & Zhao, D. (1995). Mechanical properties of fiber glass and kevlar woven fabric reinforced composites. *Composites Engineering*, 5(9): 1159-1175.
- Wang, Y., & Xia, Y. (1998). The effects of strain rate on the mechanical behaviour of kevlar fibre bundles: an experimental and theoretical study. *Composites Part A: Applied Science and Manufacturing*, 29(11): 1411-1415.
- Wang, Y., & Xia, Y. (1999). Experimental and theoretical study on the strain rate and temperature dependence of mechanical behaviour of Kevlar fibre. *Composites Part A: Applied Science and Manufacturing*, 30(11): 1251-1257.

- Weitsman, Y. J. (1995). Effects of Fluids on Polymeric Composites-A Review: DTIC Document.
- Xue, Y., Du, Y., Elder, S., Wang, K., & Zhang, J. (2009). Temperature and loading rate effects on tensile properties of kenaf bast fiber bundles and composites. *Composites Part B: Engineering*, 40(3): 189-196.
- Yahaya, R., Sapuan, S., Jawaid, M., Leman, Z., & Zainudin, E. (2014a). Effect of Post Curing, Fibre Content and Resin-Hardener Mixing Ratio on the Properties of Kenaf-Aramid Hybrid Composites. *Applied Mechanics and Materials*, 548: 7-11.
- Yahaya, R., Sapuan, S., Jawaid, M., Leman, Z., & Zainudin, E. (2014b). Mechanical performance of woven kenaf-Kevlar hybrid composites. *Journal of Reinforced Plastics and Composites*, 33(24): 2242-2254.
- Yahaya, R., Sapuan, S., Jawaid, M., Leman, Z., & Zainudin, E. (2014c). Quasi-static penetration and ballistic properties of kenaf-aramid hybrid composites. *Materials & Design*, 63: 775-782.
- Yahaya, R., Sapuan, S., Jawaid, M., Leman, Z., & Zainudin, E. (2015). Effect of layering sequence and chemical treatment on the mechanical properties of woven kenaf-aramid hybrid laminated composites. *Materials & Design*, 67: 173-179.
- Yang, H. (1993). *Kevlar aramid fiber*. New York, USA: John Wiley & Sons.
- Yong, C. K., Ching, Y. C., Chuah, C. H., & Liou, N.-S. (2015). Effect of Fiber Orientation on Mechanical Properties of Kenaf-Reinforced Polymer Composite. *BioResources*, 10(2): 2597-2608.
- Zampaloni, M., Pourboghra, F., Yankovich, S. A., Rodgers, B. N., Moore, J., Drzal, L. T., Mohanty, A. K., & Misra, M. (2007). Kenaf natural fiber reinforced polypropylene composites: A discussion on manufacturing problems and solutions. *Composites Part A: Applied Science and Manufacturing*, 38(6): 1569-1580.
- Zhang, D., Sun, Y., Chen, L., Zhang, S., & Pan, N. (2014). Influence of fabric structure and thickness on the ballistic impact behavior of Ultrahigh molecular weight polyethylene composite laminate. *Materials & Design*, 54: 315-322.
- Zhang, T. (2003). *Improvement of kenaf yarn for apparel applications*. (M. Sc. Thesis), Beijing University of Chemical Technology, Beijing, China.
- Zhong, L. X., Fu, S. Y., Zhou, X. S., & Zhan, H. Y. (2011). Effect of surface microfibrillation of sisal fibre on the mechanical properties of sisal/aramid fibre hybrid composites. *Composites Part A: Applied Science and Manufacturing*, 42(3): 244-252.
- Zhu, H., Wu, B., Li, D., Zhang, D., & Chen, Y. (2011). Influence of Voids on the Tensile Performance of Carbon/epoxy Fabric Laminates. *Journal of Materials Science & Technology*, 27(1): 69-73.