PROPERTIES AND PERFORMANCE OF KENAF FIBER-SAWDUST POLYMERIC SANDWICH BIO-COMPOSITES

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DEDICATION

This thesis is dedicated to my parents, Chief Williams Adole (late) and Mrs. Regina Adole.

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ABSTRACT

The increasing demand for environmentally friendly and sustainable structures have led the engineers and scientists to develop new bio-based composites. Natural fibers in composites present many advantages which include high strength and stiffness to low weight ratios, biodegradability, renewability, economic viability and so on. Currently, the use of mechanical fastening joints exists in the production of sandwich composite structures, but literature indicates that it has unavoidable drawbacks such as the structure failing prematurely with a load far below the maximum strength of component parts. As a result, an adhesively bonded joint is a better method of joining.This research investigates the properties and performance of a novel sandwich composites incorporating kenaf fiber-polyester matrix as skin material and sawdust-polyester matrix as core material, respectively. To this end, the kenaf fiber-polyester skin was fabricated in a unidirectional orientation with fiber volume fraction of 40 % from preliminary study, while the sawdust-polyester core was produced in a random arrangement with fiber volume fraction of 20%, also from preliminary study and this was produced by varying the thickness of the core. Both the Kenaf Fiber Reinforced Polyester (KFRP) skins and the Sawdust Reinforced Polyester (SDRP) core were tested interm of tension, flexure, compression, and shear. These tests were carried out to determine their constituent material properties. Consequently, three types of bio-composites sandwich were manufactured based on geometry, and was subjected to flexural load through three-point bending test to establish the flexural properties. Numerical investigation was carried out using ABAQUS FEA code to validate experimental results. Besides, it has been observed from literature that the use of natural fiber composites have been restricted to non-structural and semi-structural applications due to not having sufficient test data on fracture toughness at adhesive joint. Therefore, the adhesive bond behaviour of the KFRP adherend and the SDRP adherend sandwich composites was carried out through the Double Lap Shear (DLS) joint test to ascertain the bond shear strength and stresses at the joints. The DLS joints were fabricated with different bond lengths and bond widths using polyester adhesive as joint material and subjected to direct axial compression load. Numerical simulation was implemented to validate experimental results. The results of the KFRP tensile properties shows that stiffness and strength were found to be highest in the longitudinal direction and least in the transverse direction with percentage difference of 152.50 % for the modulus of elasticity and 175.24 % for tensile strength, respectively. Also observed is that there exist a considerably variability in the SDRP tensile, compressive and flexural strengths, nevertheless, their stiffnesses are comparably closed to each other. The results of the core shear stress and facing bending stress of the bio-composites sandwich revealed an increment of 13.90 % was recorded as the core thickness increased from 10 mm to 20 mm for core shear stress, while the facing bending stress saw an increment of 13.93 % as the core thickness increased from 10 mm to 20 mm. Excellent agreement was reached between the numerical simulations and the experiments in predicting the flexural properties. Furthermore, it was found that the lap length and bond width increases the load carrying capacity of the joints but decreases the bond shear strength. The numerical analysis results were in good accord with the experimental results, and the use of KFRP and SDRP in bonded assemblies have demonstrated promised with good potentials for use in structural applications.

ABSTRAK

Permintaan yang semakin meningkat untuk struktur yang mampan dan mesra alam mendorong para jurutera dan saintis untuk membangunkan komposit berasaskan bio baharu. Gentian semulajadi dalam komposit mempunyai banyak kelebihan termasuk kekuatan yang tinggi, kekukuhan kepada nisbah berat yang rendah, kebolehan biodegradasi, kebolehbaharuan, daya maju ekonomi dan sebagainya. Buat masa ini, penggunaan sambungan pengikat mekanikal wujud dalam pengeluaran struktur komposit sandwic tetapi kajian sebelum ini menunjukkan ia mempunyai kelemahan yang tidak dapat dielakkan seperti struktur gagal sebelum waktunya dengan beban yang ditanggung berada di bawah paras kekuatan maksimum pada bahagian komponen. Akibatnya, sambungan yang diikat dengan pelekat didapati menjadi kaedah penyambungan yang lebih baik. Kajian ini mengkaji sifat dan prestasi komposit sandwic baru yang menggabungkan matriks gentian kenaf-poliester sebagai bahan kulit dan matriks habuk papan-poliester sebagai bahan teras. Untuk tujuan ini, kulit gentian-poliester kenaf telah dibuat dalam orientasi satu arah dengan pecahan isipadu gentian sebanyak 40 % yang didapati daripada kajian awal. Teras habuk papan-poliester pula dihasilkan dalam susunan rawak dengan pecahan isipadu gentian sebanyak 20 %, juga daripada kajian awal dan ianya dihasilkan dengan mempelbagaikan ketebalan teras. Kedua-dua kulit *Kenaf Fiber Reinforced Polyester* (KFRP) dan teras *Sawdust Reinforced Polyester* (SDRP) telah diuji sepenuhnya dari segi ketegangan, kelenturan, kemampatan dan kericihan. Ujian ini dijalankan untuk menentukan unsur sifat bahan tersebut. Hasil daripada itu, tiga jenis sandwic bio-komposit telah dihasilkan berdasarkan geometri, dan tertakluk kepada beban lentur melalui ujian lenturan tiga titik untuk mewujudkan sifat lenturan. Penyiasatan berangka telah dijalankan menggunakan kod ABAQUS FEA untuk mengesahkan keputusan eksperimen. Kajian terdahulu mendapati penggunaan komposit gentian semula jadi telah dihadkan kepada aplikasi bukan struktur dan separa struktur kerana data ujian yang tidak mencukupi berkenaan kekuatan menahan patah pada sambungan pelekat. Oleh itu, ujian terhadap sifat ikatan pelekat bagi komposit KFRP dan komposit sandwic adheren SDRP telah dijalankan melalui kaedah sambungan *Double Lap Shear* (DLS) untuk memastikan kekuatan ricih ikatan dan tekanan pada sambungan. Sambungan DLS telah direka dengan panjang dan lebar ikatan yang berbeza menggunakan pelekat poliester sebagai bahan sambungan dan tertakluk kepada beban mampatan paksi terus. Simulasi berangka telah dijalankan untuk mengesahkan keputusan eksperimen. Keputusan sifat tegangan KFRP menunjukkan kekakuan dan kekuatan didapati berada pada ukuran paling tinggi pada arah membujur dan paling sedikit pada arah melintang dengan peratus perbezaan masing-masing 152.50 % untuk modulus keanjalan dan 175.24 % untuk kekuatan tegangan. Hasil kajian juga mendapati terdapat kebolehubahan yang ketara dalam kekuatan tegangan, mampatan dan lentur SDRP. Bagaimanapun, bagi kekakuan, hasil keputusannya hampir sama antara satu sama lain. Keputusan tegasan ricih teras dan tegasan hadap lentur sandwic bio-komposit menunjukkan peningkatan sebanyak 13.90 % apabila ketebalan teras meningkat daripada 10 mm kepada 20 mm untuk tegasan ricih teras, manakala tegasan lenturan menghadapi peningkatan sebanyak 13.93 % kerana ketebalan teras meningkat daripada 10 mm kepada 20 mm. Persetujuan yang sangat baik telah dicapai antara simulasi berangka dan eksperimen dalam meramalkan sifat lentur. Kajian juga mendapati bahawa panjang pusingan dan lebar ikatan mampu meningkatkan keupayaan membawa beban sambungan tetapi ia mengurangkan kekuatan ricih ikatan. Keputusan analisis berangka adalah selari dengan keputusan eksperimen, dan penggunaan KFRP dan SDRP dalam pemasangan terikat telah menunjukkan potensi yang baik untuk digunakan dalam aplikasi struktur.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AE	-	Acoustic Emission
ASTM	-	American Society for Testing and Materials
CZM	-	Cohesive Zone Modelling
DIC	-	Digital Image Correlation
DLS	-	Double Lap Shear
XFEM	-	Extended Finite Element Method
FEA	-	Finite Element Analysis
FEM	-	Finite Element Method
F	-	Force
GFRP	-	Glass Fiber Reinforced Polymer
KF	-	Kenaf Fiber
KFRP	-	Kenaf Fiber Reinforced Polyester
MEKP	-	Methyl Ethyl Ketone Peroxide
NFC	-	Natural Fiber Composites
OMF	-	Oil Palm Mesocarp Flour
OPS	-	Oil Palm Shell
PET	-	Polyethylene Terephthalate
PLA	-	Polylactic Acid
PP	-	Polypropylene
PU	-	Polyurethane
PVC	-	Polyvinyl Chloride
SDRP	-	Sawdust Reinforced Polyester
RTM	-	Resin Transfer Molding
RWF	-	Rubber Wood Flour
NaOH	-	Sodium Hydroxide
SIP	-	Structural Insulated Panel
UB	-	Unit Break
UPR	-	Unsaturated Polyester Resin
WF	-	Wood Flour
WPC	-	Wood Polymer Composites

LIST OF SYMBOLS

V_f	-	Fiber volume fraction
ρ_m	-	Density of resin
ρ_f	-	Density of fiber
W_f	-	Weight per unit area of dry fiber
W_m	-	Weight per unit area of matrix
V_m	-	Matrix volume fraction
E_1	-	Longitudinal modulus
E_2	-	Transverse modulus
$\mathcal{V}_{12}$	-	Longitudinal Poisson's ratio
G_{12}=G_{13}, and G_{23}	-	Shear moduli
E_m	-	Matrix modulus
G_m	-	Shear modulus of matrix
E	-	Elastic modulus
σ	-	Stress
ε	-	Strain
δ	-	Bending stress
∂	-	Core shear stress
τ	-	Shear bond strength
$\mathcal{V}_{23}$	-	Minor Poisson's ratio
S_C	-	Transverse shear strength
S_T	-	Longitudinal shear strength
X_C	-	Longitudinal Compressive Strength
X_T	-	Longitudinal tensile strength
Y_C	-	Transverse compressive strength
Y_T	-	Transverse tensile strength

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 General Appraisal

Sandwich construction, which combines composite skins with a variety of core materials, is becoming increasingly common for a variety of structural applications. Sandwich structured composites according to Sadeghian *et al.* (2016a), are special class of composite materials which have become very popular due to its high strength to weight ratio, high specific strength and stiffness, good fatigue resistance, low thermal expansion, good dampness property and in particular, the ability to give explicitly tailored material properties. These properties make sandwich composites suitable in the field of civil infrastructures, aeronautical engineering, automobile engineering and marine applications. In the past, sandwich panel usage was limited to aeronautical applications, however, they have recently been ustilized as structural components in buildings. A sandwich structure usually consists of two stiff, strong sheets of composite material separated by a relatively thick core layer. The necessity to combine high mechanical stiffness with a lightweight structure prompted the development of sandwich construction. This is accomplished by increasing the distance between the skins, which increases the inertial moment and hence increases the structure's bending stiffness (Vitale *et al.*, 2017).

Over the years, synthetic fiber such as carbon, glass, aramid and so on have been the traditional reinforcing agents in sandwich composite skin, while the core material usually composed of aluminum, or polymer materials such as expanded polystyrene, extruded polystyrene, polyisocyanurate, polyurethane or phenolic resin. However, these materials are relatively expensive, in addition, the rising environmental awareness of industrial pollution, combined with depletion of petroleum resources and high energy consumption, is forcing the construction and manufacturing industries to look for innovative materials that are reliable and sustainable to replace conventional materials in sandwich composite structures (CoDyre *et al.,* 2016; Silva *et al.,* 2008).

Natural fibers such as sisal, jute, cotton, flax, hemp, kenaf, and others have already been considered as viable replacements because of their environmental pleasantness, availability in fibrous form, and low cost of extraction from plants (Joshi *et al.,* 2004). On the other hand, residues of wood industry in form of sawdust are accumulating in an alarming rate, it then becomes a huge challenge to expand the profitable and sustainable use of these waste residues as raw material for value-added products in composite (Ahmed *et al.,* 2015; Ashori & Nourbakhsh, 2008). Other advantages of natural fibers as highlighted by Karaduman & Onal (2016a), are renewability, sustainability, environmental friendliness, low density, flexibility of usage and biodegradability. Furthermore, natural fiber composites have a variety of recycling and degrading options at the end of their life cycle, depending on the type of polymer utilized. The worst-case scenario is the burning of natural fiber composites in an incinerator to create electricity, which decreases the volume of materials to bottom ash, which has numerous applications in concrete (Sadeghian *et al.,* 2016a).

Natural fiber reinforced polymer composites have attracted a lot of attention because of their advantages over synthetic fiber-based polymer composites. Although numerous types of natural fiber composites have been developed, their joining using adhesive bonding has not been fully investigated. Most instances, the composites to composites are joined using the traditional methods such as bolts and rivets. However, these traditional methods are not suitable for composites to composites joining because of stress concentration at the joint that usually resulted to premature failure. Therefore, an ideal joining method is the adhesive bonding. Adhesive bonding presents many advantages such as high strength to weight ratio, uniformly transfer of shear stresses between structural materials, good electrical and/or thermal insulation properties, corrosion and fatigue resistance over traditional mechanical fastened, riveted and bolted joints (Budzik, 2010; Durmuş & Akpinar, 2020; Singh, Castillo & Ingham, 2019).

The use of natural fiber in polymer composites either in form of fibrous composites or particulate composites have been reported by Verma *et al.* (2013). Fibrous composites contain fibers that are held together by a polymeric matrix while particulate composites are made up of fibrous particles incorporated in a polymeric matrix.

The usage of kenaf fiber-polyester reinforced composite as skin material and saw dust-polyester reinforced composite as core material in sandwich composite structures is lacking in literature. Also, in order to extend the application of this novel sandwich composite structure, the strength and failure mechanisms of the bonded joints between these two bio-fiber composites need to be understood completely. It is therefore important to investigate the characteristics of the aforementioned composites in sandwich materials system since this approach is still deficient in literature for now.

1.2 Background of the Problem

The increasing need for structures to have properties such as low self-weight, high strength and stiffness, and durability has made composite materials more attractive in a wide range of engineering applications of which sandwich composite structures is a good example (Yaman & Onal, 2016). Sandwich composite structures according Russo & Zuccarello (2007) are more preferred in various industrial applications over conventional materials in the sense that a composite beam has a far better shear stiffness to weight ratio than a beam built only of the core or skin materials.

However, sandwich construction offers a variety of possible issues due to the various interfaces. These interfaces could serve as a source for failure initiation and growth. In addition, Ammar *et al.* (2017) stated that during fabrication or under service conditions of sandwich composite structures, failure can occur through modes of damage mechanism such as delamination (skin-core debonding), core indentation failure, core shear failure, local skin wrinkling, and skin compression/tensile failure. Among the aforementioned mode of failures, skin-core interface debonding is of major importance because of its frequent occurrence and adverse effects. Therefore, the advancement in joining technologies is of great importance in sandwich composite structures. The traditional method of structure assembly is a mechanically fastened joint. However, the addition of a hole and bolt causes stress concentration, weight penalty, and fiber breakage in composites, resulting in multiple failures. Adhesive bonding is the most effective approach for joining two composite structures together. Adhesively bonded joints are increasingly being utilized instead of mechanically attached joints because load transmission between composite components is more evenly distributed (Jeevi *et al.*, 2019).

The development of fiber reinforced polymer sandwich composite structures has been quite exciting in terms of volume and applications over the years. Their primary applications are in the aerospace, automotive, and maritime industries due to weight reduction compared to aluminium and other metallic elements, fuel consumption efficiency will improve. The advancement of sandwich composite structures with improved green material systems has allowed this material to be used in more civil infrastructure applications. The development and use of natural-fiber sandwich composite structures in civil engineering and construction are currently generating a lot of interest. Sandwich composites' reduced weight and therefore makes assembly easier, lowers installation and transportation costs, and lowers the cost of the foundation and its supporting sections even more. They also provide corrosion-resistant construction that requires minimal maintenance (Fajrin *et al.*, 2013).

Similarly, Vitale *et al.* (2017) observed that research and engineering attention have been moving from conventional materials to natural fiber polymeric composite materials. Natural fiber in polymer composites has sparked a lot of attention in numerous engineering field including structural applications, as result of their low cost, carbon dioxide neutrality and comparatively small density as compared to when carbon, aramid or glass fibers are used in composites. Kenaf fiber as a natural fiber is becoming very popular due to environmental issues and its remarkable properties in composites and these have been reported in several research works (Bharath Raman, Ramnath Vijaya & Manoharan, 2015; Mahjoub *et al.*, 2014; Hifizah *et al.*, 2014). Kenaf is a highly efficient plant that grows quickly with little nutrients, energy, or chemical fertilizer. Kenaf is also noted for producing more biomass per acre than any forest plantation while requiring less planting space. (Akil, Omar, Mazuki, & Safiee, 2011). According to Mohd (2008), the Kyoto Protocol recognizes kenaf as an environmentally acceptable industrial organic materials that is effective in decreasing global warming. As a result of this acknowledgment, the Malaysian government has pushed the planting of kenaf to replace tobacco. Though the market for kenaf is yet unknown in Malaysia due to its newness, kenaf fiber has the ability to be marketed as a bio-composite material that can be utilized for a variety of structural applications. On the other hand, Curtu *et al.* (2011) pointed out that wastes wood in combination with other materials offers a variety of benefits and uses, and it's becoming a hot topic in research, with new concepts being tested and developed.

Joints constitute is the weakest zones in sandwich composite structure. Therefore, to fully utilized the potential of kenaf fiber reinforced composite as skin material and sawdust reinforced composite as core material in sandwich system, the strength and stress distribution in the joints has to be fully understood so that suitable configuration can be chosen for various application. Is to this end, that effort is geared towards investigating the technical feasibility of using kenaf fiber-polyester and sawdust-polyester material systems in sandwich composites through experimental and numerical approaches.

1.3 Statement of the Problem

Synthetic fiber such as glass, carbon or aramid have played a dominant role for a long time as fiber reinforcement in composites production for variety of structural applications. However, in recent years, growing environmental issues coupled with the uncertainty about petroleum resources and high energy consumption during processing have triggered much interest in developing composite materials from bio-fibers. Also, the widespread usage and disposal of conventional composite materials presents a significant challenge. Natural fibers on the other hand, have been gaining considerable attention for their potential contribution to addressing environmental issues, such as carbon dioxide neutrality and the saving of fossil resources. Bio-fibers such as kenaf fiber and sawdust could be the main candidates for bio-composites as reinforcing fibers since they are found abundant in Malaysia. Therefore, characterization of these fibers in composites to serve as materials for sandwich structures become paramount subject for discussion.

The biggest potential drawback of the sandwich composite structure is the possibility of decohesion at the interface between the skins and the core, which have very different mechanical properties. This may lead to skins-core debonding due to energy absorption under loading. If the interface between the load-bearing skin material and the thick core fails, the composite may lose its structural integrity completely. Therefore, to ensure the used of kenaf fiber reinforced polymer skin and sawdust reinforced polymer core in sandwich materials system, an understanding of the bonding mechanism and fracture toughness is highly essential.

Numerious research works have been carried out to give a reliable prediction data of adhesive bonding mechanism of conventional composite structures. Other researchers have used analytical approach and numerical methods to evaluate the bond strength (stress analysis) in adhesively bonded joints of conventional composite materials. However, bio-fiber composites are left unexplored and this has limited its application to non-structural components due to lack of enough data and knowledge of the bonded interfaces and bond behavior of these materials. The structural performance of any sandwich construction depends largely on the quality of the adhesive bond between skin and core. Thus, it is highly necessary to investigate the adhesive joints between kenaf fiber reinforced polymer composite/sawdust reinforced polymer composite, to assess the feasibility of joining, and their bonding performance as sandwich structure's materials.

1.4 Aim and Objectives

The aim of this research is to investigate the properties and performance of kenaf fiber reinforced polymer composite/sawdust reinforced polymer composite as sandwich composite structure constituent materials. The specific objectives of this study are as follows:

(a) To characterize the mechanical and physical properties of kenaf fiber reinforced polymer composite and sawdust reinforced polymer composite.

(b) To investigate experimentally and numerically the flexural performance of kenaf fiber-sawdust sandwich bio-composite, through the optimization of core thicknesses.

(c) To examine the adhesive bond mechanical performance of kenaf fiber reinforced polymer composite/sawdust reinforced polymer composite as constituent materials in sandwich system.

(d) To determine and validate the stress distribution in the adhesive joints of kenaf fiber reinforced polymer composite/sawdust reinforced polymer composite.

1.5 Scope of the Study

This research work covers the understanding of the overall project need through literature survey, and it is experimental and numerical in nature which is within the limit of the set objectives. The scope of the study is divided into four stages:

(a) Characterization of the constituent materials of kenaf fiber reinforced polymer composite at 40% volume fraction and sawdust reinforced polymer composite at 20% volume fraction, by identifying their mechanical and physical properties such as tensile test, compressive test, flexural test, shear test and density, and it is done in compliance with ASTM standard specification.

(b) Flexural properties of the sandwich system with various core thicknesses developed from the kenaf fiber reinforced polymer composite skin and sawdust reinforced polymer composite core is investigated and experimental results validated numerically using ABAQUS software.

(c) Double lap shear joint fabrication and testing with different overlap length and adherend width are investigated. The specimen preparation, test procedure, and instrumentation are all discussed. Furthermore, the experimental data for each type of double lap shear joint is shown, including bond shear strength, load-displacement curves, and failure of the various surfaces.

(d) Parameters such as load-displacement response, von Mises stress distribution as well as the shear stress distibution (SS13) and peel stress distribution (SS33) using ABAQUS software were implemented for the double lap shear joint. The structural integrity of the kenaf fiber reinforced polymer adherend skin, the sawdust reinforced polymer adherend core and the polyester adhesive were investigated and discussed. The data from the analysis was compared with the experimental data.

1.6 Significance of the Study

One of the most pressing issues facing the construction sector today is to improve its image in terms of sustainability. Therefore, using green materials to the best of their abilities is one of the key strategies to achieving sustainable construction. The utilization of synthetic fiber such as glass fiber, carbon fiber or aramid fiber as skin material and polymer materials such as expanded polystyrene, extruded polystyrene, polyisocyanurate, polyurethane or phenolic resin as core material in sandwich composite structures presently exits worldwide, but the aforementioned materials are non-renewable materials and therefore cannot be sustained (Lim & Kang, 2006; Liu *et al.*, 2006; Pickering *et al*., 2016; Ramesh *et al*., 2017; Sharaf & Fam, 2005).

That is why the current attention is shifting to replacing synthetic and polymer materials with green and renewable materials for sustainable development. Also, the results obtained from this research are expected to make contribution in the understanding of the adhesive bonding performance of bio-fiber composite structures, particularly, kenaf fiber polymer composite/sawdust polymer composite. The current research is hereby set towards the following outcomes:

(a) The information obtained from this research work will promote the use of bio- fibers such as kenaf fiber and sawdust in composite as against synthetic and polymer materials because of its sustainability and light weight. Also, to reduce the adverse effect on the environment from the production of synthetic and polymer materials which is one of the major contributors of green gas emission that is implicated in global warming and climate change (Thakur, 2014).

(b) Sandwich structures are notable for being lightweight, while bio-fibers composites offer numerous preferences that make them appropriate as alternative materials for numerous applications. Thus, the utilization of bio-fibers composites like kenaf fiber composite and sawdust composite in sandwich structure is likely to yield added advantages in the design of lightweight structures, leading to environmentally sandwich structures.

(c) The information from this research will provide a wealth of new experimental and numerical data about connecting system of bonded joint of kenaf fiber reinforced composite/sawdust reinforced composite. This is necessary because prediction of strength and stress distribution in kenaf fiber composite/sawdust composite joints with satisfactory degree of accuracy is required in the construction industry. Besides, eliminating problems of bonding at advanced stage of construction and also at the service stage, a reliable prediction model will reduce construction cost when time dependent experiment can be omitted.

(d) The utilization of bio-fibers composite like kenaf fiber composite and sawdust composite as against synthetic fiber reinforced polymer composite is likely to lessen the harmful effects of synthetic fiber reinforced composite handling on human health, such as respiratory irritation. Also, to promote the provision of innovative, affordable and sustainable housing in localities where these agricultural natural resources and agricultural wastes (kenaf fiber and sawdust) are abundant.

1.7 Thesis Organization

In line with the specific requirements spelt out in the UTM thesis manual, the research was organized and documented. Consequently, the whole thesis was presented in seven chapters: Chapter 1 presents a general appraisal and a brief description of the background problem. More so, the aim and the objectives, scope and limitation, significance of the research and research approach are presented. Chapter 2 provides comprehensive knowledge of the relevant subject presented in this thesis. It presents research works carried out by past investigators on the relevant and related literature. Chapter 3 presents information of the raw materials used, fabrication techniques, test procedures and employing appropriate standard where necessary in conducting the tests for the successful completion of the research. Chapter 4 focuses on the constituent materials' characterisation, comprising of kenaf fiber reinforced composite and sawdust reinforced composite. Tests falling in this category include physical test such as density and mechanical tests such as tensile test, compressive test, shear test and flexural test. These tests were carried out to established the constituent's material properties which formed the sandwich bio-composite panels. Chapter 5 focuses on the flexural characteristics of the sandwich bio-composite produced with kenaf fiber reinforced composite and sawdust reinforced composite. Three-point bending test was considered and experimental results are compared and validated with the numerical simulation. Chapter 6 focuses on the double lap shear joint's experimental investigations and numerical simulation. The experimental results, which include load-displacement curves, bond shear strength and failure surface for each type of the sandwich joints were presented. Numerical simulations to identify critical stress and FE validation were implemented. Chapter 7 provides the conclusion of this thesis by stating the outcomes and, success of the study and contribution of the research to the existing knowledge. Recommendations are proposed for further research work in related areas.

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LIST OF PUBLICATIONS

No	Paper Information	Publication type	Status
1	**Adole, M.A**., Jamaludin, M.Y., Suhaimi, A.R. and Norazura, M.A. (2018). Potentials of Wood Fiber Reinforced Polymeric Composites: An Overview. *Journal of Polymer Science and Technology*, *3*(1), 19-31.	Journal Article, Indexed in MyJurnal and Google Scholar.	Published
2	**Adole, M.A**., Jamaludin, M.Y., Suhaimi, A.R., Othman, A. and Norazura, A. M. (2019). Kenaf Fiber and Its Bio-based Composites: A Conspectus. *Pertanika Journal of Science and Technology*, 27(1), 297-329	Journal Article, Indexed in SCOPUS, MyJurnal, Google Scholar.	Published
3	**Adole, M.A.,** Jamaludin, M.Y. and Suhaimi, A.R. (2021). Manufacturing and Characterization of Sandwich Composite Structures Composed of Kenaf Fiber Skin and Sawdust Core. *Composite Structures.*	Journal Article Indexed in SCOPUS	Submitted