UNIVERSITI PUTRA MALAYSIA

MECHANICAL PROPERTIES OF HYBRID HONEYCOMB SANDWICH STRUCTURE HAVING FACESHEETS REINFORCED WITH FLAX, KENAF AND GLASS FIBERS

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By

WAQAS ASHRAF

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

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DEDICATION

This thesis is dedicated to my parents and teachers for their guidance, support, and help that I am able to complete my Ph.D.

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

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The honeycomb sandwich structures are consisted of two thin facesheets and a thick honeycomb core. The commercially available sandwich structures used in aircraft interiors are based on synthetic fiber composite facesheet but have limitations like recycling, non-biodegradability and disposal problems. These factors push the need for environmentally friendly materials. From the literature review, it has been identified that the studies reported on the natural fiber-based composite facesheet with a honeycomb core are minimal. In this research, a new class of sandwich structures with glass fiber and natural fiber like flax and kenaf composite facesheet has been fabricated using the pre-cure fabrication technique. Two layers of the epoxy adhesive film sheet were used each to bond the top and bottom pre-cured facesheets with an aluminium honeycomb core. The mechanical properties of the sandwich structure specimens under various loads (Tensile, edgewise compression, and flexural) with respect to the fiber stacking sequence and natural fiber treatment were studied. The peel strength was measured through the climbing drum peel test to analyze the facesheet and core bonding strength. The low-velocity impact behavior was analyzed by the drop weight impact test, and the residual strength of the impacted specimen was characterized through the bending test. Among the studied configurations, the glass composite facesheet revealed the highest mechanical performance than the natural composite facesheet. However, the compression strength and flexural stiffness of the natural fiber were improved when they were combined with synthetic material by around 38% and 66 % in flax/glass hybrid and 52% and 83% in kenaf/glass hybrid facesheet, respectively, compared to their non-hybrid composite. The mechanical performance of the sandwich structure was further enhanced by around 7% to 15 % when alkali-treated natural fibers were used in a hybrid combination. Overall, the hybrid combination, which has glass in the outer layer, showed better mechanical performance than stacking it in the middle. The flax/glass hybrid composite facesheet exhibited competitive performance by achieving 96% edgewise compression, 92% flexural facing stress, and 94 % flexural stiffness of the sandwich structure having a glass composite facesheet. The drum peel strength revealed the competitive strength by using the pre-cure method of sandwich structure fabrication.

The low-velocity impact results revealed that the hybrid composite facesheet showed promising results compared to the glass composite sandwich structure. The hybrid composite sandwich structure showed more penetration of the impactor, resulting in better energy absorption by around 5% to 18 % than the glass composite. The glass and both hybrid facesheet combinations exhibited similar residual bending performance when results were compared with their counter non-impacted specimens. Based on the findings in this work, the results showed the potential of using hybrid reinforcement to improve the structural performance compared to non-hybrid flax and non-hybrid kenaf composite and revealed the promising and comparable structural performance compared with pure glass composite facesheet. The sandwich structure with hybrid composite facesheet sandwich structure can substitute existing sandwich structures in aerospace and ground transportation such as railways and the automobile sector with the benefit of low cost, low density, and low environmental impact.

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

SIFAT MEKANIKAL STRUKTUR SANDWIC SARANG LEBAH HIBRID YANG MEMPUNYAI LAPISAN PERMUKAAN YANG DIPERKUAT DENGAN FLAX, KENAF DAN GENTIAN KACA

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Struktur sandwic sarang lebah adalah strukktur yang disusun dengan dua lapisan permukaan nipis diantara teras sarang lebah yang tebal. Secara komersialnya, struktur sandwic yang telah digunakan dibahagian dalam kapal terbang berdasarkan lembaran sintetik komposit pada lapisan permukaan namun demikian ia mempunyai beberapa kesan buruk proses kitar semula, bukan bahan yang mesra alam dan, masalah perlupusan. Kekurangan ini meningkatkan tren untuk penggunaan bahan yang lebih mesra alam. Berdasarkan tinjauan literatur, telah dikenal pasti bahawa kajian mengenai lembaran komposit berasaskan serat semula jadi dengan inti sarang lebah sangat terhad. Dalam kajian ini, satu kelas struktur sandwich baharu telah dihasilkan menggunakan gentian kaca dan gentian semula jadi seperti lapisan permukaan komposit flaks dan kenaf yang menggunakan teknik pra-rawatan. Dua lapisan helaian filem pelekat epoksi digunakan setiap satu untuk mengikat helaian lapisan muka atas dan bawah bersama teras sarang lebah aluminium. Sifat mekanikal spesimen struktur sandwic di bawah pelbagai beban (Tegangan, mampatan tepi, dan lentur) berkenaan dengan urutan susunan gentian dan rawatan gentian semula jadi telah dikaji. Kekuatan lapisan permukaan diukur melalui ujian kupasan lapisan permukaan dram untuk menganalisis lapisan muka dan kekuatan ikatan teras. Ujian hentaman berat menganalisis kesan hentaman halaju rendah, dan kekuatan sisa spesimen impak telah dicirikan melalui ujian lenturan. Antara konfigurasi yang dikaji, lapisan muka komposit kaca menunjukkan prestasi mekanikal tertinggi daripada lapisan muka komposit semula jadi. Walau bagaimanapun, kekuatan mampatan dan kekukuhan lentur gentian semula jadi bertambah baik apabila ia digabungkan dengan bahan sintetik sebanyak kira-kira 38% dan 66% dalam hibrid rami/kaca dan 52% dan 83% dalam helaian muka hibrid kenaf/kaca, berbanding dengan komposit bukan hibrid mereka. Prestasi mekanikal struktur sandwic telah dipertingkatkan lagi sekitar 7% hingga 15% apabila gentian semulajadi yang dirawat alkali digunakan dalam gabungan hibrid. Secara keseluruhan, Gabungan hibrid, yang mempunyai kaca di lapisan luar, menunjukkan prestasi mekanikal yang lebih baik daripada menyusunnya di tengah. Helaian muka komposit rami/kaca hibrid mempamerkan prestasi kompetitif dengan mencapai 96% mampatan mengikut tepi, 92% tegasan menghadapi lentur dan 94%

kekakuan lentur struktur sandwic yang mempunyai helaian muka komposit kaca. Kekuatan kupasan lapisan permukaan dram mendedahkan kekuatan daya saing dengan menggunakan kaedah pra-rawatan fabrikasi struktur sandwic.

Keputusan impak halaju rendah mendedahkan bahawa lapisan muka komposit hibrid menunjukkan hasil yang sangat baik berbanding struktur sandwic komposit kaca. Struktur sandwic komposit hibrid menunjukkan lebih banyak penembusan impaktor, menghasilkan penyerapan tenaga yang lebih baik sekitar 5% hingga 18% daripada komposit kaca. Gabungan kaca dan kedua-dua lapisan muka hibrid mempamerkan prestasi lenturan sisa yang serupa apabila keputusan dibandingkan dengan spesimen kaunter yang tidak terjejas. Berdasarkan hasil kajian ini, keputusan menunjukkan potensi penggunaan bahan hibrid untuk meningkatkan prestasi struktur berbanding komposit flaks bukan hibrid dan kenaf bukan hibrid mendedahkan prestasi struktur yang menjanjikan kebaikan dan setanding berbanding dengan lapisan muka komposit kaca tulen. Struktur sandwic dengan struktur sandwic muka surat komposit hibrid boleh menggantikan struktur sedia ada dalam aeroangkasa dan pengangkutan darat seperti kereta api dan sektor automobil dengan memberi faedah kos rendah, ketumpatan rendah dan impak alam sekitar yang rendah.

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

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LIST OF ABBREVIATIONS

AlHC	Aluminium honeycomb core
AHC	Aramid honeycomb core
ASTM	American Society of Testing and Materials
CPD	Climbing drum peel
FRC	Flax-reinforced composite
FF	Flax fiber composite facesheet
FG	Flax/glass hybrid composite with outer flax layer
FRP	Fiber-reinforced polymer composite
FS	Facesheet
GG	Glass fiber composite
GFRP	Glass flax hybrid composite
GF	Glass/flax hybrid composite with outer flax layer
GF(T)	Glass/flax hybrid composite with outer glass fabric layer and treated natural fiber
GK	Glass/kenaf hybrid composite with outer glass fabric layer and treated natural fiber
GK	Glass/kenaf hybrid composite with an outer glass layer
GPa	Giga Pascal
HC	Honeycomb core
KG	Kenaf/glass hybrid composite with outer kenaf layer
KRC	Kenaf-reinforced composite
KK	Kenaf composite facesheet
mbar	millibar
MPa	Mega Pascal
NaOH	Sodium hydroxide
NFCs	Natural fiber-reinforced composites
PP	Polypropylene

CHAPTER 1

INTRODUCTION

1.1 Background

The honeycomb (HC) sandwich structures are known for their high bending strength and stiffness at low weight. The sandwich structure provides an efficient technique to improve the bending stiffness by adding HC to create distance between the upper and lower facesheets (FS) from the neutral axis, where the higher tensile and compression stresses are developed (Scarponi, 2016). The core in the sandwich structure acts like an I-beam and provides structural integrity by taking the shear load. The core region in the sandwich structure is spread over the entire area providing better torsional rigidity than the I-beam structure in which the web is concentrated in the middle section only, as shown in Figure 1.1 (Belouettar et al., 2009).

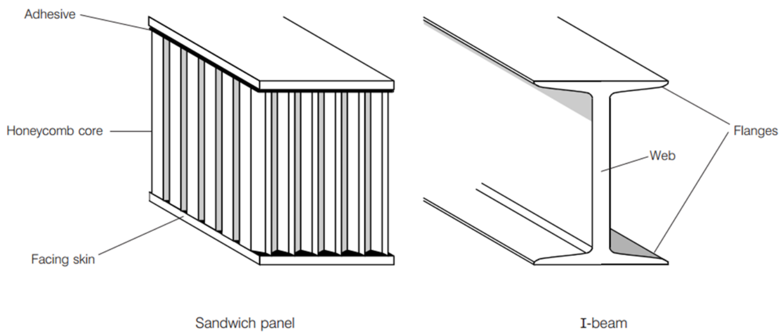

Figure 1.1: Sandwich structure and I-beam
(Belouettar et al., 2009)

The HC sandwich structure is preferably used for high-strength areas like aerospace, railways, automobile, and marine applications (Ramnath et al., 2019). The typical usage of the sandwich composite was reported in aircraft interiors such as floor panels, interior walls, food-handling galleys, and passenger storage racks. The sandwich panel is being utilized in ground transportation, including cargo pallets, shipping containers, refrigeration panels, rapid transit floor panels, railways car bodies, and sports car bodies. The usage of sandwich panels is also reported in construction, such as architectural curtain walls, floor panels, partitions and divider panels, and expandable hospital shelters (Scarponi, 2016).

The FS of the sandwich structure is generally strong and stiff to carry higher stiffness, while the core supports the shear and transverse loads (Birman & Kardomatea, 2018). The core in the sandwich structures must ensure to transfer the load from one face to the other through the adhesive used to bond the core and FS. The FS of the sandwich structure relatively has better elastic properties and high stiffness compared to the core (Ukken & Beena, 2017). The metallic and fiber-reinforced polymer (FRP) is being used as FS materials. There has been increasing interest in using FRP as FS materials due to its superior design ability, fatigue properties, high specific strength, better chemical stability, and corrosion resistance compared to metal counterparts (Manoj Prabhakar et al., 2019).

The demand for synthetic fiber-based composite materials has increased because of their better strength and durability over the past few years. The sandwich structure generally used in aircraft interior comprises glass-reinforced composite FS with aluminium honeycomb core (AlHC) (Akatay et al., 2015). The disadvantages of these materials are poor environmental effects such as non-biodegradable, complicated recycling process, disposal requirements, and emission of toxic gases (P Sadeghian et al., 2018). These are the factors that urged researchers and manufacturers to research and replace them with environmentally friendly materials.

The applications of natural fiber composites (NFCs) are growing rapidly in various engineering fields. The growing interest in NFCs in a polymer composite group is due to their high relative strength, low specific weight, low cost, totally biodegradable, availability, good mechanical and fatigue properties, and renewable compared to synthetic fibers (Peças et al., 2018).

Among the different sources of natural fiber, the bast fiber (flax, kenaf, hemp) is the most commonly preferred fiber because of its superior technical properties and is easy to exact from raw sources compared to other plant-based natural fiber (Peças et al., 2018). Kenaf fiber is found to be a good source of fiber as reinforcement for composite materials and other applications (Salman et al., 2015). Kenaf fiber is abundantly available in Malaysia. Kenaf fiber is a tropical crop considered a low-cost fiber globally (Subramaniam et al., 2019). Kenaf fiber offers many advantages such as rapid growth, low density, low cost, renewability, and biodegradability (Abdi et al., 2014). Flax is cultivated abundantly in Europe, and there have already found successful applications in the automotive industry. The flax fiber has a very low density and specific modulus marginally equivalent to the E-glass fiber, and it could be a potential substitute for synthetic reinforcement in composite (Yan et al., 2014).

The HC sandwich structure is subjected to in-plane (axial compression) and out-of-plane (flexural, impact) loadings during its service life. A vast amount of research work has been reported to date on the mechanical behavior and failure mechanism of HC sandwich structure with FRP FS (Jeon & Shin, 2012; Song et al., 2017; Zhu & Chai, 2016). Over the past few years, there has been an increasing trend to replace synthetic materials with sustainable materials to reduce the environmental impact. The NFCs as FS material of sandwich structure have been emerging as new materials. The research work reported on sandwich structure focus on the initial development and mechanical characterization of natural fiber FS like flax and jute with a cork core and balsa wood core (Balcıoğlu, 2018; Betts et al., 2018; CoDyre et al., 2018; Kandare et al., 2014; P Sadeghian et al., 2018; Pedram Sadeghian et al., 2016).

1.2 Research Problems

The demand for synthetic fiber-based composite materials has increased because of their better strength and durability over the past few years. The disadvantages of these materials are poor environmental effects such as non-biodegradable, complicated recycling process, disposal requirements, and emission of toxic gases (P Sadeghian et al., 2018). The use of natural fiber in sandwich composite could be a potential application, but minimal literature is available so far on using flax and kenaf fiber-based composite FS in the sandwich composite with ALHC.

The bonding interface between the HC cell walls and FS is always crucial because of the minimal surface area available on the HC for bonding with FS. The bonding in this case primarily relies on the fillet formed at the edges of cell walls and FS. The co-cure technique is generally used to cure the FS and bond the core with FS simultaneously (G. Kim et al., 2018). The problems associated with the co-cured method, especially the telegraphing of FS and uneven pressure applied in the laminated composite FS case, can be avoided by adopting the pre-cure process. However, the literature available on the filler formation and drum peel strength of the sandwich structure fabricated with a pre-cured process is very limited. For this reason, there is still needed to investigate the effect of fillet formation and drum peel strength in the pre-cure fabrication technique.

Natural fibers have advantages like low density, biodegradability, and abundant availability (Célino et al., 2014). However, the natural fiber and its composites have inferior strength than the synthetic fiber and their composites. One way to eliminate this limitation is to hybridize with high synthetic fibers. Hybrid composites based on synthetic/natural fibers possess excellent mechanical properties, and they could be implemented in high-performance applications (Yogesha et al., 2018; Y. Zhang et al., 2013).

The mechanical strength of fiber-reinforced composite mainly depends on the adhesion between reinforcement fiber and the surrounding matrix. The better adhesion provides a better stress distribution. Different amorphous materials like hemicellulose, pectic, and lignin on natural fiber decrease the adhesion with the matrix (Ali et al., 2018; Hashim et al., 2017; Sahu & Gupta, 2020).

The low-velocity impact can be caused by several damage sources such as hailstone, tool drops, and debris thrown up from runways. Although much research is already available and reported on the low-velocity impact behavior of sandwich structures with different core materials (Akatay et al., 2015; Vincenzo Crupi et al., 2018; Shin et al., 2008). The behavior of the new FS material of the sandwich structure is challenging to predict, and it needs to characterize the failure mechanism induced by a drop-weight impact test. Although the induced damage is barely visible and such damage could be very minimal and cause catastrophic failure. Therefore, it is essential to carry out the residual strength and damage tolerance properties of the sandwich structure.

1.3 Research Objectives

This research aims to study the mechanical performance of natural fiber and its hybrid reinforcement in the FS of the sandwich composite. The study involves the following objectives.

1. To fabricate and investigate the mechanical and adhesion properties of HC sandwich structures made of natural and synthetic fiber-reinforced composite FS.
2. To analyze the effect on mechanical properties of the sandwich structure by hybridizing glass with flax and kenaf fiber in composite FS
3. To examine the effect of alkali treatment on the mechanical properties of the best two combinations of hybrid composite FS
4. To evaluate the impact properties, impact damage, and residual strength of hybrid FS sandwich structures at three energy levels.

1.4 Scope of Research

The present research was carried out only within the following scope.

i. The sandwich structures were fabricated using the pre-cure technique. The laminated composite FS with different natural and synthetic fabrics was fabricated by vacuum infusion technique using epoxy resin. The pre-cure peel-ply rough surface was used for secondary bonding with the core. The HC was bonded with the core using epoxy adhesive film in hot-press in the second phase.

ii. This research uses the flax and kenaf woven fabric as reinforcement in pure or combined with glass fiber in the hybrid composite FS of the sandwich structure. Due to the unavailability of kenaf fiber-based prepreg materials, the dry fabric of flax, kenaf, and glass fiber as reinforcement with epoxy resin are used for consistency and comparison.

iii. In this research, the glass, flax, and kenaf fabric were used in woven mats were directly purchased from the supplier. The physical paraments like areal density ($g.m^{-2}$) of woven fabric were analyzed for untreated and treated fabric.

iv. The modulus of the FS of the sandwich structure was characterized through tensile loading, while the sandwich structures were analyzed through edgewise compression, flexural test, impact test, and compression after impact test as per the American Society of Testing and Materials (ASTM) standard. The qualitative analysis of the peel-ply surface was analyzed through the optical microscope image.

1.5 Thesis layout

The thesis has been divided and arranged into five chapters. A brief description of each chapter is given in the following section.

i. Chapter 1

This chapter presents the concept of the HC sandwich structure, its historical development, and its current application. The problems associated with current materials used in a sandwich structure, the focus of this present study, objectives, and scope of this recent research are further discussed in this chapter.

ii. Chapter 2

This chapter presents a detailed literature review in terms of different factors affecting the performance of the sandwich structure within the scope of this study. The behavior of natural/synthetic hybrid composite in different loading conditions is also included in this chapter.

iii. Chapter 3

This chapter highlights the materials and methodology used to fabricate and characterize the sandwich structure in the present study. Materials specification, fabric treatment, surface preparation of pre-cure FS, pre-cure fabrication process, sample preparation, testing method, and properties evaluated in each testing method have been discussed in this chapter.

iv. Chapter 4

This chapter contains the result and discussion of the testing in this study. The present study results were compared and analyzed with existing literature on natural/synthetic hybrid composite.

v. Chapter 5

This chapter concluded with the research findings and recommendations for future research.

1.6 Thesis Contributions

The outlines indicate the research contributions from this study are as follows.

1- Use of flax and kenaf reinforced composite as FS material of AlHC sandwich structure.

2- Analyze the effect of hybrid composite FS with different ratios and staking sequences of natural and synthetic material on the mechanical properties of the sandwich structure.

3- The effect of alkali treatment of natural fiber on the mechanical properties of the sandwich structure was analyzed with both actual and normalized results.

4- The impact response of the hybrid FS of the sandwich structure was analyzed through drop weight impact testing, and the residual strength of impacted samples was evaluated through the bending test.

5- Determine the possibility of using hybrid composite as FS materials to replace the existing non-hybrid glass composite FS (GG).

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