UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Faculty of Mechanical Engineering

FATIGUE LIFE CHARACTERISTIC OF HYBRID KENAF/GLASS FIBRE REINFORCED METAL LAMINATES

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DECLARATION

I declare that this thesis entitled "Fatigue Life Characteristic of Hybrid Kenaf/Glass Fibre Reinforced Metal Laminates" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : ……………………………

Name : .……NG LIN FENG …….

Date : ……………………………

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Mechanical Engineering.

Signature : ……………………………

Supervisor Name : PROFESOR MADYA DR. SIVAKUMAR

Date : ……………………………

DEDICATION

To my beloved mother and father

ABSTRACT

The fatigue life of hybrid composite reinforced metal laminates (FMLs) is worth investigating since such materials offer several superior characteristics over conventional metallic alloys. FML has been applied in a wide variety of applications especially in aircraft industry during the past decades. The increasing demand in industry for lightweight and high performance materials has stimulated the research interest towards FML characteristics. The majority of researches have focused on the mechanical properties of hybrid composite materials and conventional synthetic based FMLs such as Glass Reinforced Aluminium Laminate (GLARE) and Aramid Reinforced Aluminium Laminate (ARALL). However, the fatigue life behaviour of hybrid composite reinforced FMLs still remains unexplored. This study investigated the fatigue life of a hybrid kenaf/glass reinforced metal laminate with different fibre configurations, orientations and stress ratios. The FML was manufactured through the hot press moulding compression method using annealed aluminium 5052 as the skin layers and the composite laminate as the core constituent. A tensile test was conducted at a quasi-static rate in accordance with ASTM E8, while a tension-tension fatigue test was conducted at force-controlled constant amplitude according to ASTM E466. The results revealed that hybridization improved the overall tensile and fatigue properties of the laminate. This was more prominent when specific properties were considered. The specific tensile strength of [G/K/G] FMLs is 2.27 % and 3.29 % higher than [G/G/G] FMLs for fibre orientation of 0º/90º and ±45º respectively. However, [K/G/K] FMLs showed the highest endurance strength which is 4.18 % and 13.90 % higher than [G/G/G] FMLs for both fibre orientations at stress ratio of 0.1. In terms of fatigue sensitivity, [K/G/K] FML was the lowest compared to other fibre configurations regardless of the fibre orientations and stress ratio. The FMLs, with a fibre orientation of 0º/90º, exhibited better tensile and fatigue strength than the FMLs with a fibre orientation of ±45º, regardless of the woven-ply fibre configuration and the FMLs with the fibre orientation of ±45º possessed lower fatigue sensitivity, thereby indicating that it was less sensitive to fatigue loading. Besides that, it was revealed that a higher stress ratio improved the fatigue life cycle of the FMLs structure as less damage was induced during the fatigue test. The overall results show the potential of using kenaf fibres as a substitution for glass fibres in FML sandwich structure.

ABSTRAK

Hayat lesu komposit hibrid bertetulang lamina logam (FML) penting untuk disiasat kerana bahan jenis ini menawarkan beberapa ciri-ciri unggul berbanding dengan aloi logam konvensional. FML telah digunakan dalam pelbagai aplikasi terutamanya dalam industri pesawat pada dekad yang lalu. Permintaan yang semakin meningkat dalam industri untuk bahan-bahan berprestasi tinggi dan ringan telah merangsang minat penyelidikan ke arah ciri-ciri FML. Majoriti penyelidik telah memberi tumpuan pada sifat-sifat mekanik komposit hibrid dan FMLs konvensional seperti kaca bertetulang lamina aluminium (GLARE) dan aramid bertetulang lamina aluminium (ARALL). Walau bagaimanapun, sifat hayat lesu komposit hibrid bertetulang FMLs masih belum diterokai. Kajian ini telah menyiasat hayat lesu hibrid kenaf/kaca bertetulang lamina logam dengan konfigurasi serat, orientasi serat dan nisbah tekanan yang berbeza. FMLs telah dihasilkan melalui kaedah pengacuan penekanan panas dengan menggunakan aluminium sepuh lindap 5052 sebagai lapisan kulit dan lamina komposit sebagai bahan teras. Ujian tegangan telah dijalankan pada kadar kuasi-statik berdasarkan ASTM E8 manakala ujian lesu tegangan-tegangan telah dijalankan pada daya amplitud malar mengikut ASTM E466. Keputusan menunjukkan bahawa penghibridan dapat meningkatkan sifat-sifat mekanik keseluruhan lamina. Kesan ini menjadi lebih menonjol apabila sifat-sifat khusus telah dipertimbangkan. Kekuatan tegangan khusus [G/K/G] FMLs adalah 2.27 % and 3.29 % lebih tinggi daripada [G/G/G] FMLs untuk orientasi serat 0º/90º dan ±45º masing-masing. Namun demikian, [K/G/K] FMLs menunjukkan kekuatan lesu yang tertinggi, iaitu 4.18 % and 13.90 % lebih tinggi daripada [G/G/G] FMLs untuk kedua-dua orientasi serat pada nisbah tekanan 0.1. Dari segi kepekaan lesu, [K/G/K] FMLs adalah paling rendah berbanding dengan konfigurasi serat yang lain tanpa mengira orientasi serat dan nisbah tekanan. FMLs dengan orientasi serat 0º/90º mempamerkan kekuatan tegangan dan lesu yang lebih baik daripada FMLs dengan orientasi serat ±45º tanpa mengira konfigurasi serat lapisan tenunan dan FMLs dengan orientasi serat pada ±45º menunjukkan kepekaan lesu yang lebih rendah, menunjukkan orientasi serat pada ±45º kurang sensitif kepada pembebanan lesu. Selain itu, kajian ini telah mengenalpasti bahawa nisbah tegangan yang lebih tinggi meningkatkan kitaran hayat lesu struktur FMLs kerana kurang kerosakan berlaku semasa ujian lesu. Keputusan keseluruhan menunjukkan potensi penggunaan serat kenaf sebagai penggantian untuk serat kaca dalam struktur sandwic FMLs.

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LIST OF SYMBOLS/ABBREVIATIONS

FML	-	Fibre metal laminate
ARALL	-	Aramid reinforced aluminium laminate
GLARE	-	Glass fibre reinforced aluminium laminate
MMC	-	Metal matrix composite
CMC	-	Ceramic matrix composite
PMC	-	Polymer matrix composite
FRP	-	Fibre reinforced plastic
PP	-	Polypropylene
PE	-	Polyethylene
ASTM	-	American society for testing and material
MAPP	-	Maleic anhydride graft polypropylene
CSM	-	Chopped strand mat
Curv	-	Self-reinforced polypropylene prepreg
Twintex	-	Glass fibre polypropylene prepreg
L_c	-	Critical length
D	-	Diameter
σ_f	-	Ultimate tensile strength of fibre
τ_y	-	Shear strength
V_f	-	Fibre volume fraction
ρ_c	-	Density of composite laminate
W_f	-	Fibre weight fraction
ρ_f	-	Fibre density
ρ_T	-	Theoretical density of composite laminate
ρ_{Exp}	-	Experimental density of composite laminate
W_c	-	Composite weight
σ_{ult}	-	Ultimate tensile strength
E	-	Modulus of elasticity/Young modulus
ε_{ult}	-	Ultimate strain

LIST OF PUBLICATIONS

Journals

1. **Ng, L.F.**, Sivakumar, D., Zakaria, K.A., and Selamat, M.Z., 2017. Fatigue Performance of Hybrid Fibre Metal Laminate Structure. *International Review of Mechanical Engineering (IREME)*, 11(1), pp.61-68. (Scopus Q3)
2. **Ng, L.F.**, Sivakumar, D., and Zakaria, K.A. Investigation on the Fatigue Life Characteristic of Kenaf/Glass Woven-Ply Reinforced Metal Sandwich Materials. *Journal of Sandwich Structures and Materials*. (Accepted Manuscript; Scopus/ISI Q1)
3. **Ng, L.F.**, Sivakumar, D., Zakaria, K.A., Bapokutty, O., and Sivaraos. Influence of Kenaf Fibre Orientation Effect on the Mechanical Properties of Hybrid Structure of Fibre Metal Laminate. *Pertanika Journal of Science & Technology*. (Accepted Manuscript; Scopus Q3; ISI)

CHAPTER 1

INTRODUCTION

1.1 Background

Fibre metal laminates (FMLs) have been introduced into the manufacturing processes of various mechanical structures in several sectors, particularly in the aerospace and marine fields (Carrillo and Cantwell, 2009). FML is actually a hybrid material system which is formed from the bonding of metallic layers to a fibre-reinforced composite. It is a relatively new material with great potential over traditional metallic alloys, such as high damage tolerance, high impact resistance, high fatigue resistance and lightweight characteristics (Sadighi et al., 2012; Sivakumar et al., 2017b). Due to its several advantages, it has gained wide acceptance as a structural material for enhancing the performance and prolonging the life of an entire mechanical system.

FMLs are part of the third evolution of advanced aircraft structural materials which combine the advantages of both composites and metals, hence leading to a significant improvement in mechanical strength. The evolution of materials in aircraft is leading the entire aircraft system towards being one that is energy saving, low cost and environmental friendly. Wood was the first generation of materials to be used in aircraft structures from 1903, when the Wright brothers, the inventors of the world’s first successful airplane, used spruce wood as the construction material (Paul and Pratt, 2004). Wood has been widely used for multiple purposes because of its availability and low cost. However, wood is a material with a short service life due to its low resistance to external interference. This kind of material is susceptible to various environmental impacts such as moisture absorption, termite attacks, and deterioration after a certain period of time. The use of aluminium alloy, as the second generation of materials in aircraft structures, started in the 1930s. Aluminium alloy was preferred as it has high strength to weight ratio compared to other metallic alloys. In the 1930s, aluminium alloy was introduced in the construction of the Douglas C-47 military transport aircraft, and the technology evolved again towards the utilization of composites in the 1990s (Paul et al., 2002).

The first generation of FMLs was Aramid reinforced aluminium laminate (ARALL), which uses the synthetic fibre, Kevlar, as the reinforcement, epoxy as the matrix, and thin aluminium alloy as the skin layers. It was successfully introduced by Vlot and Vogelesang from the Delft University of Technology (TU Delft) in 1978. This material gained the permanent interest of experts from various fields as it had been revealed that the fatigue crack growth rate in such material could be reduced significantly (Homan, 2006). Moreover, hybrid structural material, FMLs, were able to overcome most of the separate shortcomings of the composite and aluminium alloy. In 1990, a second generation of FMLs, known as glass fibre reinforced aluminium laminate (GLARE) was developed successfully to improve the overall strength of FMLs as the mechanical strength of glass fibre is even higher than that of aramid fibre (Asundi and Choi, 1997).

Nowadays, the application of FMLs has been extended to other mechanical fields and they are recently being proposed in the automotive sector. As scientists attempt to reduce the dependence on petroleum-based products and petroleum as an energy source in vehicles, it is necessary to investigate promising and environmental friendly materials as substitutes for existing non-environmental friendly materials. Reducing the weight of the vehicle is one of the known strategies for reducing energy consumption. In order to reduce the weight of the vehicle, FMLs were introduced into the manufacturing process of the automotive industry. Weight reduction in vehicles will lead to an increase in the efficiency of automobiles and aircraft, resulting in reduced energy consumption, petroleum dependence and contaminant emissions. The alternate stacked arrangement of the FML gives it its excellent mechanical properties, especially its high fatigue resistance via a fibre-bridging mechanism, and high impact resistance (Zhou et al., 2015). FMLs combine the superior advantages from composites and metallic alloys, and hence it offers high strength and durability. The superior fatigue crack resistance properties in the FMLs increase the inspection interval, and hence, secondary damage in the mechanical structure can be avoided.

On the other hand, the demand for composites have been continuously increasing among manufacturers over the last decade as they allow significant weight reduction in the mechanical structure and exhibit high fatigue resistance. However, composite materials are unable to achieve the excellent impact and residual strength properties as in metallic alloys for any mechanical structure. Therefore, the FML, which is a hybrid system, plays a vital role in improving the performance and efficiency of vehicles and aircraft. This material has been incorporated into these areas as the conventional aluminium alloy is unable to withstand high pressure, resulting in fatigue crack initiation and propagation (Pawar et al., 2015). Moreover, composites and metallic alloys have their own unique disadvantages. The low impact and residual strength of composites has become the main limitation and constraint in various load-critical applications such as in the fuselage of aircraft, while poor fatigue resistance and a high crack growth rate are the limitations in metallic alloys. In order to avoid various disadvantages in composites and metallic alloys respectively, a new material, which bonds a composite and metallic alloy together, has been introduced. FMLs combine the advantages of both composites and metallic alloys, thereby overcoming the disadvantages of low bearing strength, impact resistance and the difficulty of repairing in composites, and the low fatigue and corrosion resistance in metallic alloys (Sinmazcelik et al., 2011).

Fatigue failure is the most common mechanism that occurs in the majority of mechanical structures in industries. This kind of failure mechanism is still not well understood as there is limited research on this topic. Critical factors such as temperature, humidity, vibration and material properties trigger the initiation of cracks in materials. Defects during the manufacturing of the material will eventually worsen the crack initiation due to the high concentration of stress near the defects. Fatigue can result in the premature failure of a structure due to repeated cyclic loading, which will lead to the development of micro-cracks and an increase in the local stress level near to the crack tip. The crack will continue to grow and propagate until the structure fails. Therefore, the development of FMLs was intended to enhance the performance of structures as well as prolong the useful life of the material. In this study, the fatigue life performance of a hybrid composite reinforced metal laminate was investigated based on the availability of the constituent materials and their promising environmental friendly characteristics.

1.2 Problem Statement

The weight of vehicles is the main concern among researchers as the existing conventional material that is being used is heavy, resulting in high energy consumption, increased petroleum demand and high contaminant emissions. Petroleum is a non-renewable energy resource and it is the main energy used for transportation, such as in aircraft and vehicles. The extensive demand for petroleum will eventually lead to the depletion of this energy resource. On the other hand, the combustion of fuel as a driving force in vehicles produces large amounts of toxic contaminants which can affect human health and the entire ecosystem. By-products such as unburned hydrocarbon, carbon monoxide, carbon dioxide and nitrogen oxide after the combustion of fuel will be emitted to the atmosphere and cause a high level of air pollution. Helms and Lambrecht (2003) revealed that reducing the weight of a vehicle by 100 kg can reduce the emission of contaminants by up to nine grams per kilometre. Therefore, FML is being proposed in automotive fields as a lightweight material for car body panel to reduce the vehicle weight. The current FMLs applied in transportation field mainly consist of synthetic fibres such as carbon fibres and glass fibres. However, these synthetic fibres have several drawbacks such as high processing cost, machine abrasion, non-recyclable and non-biodegradable after their useful life. Moreover, the extensive use of synthetic fibres has led to the catastrophic health hazard as well. Therefore, exploring viable alternatives such as natural fibres to substitute the use of synthetic fibres is necessary to remedy the problems.

1.3 Objectives

The objectives of this research work were:

1. To provide a thorough comparison of the tensile and specific tensile properties of FMLs with different fibre configurations.
2. To study the fatigue properties of FMLs with different fibre configurations.
3. To determine the effect of fibre orientations on the fatigue properties of FMLs.
4. To investigate the effects of stress ratio on the fatigue properties of FMLs.

1.4 Scopes

1. Material selection for experimental investigation.
2. Fabrication of woven fibre reinforced composite laminates and FMLs.
3. Specimen preparation for tensile and fatigue tests.
4. Determine the density of FMLs with different fibre configurations.

5. Conduct tensile test on FMLs to determine the tensile strength, tensile modulus and elongation with reference to ASTM E8.
6. Conduct fatigue test on FMLs to obtain endurance limit and fatigue life cycle with reference to ASTM E466.
7. Study the fracture mechanisms using optical microscope and SEM.
8. Analyse and discuss the experimental data and results.

1.5 Significance of the Study

Due to the need of reducing vehicle weight without compromising the safety performance, interest for environmental friendly and lightweight materials has arisen. Efforts in developing a natural fibre based FMLs apparently contribute towards green materials. The main limitations of utilizing natural fibres as reinforcement are the hydrophilic behaviour and relatively low mechanical strength. Hybridization of synthetic fibres and natural fibres is one of the alternative methods to remedy the major shortcomings of both fibres. Improvement in mechanical strength and reduction in moisture sensitivity of the laminates can be achieved in hybrid composites. The relatively low cost and high mechanical strength of glass fibres and ease of cultivation as well as high economic value of kenaf fibres lead to the potential of both fibres being reinforcements in hybrid FMLs in this study.

The majority of structural failure is mainly due to fatigue loading. The structural components are subjected to fatigue failure when the fatigue life cycle of the material exceeds a certain level. The fatigue failure happens in a fast and catastrophic manner that can cause the secondary failure of other components in the entire structures. Thus, it is vital to investigate the fatigue life behaviour and endurance strength of each respective material in order to preserve the safety and integrity of the structures.

1.6 Thesis Outline

Chapter 1 provided the background of composite materials and FMLs in several applications. The potentials of FMLs which combines the advantages of each individual constituent were also highlighted. Significance of the study, problem statement, objectives and scopes were presented as well. Chapter 2 demonstrated the detail literature studies on the research of hybrid composite reinforced FMLs associated with their corresponding surface treatment, coupling agent and mechanical characterization. Chapter 3 described the methodology used in this study, including material preparation, specimen preparation, mechanical testing and data collection. Chapter 4 described the results on the density, tensile properties, specific properties, fatigue properties, modulus degradation during fatigue loading and fracture mechanism of FMLs. Analysis and discussion on the results and findings from the experimental works were included in this chapter as well. Chapter 5 presented the overall conclusions and major contributions from this study. Future recommendation was also mentioned in the same chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter is basically a review of previous research works in relation to this study. This was necessary in order to obtain critical and supportive information to justify and provide reasons for this work. The previous works that had been carried out investigated the mechanical properties of FMLs with different parameters, and the manufacturing process to enhance the overall performance. Therefore, the results of previous studies were taken into consideration during the entire research work to avoid unnecessary mistakes and to improve the reliability of the data obtained.

2.2 Fibre Metal Laminate Hybrid Structure

FMLs have been widely used in diverse structural applications over the past decades. Recently, the superior properties of FMLs and current background knowledge on it have been driving the development of the next generation of FMLs for the purpose of obtaining specific structural properties. Therefore, the investigation into the mechanical properties is vital to improve the performance of the entire system without compromising safety measures. The development of FMLs at Delft University was motivated mainly by its excellent fatigue resistance properties, which are drastically higher than conventional aluminium alloy for use as fuselage material. Surprisingly, the improvement in the impact properties of FMLs over aluminium alloy triggered the need for such a material in the automotive sector. Moreover, the metallic alloy at the outer layers acts as a protective