UNIVERSITI PUTRA MALAYSIA

MECHANICAL PROPERTIES OF FIBRE METAL LAMINATES REINFORCED WITH CARBON, FLAX AND SUGAR PALM FIBRE-BASED COMPOSITES

CHANDRASEKAR MUTHUKUMAR

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By

CHANDRASEKAR MUTHUKUMAR

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

March 2019

DEDICATION

To my loving Father, caring Mother and wonderful Sister

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

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March 2019

Chair: Mohamad Ridzwan Bin Ishak, PhD
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Fibre metal laminate (FML) consists of sheet metal and fibre prepreg stacked alternatively in 2/1 or 3/2 lay-up and cured to form the laminate. The commercially available FML such as CARALL (Carbon fibre reinforced aluminum metal laminate), GLARE (Glass laminate aluminum reinforced epoxy) and ARALL (Aramid fibre reinforced aluminum metal laminate) based on the synthetic fibres have limitations like difficulties in recycling, degradability and disposal problems. These factors push the need for environment friendly material. From the literature review, it has been identified that the studies on the natural fibre reinforced FML and the metal surface treatments other than the standard chromic acid anodizing are limited. Also, the impact of aging effects on the mechanical properties of natural fibre reinforced FML has never been studied. In this research, a new class of FML reinforced with the carbon fibres and natural fibres like flax and sugar palm has been fabricated using the hand lay-up and hot press technique. Their mechanical properties under various loads with respect to the metal surface treatment, fibre stacking sequence, hygrothermal and sub-zero aging effects were studied. Based on the results from the experiments, it could be seen that sanding followed by silane treatment could be used as a metal surface treatment for FML, as it provides superior properties over the FML with sanded metal surface. Among the studied configurations, FML with the pure flax fibres exhibited the highest strength, stiffness and fatigue life. Hybridization of flax with sugar palm also has led to significant improvement in the properties compared to the FML with sugar palm fibres. On the other hand, FML specimens exposed to the aging under the moisture/temperature, failed at lower loads, possessed lower strength and stiffness than the unexposed or dry specimens. The degradation in properties was more severe in case of hygrothermal conditioning than the sub-zero exposure. This is because hygrothermal conditioning resulted in 6-8% increase in thickness swelling due to the moisture absorption by natural fibres in the

laminate, weakening of the interfacial bonding strength and degradation of the natural fibre reinforced composite ply as evident from the presence of multiple cracks in the microstructure of the hygrothermally aged FML specimens. To summarize, FML with the pure flax fibres has shown better mechanical properties; longer fatigue life and fibre bridging effect which is critical to sustain larger number of cycles before the failure. The degradation in mechanical properties and physical changes in the FML due to the aging indicates the need to evaluate their behavior if they are required to use in the structures operating under such environmental conditions.

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

SIFAT MEKANIKAL BAHAN BERLAMINA GENTIAN LOGAM BERTETULANG GENTIAN KARBON, FLAKS DAN ENAU BERASASKAN KOMPOSIT

Oleh

CHANDRASEKAR MUTHUKUMAR

Mac 2019

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Lapisan logam bergentian (FML) terdiri daripada lapisan logam dan gentian dalam bentuk prepreg yang disusun secara selang-seli dalam susunan 2/1 atau 3/2 telah difabrikasi bagi membentuk susunan lamina. Secara komersialnya, FML sedia ada seperti CARALL (Carbon fibre reinforced aluminum metal laminate), GLARE (Glass laminate aluminum reinforced epoxy) and ARALL (Aramid fibre reinforced aluminum metal laminate) yang terdiri daripada gentian sintetik mempunyai masalah seperti sukar untuk dikitar semula dan diurai bagi tujuan pelupusan. Berdasarkan faktor-faktor ini, ia mendorong kepada keperluan untuk membangunkan bahan mesra alam. Berdasarkan kajian literatur, kajian dan ilmu berkenaan gentian semula jadi FML dan rawatan permukaan logam termasuklah anodizing asid kromik adalah sangat terhad. Selain itu, kesan-kesan penuaan pada sifat mekanik untuk gentian semulajadi dalam FML masih belum dikaji sepenuhnya. Dalam kajian ini, FML yang diperkuat dengan gentian karbon dan gentian semulajadi seperti flaks dan enau telah dihasilkan menggunakan teknik belangai tangan dan teknik tekan panas. Ciri-ciri mekanik di bawah pelbagai beban telah dikaji dengan rawatan permukaan logam, susunan gentian, kesan hygrothermal dan sub-sifar. Berdasarkan keputusan daripada eksperimen, ianya boleh dilihat bahawa pengasaran permukaan logam dan diikuti dengan rawatan silane boleh digunakan sebagai rawatan permukaan logam untuk FML, kerana ia memberikan sifat yang lebih baik untuk FML dengan permukaan logam yang telah dirawat. Berdasarkan konfigurasi di atas, FML dengan gentian flaks tulen menunjukkan sifat kekuatan, kekakuan dan keletihan yang tertinggi. Hibridisasi gentian flaks dengan enau menyebabkan peningkatan yang ketara dalam sifat-sifat berbanding dengan FML dengan gentian enau. Sebaliknya, spesimen FML yang terdedah kepada penuaan di bawah pelbagai kelembapan/suhu menunjukkan ianya gagal pada beban yang lebih rendah dan juga menghasilkan sifat kekuatan dan kekakuan yang lebih rendah daripada spesimen yang tidak terdedah kepada

pelbagai kelembapan/suhu. Degradasi dalam sifat ini akan bertambah sekiranya keadaan hygrothermal terdedah pada keadaan sub-sifar. Ini akan menyebabkan keadaan hygrothermal menghasilkan kenaikan ketebalan terhadap pembengkakan spesimen sebanyak 6-8 % yang disebabkan oleh penyerapan kelembapan oleh gentian semulajadi dalam lamina. Hasilnya, ia melemahkan kekuatan ikatan antara muka dan kemerosotan pada komposit gentian semulajadi yang dibuktikan dengan penghasilan retak yang banyak dalam struktur mikro spesimen FML secara hygrothermal. Sebagai ringkasanya, FML dengan gentian flaks tulen menunjukkan sifat mekanikal yang lebih baik; jangka hayat kelesuan yang lebih panjang dan memberi kesan yang sangat penting terhadap penyambungan gentian untuk mengekalkan jangka hayat bahan sebelum gagal. Input daripada kerosakan dalam sifat-sifat mekanikal dan perubahan fizikal dalam FML yang disebabkan oleh penuaan ini akan menentukan keperluan-keperluan penyelidikan dan pembangunan FML bergentian semula jadi pada masa akan datang bagi menilai sifat-sifatnya di bawah aplikasi persekitaran hygrotermal dan sub-sifar.

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I would like to take this opportunity to appreciate and thank everyone who has supported me throughout this PhD journey.

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I certify that a Thesis Examination Committee has met on 15 March 2019 to conduct the final examination of Chandrasekar Muthukumar on his thesis entitled "Mechanical Properties of Fibre Metal Laminates Reinforced with Carbon, Flax and Sugar Palm Fibre-Based Composites" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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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

Al	Aluminium
Al_S	Al substrate treated with sanding
Al_{S+S}	Al substrate treated with sanding and silane
$\gamma - APS$	gamma-aminopropyltriethoxy silane
ARALL	Aramid fibre reinforced Aluminium Laminate
ASTM	American Society for Testing and Materials
C	Carbon fibre prepreg
CAA	Chromic acid anodizing
CAE	chromic–sulphuric acid
CAFRALL	Carbon and flax reinforced Aluminium Laminate
CAJRALL	Carbon and Jute fibre reinforced Aluminium Laminate
CAKRALL	Carbon and Kenaf fibre reinforced Aluminium Laminate
CARALL	Carbon fibre reinforced Aluminium Laminate
CFRP	Carbon fibre reinforced plastic
CPS	chloropropyl-trimethoxy silane
CTE	co-efficient of thermal expansion
E	Epoxy adhesive layer
F	Flax fibre
F/F	Flax based FML
F/F(S)	Flax based FML with sanded metal surface
F/F(S+S)	Flax based FML with sanding and silane treated metal surface
F/F(S+S-h)	Flax based FML with sanding and silane treated metal surface after hygrothermal exposure
F/F(S+S-sz)	Flax based FML with sanding and silane treated metal surface after sub-zero exposure
F/S	Flax/Sugar palm hybrid FML

F/S(S)	Flax/Sugar palm hybrid FML with sanded metal surface
F/S(S+S)	Flax/Sugar palm hybrid FML with sanding and silane treated metal surface
F/S(S+S-h)	Flax/Sugar palm hybrid FML with sanding and silane treated metal surface after hygrothermal exposure
F/S(S+S-sz)	Flax/Sugar palm hybrid FML with sanding and silane treated metal surface after sub-zero exposure
FML	Fibre Metal Laminates
FML(S)	Fibre Metal Laminate with sanded metal surface
FML(S+S)	Fibre Metal Laminate with sanding and silane metal surface
FML(S+S-h)	Fibre Metal Laminate with sanding and silane metal surface - - hygrothermally exposed
FML(S+S-sz)	Fibre Metal Laminate with sanding and silane metal surface - sub-zero exposed
FML(S-h)	Fibre Metal Laminate with sanded metal surface – hygrothermally exposed
FML(S-sz)	Fibre Metal Laminate with sanded metal surface – sub-zero exposed
FPL	Forest Product Laboratory
G	Glass fibre prepreg
h	Hours
GLARE	Glass fibre reinforced Aluminium Laminate
GPa	Giga Pascal
GPS	3-glycidoxypropyltrimethoxy silane
IBED	Ion beam enhanced deposition
ILSS	Inter-laminar shear strength
k	kelvin
L/h	Span:depth
Li	Lithium
MeOH	Al metal surface oxide

MeOSi	Metal-siloxane bond
Mg	Magnesium
MPa	Mega Pascal
NaOH	Sodium hydroxide
NFC	Natural fibre reinforced composite
Obj	Objective
OPEFB	Oil Palm Empty Film Bunch
P2	Sulfo-ferric acid etches
PAA	Phosphoric acid anodizing
PP	Polypropylene
R	Stress ratio
S	Sugar palm
ΔS	Range of stress
S/F	Sugar palm/Flax hybrid FML
S/F(S)	Sugar palm/Flax hybrid FML with sanded metal surface
S/F(S+S)	Sugar palm/Flax hybrid FML with sanding and silane treated metal surface
S/F(S+S-h)	Sugar palm/Flax hybrid FML with sanding and silane treated metal surface after hygrothermal exposure
S/F(S+S-sz)	Sugar palm/Flax hybrid FML with sanding and silane treated metal surface after sub-zero exposure
S/S	Sugar palm based FML
S/S(S)	Sugar palm based FML with sanded metal surface
S/S(S+S)	Sugar palm based FML with sanding and silane treated metal surface
S/S(S+S-h)	Sugar palm based FML with sanding and silane treated metal surface after hygrothermal exposure
S/S(S+S-sz)	Sugar palm based FML with sanding and silane treated metal surface after sub-zero exposure
S_a	Alternative variable stress

SAA	Sulphuric acid anodizing
SBS	Short Beam Shear test
SEM	Scanning Electron Microscope
SiOH	Silanol group
SiOSi	Silane film
SiRAL	Sisal fibre reinforced Aluminium Laminate
S_m	Mean steady stress
S_{max}	Maximum stress in one cycle
S_{min}	Minimum stress in one cycle
SS	Stainless Steel
Ti	Titanium
TS	Thickness swelling
VS	Vinyltrimethoxy silane
γ-MCPS	gamma-mercaptopropyltrimethoxy silane
γ-UPS	gamma-ureidopropyltrialkoxy silane

CHAPTER 1

INTRODUCTION

1.1 Background

Fibre metal laminate (FML) is an advanced hybrid material that consist of thin sheets of high strength Aluminium alloy (Al) alternatively bonded with the fibre reinforced composite prepregs as shown in Figure 1.1 (Asundi & Choi, 1997). A fibre prepreg is made up of a fibres or fibre fabric impregnated with liquid polymer resin (Saunders, Dickson, Singh, Carmichael, & Lopata, 1988). The prepregs used in aircrafts are made up of epoxy resin and is normally stored in a freezer below 0 °C. Prior to the fabrication, it should be allowed to reach room temperature which in turn gives a sticky texture.

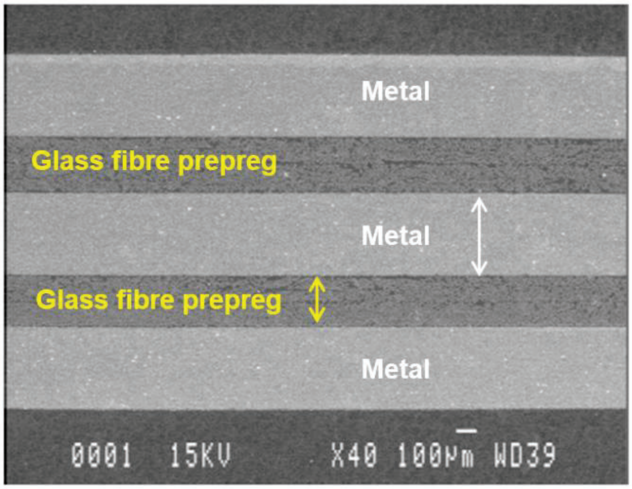

Figure 1.1: 3/2 layup of FML (Lopes, Remmers, & Gürdal, 2008)

FML was invented in the Delft University of Technology, Netherlands and patented by Schijve, Vogelesang and Marissen. The first successfully produced FML was based on the aramid fibre prepreg named as ARALL by the Faculty of Aerospace Engineering Delft University of Technology. ARALL was then commercialized by ALCOA in 1984. FML has been widely used in aircraft structures due to their advantages like excellent damage tolerant characteristics such as the longer fatigue life, impact resistance, high strength to weight ratio along with the reduced moisture absorption compared to the composites (Sinmazçelik, Avcu, Bora, & Çoban, 2011). In the initial stages of development, ARALL found applications in the wing structure of F-27 and Fokker 50 and in the C-17 cargo door (Vlot & Gunnink, 2011). Other commercially available FML materials such as CARALL and GLARE are made up of carbon (C) and glass (G) fiber based prepreg sandwiched between Al sheets (Muthukumar

Chandrasekar et al., 2018). Over the years, ARALL has been replaced by GLARE in the wing structures and it was also used in the fuselage, passenger floors and cargo barriers of the aircraft (Vlot & Gunnink, 2011). Applications for CARALL include helicopter struts and aircraft seats (Sinmazçelik et al., 2011). The general production process of FML involves stacking of the metal and prepregs together and curing under the vacuum and high temperature using an autoclave. The combined effect of temperature and pressure allows the excess resin to flow out and consolidates the plies to obtain FML with least amount of voids (Romli et al., 2017). The mechanical properties of FML highly depend on the constituent's individual properties. Variants of FML can be obtained by the use of different alloy grades and various fibre architectures according to the strength requirements of an application. The most commonly used aerospace grade Al alloy in FML include 2024-T3, 7075-T6 and 6061-T6 sheets of thickness 0.2 - 0.5mm.

The interfacial bonding characteristic between the metal/composite plies is one of the main factors influencing the mechanical properties and failure behavior of FML. The smooth surface of Al substrate results in poor interfacial adhesion with the composite plies. Thus, surface treatment of Al prior to the fabrication of FML has been performed. Al substrate to be bonded with composite ply is surface treated by various techniques such as mechanical abrasion, coupling agents, electrochemical and dry surface treatments which ensure good interfacial adhesion.

The aircraft structures are subjected to the static loads like tensile, flexural, compressive, impact and fatigue loading during its lifetime (Almeida, Damato, Botelho, Pardini, & Rezende, 2008). The aircraft also operates in different weather conditions and altitudes with a varying temperature range between -55°C and 70°C. The environmental factors such as temperature, humidity and radiation could also affect the material properties (Ypma & Borgonje, 2013).

Vast amount of research works on CARALL, GLARE and ARALL could be found in the literature (Afaghi-Khatibi, Lawcock, Ye, & Mai, 2000; Fan, Guan, & Cantwell, 2011; Kawai, Hachinohe, Takumida, & Kawase, 2001; Khan, Alderliesten, & Benedictus, 2009; GD Lawcock, Ye, Mai, & Sun, 1998; Linde, Pleitner, de Boer, & Carmone, 2004; Mahesh & Senthil Kumar, 2013; Ritchie, Yu, & Bucci, 1989; Rodi & Benedictus, 2010; Schijve, 1993; Shim, Alderliesten, Spearing, & Burianek, 2003; Takamatsu, Matsumura, Ogura, Shimokawa, & Kakuta, 1999; Vašek, Polak, & Kozak, 1997; C. A. J. R. Vermeeren, 1990; G. Wu & Yang, 2005). The factors governing the mechanical properties and failure behavior of FML has been well documented till date. In the past few years, natural fibre reinforced FML has been emerging as a new class of material with the research works on FML has been focused on the use of natural fibres like kenaf (Mohammed et al., 2018; L. F. Ng, Sivakumar, Zakaria, Bapokutty, & Sivaraos, 2017; Lin Feng Ng, Sivakumar, Zakaria, & Selamat, 2017; Sivakumar, Ng, & Selamat, 2017), oil palm (Dhar Malingam, Selamat, Said, & Subramonian, 2016), flax (Afaghi Khatibi, Kandare, & Yoo, 2016; Kandare, Yoo, & Afaghi Khatibi, 2016), sisal (Vieira, dos Santos, Panzera, Rubio, & Scarpa, 2017), jute (Vasumathi & Murali, 2016a), etc.

1.2 Problem statement

GLARE, CARALL and ARALL are synthetic fibre based thermoset materials. These synthetic thermoset based materials have limitations due to environmental impacts such as difficulties in recycling, lower degradability, disposal requirements and emission of greenhouse gases associated with the production of synthetic fibres (Pervaiz & Sain, 2003; Ribeiro et al., 2016; Roberts, 2011). Also, widespread application of synthetic fibre reinforced composites in various industrial applications like construction, automobile, wind energy, etc. has led to increase in demand for the synthetic fibres (Beauson, Lilholt, & Brøndsted, 2014; Zaman, Gutub, & Wafa, 2013). These aspects have urged the researchers and manufacturers to focus on the environmentally friendly and cost effective materials which could substitute the synthetic materials. Use of natural fibres in FML could be a promising solution. The research on pure natural fibre based FML and natural/synthetic fibre based FML has been gaining increased attention among the researchers as mentioned in section 1.1. However, till date, the literature on natural fibre based FML is very limited.

Natural fibres have advantages like low density, biodegradability and they are abundantly available (Muralidhar, 2013; J. Sahari, S. Sapuan, E. Zainudin, & M. A. Maleque, 2013; Yan, Chouw, & Jayaraman, 2014). However, the natural fibre and their composites have inferior strength compared to the synthetic fibre and their composites (Begum & Islam, 2013). So, one way to eliminate this limitation is to hybridize with other fibres (Gupta & Srivastava, 2016). Hybrid composites based on the synthetic/natural fibres possess good mechanical properties and they could be implemented in the high performance applications (Jawaid & Khalil, 2011). In this research, flax and sugar palm fibres have been chosen as reinforcements. Among the natural fibres, flax has superior strength and modulus equivalent to E-glass fibres (Célino, Fréour, Jacquemin, & Casari, 2013; Kabir, Wang, Lau, & Cardona, 2012; Phillips, Baets, Lessard, Hubert, & Verpoest, 2013). This makes them a potential candidate for the high performance applications. On the other hand, sugar palm fibres have lower density and are suitable for reinforcement in the composite materials. Since sugar palm is a native crop of Malaysia, their use as reinforcement in composites and FML could be of benefit to the financial point of view in generating income, business opportunities and various products. The fibres can also be extracted without cutting the tree, thereby no damage to the environment (Ishak et al., 2013). To date, sugar palm fibres were not used as reinforcements in FML and their mechanical properties remain unexplored. In order to determine their response to various mechanical loads and their failure behavior under such loads, it is necessary to assess their mechanical performance under various loads.

Interfacial bonding between the metal alloy and the composite ply is crucial for the overall performance of the material. Lack of sufficient bonding between the metal and the composite layers can lead to the delamination and pre-mature failure. Ostapiuk et al fabricated CARALL without any metal surface treatment and found that there was no bonding between the metal layer and the prepregs after curing as shown in Figure 1.2 (Ostapiuk, Surowska, & Bieniaś, 2014). Similar observation on GLARE was reported by Benedict in his thesis work. GLARE coupons manufactured without any surface preparation displayed delamination post curing while a simple sandblasting of Al helped in bonding (Benedict, 2012). This implies that smooth surface of Al cannot ensure good bonding with the prepreg.

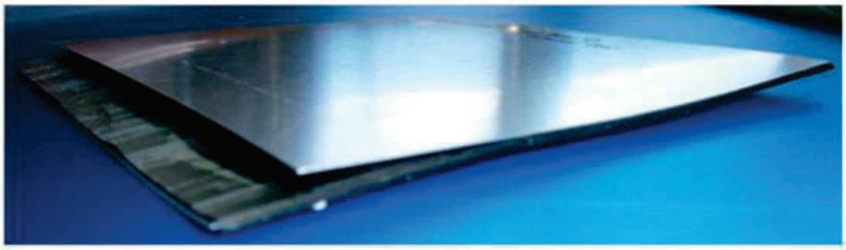

Figure 1.2: Delamination between the metal/prepreg in FML with smooth metal surface without any treatment (Ostapiuk et al., 2014)

Thus, surface preparation of Al before the fabrication process is an important pre-requisite. Various metal surface treatment techniques have been used by the researchers and aircraft manufacturers to achieve good interfacial bonding. Those include mechanical abrasion, chemical etching, electrochemical treatment and use of coupling agents (Sinmazçelik et al., 2011).

FML has superior resistance to the combined effect of moisture/temperature due to the presence of Al on the top and bottom surface and it acts as a barrier. The moisture can seep through these damages, micro-cracks, holes, gaps and free edges and this could lead to deteriorating effect on the mechanical properties of FML. A number of research works on the effect of combined moisture/temperature on mechanical properties of the synthetic fibre reinforced FML could be found in the literature. In most of the studies, GLARE and CARALL has been exposed to the freezing temperature (below 0 °C to cryogenic temperature) and hygrothermal conditions (70 °C - 80 °C). Both GLARE and CARALL displayed marginal decrease in the mechanical properties due to these conditions. However, hygrothermal conditioning could have much higher impact on the performance of natural fibre based FML. This is because of the hydrophilic nature of the natural fibres which are susceptible to degradation under hygrothermal conditions (Scida, Assarar, Poilâne, & Ayad, 2013). As per the researcher's knowledge, none of the studies exist on the degradation effects of natural fibre based FML exposed to the freezing temperature and hygrothermal conditions. Hence, it is necessary to understand the impact of such factors on the mechanical properties of the natural fibre based FML.

1.3 Research objectives

The general aim of this research is to fabricate and evaluate the mechanical properties of FML with carbon prepreg, flax and sugar palm fibres under various conditions. The study involves the following objectives:

1. To investigate the influence of surface treatments of Al and natural fibre stacking sequence on the mechanical properties of FML.
2. To study the influence of hygrothermal conditions on the physical/mechanical properties and failure behavior of the fabricated FML.
3. To determine the effect of sub-zero temperature on the physical/mechanical properties and failure behavior of the fabricated FML.
4. To study the fatigue properties of unexposed, hygrothermal and sub-zero conditioned FML.

1.4 Scope and Limitations of the study

The main novelty of the study is credited to the fabrication and characterization of FML with flax and sugar palm fibres through the experimental approach. Variants in FML with pure flax, pure sugar palm, and hybrid combination with flax/sugar palm in the outer layer/core and vice-versa are fabricated by the hand layup and hot press technique. The metal surface has been prepared by sanding as a stand-alone process and sanding & silane surface treatments. Their mechanical properties such as tensile, flexural, compressive, inter-laminar shear and fatigue properties are determined before and after the exposure to the hygrothermal and sub-zero conditions. Hygrothermal conditioning is performed in a water bath at 80 °C for 120 h and sub-zero conditioning was carried out in a freezer at -40 °C for 72 h. The failure behavior is discussed with visual images and scanning electron microscope (SEM) images to understand the failure behavior and changes to microstructure due to the conditioning.

In this research, flax and sugar palm fibre reinforcements are used in FML. Flax fibres are readily available in long fibres, mat and chopped form for reinforcement in the composites as well as in prepreg form impregnated with the epoxy resin from Lineo^{TM},France (Lineo). However, the price range for the material is between 1000 EUR – 2000 EUR for 30 - 60 m2 roll excluding the excise duty and equivalent to the price of synthetic fibres. Despite of their higher cost, the superior strength and modulus offered by the flax fibres is the driving factor for their use in this research. Thus, with the availability of natural fibre based prepregs at low cost, this limitation could be addressed. Due to the unavailability of sugar palm fibre based prepreg, flax and sugar palm reinforced epoxy composite plies are used for the purpose of consistency and comparison. The objective of the research work is to develop an environment friendly FML without compromising the strength requirements.

1.5 Thesis layout

Chapter 1 presents the concept of FML, historical development and their current applications. The problems associated with the present material, current research focus, objectives and scope of the study are further discussed.

Chapter 2 provides a detailed literature and critical review on the factors influencing the mechanical properties of FML within the scope of the study. The response of FML to various loads and its failure behaviour under the various conditions are explained.

Chapter 3 covers the details on materials and methodology followed in the fabrication and testing. Material specifications, fabrication procedure, metal surface treatment techniques, exposure conditions, parameters such as dimensions, cross head speed and properties assessed in each testing method has been provided.

Chapter 4 contains the results, observations and discussions from the study. A comparison of the obtained material properties and failure behaviour with the existing literature on the natural fibre reinforced FML and synthetic fibre based FML are made.

Chapter 5 concludes the study with research findings and recommendations for the future research.

1.6 Contribution of the Thesis

The research contributions from the present study are as follows:

- Use of flax and sugar palm fibres in combination with the Al/adhesive layer/carbon to fabricate hybrid FML.
- Fabrication of the 2/1 lay-up hybrid FML with hand lay-up and hot press technique.
- Examine the effect of fibre stacking sequence and metal surface treatment on the mechanical properties of hybrid FML.
- Identify the extent of degradation effects on physical and mechanical properties of hybrid FML due to the hygrothermal conditioning and sub-zero exposure.
- Determine the possibility of using hybrid FML with the natural/synthetic in structural applications of the aircraft.

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LIST OF PUBLICATIONS

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Chandrasekar, M., Ishak, M. R., Sapuan, S. M., Leman, Z., & Shahroze, R. M. (2019). Effect of Freezing Temperature and Stacking Sequence on the Mechanical Properties of Hybrid Fibre Metal Laminates Made with Carbon, Flax, and Sugar Palm Fibres. *BioResources*, *14*(2), 3042-3056.

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