FATIGUE ANALYSIS ON BONDING OF ALUMINIUM AND CARBON LAMINATE COMPOSITE

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A report submitted
in fulfillment of the requirements for the degree of
Bachelor of Mechanical Engineering (Structure & Materials)

Faculty of Mechanical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2017

DECLARATION

"I hereby declare this thesis is the results of my own research except as cited in the references"

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APPROVAL

I hereby declare that I have read this project report and in my opinion this report is sufficient in terms of scope and quantity for the award of the degree of Bachelor of Mechanical Engineering (Structure & Materials).

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DEDICATION

To my beloved mother and father

ABSTRACT

Adhesive bonding at the structural component has become an alternative method in industries compared to other conventional methods and the adhesive used in this research was made up by the mixture of aluminium powder-epoxy adhesive. In this research, fatigue testing was conducted and analysed the fatigue life on bonding of aluminium and carbon laminate composite. Percentage of stress level influence the fatigue life of single lap joint between aluminium and carbon laminate composite. Experimental results showed that the higher percentage of stress level gives a small number of cycles to failure and the lower percentage of stress level gives a large number of cycles to failure. The fatigue life of single lap joint for 10% stress level is 1 229 323 cycles whereas the average life cycles for 80% stress level is 14 cycles. The type of bond failure can be identified as the specimens fail under the fatigue testing either it is an adhesion failure or cohesion failure.

ABSTRAK

Ikatan pelekat pada struktur komponen telah menjadi cara alternatif di dalam industri dibandingkan dengan cara konvensional yang lain dan pelekat yag digunakan di dalam penyelidikan adalah di buat daripada campuran serbuk aluminium-pelekat epoxy. Dalam penyelidikan ini, ujian kelesuan telah dilakukan dan jangka hidup kelesuan bagi ikatan aluminium dan karbon lamina komposit. Peratusan tahap tekanan mempengaruhi jangka hidup kelesuan antara gabungan tunggal aluminium dan karbon lamina komposit. Keputusan kajian menunjukkan bahawa kadar peratusan tahap tekanan yang tinggi akan menyebabkan jangka hidup kelesuan yang rendah dan kadar peratusan tahap tekanan yang rendah akan menyebabkan jangka hidup kelesuan yang tinggi. Jangka hidup kelesuan bagi gabungan tunggal untuk 10% tahap tekanan adalah 1 229 323 kitaran manakala purata jangka hidup kelesuan untuk 80% tahap tekanan adalah 14 kitaran. Jenis kegagalan ikatan dapat dikenal pasti setelah spesimen gagal pada ujian kelesuan sama ada kegagalan pelekat ataupun kegagalan kepaduan.

ACKNOWLEDGEMENT

In the name of God, the most kind and merciful, first of all, I am grateful to Allah S.W.T for blessing me with a good health and well-being, opportunities and courage to complete my research and especially throughout all eight semesters in Universiti Teknikal Malaysia Melaka.

Next, I would like to express my deepest gratitude to my supervisor, Prof. Madya Ahmad Rivai for giving me chances and trust to finish this project. Thank you for his time, guidance and willingness to share his ideas and views in order to make this research a reality. The encouragement and under supervise of Prof. Madya Ahmad Rivai, I manage to understand and complete my final year project successfully.

Lastly, my gratitude goes to my lovely families for their encouragement, constant support and emotional understanding throughout my studies here. Their sacrifices and caring towards me are really priceless. They are my source of strength to face all the obstacles in finishing this dissertation.

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Fatigue is the most reason of failures in the mechanical structures and it is happen where the structure fail due to a cyclic load or repeated load applied on it. Fatigue failure is happen to all structure such as automobile, aircraft and turbine. As world of technologies getting advanced, the usage of metal are also increases with more failure of structures are recorded due to the repeated load. The high strength material with a higher performance was current demand for the manufacturer and users today to avoid the structural fatigue and increase the life time of the structures from failures.

An axial test machines is capable for tension and compression loading in both high cycle fatigue and low cycle fatigue ranges. This machine is closed-loop servohydraulically controlled and can be programmed with any desired fatigue spectrum. The present of frequency (f) in unit Hz influence the behaviour of fatigue with environmental effect such as temperature. Between 1852 and 1870, the German railway engineer August Wöhler's has conducted the first investigation on systematic fatigue. The data from Wöhler's are for Krupp axle steel were plotted in terms of nominal stress (S) versus number of cycles to failure (N), which has known as S-N diagram which is shown in Figure 1.1. (Anonymous, n.d)

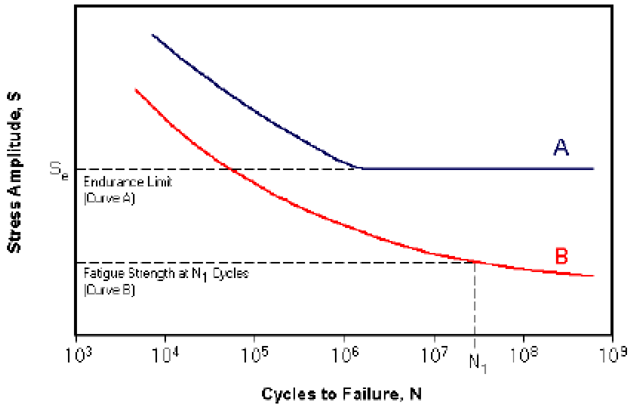


Figure 1.1: S-N Curves (Anonymous, n.d)

Aluminium is a metal and it is the third large element after oxygen and silicon. Aluminium is a silvery-white metal and has a very light density. The light weight of aluminium with high strength makes it as the most use in transportation industries. This material can be easily fabricated into different structure and shape. Besides, aluminium has high mechanical strength by alloying and heat treatments even though the tensile strength of pure aluminium is not high. Adhesive bonding of aluminium is successfully employed in many applications such as car bodies and aircraft components.

Carbon laminate composite are strong, high stiffness and lightweight materials. Composite material is a combination of materials which are made up of two or more materials to produce different structural properties. In this project, carbon laminate composite were chosen as the properties of the material are strong and light weight.

One of the matrix materials is epoxy. Epoxies will be used as the matrix materials in this studies, it is widely used in resins for structural adhesives. Epoxies have low levels of volatiles, good adhesion, low shrinkage and ease of processing. The curing of epoxies is quite slower which vary from room temperature to approximately 350ºF (180ºC). This type of adhesives can bond a wide variety of substrates with high strength such as attach aluminium skins to the struts of aircraft wings and tail sections (Anonymous, 2013). Plus, an aluminium powder is added on the neat epoxy adhesive to enhance the strength of the bonding.

Single lap joint is a joining of two materials with an overlapping bond. The joining of the materials can be done through the process of adhesive bonding which is the common type of bonding use nowadays especially in the aircraft industries or by the traditional methods. Many types of materials can be joined together such as metal to metal, metal to composite, composite to composite and etc. There are also many types of joint such as double lap, double tapered strap lap and single strap lap.

1.2 Problem Statement

Nowadays, the usage of adhesive bonding in the industries such as automotive, aerospace, construction and marines are frequently been heard. Before the development of adhesives bonding, other traditional metal working methods have been used to attach the surface of structural, material and component of a substance. The examples are welding, bold and nut, fastener, rivets and brazing. Adhesives bonding on fatigue analysis have not been discovered deeply since before. In this study, I will do a research on adhesives bonding by fatigue analysis which the type of adhesives is epoxies with an addition of aluminium powder at the epoxy. The fatigue analysis will be determined by using S-N Curve, in terms of nominal stress (S) vs number of cycles to failure (N). The fatigue life is the number of cycles to failure at specified stress level and the fatigue strength is the stress below which failure does not occur. Only the fatigue life will be observed throughout this study.

1.3 Objectives

The objectives of this project are:

1) To conduct fatigue testing on bonding of aluminium and carbon laminate composite.
2) To determine fatigue life on bonding of aluminium and carbon laminate composite.

1.4 Scope of Project

The bonding of aluminium and carbon laminate composite will go through fatigue analysis under fatigue testing by using 25kN Universal Testing Machine (INSTRON-Model 8802). The scopes of this project are:

1) Literature review on fatigue, adhesive bonds, aluminium and carbon laminate properties.

2) The design of aluminium and carbon laminate composite is determine with suitable dimensions that can be fit at the testing machine.
3) Manufacturing of specimens which are aluminium by cutting the plate with require dimensions while carbon laminate by hand lay-up process.
4) Fatigue test is conduct by using 25kN Universal Testing Machine (INSTRON-Model 8802).

CHAPTER 2

LITERATURE REVIEW

As the technology of industries develop parallel with the transformation of revolution. The development gives an impact on automotive, aerospace, marine and construction industries to produce an advanced mechanisms or methods between the bonding of structure, material and component surface. In this study, adhesive bonding is the chosen method as the usage of the attachment by using adhesive bonding does not been fully discovered compare to traditional method. Fatigue test will be conducted to aluminium and carbon laminate composite in order to determine the fatigue life of bonding.

2.1 Material

2.1.1 Aluminium

Aluminium (Al) is a metal which are relatively soft, light and an abundant element of 8% on earth crust. The three main properties on which the application of aluminium are low density, high mechanical strength that can be achieved by alloying and heat treatments, and high corrosion resistance of the pure metal. Alloying constituents such as copper, magnesium, silicon, manganese, nickel and zinc were added to aluminium to increase the strength of pure aluminium. (Shakhashiri, 2008).

The 5000 series which is alloying between aluminium and magnesium (Al-Mg alloys) are used for structural and architectural applications. In this research, type of aluminium-5083 (Al-5083) was chosen. The aluminium-5083 is known for exceptional performance in extreme environments and highly resistant to seawater and industrial chemical environments (Ferrous, A, et.al, 2015). The applications of aluminium alloy 5083 are mostly used in vehicle bodies, shipbuilding and vehicle bodies. The chemical composition, physical properties and mechanical properties for aluminium alloy 5083 is shown in Table 2.1, Table 2.2 and Table 2.3 respectively.

Table 2.1: Chemical composition for aluminium alloy 5083 (Ferrous, A, et.al, 2015)

Element	% Present
Si	0.4
Fe	0.4
Cu	0.1
Mn	0.4-1.0
Mg	4.0-4.9
Zn	0.25
Ti	0.15
Cr	0.05-0.25
Al	Balance

Table 2.2: Physical properties of aluminium alloy 5083 (Ferrous, A, et.al, 2015)

Property	Value
Density	2650 kg/m^3
Melting Point	570°C
Modulus of Elasticity	72 GPa
Electrical Resistivity	0.058x10^{-6} Ω.m
Thermal Conductivity	121 W/m.K
Thermal Expansion	25x10^{-6} /K

Table 2.3: Mechanical properties for aluminium alloy 5083 (Ferrous, et.al, 2015)

BS EN 485-2:2008 Plate 6.3mm to 80mm Property	Value
Proof Stress	115 Min MPa
Tensile Strength	270 - 345 MPa
Hardness Brinell	75 HB

2.1.2 Composite

Composite materials are made up by combining of two or more materials which consists reinforcing elements, fillers and composite matrix binder. There are three types of geometry of reinforcements which are particle reinforced, fibre reinforced and structural. A particle reinforcement have dimensions that are equal in all directions with the orientation either random or with preferred orientation and fibrous reinforcement is characterized by its length. In single layer composites, there are long fibres and short fibres which called continuous fibre reinforced composites and discontinuous fibre composites respectively. Multilayered composites are another category of FRP, classified either as laminates or hybrids.

Laminate are composites in which layers of different materials are bonded together with adhesive, to give added strength and durability. The primary load of composite carrying material is fibre. The directions of fibre determine the strength and stiffness of the composite material. Unidirectional composites have predominant mechanical properties in one direction and are to be anisotropic, having mechanical or physical properties that vary with direction relative to natural reference axes inherent in the material (F.C, 2010).

Matrix is the constituent that is continuous and present on the greater quantity in the composite. The properties of matrix are improved by incorporating another constituent to produce a composite. Reinforcement is the second constituent in a composite system and it reinforces the mechanical properties of the matrix. Reinforcement is much harder, stronger and stiffer compare to matrix. The fibre orientation and fibre length affect the tensile strength of the composites.

The advantages of modern composite materials are light and strong. An appropriate combination of matrix and reinforcement material can forms a new requirement of a particular application. The flexibility of composite design can moulded them into complex shapes. An advanced composite material is made of a fibrous material embedded in a resin matrix, generally laminated with fibres oriented in alternating directions to give the material strength and stiffness (F.C, 2010). The advantages of composites are high strength and stiffness, low density, improved fatigue life, corrosion resistance and low cost. The applications of composite materials include transportation, sporting goods such as tennis racquets and marine goods.

The composite materials in this research are resin bisphenolic LP-1Q-EX and woven roving glass fibre reinforcement (200 g/m^2). The volume fraction of glass fibres is equal to 40% of the composite. The comparison between composites and metals are shown in Table 2.4.

Table 2.4: Composites versus metal comparison (F.C, 2010)

Condition	Comparative behavior relative to metals
Load-strain relationship	More linear strain to failure
Notch sensitivity	
Static	Greater sensitivity
Fatigue	Less sensitivity
Transverse properties	Weaker
Mechanical property variability	Higher
Fatigue strength	Higher
Sensitivity to hydrothermal environment	Greater
Sensitivity to corrosion	Much less
Damage growth mechanism	In-plane delamination instead of through thickness cracks

2.1.3 Design of Material

Single lap joints (SLJ) are widely used and a simple way to joined between two materials via an overlapping bond, refer to Figure 2.1 for the SLJ structural design. A single lap joint is an anti-symmetric structure of two materials which known as adherends, bonded via an overlap which is adhesives while double lap joints (DLJ) as shown in Figure 2.2 are lap joints with a step like interface (Lempke, M.P., 2013) An end tabs, cut from the same material as the adherend sections, were adhesively bonded to the specimen as shown in Figure 2.3 below. This type of tabs have been introduced to reduce the eccentricity of the load path that causes out of plane bending moments which resulting in high peel stresses and non-uniform shear stresses in the adhesive layer (Broughton, W.R., et.al, 1996)

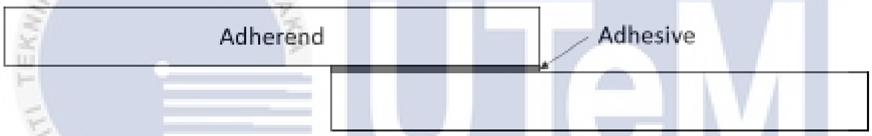


Figure 2.1: A single lap joint (Lempke, M.P., 2013)

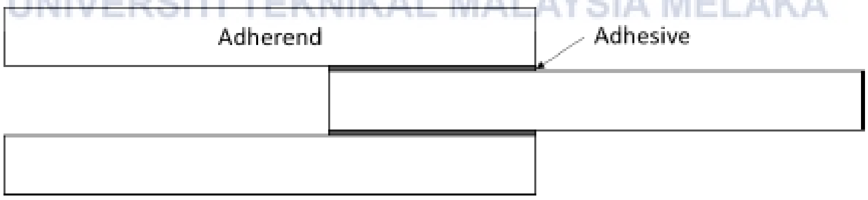


Figure 2.2: A double lap joint (Lempke, M.P., 2013)

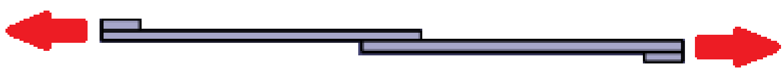


Figure 2.3: A single lap joint with an end tabs

Refer to Figure 2.3, when a single lap joint is loaded as shown in the direction of the arrows, the adhesive at the joint is subjected to primarily shear loads with an element of tensile loading.

2.2 Adhesive Bonding

Bonding is a joining of two or more surfaces whether metal to metal, non-metal to non-metal or metal to non-metal. There are various types of bonding and one of them is traditional method such as bold and nut, welding and fastener. Nowadays, industries tend to use an alternative method to mechanical joints in engineering applications as many advantages were provided.

An adhesive is a substance capable of holding materials together by surface attachment and have been use for thousand years. The first evidence of a substance being used as an adhesive dates back to 4000 B.C. Since before, there are various types of adhesives and their uses on daily life such as animal glues, fish glue, casein glue, starch, cellulose adhesive, rubber-based solvent cements, hot melt adhesives, RTV silicone adhesives, anaerobic adhesives and epoxies. The development of adhesive have change and improve the properties such as flexibility, toughness, temperature, curing and chemical resistance (Nicholson, C., et.al, 1991)

The joining of aluminium and carbon fibre called as joining dissimilar materials, and it is difficult than joining of same material. This type of joining processes is applicable by using adhesive bonding. The elements that need to be taken when designing a dissimilar material are joint design, material thickness, material combination and performance requirements.

2.2.1 Epoxy Adhesives

In this research, bonding by method of epoxy adhesives will be focus as it is widely used and the most diverse in term of variants available. Epoxies are made by polymerizing a mixture of two compound, resin and hardener. Epoxy resin is a combination with over 70 different curing agents from simple amines to complex anhydrides. Although there are variety of epoxies, the mechanisms of curing throughout all the variations is always the same. Epoxies can be functioning as adhesives, binding resins, coatings and an excellent of abrasion resistance and chemical resistance. The selection of an adhesive is important because some factors need to be considerate such as the suitability of an application procedure.

Besides, epoxy resins are also known to have hydrophilic sites which can take up water. Excessive amount of water absorbed are due to the incorporated of impurities or filler during the processing. Mechanical properties of composite materials can decrease as the process of water absorption occurs while the physical properties of epoxy resins can be refine by the addition of flexibilizers and dilutents or solvents (Society for Adhesion and Adhesives, 2005)

The advantages of epoxies are high strength and modulus, low levels of volatiles, good adhesion, low shrinkage and good chemical resistance. Although the epoxies have a lot of advantages, it is also has disadvantages such as brittleness and reduction of properties as there is a presence of moisture.

2.2.2 Mechanism of Adhesion

To understand adhesive bond failures, it is important to understand the function of adhesives. Adhesives depend upon chemical bonds formed at the interface between the adhesive and adherend as the adhesive is cured (Hart-Smith, L.J., 1973) There are three types of adhesion which are specific adhesion, mechanical adhesion and effective adhesion. Specific adhesion is the molecular attraction between contacting surfaces. Next, mechanical adhesion occur as adhesive flows into the microstructure of the surfaces to be bonded. Mechanical adhesion for optimum joining strength is known as effective adhesion (Adhesives.Org and Sealants.Org, n.d).

2.2.3 Failure of Adhesive Bond

Adhesive failure is failure of a bonded joint between the adhesive and the adherend. The failure is primarily due to a lack of chemical bonding between the adhesive and the adherend. It is also can cause by the poor surface preparation or contamination. Basically, there are three types of bond failure which are cohesion failure, adhesion failure and mixed-mode failure. Cohesion failure is the fracture of adhesive while adhesion failure is a slick failure at the interface between the adhesive and adherend. The substrate failure is a combination of cohesion and adhesion failures. Figure 2.4, Figure 2.5 and Figure 2.6 shows an example of cohesive failure, adhesive failure and substrate failure respectively.

Figure 2.4: Cohesive Failure Mode (Adhesives.Org and Sealants.Org, n.d)

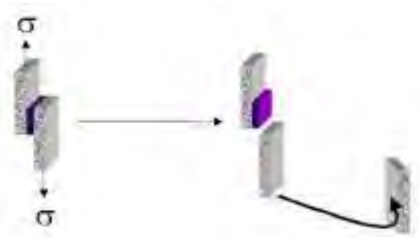


Figure 2.5: Adhesive Failure Mode (Adhesives.Org and Sealants.Org, n.d)

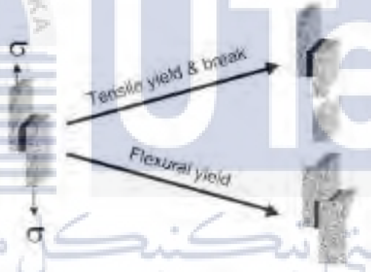


Figure 2.6: Substrate Failure (Adhesives.Org and Sealants.Org, n.d)

2.3 Fatigue

Early observation in 1800, the investigators in Europe had recognized a problem related to bridge and railroad components due to the repeated loading that cause crack. In this century, structural fatigue has assumed an even greater importance as the result of increasing use of high strength materials (ASM International, 2008)

Fatigue has been recognized that material under a repetitive or fluctuating load will fail at a stress level lower than required to cause failure under a single application of the same load. Fatigue is the most popular failures happen in mechanical structures such as in aerospace components, automotive and construction.

Advantages of using adhesives as the bonded joint are higher resistance of fatigue and longer life time of fatigue compare to the other type of conventional joining method. Besides, the advantages are light weight, ability to joint between the dissimilar materials, low manufacturing cost, good vibration and damping properties. As the lightweight materials are required for aerospace and automotive, the adhesively bonded joints were the common method used widely for the industries.

2.3.1 Fatigue Damage in Adhesively Bonded Joint

Damage in adhesively bonding is due to the fatigue loading especially cyclic loading is quite familiar happen in a structural component. The structural may fail at a low percentage of static strength when in a fatigue loading regime. The prediction of structural failure is needed for fail safe or damage tolerance design from the fatigue analysis and fatigue strength. The difficulty to predict exact fatigue life are due to the geometry of bonded joints and complex material behaviour under loading and unloading regimes (Wahab, A. And Corporation, H.P, 2012)

There are many types of method that can be use to predict the fatigue life time and one of the method is by total life approach. The total life approach is use to predict the fatigue life time and the disadvantage of this method is not able to signify the damage of the structural during the fatigue loading.

Fatigue life is the number of stress cycles of an object before it undergoes failure. Mechanical and scientific are the terms that related on how long an object can hold on before it is fail due to the concentrated stress. Factors that affect the fatigue life are type of material, structure and shape of material and temperature changes. Theoretically, fatigue damage does not depend on their frequency, but it depends on the number of cycles.

2.3.2 Stress Cycle of Fatigue

A load cycle is the duration of one peak to another peak and the amplitude of each cycles are not the same. There are three factors that cause fatigue which are: (ASM International, 2008)

i. A maximum tensile stress of sufficiently high value.
ii. A large enough fluctuation in the applied stress.

iii. High number of cycle to the applied stress.

Fluctuating stress is made up of two components which are mean stress, σ_m and alternating stress, σ_a. The stress varies between a maximum stress, σ_{max} and minimum stress, σ_{min}. The difference of maximum and minimum stress is stress range, σ_r where;

$$\sigma_r = \sigma_{max} - \sigma_{min} \qquad \text{(Equation 1)}$$

The mean stress is the average of the maximum and minimum stress in the cycle where;

$$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2} \qquad \text{(Equation 2)}$$

The alternating stress is one-half of the stress range which can give by;

$$\sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2} \qquad \text{(Equation 3)}$$

Figure 2.7, Figure 2.8, Figure 2.9 and Figure 2.10 below shows the cyclic loading with the label of parameters, an example of fully reversed cycle, zero to max and zero to min respectively.

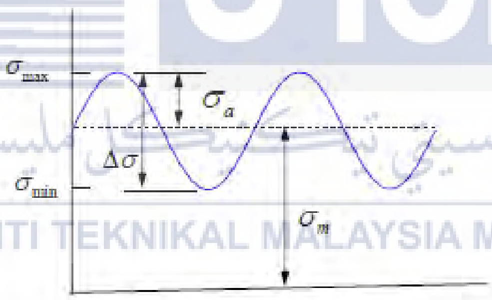


Figure 2.7: Cyclic loading (Anonymous, 2004)

There are two ratios of frequency used in presenting fatigue data which are;

$$\text{Stress ratio, R} = \frac{\sigma_{min}}{\sigma_{max}} \qquad \text{(Equation 4)}$$

$$\text{Amplitude ratio, A} = \frac{\sigma_a}{\sigma_m} = \frac{1-R}{1+R} \qquad \text{(Equation 5)}$$

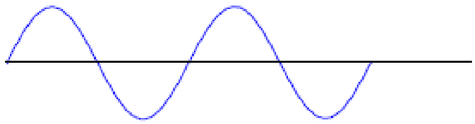


Figure 2.8: Fully Reversed (Anonymous,2004)

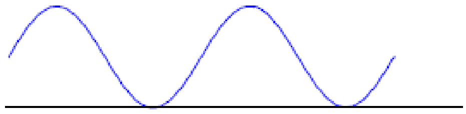


Figure 2.9: Zero to Max (Anonymous, 2004)

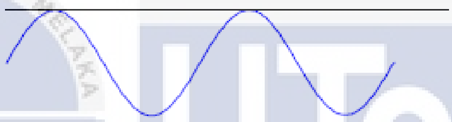
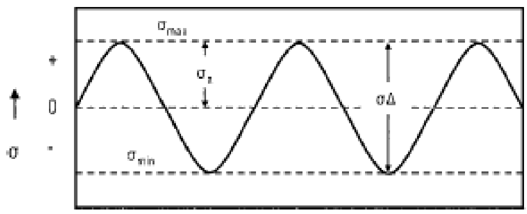
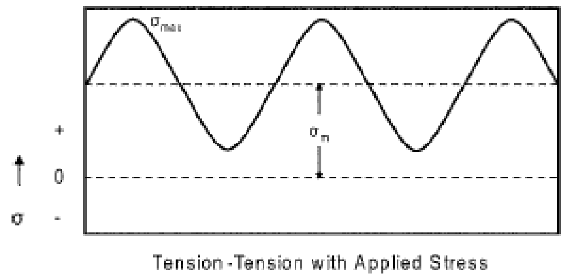


Figure 2.10: Zero to Min (Anonymous, 2004)

The types of loading cycles are fully reverse loading, tension-tension with applied stress and random of spectrum loading. The fully reverse loading is happened when the value of maximum and minimum stresses are equal. Next, the tension-tension with applied stress is where the both stress on top of the maximum and minimum stresses. The condition is both cyclic and applied stresses are greater than zero. The random of spectrum loading is when the component is subjected to random load during services. The value of R for the loading conditions are R=-1 and R=0 for fully reverse loading and tension-tension with applied stress. Figure 2.11 below shows the cyclic loading for these three types of loading cycles.



Fully Reversed Loading



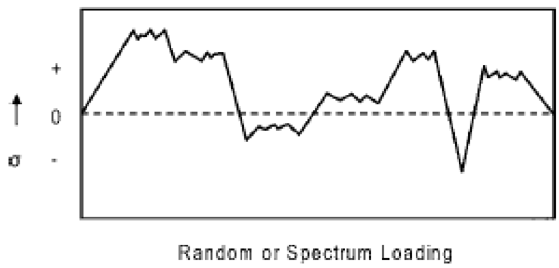


Figure 2.11: Types of Fatigue Loadings (ASM International, 2008)

High cycle fatigue involves with a large number of cycles which the number of cycles are larger than 10^5 cycles. This cycle is an elastically applied stress and can be carried out until 10^7 cycles. Low cycle fatigue occurs in an elastic region, which the stress and strain are related to the elastic modulus. This type of cycle is applicable for short-lived devices where overloads may occur at low cycles.

2.3.3 Stress Life

S-N curve (stress-number of cycles) is known as the Wöhler curve or endurance curve. From this curve, it can be differentiate into four different regions. The regions are low cycle fatigue, monocycle fatigue, endurance and gigacycle fatigue. In the first region, which are the low cycle fatigue, fracture occurs at a low number of cycles which from 10^2 to 10^4 with a significant plastic deformation. Second region is monocycle fatigue, where the endurance is limited. The third region is an endurance region, where an infinite lifetime has been considered. The fourth region is the gigacycle fatigue which is significant for a number of cycles. (Bathias, C., and Pineau, A., 2010)

Stress life or S-N method is commonly refers as total life of the components as it undergoes failure. S is represent as maximum stress, σ_{max} and minimum stress, σ_{min} or stress amplitude, σ_a while N is represent as number of cycles at the log scale. The S-N relationship is determined by the specified value of mean stress, ratio or amplitude. The endurance limit, σ_e or also known as fatigue limit is the limit that shows the component has an effectively infinite life when the stress is below the limit. Endurance can be defined as the strength capability of entire structures before the development of fatigue. The graph of S-N curve can refer to Figure 2.12 below.

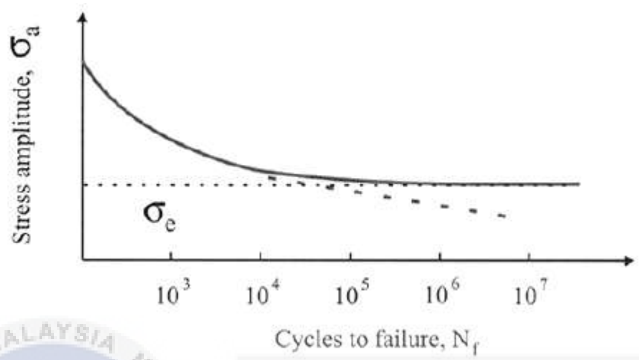


Figure 2.12: S-N Curve (Anonymous, n.d)

CHAPTER 3

METHODOLOGY

There are various types of method and standard use to conduct the fatigue test and determine the fatigue life. In this chapter, step by step from process of the material, tensile testing and fatigue testing are explains. The information and theory regarding to the types of material, suitable process of making the composite and standard use to conduct the experiment will be explain further in methodology. The flow chart to complete this project is included to show the flow process.

3.1 Flow Chart

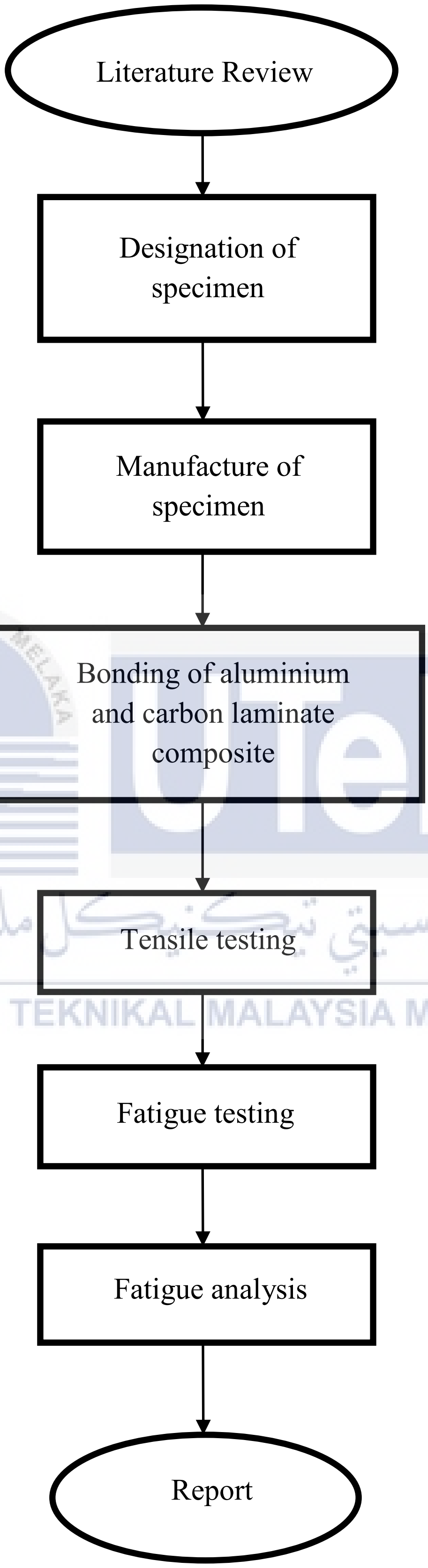


Figure 3.1: Flow chart of methodology

3.2 Process of Carbon Laminate Composite

Technique for the making of carbon laminate composite is by hand lay-up process. Hand lay-up process is the simplest method of composite processing and the materials used to develop composite of the process are mold, release agent, resins which is epoxies and reinforcement fibre. Figure 3.2 shows the illustration of hand lay-up method.

First of all, the preparation of mold is needed before the process is started. A release agent is applied onto the surface of mold to avoid the resin stick on it. Next, the resin and hardener is mixed. Mixing between the materials is done slowly to avoid the excess of bubbles in the resin. After the mixture is blend properly, a roller is used to spread the mixture at the surface of mold. The first layer of fibre reinforcement is then laid. After each layer of fibre reinforcement was done, the layer has to be wetted with resin over the top of it and spread around. This step is repeated until the required thickness is obtained. Then, the composite is cured at room temperature and the time taken for epoxy based is 24-48 hours.

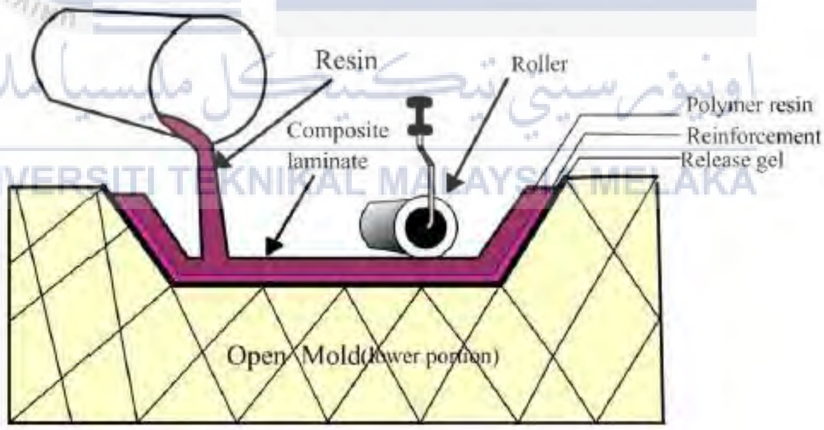


Figure 3.2: Hand lay-up method (Stuart, W.J, 2010)

3.3 Adhesive Bonding Process between Aluminium and Carbon Laminate Composite

Adhesive bonding is a joining process of a material in which an adhesive were placed between aluminium and carbon laminate composite. Bonding between the aluminium and carbon laminate composite is by the mixture of epoxy adhesive with the type used is eposchon and aluminium powder used for filling the epoxy. The adhesive thickness for all specimens is 0.5 mm. The aluminium plate is cut into desired dimension. An end tabs of both aluminium and carbon laminate were joint at each end of the materials to reduce the eccentricity of the load path. The ASTM for the adhesive standard is D6412/D6412M-99 which is the standard specification for epoxy adhesive for bonding metallic and non-metallic material. Sketch of the single lap joint is shown in Figure 3.3 with dimension in milimeter (mm).

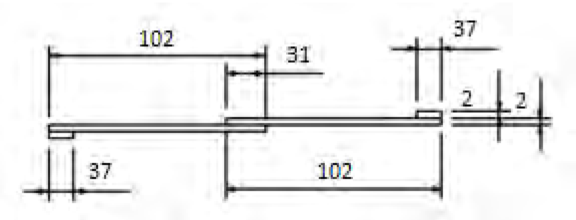


Figure 3.3: Sketching of testing specimen by using catia

The testing specimen consisted of two rectangular sections with 25 mm width, 173 mm long and 2 mm of thickness. The specimen is bonded together with 31 mm of an overlap length. The end tabs for both specimen is 37 mm respectively. From Figure 3.3, the structural of the specimen is known as a single lap joint since the bonded surface are at only one sided of each adherend.

3.4 Tensile Testing

Tensile testing also known as tension testing that is a fundamental materials science test where the sample is subjected to a controlled tension until failure. The results obtained from the test are used to select materials for an application for quality control and to predict the behaviour of the materials when forces are given. Tensile test can be used to determine the elastic and plastic deformations of the material, the tensile and ultimate strengths of the test material and the ductility of the material in terms of percentage of elongation and percentage reduction in cross-sectional area. In this research, tensile test is conducted to investigate the strength of the adhesive bonding between aluminium and carbon laminate composite.

The 25kN Universal Testing Machine (INSTRON-Model 8802) as shown in Figure 3.4, complete with the clip gage and software to control the test. The standard use to conduct the lap shear test is ASTM D5868, which is suitable for fibre reinforced plastics (FRP) against itself or metal.

A single lap joint specimen is tested in a lap shear test to determine the shear strength of adhesive bonding. (plc, I.G, n.d)

The tensile specimen is pulled in an axial tension until fracture occurs. The machine continuously record the incremental values of load and elongation of the specimen. A graph of load versus extension curve is obtained from tensile test as shown in Figure 3.5 (ASM International, 2004). The joint strength can be calculated as follows:

$$\text{Joint strength} = \frac{P_{max}}{A} \qquad \text{(Equation 6)}$$

Where;

P_{max} is the maximum applied load during the test and A is the adhesive area.

Figure 3.4: 25kN Universal Testing Machine (INSTRON-Model 8802)

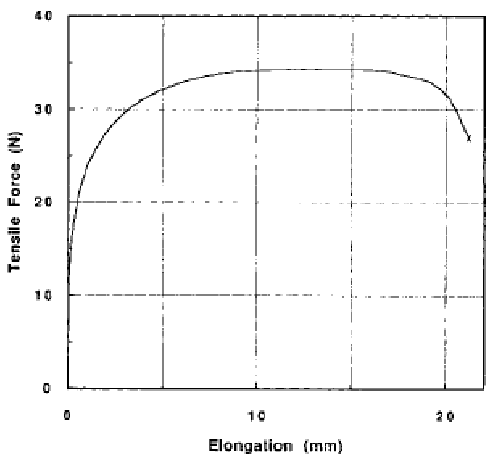


Figure 3.5: A graph of load versus extension (ASM International, 2004)

3.5 Fatigue Testing

The test machine for fatigue testing is similar to the tensile testing which is 25kN Universal Testing Machine (INSTRON-Model 8802). For high cycle fatigue (HCF), the load applied to the specimen is at 30 to 60 cycles per second and usually at higher frequencies which involves a large number of cycles is while for low cycle fatigue (LCF) the stresses are remain below the average life. A graph of stress versus number of cycles is obtained. Fatigue life is generally divided into three stages as shown in figure 3.6 below.

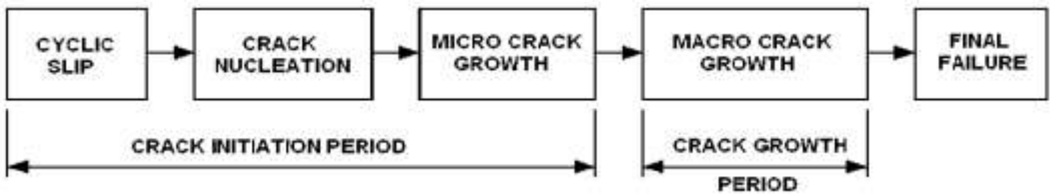


Figure 3.6: Phases of fatigue life (Azeez.A.A, 2013)

The fatigue tests are carried out on several specimens at different levels of maximum alternating stresses. The data is then plotted on a semi-log or log-log scale in the form of S-N curve. The horizontal portion represents as infinite life region where the infinite life is known as fatigue limit of the material while the vertical portion represents as fatigue strength of the material.

The applied stresses are described by three parameters which are mean stresses, S_m the average of maximum and minimum stresses in one cycle. The mean stress is zero for the completely reversed cycle test and the range of stress is the difference between maximum and minimum stresses in one cycle while the stress amplitude is one half the range of stress. The results from fatigue test can be plotted as S-N curves. At zero mean stress, the allowable stress amplitude is the effective fatigue limit for a specified number of cycles. At a mean stress equal to the ultimate tensile strength of material, the permissible amplitude is zero (Boyer, H.E, 2015).

Result from static testing is needed as reference to determine new maximum load for fatigue testing according to the chosen stress level. The other parameters such as minimum load, amplitude and mean are obtained from the calculation based on the formula as mention in literature review. Technique and skill on handling the Universal Testing

Machine (INSTRON-Model 8802) is needed. The calculated value is keys in into the system by step. The steps to key in the data are listed below;

1. Calibrate and balance the system
2. Install specimen at the machine
3. Set upper limit value based on the system stated values.
4. Set upper and lower limit based on the calculated maximum and minimum load
5. All the data key in is transferred immediately into the system
6. Make sure the mode chosen, and the value of mean is correct
7. Start the testing

The recommended standard use to conduct the fatigue testing is ASTM D5656 test standard for tension loading under the displacement control mode. The fatigue test will be conducted in load control a various maximum fatigue load levels. Three tests will be repeated for one specimen with different percentages of the average static strength that gained from the lap shear test.

CHAPTER 4

DATA AND RESULTS

4.1 Tensile Test Results

The static tensile test was performed three times with three different specimens by using a 25kN Universal Testing Machine (INSTRON-Model 8802) as shown in Figure 4.1. The tensile strength of all three specimens was determined as it shows the maximum stress that a material can handle before breaking. The results of tensile test are used to calculate the shear stress of the specimens based on the maximum load applied to the specimens and the adhesive area. Shear stress has been used to explain the mechanism of bonding failure between aluminium and carbon laminate composite.

$$\tau = \frac{F_{max}}{A} \text{ (Pa)} \qquad \text{(Equation 7)}$$

Figure 4.1: Static tensile test

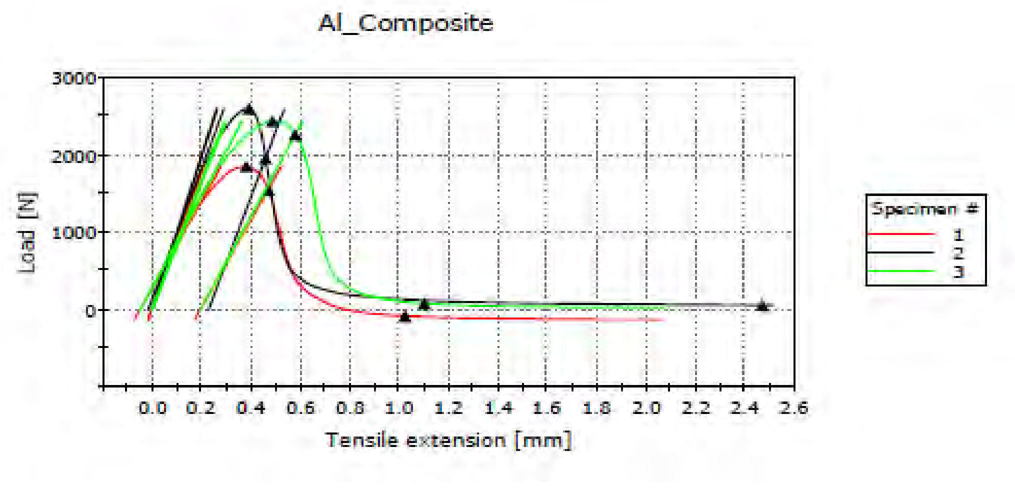


Figure 4.2: Load (N) versus Tensile Extension (mm)

Table 4.1: Result of tensile test

Specimen	Maximum Load (N)	Tensile stress at Maximum Load (MPa)	Extension at Maximum Load (mm)	Load at Yield (Offset 0.2%) (N)	Tensile stress at Yield (Offset 0.2%) (MPa)
1	1847.9988	18.4800	0.3807	1550.7203	15.5072
2	2588.5273	25.8853	0.3920	1952.8731	19.5287
3	2427.9302	24.2793	0.4874	2257.9660	22.5797

From Figure 4.2, specimen 2 shows the highest curve with high load applied to undergo failure compare to specimen 1 which is the lowest curve with low applied load to undergo failure. From Table 4.1 shown above, it shows that the specimen 2 has the highest maximum load which is 2588.5273 N compare to specimen 1 and specimen 3 which the value of maximum load are 1847.9988 N and 2427.9302 N respectively.

4.1.1 Shear stress

Shear stress for all three specimens can be calculated by using the equation as stated in equation 7 which is $\tau = \frac{F_{max}}{A}$. The value of F_{max} can be determined from the table

4.1 which is the maximum load applied (N). The adhesive area can be determined from the adhesive area for each specimen by using vernier calliper.

Table 4.2: Calculation based on equation shear stress equation

Specimen	**Maximum load (N)**	**Area (m^2)**	**Shear stress (MPa)**
Specimen 1	1847.9988	7.6608×10^{-4}	2.41
Specimen 2	2588.5273	8.316×10^{-4}	3.11
Specimen 3	2427.9302	7.3332×10^{-4}	3.31

From Table 4.2, it shows that the specimen 3 has the highest shear stress which is 3.31 MPa compare to specimen 1 and specimen 2 which are 2.41 MPa and 3.11 Mpa respectively. Even though the specimen 2 has the highest maximum load applied compare to the specimen 3, but the adhesive area for specimen 2 are much larger compare to specimen 3 which are 8.316×10^{-4} m^2 and 7.3332×10^{-4} m^2 respectively whereas the area for specimen 1 is 7.6608×10^{-4} m^2. Therefore, specimen 3 has the highest value of shear stress.

4.1.2 Bond Failure

The adhesive bond failure of the three specimens was recognized based on the mode of bond failure. The modes of bond failure are cohesion failure, adhesion failure and substrate failure. As the tensile test was performed, the failure mode of the specimens can be identified. Specimen 1 and specimen 2, from Figure 4.3 and Figure 4.4 were under the adhesion failure mode as it occur at the interface between the adhesive and adherend that can seen the remaining of residual adhesive at both surfaces while specimen 3 refer to Figure 4.5 were under the cohesion failure which is the presence of adhesive material on the matching faces of both adherend. The adherend are represent the aluminium and carbon laminate composite while the adhesive is represented by the epoxy and aluminium powder.

Figure 4.3: Specimen 1

Figure 4.4: Specimen 2

Figure 4.5: Specimen 3

4.2 Fatigue Test Results

Fatigue testing can determine the behaviour of the material under fluctuating loads. The testing was done by using a 25kN Universal Testing Machine (INSTRON-Model 8802). The experiment is repeated by an identical specimen and different percentage of stress level. In fatigue experimental, nine specimens were tested with four different stress levels which are 80%, 50%, 30% and 10%. The specimen was done under totally reverse cyclic loading and the mean load for all specimen is zero mean load. Since different stress level was used, each maximum load, minimum load and amplitude of the specimen are different.

The average maximum load was taken from the tensile test which is the maximum load for specimen 2 and specimen 3 which are 2588.5273 and 2427.9302 respectively. So the average of maximum load is calculated as below;

$$\text{Average maximum load} = \frac{2588.5273 + 2427.9302}{2}$$

$$= 2508.29 \text{ N}$$

4.2.1 Parameters of fatigue testing

From the value of average maximum load which is 2508.29 N, 80% of the stress level is calculated as shown below;

$$\text{80\% of maximum load} = \text{average maximum load x } \frac{80}{100}$$

$$= 2508.29 \text{ N x } \frac{80}{100}$$

$$= 2006.58 \text{ N}$$

Since the testing is a fully reversed cycle, so the stress ratio, R = -1. So the value of minimum load can be determined by using the formula;

$$\text{Minimum load} = \text{R (80\% maximum load)}$$

$$= -1\ (2006.58)$$

$$= -2006.58 \text{ N}$$

From the value of maximum load and minimum load, the amplitude can be calculated as below;

$$\text{Amplitude} = \frac{maximum\ load - minimum\ load}{2}$$

$$= \frac{2006.58-(-2006.58)}{2}$$

$$= 2006.58$$

Next, the mean load can be calculated as below;

$$\text{Mean load} = \frac{maximum\ load + minimum\ load}{2}$$

$$= \frac{2006.58 + (-2006.58)}{2}$$

$$= 0$$

Therefore, the parameter for 80% stress level can be summarized as below;

Stress ratio, R = -1

Maximum load = 2006.58 N

Minimum load = -2006.58 N

Amplitude = 2006.58

Mean load = 0

By using the same formula and calculation, the parameters for other stress level can be determined as shown in Table 4.3.

Table 4.3: Parameters of fatigue testing

Stress level	**Stress ratio**	**Maximum load**	**Minimum load**	**Amplitude**	**Mean load**
50%	-1	1254.11 N	-1254.11 N	1254.11 N	0
30%	-1	752.47 N	-752.47 N	752.47 N	0
10%	-1	250.82 N	-250.82 N	250.82 N	0

4.2.2 Stress amplitude

Stress can be determined by using formula of $\tau = \frac{P}{A}$

Where; P is the amplitude

A is the adhesive area

For specimen one of 80% stress level;

Stress, $\tau = \frac{P}{A}$

$$= \frac{2006.58}{25\ x\ 27.5\ x\ 10^{-6}}$$

= 2.92 MPa

The value of stress amplitude for each specimen is different eventhough the stress levels are the same because the area of the adhesive joint between the aluminium and carbon laminate composite are different. Table 4.4 shows the adhesive area of each specimen.

Table 4.4: Adhesive area of specimens

Stress level	Specimen	Adhesive area
80%	1	25 mm x 27.5 mm
	2	25 mm x 29.2 mm
	3	25 mm x 27.1 mm
50%	1	25 mm x 30.7 mm
	2	25 mm x 30.6 mm
	3	25 mm x 30.2 mm
30%	1	25 mm x 27.5 mm
	2	25 mm x 27 mm
10%	1	25 mm x 27 mm

By using the same formula, stress amplitude for each specimen can be determined. The results are tabulated in Table 4.5.

4.2.3 Cyclic fatigue tests

Constant amplitude fatigue tests were carried out under load control at a variety frequency depends on the stress level. The frequencies used are 1 Hz, 3 Hz and 8 Hz for 80%, 50%, 30% and 10% respectively. These load levels were selected to give a representative range of fatigue life. There were three specimens for 80% and 50% of maximum fatigue load levels, then two specimens and one specimen for 30% and 10% of maximum fatigue load levels respectively. As the specimen fail, the surface of failure was observed and can determine the type of the bond failure either it is cohesion failure or adhesion failure. Table 4.5 shows the result of the experiment, all specimens reached the set limit and undergoes fracture. The only one specimen which is the 10% of stress level does not undergo fracture even though already over than 1 million cycles and this can be characterized as high cycle fatigue.

Table 4.5: Results of fatigue testing

Stress level	Amplitude (N)	Frequency (Hz)	Specimen	Stress amplitude (MPa)	Cycles to failure	Remarks
80%	2006.58	1	1	2.92	20	Fracture
			2	2.75	26	Fracture
			3	2.96	8	Fracture
50%	1254.11	3	1	1.63	247	Fracture
			2	1.64	476	Fracture
			3	1.66	3 060	Fracture
30%	752.47 N	8	1	1.09	66 995	Fracture
			2	1.11	72 483	Fracture
10%	250.82 N	8	1	0.37	1 229 323	Not fracture

From the Table 4.5, the S-N curve can be draw since the results are complete. Three figures below show the graph of stress amplitude versus number of cycles to failure.

4.2.3.1 80% stress level

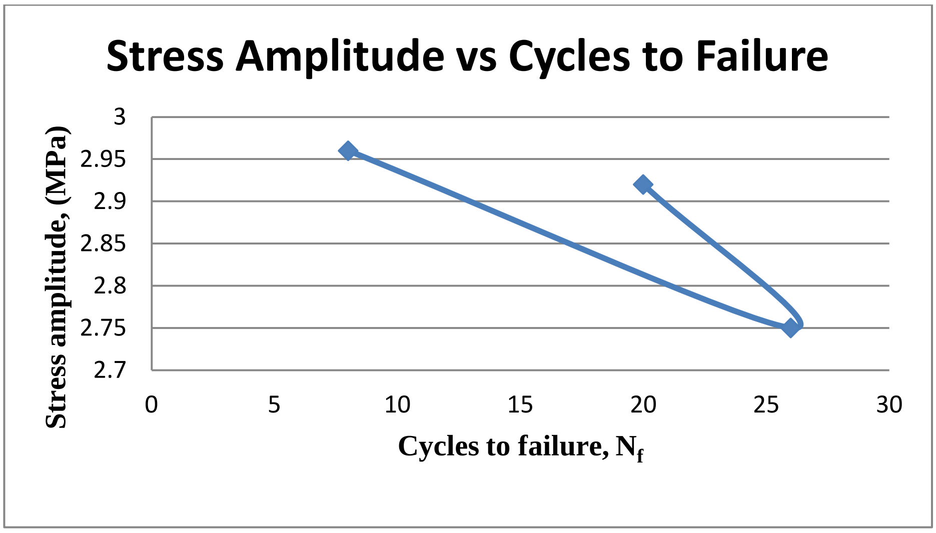


Figure 4.6: Stress amplitude versus cycles to failure for 80% stress level

Figure 4.7: Specimen for 80% stress level

From Figure 4.7, the left hand side is the first specimen, followed by specimen two and lastly the right hand side is the third specimen. All of the specimens are fractured with 20 cycles, 26 cycles and 8 cycles respectively. First and second specimen undergoes adhesion failure, while the third specimen is under cohesion failure. Based on Figure 4.6, it can be summarized that the higher the stress amplitude, the smaller the number of cycles and the lower the stress amplitude, the larger the number of cycles.

4.2.3.2 50% stress level

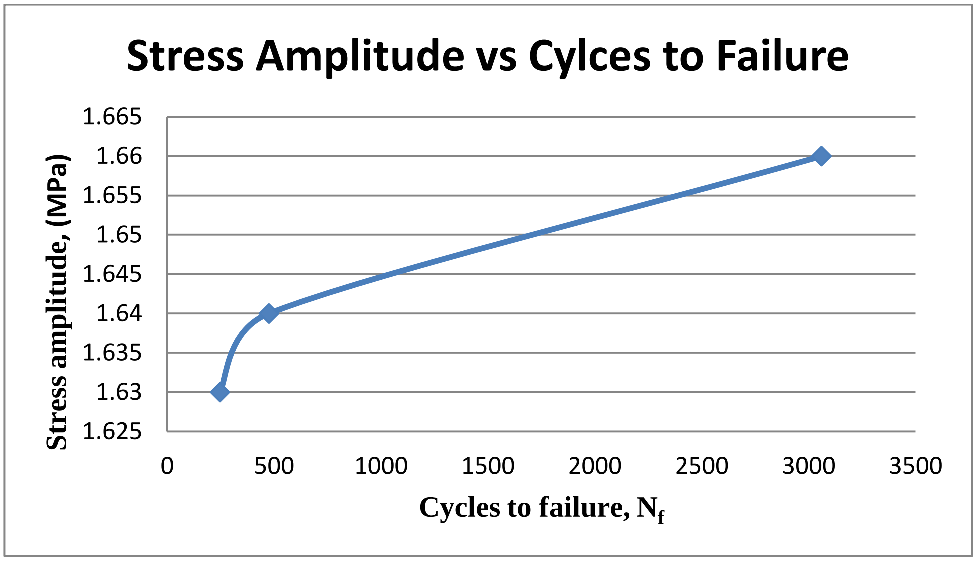


Figure 4.8: Stress amplitude versus cycles to failure for 50% of stress level

Figure 4.9: Specimen for 50% stress level

Figure 4.9 shows the specimen for 50% of stress level, the specimen is organized followed by the first specimen, second specimen and third specimen. The first specimen can be determined clearly that the specimen is an adhesion failure as the adhesive that attached the aluminium and carbon laminate composite is detached from both surfaces. The second specimen is a cohesion failure as the failure of the specimen is nicely fail at the adhesive. The third specimen is also under adhesion failure as the mixture of aluminium powder and epoxy were detached from carbon laminate composite surfaces. Figure 4.8 can be conclude as Figure 4.6 where the level of stress amplitude affect the number of cycles to failure.

4.2.3.3 30% stress level

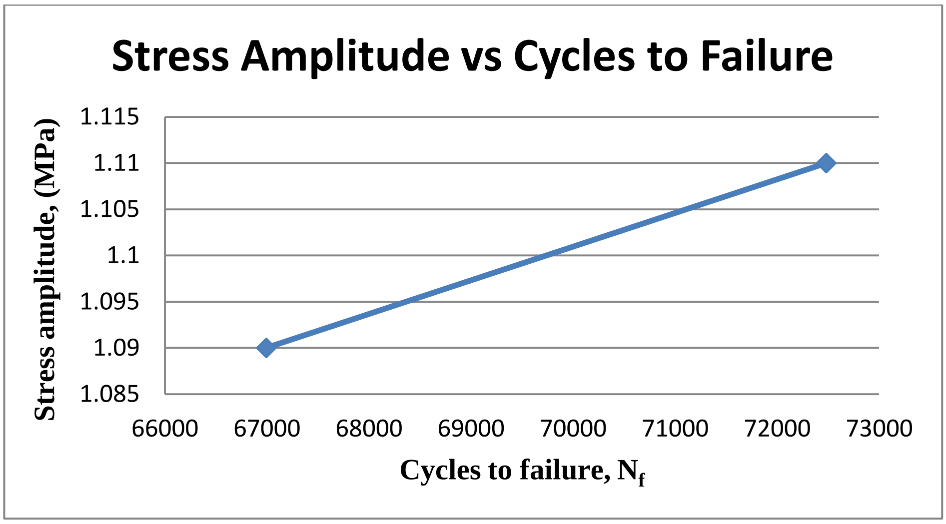


Figure 4.10: Stress amplitude versus cycles to failure for 30% of stress level

Figure 4.11: Specimen for 30% stress level

There are two specimens for 30% stress level which can refer to Figure 4.11, both of this specimen undergoes adhesion failure. The epoxy and aluminium powder were detached from aluminium surfaces for both specimen. The detached epoxy and aluminium powder were attached at the adhesive of carbon laminate composite surfaces. Figure 4.10 shows the number of cycles to failure based on the stress amplitude of the specimen.

4.2.3.4 10% stress level

Figure 4.12: Specimen for 10% stress level

Figure 4.12 is the specimen for 10% of stress level, the cycles of this specimen is over one million cycles. Therefore, this specimen can be categorized as a high cycle fatigue (HCF) since involves a large number of cycle which is ($N>10^5$ cycles).

4.2.3.5 Bond failure

Table 4.6: Type of bond failure

Stress Level	Specimen	Bond Failure
80%	1	Adhesion
	2	Adhesion
	3	Cohesion
50%	1	Adhesion
	2	Cohesion
	3	Adhesion
30%	1	Adhesion
	2	Adhesion

From the Table 4.6, it shows the bond failure of the specimen except the 10% stress level because it does not undergoes failure yet, so the type of bond failure cannot be determined. As we can seen from the table, mostly the type of bond failure observe from the specimen is adhesion bond failure, and only two specimen were under cohesion bond failure. The third specimen of 80% stress level and the second specimen of 50% stress level with the number of cycles to failure are 8 and 476 cycles respectively.

CHAPTER 5

DISCUSSION AND ANALYSIS

Previously in Chapter 4, the data and results of the fractured specimen were shown. The number of cycles and type of the adhesive bond failure has been determined. The reason and causes of the results of adhesive bond failure, the number of cycles obtained as the specimen fractured will be discuss in this chapter.

5.1 Experimental Results

Fatigue testing is performed to determine the number of cycles before the specimen is fail. Before conduct the fatigue testing, the static tensile test were performed to determine the maximum stress of the material. The maximum stress obtained from the tensile test was used as the reference for the stress level in fatigue testing. The lowest stress level which is 10% stress level with the stress amplitude is 0.37 Pa has the largest number of cycles compare to the other specimen which is 1 229 323 cycles. Even though this specimen already reached the million cycles but still the specimen is not fracture yet. The largest stress level is 80% stress level with the stress amplitude is 2.92 Pa, 2.75 Pa and 2.96 Pa for the first specimen, second specimen and third specimen with the number of cycles obtained are 20 cycles, 26 cycles and 8 cycles respectively. The stress amplitude of the specimen is different from each other because the length of the adhesive area is not equal. As we can see the difference between the lowest and highest stress level are the lower the stress level, the larger the number of cycles.

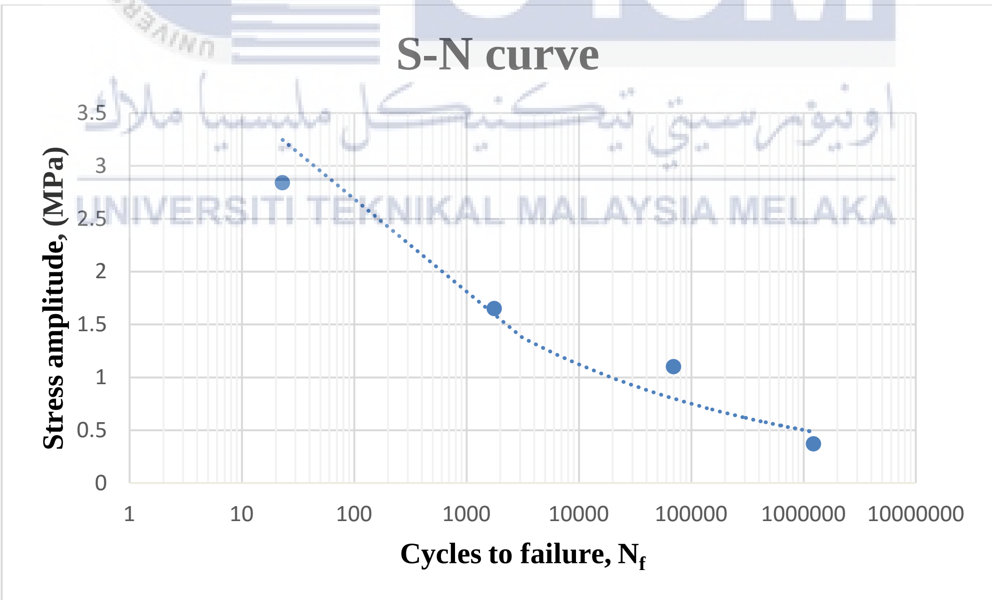


Figure 5.1: S-N curve

The results shows from the fatigue testing which can observed from the Figure 5.1 which is the S-N curve, graph of stress amplitude versus cycles to failure. The data of the specimen is obtained by undergoes repeatedly cyclic loading until failure. Usually, the testing is begins with the highest peak of stress where the number of cycles can be expected to be shorter and take less time to fail. Testing is then continued with decreasing stress level and the number of cycles is getting bigger plus the longer time taken to break the test specimen. However, the data obtained from the fatigue testing is different even the stress level is equivalent. The S-N curve was plotted by take the average of two specimens for each of the stress amplitude.

The short comings of fatigue data can be considered on many factors and conditions such as the loading, geometry, manufacturing and environment. The thickness of bonded materials and the adhesive, the adhesive area, fabrication of the carbon composite and the adhesive itself which the combination of aluminium powder and epoxy may be the factors of fracture.

5.2 Failure of Joint

The aluminium powder is in a form of small particle meanwhile the epoxy is in the form of liquid. So, as the specimens of the single lap joint were under fatigue testing, the stress given is a tension-compression since it is a fully reversed. Shearing stress is the cause of the specimen to fail when the aluminium and carbon laminate composite reached the maximum limit and slip from each other. The differences in shear stress value as calculated and tabulated in Table 4, are due to the difference in adhesive area which is the length and width of the bonded joint. The formula of shear stress is given by:

$$\tau = \frac{P}{A}$$

where τ = Shear stress

P = Amplitude

A = adhesive area

Fatigue crack initiation usually obtained from the concentration of plastic deformation that occurs within a small region of finite dimension. The different number of cycles of failure was affected by the localized plastic deformation. The stresses that applied on the specimen cause the localized of aluminium powder and epoxy as undergoes the repeated loading. The localization at the mixture of adhesive causes the failure of the joint.

As failure occurs, the surface of the adhesive area can be observed at the both side of the specimen. From table 4.4, the bond failure of the specimen has been determined. There are two types of bond failure which are adhesion and cohesion bond failure. The adhesion bond failure is the most failure occurs at the adhesive bonding, which can be identified easily when the adhesive detached from the aluminium or carbon laminate composite. Thus, the surfaces for one of the specimen have some empty space due to the detached of the adhesive which shown in figure below.

Figure 5.2: Example of adhesion bond failure

Based on Figure 5.2, the adhesion bond failure happen at both surfaces of the specimen because the detached of the adhesive on both surfaces. The interactions between adherend is rely by the strength of adhesion of the two materials, and the surface area of the adhesive were also important to determine the strength of adhesion between aluminium and carbon laminate composite. The adhesive failure may occur due to excessively fast cure, because sometimes cure rapidly can lower the chance of the adhesive to properly adhere to the surface. Plus, the intermolecular and chemical adhesion forces micromechanical adhesion can also involved in the adhesion failure.

Figure 5.3: Example of cohesive bond failure

Refer to Figure 5.3, it shows the cohesive bond failure which is less occurred in this experiment. There are only two out of nine specimen obtained this kind of failure. The cohesive bond failure can be identified by observed the surfaces of both adherend and seen the failure is through the adhesive bond line. The adhesive was separated equally between the adhesive itself. The causes of this failure are include the design deficiencies which include the insufficient overlap length, factors that causes high peel stresses or high thermal stresses. In addition, the presence of voids is also one of the factors of cohesion failure because it reduces the available bond overlap length below a critical size.

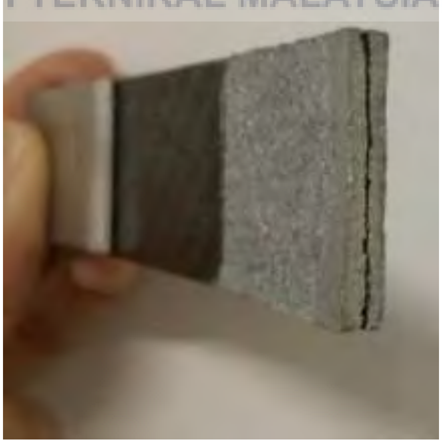


Figure 5.4: Debonding of carbon laminate composite

From Figure 5.4, debonding occurs at the carbon laminate composite. This type of failure only occurs at one piece of the specimen, it is the adherend for specimen one at 30% stress level. The failures take place when an adhesive stops sticking to an adherend and occurs if the physical, chemical or mechanical forces that hold the bond together are broken. In addition, it can causes by laminating geometry, structure geometry, state of stress and environmental condition. The bonding between the layers of the fibre decreased due to the given stresses, so the debonding leads to reduced fibre direction stresses, and the ultimate strength is increased.

CHAPTER 6

CONCLUSION AND RECOMMENDATION

6.1 Conclusion

The objective of this project is to conduct the fatigue testing and to determine the life on bonding of aluminium and carbon laminate composite. Aluminium and carbon laminate composites have differs in many aspects such as structure, physical properties and mechanical properties. Adhesive which the combination of epoxy and aluminium powder was used to bond the aluminium and carbon laminate composite. A structure of single lap joint was formed to conduct the tensile and fatigue testing. Tensile testing was performed to determine the maximum stress of materials can hold before failure. Fatigue testing was conducted to determine the number of cycles of the structure before fail, and it was carry out under various percentage of stress level. Difference percentage of stress level gives different result for the number of life cycles.

The bonded materials with structural of single lap joint undergo fatigue test at different maximum load and minimum load with a fully reversed cyclic loading. The stress level of shearing stress affect the number of life cycles for each specimen where at high level of shear stress will obtained low number of life cycles while low level of shear stress will results in high number of life cycles. The lowest stress level in this research is 10% which can be categorized as high cycle fatigue as the number of life cycles is exceed 1 million, and still does not undergoes failure. As the specimen fail, the surface of the adhesive failure for both side of the adherend was observed. The adhesive failure and cohesive failure were both due to the failure of the adhesive itself. The fast cure, intermolecular forces and micromechanical forces are the factors of the adhesive failure. Therefore, from the data and results gained in this research, it can be conclude that the level of shear stress will affect the fatigue life of aluminium and carbon laminate composite.

6.2 Recommendation

The recommendation for the future work to improve the results and analysis of this research is indeed. Foremost, a deeper understanding on the fatigue behaviour and mechanisms is important. A further reading on research and journal should be done to briefly understand on how it will work include the procedure and process before testing, during testing and after testing. Knowledge on S-N curve of stress amplitude and life cycles based on fully reversed cyclic loading is needed. Next recommendation is analyse the failure of bonded joint which is the adhesive area by using a scanning electron microscope (SEM). In SEM, the mechanism of bonding failure can be determined more precisely. So, reason and factor of the adhesive failure can be identified further.

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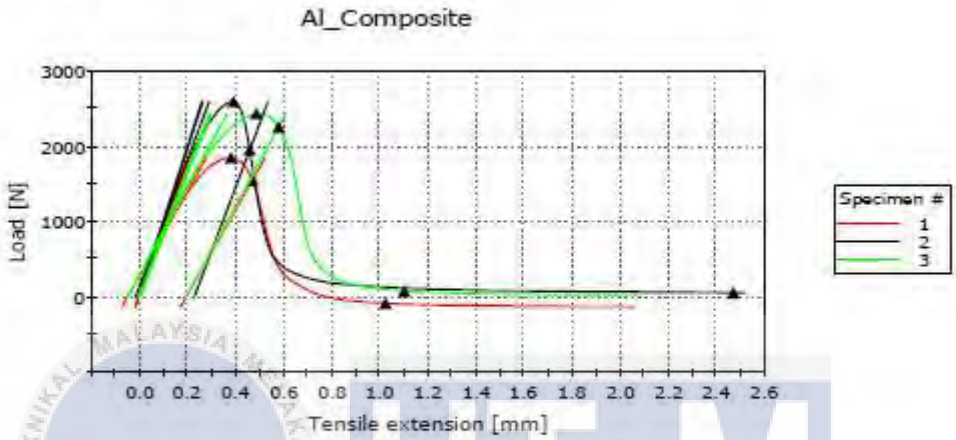
APPENDICES

Tensile Test for AL_Composite



	Maximum Load [N]	Tensile stress at Maximum Load [MPa]	Extension at Maximum Load [mm]
1	1847.9988	18.4800	0.3807
2	2588.5273	25.8853	0.3920
3	2427.9302	24.2793	0.4874

	Load at Yield (Offset 0.2 %) [N]	Tensile stress at Yield (Offset 0.2 %) [MPa]
1	1550.7203	15.5072
2	1952.8731	19.5287
3	2257.9660	22.5797

Figure A: Tensile test results

Figure B: Specimen fails under fatigue testing

Figure C: Result for number of cycles of fatigue testing