QUASI-STATIC AND FATIGUE STRENGTH OF SINGLE LAP JOINT WITH DISSIMILAR ADHEREND UNDER DRY AND HYDROTHERMAL AGEING CONDITIONS

by

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Dedication To

My Husband, Muhammad Hafas Azmi
My Son, Uwais Mikhael
And
My Parents, Majid Ahmad & Zainab Mat Hassan

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'Praised be to the Almighty, the most Gracious and most Merciful'

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LIST OF ABBREVIATIONS

ASTM	American Society for Testing and Materials
BFS	Backface Measurements
CZM	Cohesive Zone Modelling
FESEM	Field Emission of Scanning Electron Microscope
FRP	Fibre Reinforced Polymer
GRE	Glass Fibre Reinforced Epoxy
ICJ	Injection Clinching Joining
RT	Room Temperature
RFI	Resin Film Infusion
RTM	Resin Transfer Moulding
S-N	Stress-life
SEM	Scanning Electron Microscope
SLJ	Single Lap Joint
UTM	Universal Testing Machine
VIP	Vacuum Infusion Process
VIT	Vacuum Infusion Technique

LIST OF SYMBOLS

°C	Degree Celsius
%	Percentage
υ	Poisson ratio
$\mathcal{E}$	Elongation at break
E	Modulus young
σ_{ult}	Ultimate tensile stress
σ_y	Yield stress
T_g	Glass transition temperature
υ_f	Volume fraction
M_f	Final mass of specimen after combustion
M_i	Initial mass of specimen after combustion
ρ_c	Density of composite
ρ_f	Density of reinforcement
H	Overlap length
F_{ty}	Yield point of material
T	Thickness
τ	Average shear strength in adhesive bond
$M(t)$	Moisture uptake percentage
M_o	Mass of dry sample
M_t	Mass of immersed sample
δ	Displacement
$\mathcal{E}$	Strain

Kekuatan Kuasi-statik dan Kelesuan Sambungan Tindih Tunggal Dengan Bahan Yang Berbeza Di bawah Keadaan Kering dan Penuaan Hidroterma

ABSTRAK

Pengurangan berat struktur yang ketara dapat dicapai dengan memperkenalkan sambungan tindih diantara aloi ringan dan bahan komposit, berbanding dengan penggunaan bahan keluli konvensional. Walau bagaimanapun, bahan-bahan yang berbeza ini tidak boleh dilaksanakan dan digabung dengan menggunakan kaedah kimpalan konvensional. Antara permasalahan utama kajian ini adalah penyerapan air terhadap bahan ke atas kekuatan dalam sifat tegasan dan kelesuan sambungan struktur tidak dikaji sebelum ini. Secara khususnya, kesan penyerapan air terhadap tingkah sambungan hibrid tidak diperhatikan. Oleh itu, di dalam penyelidikan ini, bahan yang sama dan berbeza (aluminium / komposit) telah digunakan untuk fabrikasi sambungan tindih tunggal (SLJ) dengan konfigurasi penyambungan yang berbeza iaitu: dilekatkan secara mekanikal, diselaraskan bersama bahan pelekat dan hibrid. Bahan komposit GRE dihasilkan melalui lapisan gentian bertetulang dengan arah [0/90°]. Pelekat jenis Araldite epoxy dan pengikat mekanikal jenis Huck bolt digunakan untuk penyambungan. Pada permulaan, tingkah laku mekanikal terhadap penyambungan telah dinilai melalui kajian eksperimen pada suhu bilik (RT) 23 °C. SLJ telah digunakan sebagai rujukan untuk perhimpunan ikatan antara bahan untuk menganalisis kekuatan kuasi statik dan kegagalan mekanisma terhadap penyambungan. Di dalam eksperimen ini, kesan daripada kombinasi bahan dan konfigurasi penyambungan yang berbeza pada pemindahan beban dianalisis. Penyambungan hibrid didapati menunjukkan kekuatan bersama dan kekakuan tertinggi sebanyak empat kali lebih tinggi berbanding dilekatkan secara mekanikal dan diselaraskan bersama bahan pelekat. Mekanisme kegagalan bahan dicirikan sebagai mod campuran dan kegagalan pelekat pada permukaan AA7075. Pada peringkat kedua, kekuatan dan kegagalan mekanisma penyambungan yang tertumpu kepada pemunggahan kitaran disiasat di bawah suhu RT, dengan mengambil kira kesan daripada kombinasi bahan dan konfigurasi penyambungan yang berbeza terhadap pelbagai tahap tekanan. Hayat kelesuan pada penyambungan hibrid didapati mencapai tahap hayat yang paling lama jika dibandingkan dengan dilekatkan secara mekanikal dan diselaraskan bersama bahan pelekat pada tahap tekanan terendah dan tertinggi dengan kombinasi bahan lekatan yang berbeza iaitu, AA7075 / GRE. Perbezaan ini telah dinilaikan sebanyak 80.3% dan 12.5% pada tahap tekanan rendah 30%. Selain itu, 73.3% dan 33.3% dicatatkan pada tahap tekanan tinggi 90%. Akhir sekali, kesan alam sekitar terhadap ketahanan sendi yang terikat dan hibrid dinilai di bawah analisis kekuatan kuasi statik dan kelesuan. Kekuatan dan modulus penyambungan didapati berkurangan dengan ketara dengan peningkatan masa penuaan. Di samping itu, kombinasi gabungan bahan yang berbeza daripada AA7075 dan GRE komposit dalam hibrid mencapai kekuatan kelesuan terbesar dengan 83% dan 30.2% lebih tinggi daripada bahan yang sama iaitu AA7075 dan komposit GRE. Kajian ini merangkumi siasatan eksperimen, menilai secara menyeluruh dan menghuraikan kelakuan mekanikal SLJ dengan sambungan bahan yang sama dan berbeza; AA7075 dan GRE pada konfigurasi penyambungan dan suhu persekitaran yang berbeza.

Quasi-static and fatigue strength of Single Lap Joint with Dissimilar Adherend under Dry and Hydrothermal Ageing Conditions

ABSTRACT

Significant reduction of structure weight can be achieved by introducing the lap joint combination of light alloys and composite materials compare to conventional steel material. However, these dissimilar materials undesirably cannot be joined by conventional welding method. Another related problems that reassure the research is the environmental condition effect of water absorption on the tensile strength and fatigue properties of structural joint was not investigated previously. Specifically, the effect of water immersion on hybrid joints behaviour was not observed. Therefore, in this research, the similar and dissimilar (aluminium/composite) adherends were used for fabricating single lap joint (SLJ) with different joint configuration: mechanically bolted, adhesively bonded and hybrid joint. The glass fibre reinforce epoxy (GRE) composites were manufactured through ply layers of reinforced fibre [0/90°] woven. The adhesive and mechanical fasteners of Araldite epoxy and Huck bolt were used for joining, respectively. Initially, the mechanical behaviour of joining was evaluated in experimental study at room temperature (RT) of 23 °C. A SLJ was developed for the bonding assemblies between the adherend to analyse the quasi-static strength and failure mechanism in the joints. From these experiments, the effect of different adherend combination and different joint configuration on the load transfer was analysed. Hybrid joints, on the other hand was found to exhibits the highest joint strength and stiffness as four times higher in comparison to mechanically bolted and adhesively bonded joints. The failure mechanism of adherend was characterised as mixed mode and adhesive failure on AA7075 surface. In the second stage, the strength and failure mechanism of bonding lamination subjected to cyclic loading were investigated at RT, by considering the effect of different adherend combination and different joint configuration at various stresses level. The fatigue life of hybrid joint was found to be the longest fatigue life in comparison to mechanically bolted and adhesively bonded joints at lowest and highest stress level with adherend combination of dissimilar-AA7075/GRE. The difference has been recognised as much as 80.3% and 12.5% at low stress level of 30%. Moreover, 73.3% and 33.3% were recorded at high stress level of 90%. Finally, the effect of the environment on the durability of adhesively bonded and hybrid joints was evaluated under quasi-static and fatigue strength analysis. The strength and modulus of the joint was found to decrease significantly with increase ageing time. In addition, dissimilar adherend combination of AA7075 and GRE composites in hybrid joint achieved the greatest fatigue strength with 83% and 30.2% higher than similar adherend of AA7075 and GRE composites, respectively.

CHAPTER 1 : INTRODUCTION

1.1 Research Background

Over the years, modern aerospace and automotive manufacturers have continually strived to reduce weight, aiming for high-stiffness structures involving metallic and composite materials. Lightweight structural parts are attractive for use in design and manufacturing in automotive industries as they can provide a 20-30% reduction in total weight (Miller et al., 2000). Use of lightweight materials in the design of a structure is increasingly important in many industries, such as aerospace, automotive, marine, and wind energy (Li, Han, Thornton, Shergold, & Williams, 2014). For that, the use of these materials is expected to become more widespread in the next decade and expected to grow rapidly as much as doubled in the last 20 years in automotive industry. According to Andure et al., (2012) and Miller et al., (2000), this attention is continually focused on weight reduction and fuel consumption with high stiffness and strength of materials required. Furthermore, lightweight vehicle structure can be achieved through a combination of lightweight engineering, lightweight manufacturing, and weight reduction of material selection (Pfestorf, 2005).

In order to improve fuel economy and reduce environmental emissions, the materials used in transportation industries are changing from mostly low-carbon steels to a combination of advanced high-strength steels and lightweight alloys. This includes the use of aluminium alloys, magnesium alloys, and polymer matrix composites, which are provides an efficient means to reduce vehicle mass. Even though aluminium alloy has substantially lower strength and stiffness than steel, it is successfully compensated in the design of a car spaceframe, where a thicker material produces a smooth joining. In automotive industry applications, various joining processes are introduced, such as friction lap welding (Lambiase & Durante, 2017), laser-assisted direct joining (Lambiase & Genna, 2017; Lambiase, Genna, Leone, & Paoletti, 2017), friction riveting, and flow drilling. To satisfy the various requirements of the automotive and aerospace industries, combination of dissimilar adherends are also introduced, particularly for joining non-metals to metals, as attempted in previous research by Di Bella, Galtieri, Pollicino, & Borselliono, (2013) and Anes, Pedro, & Henriques, (2016). The mechanical properties and joining techniques of adherends are essential factors in structural applications.

For the past decades, the joining techniques used are adhesive bonding, bolt fastening, and adhesive-bolt hybrid joining. This leads to various studies on the combination of dissimilar materials and the joining methods (Li, Yan, Zhang, & Liang, 2015): single-lap (Stuparu et al., 2017), double-lap (Chuang & Tsai, 2013; Arnautov, Nasibullins, Gribniak, Blumbergs, & Hauka, 2015; Liu & Dawood, 2017), scarf (Adin, 2012; Adin, 2012b), strapped (Lee, Pyo, & Kim, 2009), and tapered joints (Stuparu et al., 2017) as shown in Figure 1.1. Mechanical fastening methods such as riveting, screw-type fasteners, washers, and bolt and nut are used in bolting condition and required holes to be drilled in the substrates. This is typically more efficient in metallic substrates than in composites, as they are more ductile. However, drilled holes on bolted joints introduce stress concentrations, resulting in a tendency to form cracks that can grow and cause failure. According to Pinto, Campilho, Mendes, Aires, & Baptista (2011), the effects of stress concentration and large deformation as a result of drilling holes never benefits the joint strength, as the joint efficiency and quality depend on machined holes. Moreover, the high stress concentration was found to be more severe in composite laminates than in metal plates (Chowdhury, Chiu, Wang, & Chang, 2016). This is because the stress concentration factor is very high at the hole edge when the fibres in a polymer composite are aligned in the load direction (i.e. Ex > > Ey). Furthermore, as an anisotropic materials, composite laminates contain several plies which possess dissimilar elastic modulus due to different fiber orientations (Junshan et al., 2017).

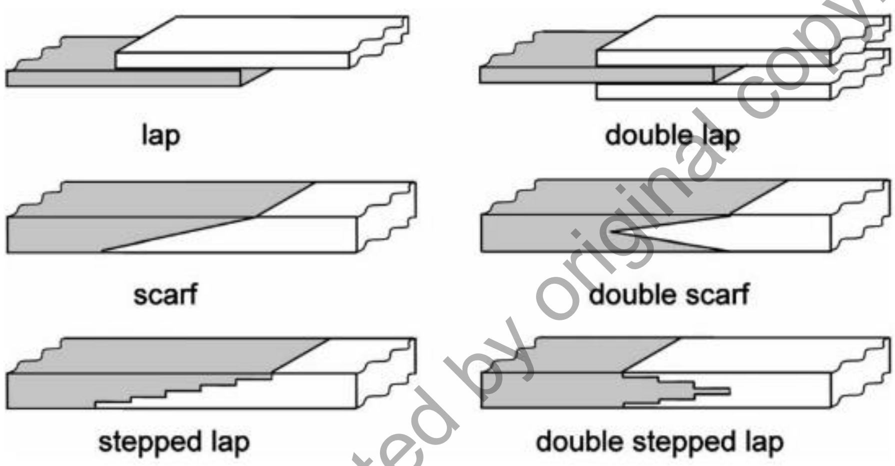


Figure 1.1 Several types of bonding (Gunnion, & Herszberg, 2006).

Adhesively bonding joints is a process requiring two or more solid parts, known as substrates/adherends, with an adhesive acting as the substance in between. The performance and durability of adhesives have been enhanced significantly with the advancement of polymer science. Moreover, this type of bonding has many advantages over the conventional joining methods of fusion and spot welding, bolting, and riveting, as it can bond dissimilar materials. This results in high stiffness, better fatigue performance, and uniform stress distribution over a large bond area (Sugita, Winkelmann, & La Saponara, 2010; Park, Song, Kim, Kweon, & Choi, 2010). Adhesive bonding is mostly part-utilised for auxiliary structures when failure does not directly affect the structural safety due to the high specific stiffness and strength, low cost, smooth configuration, and uniform stress distribution associated with the joining method (Li, Yan, Zhang, & Liang, 2015). In automotive space frames, the time consumed in the joining production process is most important and is the main concern that contributes to the disadvantages of an adhesively bonded joint. In addition, there may be difficulties in separating the adhesive bonds for regular maintenance, servicing, and repair (Lu, Broughton, & Winfield, 2014). However, according to Mittal (2002), it was stated that the stress concentration of an adhesively bonded joint is less than that of a bolted joint. This is because, bolts or rivets are often points of high stress concentration that can lead to structures having a lower static and fatigue strength than an adhesive bonded system. Though, it should be noted that in adhesive bonded joint, the extensive surface preparation of materials are required.

In order to enhance the joining performance, both mechanically bolted and adhesively bonded joints are combined to develop a joining mechanism with improved mechanical behaviour. In recent decades, this combined application has gained more attention in modern aerospace and automotive industries owing to its greater performance. This combination is known as a hybrid joint. A hybrid joint offers several advantages in automotive production over other methods in terms of processability and load-bearing capacity: superior strength, stiffness, and fatigue life (Fu & Mallick, 2001; Lee et al., 2010; Chowdhury, Chiu, Wang, & Chang, 2015). Numerous experimental studies have shown that such hybrid joints can potentially achieve higher static strengths than the underlying bonded and bolted joints could separately (Sadowski, Golewski, & Zarzeka-Raczkowska, 2011; Li et al., 2015; Islam & Tong, 2016) .

The hybrid single lap joint (SLJ) was experimentally applied in the static and fatigue loading of composite materials by Fu & Mallick (2001). The study showed that ahigher static loading and longer fatigue life were observed in hybrid joints that provide a full lateral clamping pressure compared to the adhesive joints. Islam & Tong (2016) reported that hybrid steel-glass fibre pre-pegged co-cured SLJs with stainless steel pins revealed improved static failure strengths of 58% compared to the adhesively bonded joints. The adhesive in the hybrid joint was continually studied to enhance the SLJ strength by adding mechanical fasteners. Therefore, the addition of mechanical fasteners of the bolt into bonded joints satisfies the requirements for primary aircraft structures (Lopez-cruz, Laliberté, & Lessard, 2017). Pinto et al., (2011) studied the effect of hole drilling in aluminium alloy adherends on the strength of the SLJ. The adhesive Araldite was filled in the holes to investigate the inner stress concentration and the sharp edges in the holes were located at the centre of overlap bond. The study has found that a significant deformation and stress arrest affected around the bolt hole, in which the stress concentration exceeds the cohesive strength.

Environmental factors of moisture and temperature are particularly important to be taken into account in any predictions as it significantly decrease the joint strength over the appearance of adhesive period in bonded and hybrid joint. It has been observed that these environmental effects can diffuse rapidly along the adhesive interface-adhesion, which subsequently triggers a chemical reaction, resulting in adhesion de-bonding. An extensive research on SLJs has been undertaken into short and long-term immersion behaviour (Crocombe, Hua, Loh, Wahab, & Ashcroft, 2006).

The research presented in this thesis aims to develop methodologies and joint experiments to define the joint strength and influence of environmental effects with similar and dissimilar adherends and different joint configurations. For instance, epoxy adhesives and mechanical fasteners of Huck bolts are precisely employed as an alternative approach of joint techniques in adhesively bonded, mechanically bolted, and hybrid SLJs. The proposed research is well-timed and industrially applicable in the context of modern developments in experimental techniques and methods. This is of significance for all industrial sectors including aerospace, defence, automobile, marine, and building construction.

1.2 Problem Statements

In automotive manufacturing industries, design modifications of vehicles have major impacts on customer demand. It will be more challenging when faced with the use of appropriate materials and methods to be compared with the pre-existing method. The current trend in vehicle design is influenced by awareness of environmental issues and to be less reliant on fossil fuels. Vehicle manufacturers have introduced various technologies in terms of the structure in order to reduce the weight, directly achieving low CO_2 emissions. One of the convincing methods in reducing the emissions is by applying a lightweight structure. A significant reduction of structure weight can be achieved by introducing the lap joint combination of light alloys and composite materials compared to conventional steel materials. However, these dissimilar materials cannot be joined by a conventional welding method. This is due to difficulties to joint where it has different mechanical and physical properties. It is also difficult due to high structural dissimilarities and melting temperature. In which, the polymer are degrade before the metal are melted. Thus, the use of a hybrid joint is expected to provide a better solution to establish a reliable joint. Currently, several researches on hybrid joints are focused on the combination of mechanical fastening (rivet or bolt) and adhesive bonding, as to be reviewed in Chapter 2. However, the effect of hybrid SLJs conducted with high strength mechanical fasteners of Huck bolts was not well observed previously, with the use of different adherends and different types of joint configurations. A few researches reported the influence of the overlap length of hybrid joints and the strength of Huck bolt fasteners with the types of SLJ techniques.

Another related problem that require further research is the environmental condition effects of water immersion on the tensile strength and fatigue properties of hybrid SLJs. One important remaining gap of the study is the lack of knowledge on long-term immersion period performance and durability of composite/metal materials. Furthermore, effects of water immersion on hybrid joints have not been observed previously. The current joining practice of dissimilar materials is generally limited to the use of metallic fasteners, such as in the case of trailing edge devices or the metallic hinge bolted to CFRP composite panels on the Airbus A330 undercarriage door (Nguyen, Brandt, Feih, & Orifici, 2016). Previous publications on hybrid metal-composite joints with through-thickness reinforcements provide some insight into the expected performance of the proposed joint concept. In single and double lap shear experiments, straight cylindrical reinforced pins have shown a major increase in strength and strain to failure in comparison with unpinned adhesive joints (Ucsnik, Scheerer, Zaremba, & Pahr, 2010; Nguyen, Brandt, Feih, & Orifici, 2016). The performance of the new technology of Huck bolts on joining will be tested to identify the mechanical behaviour of the lap joint.

1.3 Research Objective

The aim of this research is to develop a novel system to determine the strength of mechanically bolted, adhesively bonded, and hybrid SLJs at room temperature (RT) and elevated temperature, through static and dynamic loading. Through the study, a new technology of Huck bolt mechanical fasteners was introduced by evaluating the mechanical behaviour of the failure load and investigated the failure mechanism of joints under both conditions. Moreover, this type of joint was introduced to replace the existing welding system when two different materials, metal to composite, are combined.

Furthermore, the mechanically bolted and adhesively bonded joints will be an additional support in hybrid joints. The dynamic testing concentrated on fatigue strength and lifetime prediction of SLJ in the study. The fatigue approaches of stress-life and fatigue crack were obtained through the stress-life (S-N) curve. The ratio and frequency were maintained at a constant value. Most of the current and previous research investigated the influence of environmental effects on adhesively joints. The purpose of the task is to examine the environmental effects of elevated temperature water immersion on Huck bolt hybrid joints with similar and dissimilar materials, instead of adhesively bonded joints. The immersion was evaluated with a curing temperature according to adhesive glass transition, T_g. The main objectives of this research comprise the following tasks.

i. To evaluate the static behaviour of SLJs with the effect of different adherends and joint configurations at RT (dry conditions).

ii. To evaluate the fatigue life response of SLJs with the effect of different adherends and joint configurations subjected to constant ratio and frequency at RT (dry conditions).

iii. To compare and evaluate the influence of long-term hydrothermal ageing of similar and dissimilar SLJ adherends at elevated temperature water immersion (wet conditions) on static, as well as, fatigue performance.

1.4 Research Scope

The scope of this research is limited to develop fundamental knowledge on mechanically bolted, adhesively bonded, and hybrid SLJ mechanism and provide knowledge of the know–how of joining similar and dissimilar adherends of AA7075 and GRE composites. Thus, new mechanical fasteners have been introduced and explored the mechanical strength on the joining that will provide affordable techniques when joining the materials. The composite adherends of GRE were fabricated with a vacuum infusion technique (VIT) and a single GRE composite dumbbell shape was examined to obtain the mechanical properties for overlap length (bond length) determination. The tensile testing method for the GRE composites dumbbell shape was in accordance with the ASTM D638 standard. The specimen used in the experiment was exposed in two conditions, dry (RT) and wet for SLJ specimens. Under wet condition, the adhesively bonded and hybrid SLJ specimens were hydrothermally aged in tap water. In order to estimate their long-term performance, an ageing process was performed on both joint configuration at constant water temperature of 50 °C with variable immersion periods (20, 40, 60, 80, 100, and 120 days). Experimental tests were performed under tensile load to evaluate the ultimate tensile strength to be used for fatigue resistance of mechanically bolted, adhesively bonded and hybrid SLJs for both conditions. Different amplitude ranges of 30, 40, 50, 60, 70, 80, and 90% and constant stress ratio, R=0.1, were implemented. Meanwhile, the frequency of 5 Hz was used on fatigue testing. The fatigue test was performed to obtain the S-N and fatigue crack/propagation before and after being exposed to the environmental effects of water absorption.

1.4 Thesis Outlines

This thesis is comprised of five chapters. Chapter 1 discusses an overview on fundamental joining techniques, mechanically bolted joints, adhesively bonded joints, and hybrid SLJs. The research project involves a problem statement, objectives, and scope of research.

Chapter 2 describes a detailed review of the literature. This chapter covers the geometric study effect of joint strength. The mechanical properties and behaviour of joining are addressed into several aspects which are; different adherends, adhesive types, mechanical fasteners types, etc. The early part of the chapter provides an essential overview of the lightweight material background, for both metal and non-metal materials. Following this, the usage of these combination materials are reviewed and discussed for different joining techniques.

Chapter 3 elaborates the experimental procedure, namely the material selection, joining techniques selection and fabrication technique for the GRE test panels. The preliminary material characterisations of GRE specimens are determined, which includes burn-off experiments, and mechanical testing, are presented. The experiment continues with elaboration of the SLJ specimen preparation of different joining techniques, which includes mechanical testing under RT. The environmental effect of moisture are discussed through a water immersion experiment by adopting an elevated temperature environment.

Chapter 4 explains the experimental results obtained from the parametric studies that have been conducted under tensile and fatigue testing. The relative effects of the parametric studies on the joint strength under tensile and fatigue stress are discussed in terms of two conditions namely, dry and wet.

Chapter 5 concludes the overall findings of the research. Then, the achievement and contribution, as well as recommendations for future work are proposed.

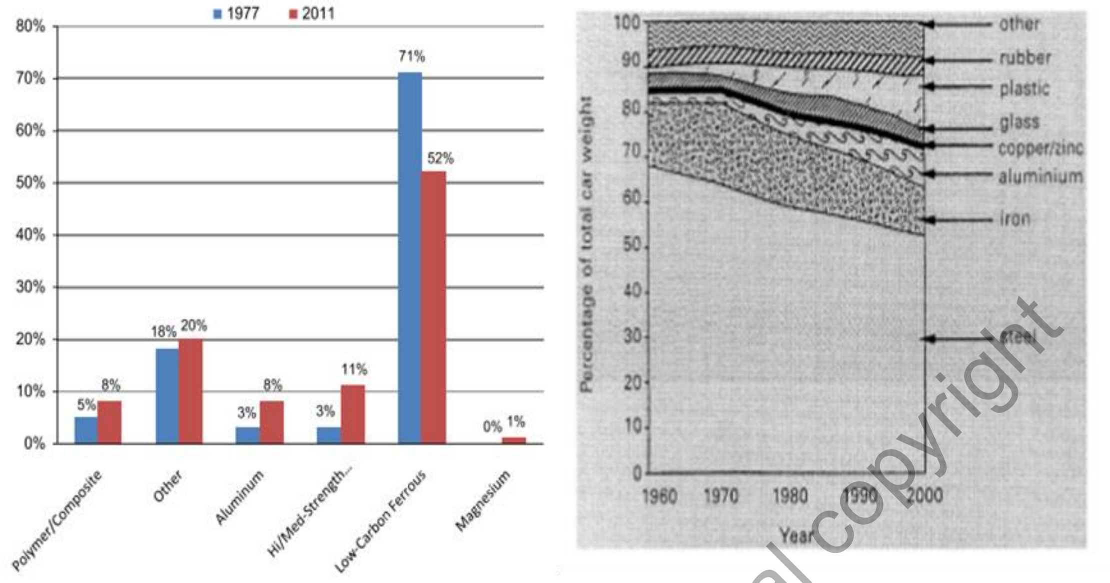
CHAPTER 2 : LITERATURE REVIEW

2.1 Introduction

This chapter provides a review on the existing researches related to the subject of this thesis. The subjects vary from the types of adherend, the types of joint configuration, the effect of geometry parameters, and the exposure under environment analyses. The chapter is organized as follows: Section 2.2 describes the background theories of lightweight materials, which are supported by the physical and mechanical properties. Section 2.3 explains the variable composite fabrication techniques which have been used. The joining techniques and parameters are presented in Section 2.4. Meanwhile, the usage of mechanical fasteners and types of adhesive used in industrial sector are highlighted in Section 2.5 and 2.6, respectively. The joint performance of SLJs is reviewed under static and dynamic loading as discussed in Section 2.7 and 2.8, respectively. In the next section of 2.9, the failure mechanism of SLJs, with the effect of geometry parameters, is reviewed. This is followed by further discussions on environmental issues throughout the durability of joints in Section 2.10 and 2.11. Finally, the summary of the review is outlined in Section 2.12.

2.2 Background Theories of Lightweight Materials

The challenge of introducing new materials into existing products and manufacturing systems has been the reality for practitioners for decades (Denzler & Wiktorsson, 2016). To achieve a lower structure weight without compromising its stiffness and safety, the combination of lightweight materials such as composite, aluminium, metal, magnesium alloys, steel, and titanium are necessarily used in automotive manufacture from the year 1997 to 2011, as shown in Figure 2.1 (a) (Lu, Broughton, & Winfield., 2014). Meanwhile, Miller et al. (2000) figured out that the use of aluminium and plastics in automotive sectors was increasing from year to year instead of steel and cast iron, due to the increasing need for weight reduction. This reduction is shown in Figure 2.1 (b). A lightweight vehicle accelerates quicker and handles better. It is possible to considerably reduce the weight of an existing designed part by utilising a lighter material. Consequently, motorcycle building materials have evolved through the decades to deliver lighter and stronger machines. It can be achieved through any combination of three different approaches of lightweight design categorized into lightweight engineering, lightweight manufacturing, and weight reduction through material selection (Pfestorf, 2005).



(a) (b)

Figure 2.1 Types of materials: (a) use in a car (Lu, Broughton, & Winfield, 2014), (b) consumption changes in an average car (Miller et al., 2000).

2.2.1 Metallic Alloy

Materials of aluminium alloys take up the main part in this research, whereas the structure and properties itself are highly disordered with a wide dispersion of cell size and cell shape. The three characteristics of pore size, relative density, and base material provide a three-dimensional design space to form a material with a wide range of material properties. The most compelling evidence is that these characteristics are applied in the ultra-lightweight industry because of their high degree of homogeneous closed-all porosity and able with the high stiffness-to-weight and strength-to-weight ratios (Aoba, Kobayashi, & Miura, 2017; Chen, You, & Gao, 2014).

Aluminium parts may be highly complicated in their design due to the high number of design solutions, like the previously mentioned extrusions and castings available in nearly any shape when they can replace a complex part consisting of several steel panels. Consequently, a reduction of parts by up to 50% is feasible (Wenlong, Xiaokai, & Lu, 2016). Generally, the fuel consumption can be reduced by 6% to 8% with every 10% of car weight reduction manufactured by aluminium. Undoubtedly, this light material is more expensive to manufacture a car body than steel, however, a comparison can be highlight in terms of CO_2 emissions and vehicle weight reduction of 30% to 40% can be made by using typical aluminium parts (Wenlong, Xiaokai, & Lu, 2016). In that investigation, aluminium was substituted in Audi A8 car and found that the average fuel consumption is 9.9L/100 km with emission of 199 g/km. Recent examples of aluminium applications in vehicles cover power trains, chassis, body structure, and air conditioning.

2.2.2 Polymer Composites

A composite is an auxiliary material produce with a combination of two or more materials at a macroscopic level and are not solvent in each other, known as the reinforcing phase and matrix. Fibre-reinforced polymer (FRP) composites are, as a rule, progressively utilized as options for ordinary materials on account of their high specific strength, specific stiffness, and tailorable properties (Aramide, Atanda, & Olorunniwo, 2013). FRP composites constitute in-homogeneous and anisotropic properties, which are totally different compared to metal alloys and the non-reinforced polymer properties. The load-carrying elements in FRP are designed to provide high strength and stiffness for the composite material. The FRP used during the course of this study is glass fibre, which is common for FRP composites.

Glass fibre-reinforced epoxy (GRE) composites were most usually utilized as a part of the manufacture of composite materials. The matrix is comprised of natural/organic, polyester, thermostable, vinylester, phenolic, and epoxy resin (Di Bella, Galtieri, Pollicino, & Borsellino, 2013). Polyester and epoxy resin cannot be depolymerised to their original constituents. The major classification, physical and mechanical properties, and chemical composition of GRE are shown in Figure 2.2 and Table 2.1, respectively (Sathishkumar, Satheeskuma, & Naveen, 2014). On the basis of their chemical composition and manufacturing cost, glass fibre can be classified into two types, namely the E-glass and S-glass. The superior mechanical properties and performance of fibres have been effectively used for many engineering applications including aerospace construction (Sugita et al., 2010), automotive industries (Machado et al., 2018), biomedical application (dentistry and orthopaedic) (Cheung, Ho, Lau, Cardona, & Hui, 2009), and others.

Table 2.1 Mechanical properties of glass fibre.

Fibre	Density (g/cm^3)	Tensile strength (GPa)	Young's modulus (GPa)	Elongation (%)	Coefficient of thermal expansion	Poisson ratio, *v*
E-glass	2.58	3.445	72.3	4.8	54	0.2
C-glass	2.52	3.310	68.9	4.8	63	-
S2-glass	2.46	4.890	86.9	5.7	16	0.22
A-glass	2.44	3.310	68.9	4.8	73	-
D-glass	2.11-2.14	2.415	51.7	4.6	25	-
R-glass	2.54	4.135	85.5	4.8	33	-
EGR-glass	2.72	3.445	80.3	4.8	59	-

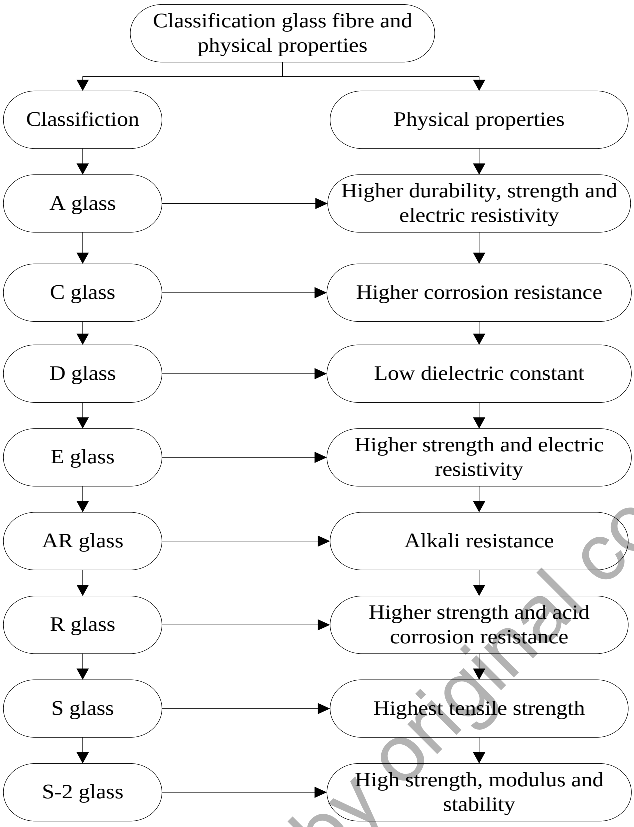


Figure 2.2 Classification and physical properties of various glass fibre (Sathishkumar, Satheeshkumar, & Naveen, 2014).

2.3 Composite Fabrication Techniques

There are various techniques for fabricating/processing composite parts such as, open moulding, resin infusion processes and high-volume moulding. However, the determination of a strategy for a specific part, along these lines, will rely on upon the materials, the part outline, and end-utilize or application. The fabrication processes involve some form of moulding tool, to shape the resin and reinforcement during manufacture.

2.3.1 Open Moulding

Hand lay-up and spray-up methods are often used in tandem to reduce labour in open moulding in one-sided moulds at a low-cost. The common processes for making fiberglass composite products are shown in Figure 2.3 and 2.4, respectively. The hand lay-up technique is the simplest method of composite processing. A release film is used to spray into the mould to avoid the sticking of the polymer between the mould surface and final product. A gel coat was applied on the top of the release film and this layer is useful for protection from external environmental agents. Thin plastic sheets are utilized at the top and base of the mould plate to create a smooth plate surface. Reinforcement in the form of woven mats or chopped strand mats are cut as per the mould size and placed at the surface of mould after the Perspex sheet. Then a thermosetting polymer in liquid form is mixed thoroughly in a suitable proportion with a prescribed hardener (curing agent) and poured onto the surface of the mat already placed in the mould. The polymer is uniformly spread with the help of a brush.

The second mat layer is then placed on the polymer surface and a roller is moved with a mild pressure on the mat-polymer layer to remove any trapped air, as well as the present excess polymer. According to Aramide, Atanda, & Olorunniwo (2013), the woven-mat glass fibre can be prepared, fully wetted, using a steel roller under and hand lay-up techniques. The preparation provided 5% to 30% of different fibre content. The operator facilitates the penetration of the resin and removes the air bubbles inside the plies with the hand roller (Cucinotta, Guglielmino, & Sfravara, 2016). The process is repeated for each layer of polymer and mat, until the required layers are stacked. A release gel is sprayed on the inner surface of the top mould plate which is then kept on the stacked layers and the pressure is applied. A primary advantage of the hand lay-up technique is its ability to fabricate large and complex parts with a quick initial start-up. However, the disadvantage is that the process is labour intensive, which can result in high cycle times and a low volume output of parts (Sevkat, Brahimi, & Berri, 2012). The schematic of the hand lay-up is shown in Figure 2.3 (Machado et al., 2018).

The spray lay-up technique can be said to be an extension of the hand lay-up method. Thus, this technique is similar to hand lay-up but, instead, it uses a spray gun to pressurise the resin and for reinforcement, which is in the form of chopped fibres. The schematic of the spray lay-up process is shown in Figure 2.4. The spray lay-up method is used for lower load carrying parts like small boats, bath tubs, fairing of trucks, etc. This method provides a high-volume fraction of reinforcement in composites and there is virtually no part size limitation in this technique.

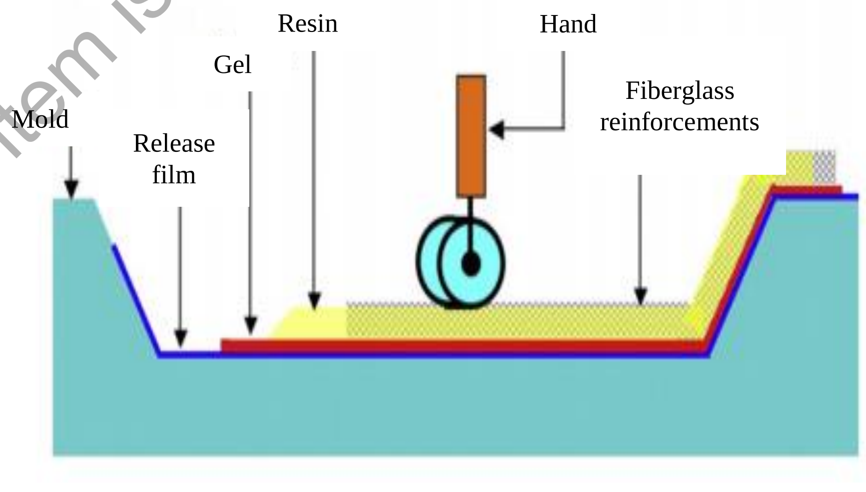


Figure 2.3 Hand lay-up technique (Machado et al., 2018).

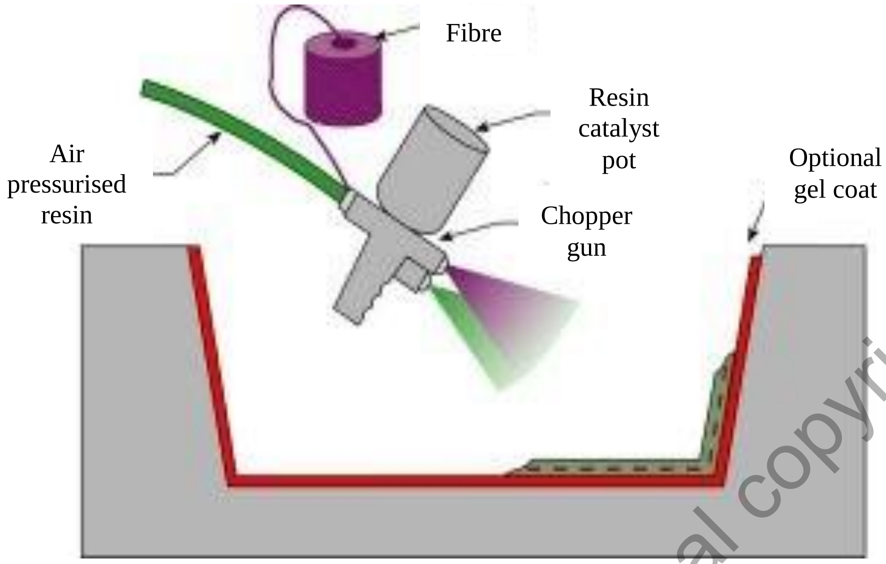


Figure 2.4 Spray lay-up techniques (netcomposites.com).

2.3.2 Vacuum Infusion Processes (VIP)

The interest and demand for faster production rates has continually squeezed the manufacturer to supplant hand lay-up with alternative fabrication processes. The vacuum infusion process (VIP) is one of many closed mould processes that bring environmental advantages where styrene emissions are minimized due to the resin curing in a closed domain. Resin Infusion (RI) processes are one of the common techniques utilized as a part of the industry for substantial composite parts production. The techniques provided a negative pressure and a vacuum is applied before the resin pre-formed into the laminate (Sánchez et al., 2015). There are several types of infusion process which include resin transfer moulding (RTM), resin film infusion (RFI), and the vacuum infusion technique (VIT).

Resin transfer moulding (RTM), also known as liquid moulding, is in the mainstream in both automotive and aerospace manufacture industries of thermoset polymers since it is an eco-friendly process (Ashworth, Rongong, Wilson, & Meredith, 2016). The method of the RTM process is shown in Figure 2.5. RTM requires placement of a fibre pre-form into a closed mould followed by injection of liquid resin under pressure to infiltrate and wet the fibres and prevent void formation. Pitch exchange shaping (RTM) is mainstream in the car and aviation businesses since it is a clean and eco-accommodating shut form to prepare. RTM requires a situation of a fibre pre-form into a shut shape taken after infusion to invade and wet the filaments and avoid void arrangement. The main challenges in the RTM manufacturing process are the design of the pre-form and of the mould, because both structural and manufacturing requirements need to be satisfied at the same time.

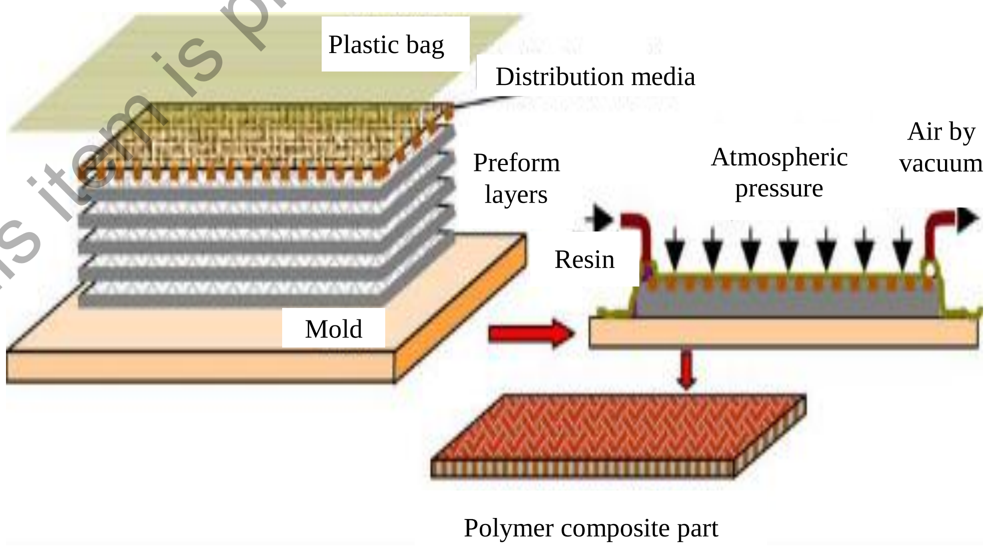


Figure 2.5 Resin transfer moulding (Gokce et al., 2005).

The optimization of the injection scheme of the mould is another challenge, especially in the manufacture of components with complex closed-shell geometry. Principle challenges in the RTM producing procedure are the plan of the pre-form and of the form, on the grounds that both auxiliary and assembling prerequisites should be fulfilled in the meantime. The improvement of the infusion plan of the form is another test, particularly in the make of segments with complex shut shell geometry.

Meanwhile, the schematic diagram of RFI and VIT are illustrated in Figure 2.6 and 2.7, respectively. Both of the fabrication methods use a vacuum pressure to drive resin which is sucked into the laminate by plastic tubing. The installation of in and out flow resin feed lines, vacuum line and bag, valves and pump pressure are important as it will affect the properties of material. Also, the reinforcements are completely impregnated, and all air voids are eliminated in the laminate structure.

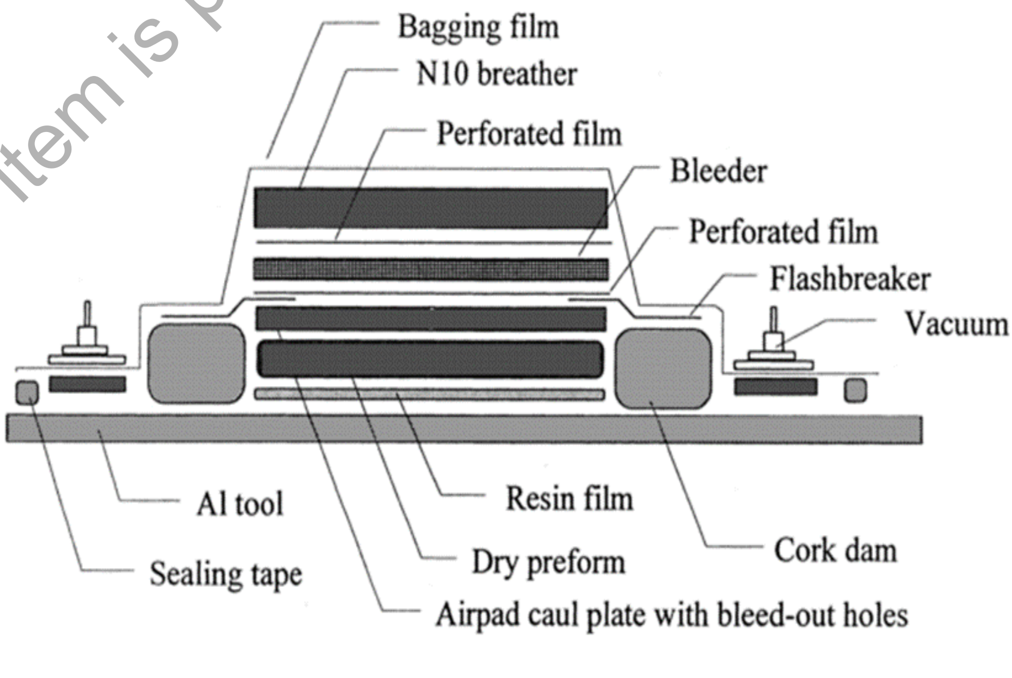


Figure 2.6 Resin film infusion (Qi, Raju, Kruckenberg, & Stanning, 1999).

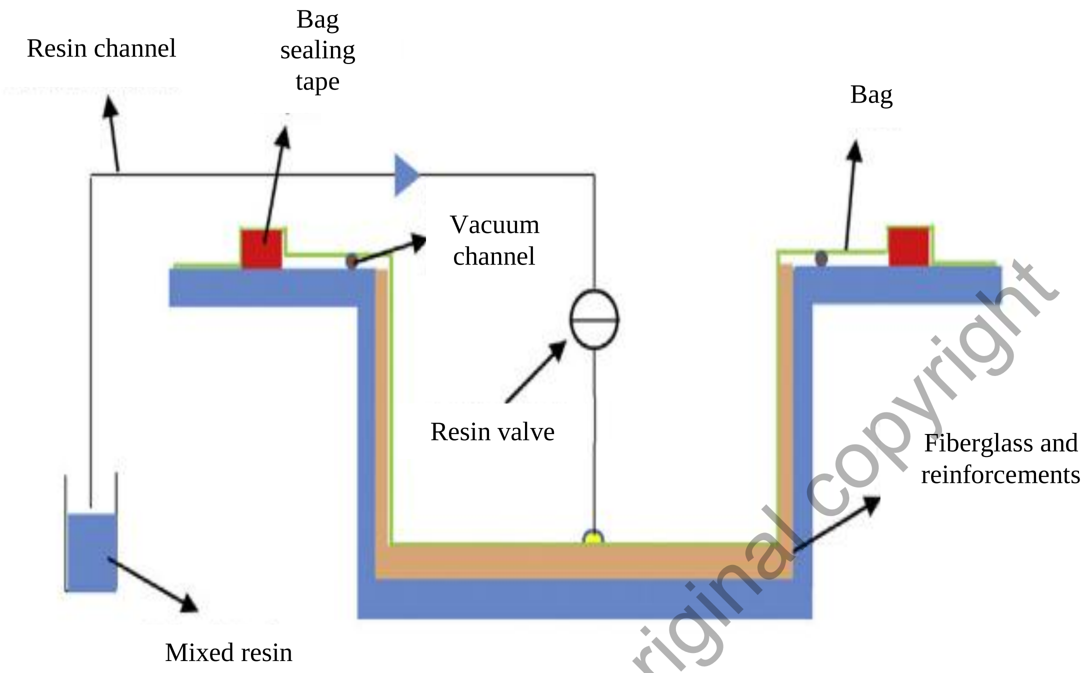


Figure 2.7 Vacuum infusion technique (Cucinotta et al., 2017).

2.4 Design Parameter Influence

The recent developments of joining technology concern the main parameters of surface treatment (da Silva, Carbas, Critchlow, Figueiredo, & Brown, 2009; Osouli-Bostanabad, Tutunchi, & Eskandarzade, 2017), joint configuration, material parameters (da Silva, Carbas, Critchlow, Figueiredo, & Brown, 2009), geometrical parameters (Moya-Sanz, Ivanez, & Garcia-Castillo, 2017), failure mode (Stuparu et al., 2017), and others that effect the performance of metallic and composite materials of bolted, bonded, and hybrid joints. Through the previous research, the effect of adherent materials and bond line length are reviewed in the next section.

2.4.1 Effect of Adherend Materials

Relative to the effect of adherend material SLJs, (Reis, Ferreira, Antunes, & Al, 2011) studied aluminium/high elastic limit steel/carbon composite subjected to tensile shear loading. The highest shear strength of joint was significantly influenced by high adherend material stiffness.

2.4.2 Effect of Overlap Length

There are many factors that affect the durability of joint strength. One of the main factors is to determine the overlap length of the bonding. The obtained results from da Silva, Carbas, Critchlow, Figueiredo, & Brown (2009) in the investigation of adhesive bonded joints between steel adherends and Araldite epoxy adhesive shows that the joint strength increases with increasing overlap length. From this observation, the adhesives properties to be used, either ductile or brittle, are the main criteria that affect the credibility of bond line length. The overlap effect increases as the adherend gets stronger. When the adherend is elastic, the adhesive can develop its full shear strength capacity and make use of the whole overlap. A fairly good agreement of overlap length was observed between the experimental measured and numerically calculated results as investigated by Moya-Sanz, Ivanez, & Garcia-Castillo, (2017). Similarity was obtained through experiment and analytical study of aluminium bonded joints as maximum failure increases with the increasing of overlap length. However, an optimal overlap length was detected at 40 mm and load carry decreased when bond line length exceed optimal overlap (Lucić, Stoić, & Kopač, 2006; Raos, Kozak, & Lucić, 2007). The beneficial