IMPACT RESPONSE OF FIBER METAL LAMINATES AND ALUMINUM COMPOSITE SANDWICH STRUCTURES

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IMPACT RESPONSE OF FIBER METAL LAMINATES AND ALUMINUM COMPOSITE SANDWICH STRUCTURES

by

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LIST OF ABBREVIATIONS

AL	Aluminum
ARALL	Aramid Reinforced Aluminum Laminate
ASTM	American Society for Testing and Materials
BVID	Barely visible impact damage
CALL	Carbon Reinforced Aluminum Laminate
C/C	Carbon fiber-reinforced carbon
CFRP	Carbon fiber-reinforced epoxy matrix
etc	et cetera
EVA	Ethylene-vinyl acetate
FMLs	Fiber metal laminates
FRP	Fiber reinforced plastics
GLARE	Glass Reinforced Aluminum Laminate
HS	High-Strength
IM	Intermediate Modulus
PAN	Polyacrylonitrile
PEEK	Polyethereketone
PMI	Polymethacrylimide
PP	Polypropylene
PPS	Polyphenylenesulfide
PS	Polystyrene
PU	Polyurethane
PVC	Polyvinylchloride
SRPP	Self-reinforced polypropylene

UHMWPE	Ultra-high-molecular-weight polyethylene
UTM	Universal Testing Machine

LIST OF SYMBOLS

E_a	Absorbed energy
E_k	Kinetic energy
E_p	Potential energy
F_c	Contact force
F_{max}	Maximum impact force
g	Acceleration due to gravity, 9.81 m/s^2
h	Drop-height of impactor
m_i	Mass of impactor
t	Time
V_i	Velocity of impactor

TINDAK BALAS HENTAMAN KE ATAS KOMPOSIT STRUKTUR BERAPIT DENGAN KOMPOSIT LAMINAR BERASASKAN GENTIAN DAN LOGAM SERTA ALUMINUM

ABSTRAK

Komposit laminar berasaskan gentian dan logam (FMLs) disediakan dengan melapiskan kepingan aluminum dan prapreg termoplastik bertetulang gentian kaca. Sifat-sifat tegangan FMLs dicirikan dengan mengunakan mesin UTM. Sebelum menjalankan ujian hentaman, struktur berapit yang terdiri daripada lapisan kulit FMLs dengan teras indung madu polypropylene (PP) dikenakan ujian lenturan bagi menentukan sifat-sifat lenturannya. Graf daya melawan masa kemudiannya diplotkan dan dianalisa dari data ujian hentaman tersebut. Perbandingan antara kulit aluminum (AL) dengan FMLs ke atas tindak balas hentaman disiasat dengan menggunakan pelbagai parameter yang peka terhadap hentaman seperti graf daya lawan masa, beban hentaman maksimum, masa sentuhan dan juga jumlah tenaga yang diserap. Didapati bahawa kedua-dua jenis kulit menunjukkan dataran tinggi beban hentaman maksimum pada tenaga hentaman melebihi atau sama dengan 12.36J. Ini memberi pendapat bahawa tenaga kerosakan akibat hentaman bagi kedua-dua jenis kulit dengan teras indung madu PP adalah pada 12.36J. Sampel FMLs menunjukkan kebolehan untuk menyerap tenaga yang lebih tinggi berbanding dengan sampel AL. Didapati bahawa masa sentuhan adalah lebih tinggi bagi sampel yang menunjukkan lenturan pada struktur apit tersebut. Penilaian kerosakan pascahentaman dijalankan bagi membuat perbandingan antara kaedah pengukuran secara optik dengan pengukuran menggunakan C-scan. Keputusan menunjukkan bahawa kaedah C-scan dapat memberi keputusan pengukuran luas kerosakan yang lebih tepat berbanding dengan kaedah optik. Sampel FMLs yang berstruktur plat menunjukkan tenaga hentaman yang lebih tinggi berbanding dengan struktur rasuk. Namun begitu, tenaga diserap oleh struktur rasuk masih kekal tinggi berbanding dengan struktur plat. Luas kawasan kerosakan pascahentaman bagi struktur plat menunjukkan peningkatan lelurus sementara struktur rasuk pula menunjukkan dataran tinggi pada 1200mm^2 disebabkan oleh lenturan struktur tersebut. Perbandingan antara ketebalan teras yang berbeza menunjukkan ketebalan pada 20mm mempunyai nilai tenaga diserap yang paling tinggi berbanding dengan 30mm dan 40mm. Apabila suhu ditingkatkan, daya hentaman maksimum yang direkodkan berkurangan dibawah nilai tenaga hentaman yang sama. Daya hentaman maksimum yang paling rendah adalah pada suhu 50°C manakala yang paling tinggi pula pada -10°C. Namun begitu, tenaga yang diserap oleh struktur apit meningkat apabila suhu dinaikkan. Walaupun luas kawasan kerosakan pada suhu 25°C dan 50°C menunjukkan ukuran yang hampir sama, namun kerosakan adalah lebih teruk pada 50°C disebabkan oleh lenturan pada struktur.

IMPACT RESPONSE OF FIBER METAL LAMINATES AND ALUMINUM COMPOSITE SANDWICH STRUCTURES

ABSTRACT

Fiber metal laminates (FMLs) were prepared by laminating aluminum sheets with glass fiber-reinforced thermoplastic prepreg. The tensile properties of the FMLs were characterized using a Universal Test Machine (UTM). The sandwich structure consists of FMLs skin and polypropylene (PP) honeycomb core is then subjected to flexural test to determine its flexural properties prior to drop-weight impact tests. Force-time history were recorded and analyzed from the impact test. Comparisons between aluminum (AL) skin and FMLs on impact response were investigated using various impact-sensitive parameters such as impact force-time history, maximum impact load, contact duration and total absorbed energy. It was found that both skin types showed plateauing of maximum impact force occurred at impact energy higher than 12.36J. This suggested that the impact damage threshold energy for both skin types with PP honeycomb core sandwich structure are 12.36J. However, FMLs samples showed a better energy absorbing capabilities compared to AL samples. It was found that the contact duration was significantly higher for samples which show global bending on the structure. Post-impact damage evaluations were also carried out by comparing the damage area between optical and C-scan method. As a result, C-scan was able to produce a more accurate measurement of damage area compared to optical method. Plate-like structure of FMLs samples showed higher maximum impact loads when compared to beam-like structure. However, absorbed energy remained higher in the beam-like structure. The post-impact damage area for plate-like structure showed linear increase while beam-like structure shows a plateauing at approximately 1200mm^2 due to the bending of the structure. Comparison also showed that 20mm core thickness sample has the highest amount of absorbed energy compared to 30 and 40mm. By increasing the temperature, maximum impact force recorded has dropped under the same impact energy, being lowest at the 50°C and highest at the -10°C. However, the energy absorbed for the sandwich structure increased when the temperature was raised. The damage area at 25°C and 50°C shows almost the same measurement of damage area, however, it is more likely that the damage is more severe at 50°C due to the bending on the structure.

CHAPTER 1

INTRODUCTION

1.1 Background

In recent years, composite had been gaining more and more interest in application throughout various industries such as transportation, construction, marine, electrical equipment, consumer and aerospace. History of modern composite material can be dated back to 1937 when the first fiberglass started being sold to interested parties around the United States. It was then continued to grow during the event of World War II where more aircrafts were build, resulted in a vast usage of composites in its tooling and also structural build of the aircraft. Many other composite improvements were also developed during that time including sandwich structure. After the war, the composite material were then converted into commercial applications such as fiberglass reinforced polyester boats and eventually made its way into the automobile industry. Some of the products made during the post-war era had become major markets for composites too, these includes application parts, trays, storage containers, and furniture. When carbon fibers and other advance fibers were introduced later, it was leading to tremendous development in aerospace, armor, sport equipment, medical devices and other high performance applications (Strong, 2002).

Until today, the composite market still continues to grow, therefore, research on acquiring the properties of the composite material for each application, either it is in transportation, construction, marine or consumer products is important. One of the important properties in sandwich structure is its impact properties. In general, when sandwich structure is subjected to an impact load, the energy of the impact is used for the elastic deformation of the material and returned back to the system. The energy in excess is then dissipated through several mechanisms, such as skin buckling, delamination in the skins, debonding between the core and skins, core crushing and deformation to the structure (Torre and Kenny, 2000). It is important that we study the performance of the material as well as its damage mechanism.

The most common materials used as skins material for sandwich structures are fiber reinforced plastics (FRP) and metal alloys mainly aluminum (AL). However, metal-composite systems such as fiber-metal laminates (FMLs) based on layers of FRP and metal had gained interest from a wide range of engineering sectors due to its superior impact and fatigue properties compared to conventional material systems (Vlot and Gunnink, 2001, Vlot et al., 1997). At present, systems such as GLARE (glass fiber/aluminum) are available and widely used in aircraft body constructions. Besides GLARE, other configuration such as ARALL (aramid fiber/aluminum) and CALL (carbon fiber/aluminum) are also available. However these are epoxy-based fiber-metal laminates, which comes with a number of limitations such as long processing cycles and low interlaminar fracture toughness. To overcome these problems, several FMLs based on thermoplastic matrices have been developed and tested (Abdullah and Cantwell, 2006; Reyes and Cantwell, 2000; Reyes, 2010). As a result, glass fiber reinforced polypropylene FMLs had shown good impact resistance to both high and low velocity impact (Reyes and Cantwell, 2000).

Cores are the main component in load carrying of sandwich structure. There are various studies carried out by researchers using different cores, such as polymeric foam (Anderson and Madenci, 2000, Muzzy et al., 2001, Hazizan and Cantwell, 2002, Schubel et al., 2007, Imielinska et al., 2008), Nomex honeycomb (Herup and Palazotto, 1997, Anderson and Madenci, 2000, Meo et al., 2005, Park et al., 2008), AL honeycomb (Besant et al., 2001, Hazizan and Cantwell, 2003, Foo et al., 2008) and etc. In most of the cases, different material will bring different impact response to the whole sandwich structure, so in order to obtain a sandwich structure with better impact properties, the energy absorbing behavior of the core must be good.

1.2 Problem statement

Composite materials are gaining interest in various applications compared to conventional materials such as metal, ceramics or polymer. This is because composites are noted for providing weight savings in structural and impact applications compared to traditional materials (Muzzy et al., 2001). However, with the increasing demand of cheaper composite materials to archive desired properties, it is important that the cost of the composites are kept at minimum without sacrificing its weight saving and impact properties.

The most common core used in sandwich structure is AL honeycomb due to its high strength to weight ratios and its low price. Despite that, AL honeycomb has to be used with caution in some applications, such as large marine structures, because of the potential corrosion problems in a salt-water environment. Nomex® honeycomb on the other hand is becoming increasingly popular in high-performance non-aerospace components due to its high mechanical properties, low density and good long-term stability. However, it is considerably much more expensive compared to other core materials (Guide to composite, 2011).

In this research, PP honeycomb core were used to replace common AL and Nomex® honeycomb cores to study its impact response as a composite sandwich structure. Reason being that it is moisture resistant compared to AL honeycomb cores and cost much lesser compared to Nomex® honeycomb cores. The other reason why PP honeycomb is being chosen is because they can be processed easily by thermoforming as well as being able to be recycled.

1.3 Objectives of Research

The main objective of this research is to study the effect of low-velocity impact on sandwich structure with polypropylene honeycomb core. With this main objective, the following studies were conducted:

1. To investigate the effect of two different skin types (FMLs and AL) on the low-velocity impact response of the sandwich structure.
2. To investigate the low-velocity impact response on two different sandwich structure’s dimension (beam and plate).
3. To investigate the influence of sandwich’s core thickness on the low-velocity impact response of FMLs/PP honeycomb sandwich structure.
4. To investigate the temperature effects on low-velocity impact response of FMLs/PP honeycomb sandwich structure.

1.4 Scope of Study

The sandwich structure used in this research consists of a FMLs skin and PP honeycomb as the core. The research covers study on the impact response of this composite material in comparison with AL skin with PP honeycomb core and also studies the effect of geometrical, core thickness and temperature on its impact properties. This project covers:

(a) Fabrication of FMLs skin and FMLs/PP honeycomb core sandwich structure

The FMLs were produced by stacking layers of AL with glass fiber reinforced thermoplastic pre-preg in a metal frame mold. It is then cut into required sizes before being bonded onto the honeycomb core.

(b) Mechanical testing

Tensile and flexural testing was carried out using Universal Testing Machine (UTM) according to ASTM D3039 and ASTM C393-00. An instrumented drop-weight impact machine is used to carry the impact test.

(c) Temperature test

A temperature chamber is used to condition the specimen prior to the impact. A thermostat is used to determine the structure temperature to make sure it is in the required temperature range before testing.

(d) Calculate absorbed energy of the structure

Absorbed energy is calculated based on kinetic energy loss of the impactor using a series of equations by acquired data from the drop weight impact test.

(e) Post-impact damage observation

Optical microscope and non-destructive C-scan is used to evaluate the damage's magnitude and its mechanism after the impact.

1.5 Thesis Organization

This thesis consists of five chapters. The first chapter gives a brief background on composite materials, problem statement, research objectives and the scope of this study. Chapter two is on the literature review on fiber reinforced composite and sandwich structures; the studies behind impact response of sandwich structure and the effects of different parameters on impact response of composite materials/sandwich structure by various researchers. The third chapter provides a detailed methodology of this research, includes preparation for the materials as well as work on the instrumented drop weight impact test. Chapter four is focusing on the analysis and discussion of the research findings. Last but not least the final chapter, chapter five provides the conclusion and suggestions for future work for this study.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Composite material or composite can be defined as two or more material combined together, which retains its identity in the finished component (Whelan, 1994). There are many types of composite, such as fiber reinforced composite, laminar composite, sandwich composite, particulate composite, smart composite and, etc. Different type of composite usually brings us different properties depending on the need of its application. Jacobs and Kilduff (2005) stated that the composite is designed to exhibit the best properties or qualities of its constituents or some properties possessed by neither. This leads to the application of composite materials ranging from engineering and aerospace structures to medical and surgery device replacing conventional materials. Some advantages composite materials offer is excellent weight/mechanical strength ratio, corrosion or chemical resistant, good energy absorption, cost reduction and easy to design (Jacobs and Kilduff, 2005).

2.2 Fiber Reinforced Composite

A fiber reinforced composite is a material system made primarily of varying amounts of a particular fiber reinforcement embedded in a protective material called a matrix (Jacobs and Kilduff, 2005). Generally, fibers are stronger and stiffer compared to the matrix. There are various types of fibers, which are available nowadays such as glass, carbon, boron, aramid and polyethylene. Other types of fibers can be in the form of whiskers, particulates or flakes. Each fiber has unique properties and somehow offers distinctive features when used in combination with the matrix (Hazizan, 2002a). There are mainly three types of matrices used in producing reinforced composite, which are polymers, metals and ceramics. The function of a matrix is to support and protect the fibers, the principal load-carrying agent, and to provide a means of distributing the load among and between the fibers without itself fracturing (Jacobs and Kilduff, 2005). Typically, the matrix has a lower density, stiffness (modulus), and strength than the reinforcing fiber material, but when the two are combined, it produces high strength and stiffness while possessing a relatively low density. The properties of the composite can be controlled by varying the fiber orientation, fiber volume fraction and also the fiber dimension (Hazizan, 2002a). Another factor which can decide the composite properties is the interphase region between the fiber and matrix. Usually, a coupling agent or bonding agent which provides a flexible layer at the interphase is used.

2.2.1 Fibers

Fibers are the main source of strength in the fiber reinforced composite material. The orientation and loading of fibers plays an important part in contributing to the composites' final properties. There are many types of fibers available currently on the market, the most common ones are, glass fibers, carbon fibers and Kevlar aramid fibers. Figure 2.1 shows the comparative cost of various types of fibers in the market.

2.2.1.1 Glass Fiber

The standard glass fiber used in glass-fiber reinforced composite material is E-glass, a borosilicate type of glass. E-glass is the first type of glass developed for use as continuous fibers. The designation E stands for electrical because E-glass is an excellent electrical insulator in addition to having high strength and a reasonable modulus. The other type of developed glass includes C and S type. C stands for corrosion because C-glass has a better resistance to chemical corrosion while S stands for the high silica content that makes the S-glass able to withstand higher temperatures than other glasses. S-glass is developed for high-tensile-strength application in the aerospace industry. It is about one-third stronger than E-glass thus its price is more expensive compared to E-glass (Chawla, 1998). Typical composition of several common types of glass fibers are shown in table 2.1.

Table 2.1: Composition in E/C/S – glass fibers (Chawla, 1998).

Composition	E-Glass	C-Glass	S-Glass
SiO_2	55.2	65.0	65.0
Al_2O_3	8.0	4.0	25.0
CaO	18.7	14.0	-
MgO	4.6	3.0	10.0
Na_2O	0.3	8.5	0.3
K_2O	0.2	-	-
B_2O_3	7.3	5.0	-

2.2.1.2 Carbon Fiber

Carbon fibers are being used in a variety of applications in the aerospace and sporting goods industries. Although the names “carbon” and “graphite” are used interchangeably when describing the fibers, carbon fibers are usually 93-95% carbon, and graphite fibers are more than 95% carbon. Carbon/matrix composites have a high strength-to-weight and stiffness-to-weight ratios which made them stronger and stiffer than equivalent steel parts at less than half the weight (Niu, 1993).

There are three categories of carbon fibers classified by Niu (1993): polyacrylonitrile (PAN), pitch, and rayon-based fibers. PAN-based fibers offer the highest strength and balance of mechanical properties in composites. These fibers are generally selected for their high strength and efficient retention properties. The pitch-based fibers are not as strong as the PAN fibers, however, they are easy to process to a higher modulus making them attractive for stiffness-critical applications. The third type is the rayon-based, which does not have high mechanical properties available as in PAN and pitch-based fibers. These fibers have recently been used almost exclusively as reinforcements in C/C composites for rocket nozzle throats, aircraft brakes, nose cones and ablative applications.

2.2.1.3 Kevlar Aramid Fibers

Aramid fiber is a generic term for a class of synthetic organic fibers called aromatic polyamide fibers. Commercial names of aramid fiber include Kevlar and Nomex, which manufactured by Du Pont company (Chawla, 1998). The Kevlar fiber has been used for structural applications since the early 1970s, combining extremely high toughness and energy-absorbing capacity, as well as tensile strength and stiffness with low density. However, the low compressive strength is one of the weaknesses in Kevlar fibers (Niu, 1993). There are various grades for Kevlar, with Kevlar 29 and Kevlar 49 being the most commons ones. Kevlar 29 provides high toughness with a tensile strength of about 3.4 GPa to be used where resistance to stretch and penetrations are important. Kevlar 49 has a high-tensile-strength modulus of 130 GPa and is used with structural composites (Jacobs and Kilduff, 2005).

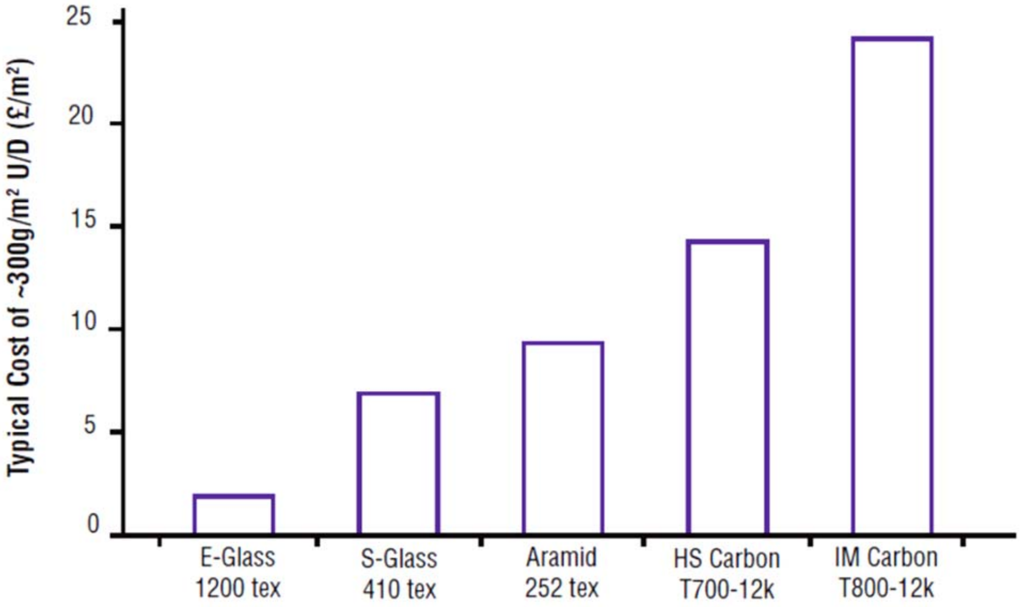

Figure 2.1: Comparative fiber cost of various types of fibers (Guide to composite, 2011).

2.2.2 Matrices

The purpose of the matrix is to bind the reinforcement (fiber) together and to transfer the load to and between fibers, and protects the fibers from environmental moisture and chemical corrosion or oxidation. It also keeps the reinforcing fibers in the proper orientation so that they can carry the intended loads, provides resistant to crack propagation and carry interlaminar shear. The use of any matrix must be chemically compatible with the fibers and should have complementary mechanical properties (Niu, 1993).

The commonly used polymeric matrices are broadly divided into the categories of thermoset and thermoplastic. Thermosets matrix systems have been dominating the composite industry because of their reactive nature (Niu, 1993). Some of the common thermosets are epoxy, polyester, phenolics, bismaleimide and polyimide. However, in recent years, thermoplastics are gaining its interest due to the faster processing cycles, infinite shelf life and recyclable properties. Popular thermoplastic resins include polyethylene, polycarbonates, polyphenylene sulfide (PPS), polyethereketone (PEEK) and PP.

2.2.2.1 Thermoset Resins

Thermosetting polymers consist of liquid resin is transformed into a solid through a chemical cross-linking process called curing. This usually happens when the composite is being formed. Curing can be done at room temperature but the common practice is to heat the resin at predetermined times to achieve an optimum density of cross linking. A high temperature post-curing is then carried out to reduce any further curing and any following changes in properties during service life. One of the properties that distinguishes between thermoset and thermoplastic resin is that thermoset do not soften or melt upon heating (Hull and Clyne, 1996). Epoxy systems are the major composite material for low-temperature application. They can provide outstanding chemical resistance, superior adhesion to fibers, good hot/wet performance and excellent dimensional stability. However, epoxies have a tendency to absorb moisture, and this absorbed moisture can lead to a decrease in mechanical properties, especially at elevated temperatures. Another widely used thermosetting resin is polyester. Polyester can be cured at room temperature and atmospheric pressure, or at a temperature up to 177°C and under higher pressure. It offers a balance of low-cost and ease of handling, along with good mechanical and electrical properties, chemical resistant properties and dimensional stability (Niu, 1993).

2.2.2.2 Thermoplastic Resins

Thermoplastic are characterized by linear chain molecules and can be repeatedly melted or reprocessed. The degree of crystallinity depends on the cool-down time of the thermoplastic because it needs time to get organized in orderly pattern of the crystalline state. Linear molecules in thermoplastics result in higher strain-to-failure values compared to thermosets. Thermoplastic matrix materials can have failure strains ranging from 30 to 100%, while the thermosets typically range from 1 to 3%. The large range of failure strains in thermoplastics stems from the variations in the amount of crystallinity (Chawla, 1998). One of the thermoplastic resins, PEEK is an attractive matrix material due to its toughness and impact properties. Its fracture toughness is 50-100 times higher than epoxies. Another advantage of PEEK is its low-water absorption, which is less than 0.5% at 23^0C compared to 4-5% for conventional aerospace epoxies (Mallick, 2008). Many thermoplastics show good resistance to absorption of water, although this is not true for the nylon (see table 2.2). Most of the thermoplastic undergoes large deformation before final fracture, and their mechanical properties are strongly dependent on the temperature and the strain rate (Hull and Clyne, 1996).

Table 2.2: Comparison between properties of thermosets and thermoplastics related to dimensional and environmental stability (Hull and Clyne, 1996).

Property	Thermosets		Thermoplastics		
	epoxy resins	polyester resins	Nylon 6.6	polypropylene	PEEK
Melting temperature (°C)	-	-	265	164	334
Distortion temperature (°C)	50-200	50-110	120-150	80-120	150-200
Shrinkage on curing (%)	1-2	4-8	-	-	-
Water absorption (24h @ 20°C)(%)	0.1-0.4	0.1-0.3	1.3	0.03	0.1
Chemical resistance	Good, attacked by strong acids	Attacked by strong acids and alkalis	Good, attacked by strong acids	Excellent	Excellent

2.2.3 Interphase Region

Interphase or interface between reinforcement and a matrix can be defined as the bounding surface between the two crosses where a discontinuity occurs (Chawla, 1998). This region plays a major role in determining the mechanical and physical properties of the composite. In any event, an interface is the region through which material parameters, such as concentration of an element, crystal structure, atomic registry, elastic modulus, density, coefficient of thermal expansion and etc. change from one side to another. It is important that the fibers are not to be weakened by flaws because of an adverse interfacial reaction, and the applied load should be effectively transferred from the matrix to the fibers via the interface.

It is not always the goal to maximize the bond strength between the matrix and reinforcement. This is because when the interface is as strong as or stronger than the higher-strength component of the composite (reinforcement), the interface will have the lowest strain to failure. The composite will fail when any cracking occurs at a weak spot along the brittle interface. A catastrophic failure will then occur, and we would have a composite with very low toughness. It is important that we have an interphase with an optimum interfacial bond strength, which will result in a composite with an enhanced toughness, but without a severe penalty on the strength parameters (Chawla, 1998).

In order to improve the strength of the bond or gain optimal bond strength, the fibers are usually treated. Glass fibers are treated with chemical coupling agents such as silanes, while carbon fiber will undergoes an oxidative process to produce acidic functional groups on the fiber surface to improve bonding with the matrix

(Hazizan, 2002a). Without a coupling agent or any treatment, stress transfer between fiber and matrix is possible owning to a mechanical interlocking that arises because of polymerization shrinkage of the matrix as well as thermal contraction of the matrix from the curing temperature. At elevated temperatures or high applied loads, the difference in expansion of fibers and matrix may relieve this mechanical interlocking, resulting in reduced mechanical properties (Chawla, 1998).

2.3 Sandwich Composite

Sandwich composite can also be classified as a laminar composite. Their outer surfaces, or facings, are made of some material higher in density than the inner material, or the core, which supports the facings. Primary purpose of sandwich composite is the achievement of high bending rigidity with less weight, specifically a high strength-to-weight ratio or specific strength. The high density facings carry most of the applied load, particularly the bending loads while the low-density core allows the facings to be placed at a relatively large distance from the neutral plane to produce a large section modulus. The core carries the shear stresses.

Based on history, sandwich construction was first used in the Mosquito night bomber of World War II, which employed plywood sandwich construction. In 1943, Wright Patterson Air Force Base designed and fabricated the Vultee BT-15 fuselage using fiberglass-reinforced polyester as the face material using both a glass-fabric honeycomb and a balsa core. Since then the sandwich era began to grow until now, where it can be found almost anywhere, from the space shuttle to satellite, boats and yachts, trains, busses and also bridges and wind energy systems (Vinson, 2005).

2.3.1 Skin Materials

In sandwich construction, the skin materials must be thin, dense and strong. It is assumed that the skin material takes most of the bending load. Basically, any structural material in the form of thin flat sheet can be used as skin material (Allen, 1993). Most commonly used skin materials can generally be grouped into two categories, which is metallic and non-metallic.

Metallic group of skin materials consists of stainless steel, aluminum and titanium alloys, while the non-metallic group consists of wood derivative products such as plywood and fiber reinforced composite. Fiber reinforced materials are capable of providing strength properties equal or higher than the metals. However, its stiffness properties are often slightly lower than metals (Hazizan, 2002a).

There's been an emerging new kind of hybrid material called fiber metal laminates (FMLs). It consists of metal layers alternating with layers of fiber-reinforced epoxy. These types of skin are being widely used in aerospace industry because of its excellent damage tolerance properties and fatigue resistance. However, it is also quite expensive compared to other normal fiber-reinforced plastics or metals.

2.3.1.1 Fiber Metal Laminates (FMLs)

FMLs is a new type of material developed at the Delft University of Technology. A FMLs consists of sheets of aluminum are alternated with sheets of fiber-reinforced composites. The first FMLs was Arall, a combination of aluminum and aramid/epoxy. In the beginning, the studies for the application of Arall focused on wing structures. The material was promising at first, but when it was under loading conditions that resembled those of the fuselage of an aircraft, the aramid fibers around a fatigue crack would break. With the aramid broken, crack growth would no longer be slowed down. So it was unsuitable as fuselage material.

In the 1980s, Delft began developing a glass/epoxy FMLs called GLARE. GLARE was intended to be an alternative to aluminum in aircraft structures. Early research showed it had benefits over both aluminum and fiberglass composites, especially in fatigue and impact. Development continued over a number of years, and the commercial breakthrough came when Airbus decided to use the material on the A380 (Volt and Gunnink, 2001).

2.3.2 Core Materials

The most common core materials can be divided into four general types; balsa wood, foams, honeycomb and corrugated materials. In each category, there are several types of materials which are quite unique in properties. Each of them has its own advantages and disadvantages, which may be the factor to be considered for various applications. The nature of the core is important in determining the crush strength of the sandwich structure.

2.3.2.1 Balsa Wood

Balsa was the first material being used as cores in load carrying sandwich structure. It was used in various applications such as the construction of cruising yachts and also snow skis. When under the microscope, balsa can be seen as a high-aspect-ratio closed–cell structure. Balsa is also very sensitive to humidity and that is why it is commonly utilized in its “end-grain” shape. They contain highly oriented grains parallel to the direction of growth; therefore, their properties are superior in the direction of growth but poor in other directions. This is why balsa wood is usually cut into cubic pieces and bonded together edge wise so that a block is produced where the fiber direction is located perpendicular to the plane of the block. The drawback of this is that all the small blocks have different densities, and the design limit must be taken from the piece having the lowest properties (Hazizan, 2002a).

2.3.2.2 Foams

Structural foam cores are manufactured from a number of thermoset and thermoplastic polymers such as polyvinyl chloride (PVC), polyurethane (PU), polystyrene (PS), and polymethacrylimide (PMI). Foams (except PUs) are produced by mixing liquid polymers and blowing agents, then pouring the mixture into metal molds and allowing a partial cure under high heat and pressure. The result is a rubbery mass, called an amoeba or an embryo, after demolded, it is placed in a second mold and heated again (with hot water or steam) in an expansion chamber, which activates the blowing agent and controls the gas expansion pressure. The result is a thick block of foam, containing closed, gas-filled bubbles or cells. Foams can be manufactured in densities ranging from 30 kg/m^3 up to 300 kg/m^3 by varying the ratio of the polymer ingredients to blowing agents and adjusting gas pressure. Polyurethane foam, a thermoset that generates gas when an isocyanate is mixed with a polyol, is either made in batches ("bun casting") or a continuous foaming process (Black, 2003).

Although polymeric foam does not offer similar stiffness to weight ratios to honeycomb cores, they offer other advantages such as lower cost and ease of manufacturing. It also has properties like good thermal insulation, acoustical damping and buoyancy on water (Hazizan, 2002a).

2.3.2.3 Honeycomb Cores

Honeycomb consists of an array of open cell, formed from very thin sheets of materials attach to each other. Usually, the cells are hexagons, but there are other cell configurations such as square cell, flex-core, under or over-expanded cell and reinforced hexagon (Bitzer, 1997). The common materials currently in use are divided into metallic and non-metallic materials. Metallic materials include: aluminum, stainless steel and titanium while nonmetallic materials are fiberglass, Nomex, Kraft paper and polymeric materials.

Thermoplastics such as polypropylene provide a greater strength-to-weight ratio than traditional polyaramid or aluminum honeycombs. The cells of the PP honeycomb are essentially circular rather than hexagonal and are fused together rather than glued. The recyclable honeycomb can be thermoformed and cut to shape easily. It has energy-absorbing and sound and vibration damping properties, and it is resistant to fungus, chemicals and moisture (PP honeycomb, 2010).

2.3.3 Adhesive

Adhesive plays an important part in joining the skin and core together during fabrication of a sandwich structure. The primary function of the adhesive is to provide sufficient bond strength to hold the skin and core materials well. The adhesive must be strong to transfer the load from side forces onto the face sheets and to resist debonding with the surface of the core. The adhesive must also be thick enough to give a good bond over the entire surface but not so thick that it becomes a point of failure. The adhesive is, after all, a non-reinforced resin layer that would have less strength than the resin-fiber laminate (Strong, 2003).

In general, the most widely used adhesive system is based on epoxy resins. This is due to the stability of the resin at room temperature and also the fact that curing can be done at room temperature (Hazizan, 2002a).

2.4 Prepreg Materials

Prepregs are rolls of uncured composite materials in which the fibers have been preimpregnated with the resin. To make prepreg, firstly the fibers are drawn from continuous fiber spools or reels and directed into a fiber guide that flattens and aligns the fibers onto a belt, thus forming a web or sheet of fibers. The fibers are then controlled at a precise thickness, and each of the fiber bundles must be oriented so that each touches the neighboring bundle without overlapping and without a gap between them. After being properly positioned, the fibers are mated with two backing sheets (top and bottom) which have been coated with resin to the proper thickness. The backing sheets are usually paper or polyethylene sheet and may have been previously coated with a release material to ensure that the prepreg will release cleanly and easily when it is used. Before being coated with the backing material, the resin would have been mixed with the proper amount of catalyst, accelerator, and any other materials, such as filler or pigments, which would normally be mixed into the resin before cure.

The sandwich of backing materials, resin, and fibers are then compacted, usually with several sets of rollers. The sandwich is heated to a precise temperature and for a certain time to cause the resin to slightly cure and therefore, slightly solidify through crosslinking. The sheet of material is then trimmed and wound up as prepreg material. Because the resin has already been initiated, the prepreg roll must be kept cool (refrigerated) to prevent premature curing.

All the common reinforcement fibers such as fiberglass, carbon fibers, aramids and UHMWPE are used in making prepregs. Most of the typical thermoset resins and some thermoplastic resins are commonly used in prepreg materials. The most common resin is epoxy, probably because the major markets for prepreg materials are in aerospace, sporting goods and electrical circuit boards where the excellent mechanical, chemical, and physical properties of epoxies are needed. Thermoplastics, which are not as popular as thermosets, are used for their toughness, solvent resistance, and some other specialized purpose (Strong, 2008).

2.5 Type of Impact Loading

Impact usually plays an important part in a composite structure or material. This is because it can fail in a wide variety of modes and contain barely visible impact damage (BVID) which severely reduces the structural integrity of the component. Since the impact damage often goes undetectable during visual inspection, the response of composite and sandwich structures under impact loading becomes important and needs to be studied. Generally, impacts are categorized into either low or high velocity, but there has been a dispute between authors, who disagree on their definition.

2.5.1 Low-velocity Impact

Richardson and Wisheart (1996) summarized that few authors classified low-velocity impact as events, which can be treated as quasi-static, varies from one to tens of ms^{-1} depending on target's stiffness, material properties and the impactor’s mass and stiffness. While some defined low-velocity as up to $10ms^{-1}$, by considering test techniques which are generally used in simulating the impact event. Few researchers have also suggested that the type of impact can be classed according to the damage occurred, where low-velocity is characterized by delamination-type damage, and high velocity by penetration or perforation-type damage. During low velocity impact conditions, the contact duration should be sufficiently long for the entire structure to respond to the impact event.

2.5.2 High-velocity Impact

High-velocity impact response is dominated by stress wave propagation through the material, in which the structure does not have time to respond, leading to a much localized damage. The boundary condition effects can be ignored because the impact event is over before the stress waves reach the edge of the structure (Richardson and Wisheart, 1996). The main damages that usually associated with high-velocity impact are penetration and perforation of the target. Penetration can occur when the fiber failure reaches a critical extent, enabling the impactor to completely penetrate the material.

2.6 Impact Test

To simulate the impact by a foreign object, there have been a number of test procedures being suggested; such as using the gas gun, drop weight and pendulum. Different test may emulate dissimilar condition to be experienced by the actual structure; therefore, it is important to select the appropriate test procedure. For example, testing with a small high-velocity projectile using the gas gun can emulate the damage caused by debris flying from the runway during an aircraft take-off and landing. Another situation is the impact of a composite structure when tools are accidentally dropped on the structure. This situation is usually emulated using a drop weight tester with a larger projectile at low-velocity. Pendulum type testers are also used to generate low-velocity impacts (Abrate, 1998).