# EFFECT OF FIBRE ORIENTATION ON THE MECHANICAL PROPERTIES OF SANDWICH COMPOSITE MATERIAL

**By**

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**ENDORSEMENT**

I, Mukhlisin Bin Aminuddin hereby declare that all corrections and comments made by the supervisor and examiner have been taken consideration and rectified accordingly.

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## DECLARATION

This thesis is the result of my own investigation, except where otherwise stated and has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any other degree.

(Signature of Student)

Date:

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# EFFECT OF FIBRE ORIENTATION ON THE MECHANICAL PROPERTIES OF SANDWICH COMPOSITE MATERIAL


## ABSTRACT

In composites manufacturing process, fibre orientation of the composites is one of the most important factor in composites manufacturing that needs to be taken account into as any misalign angle present in the fibre lay-up could lead to the decrease of the composites mechanical performances. The properties of the sandwich composites materials can be affected by every aspect especially during the manufacturing process of the composite. This study shows the effect of fibre orientation on the mechanical properties of a sandwich composite material. The manufacturing process used to manufacture the composites is a wet hand lay-up process. The orientation of the glass fibre is set to 0°, 9° and 15°. The effect of the fibre orientation is analysed by performing the mechanical test on the composites. Test to be performed is set to be compression test and bending test.  Theoretical results shows that the mechanical performance of the composite decrease as the offset angle of the glass fibre increases. Several specimens with different fibre orientation is manufacture to analyse and proof the theoretical results and the analysis shows that each fibre offset angle can affect the mechanical performance of the sandwich composite. Therefore, it can concluded that fibre orientation significantly effects the performances of the sandwich composites as even a small misalign angle could lead to a significant decrease of the composites mechanical performance.

**PENGARUH ORIENTASI FIBER TERHADAP SIFAT-SIFAT MEKANIK BAHAN KOMPOSIT SANDWICH**


## ABSTRAK

Dalam proses pembuatan komposit, orientasi fiber adalah salah satu faktor yang amat penting yang perlu diambil kira. Kewujudan sudut yang tidak sama di dalam proses fiber boleh menyebabkan kemerosotan prestasi mekanikal komposit tersebut. Sifat-sifat sandwich komposit boleh berubah dari segi pelbagai aspek terutamanya semasa proses pembuatan komposit tersebut. Kajian ini menunjukkan pengaruh orientasi fiber terhadap sifat mekanikal komposit sandwich. Proses pembuatan yang digunakan untuk membuat komposit sandwich adalah proses 'wet hand lay-up'. Orientasi fiber telah ditetapkan kepada 0°, 9° dan 15°. Kesan orientasi fiber ini dikaji dengan menjalankan ujian mekanikal terhadap komposit. Ujian yang dijalankan adalah ujian mampatan dan ujian lenturan. Hasil teoritis menunjukkan penurunan prestasi mekanikal komposit apabila sudut orientasi fiber meningkat. Beberapa spesimen dengan sudut orientasi fiber yang berbeza dibuat untuk mengkaji dan membuktikan hasil teoritis dan hasil kajian menunjukkan setiap kenaikkan sudut mempengaruhi prestasi mekanikal komposit sandwich. Daripada kajian ini, terbukti bahawa orieantasi fiber memainkan peranan yang besar dalam menentukan prestasi komposit sandwich. Ini kerana, walaupun sudut fiber yang lari sangat kecil, prestasi komposit menurun dan perbezaannya sangat ketara.

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| | | |
|---|---|---|
| $M_c$ | : | Mass of composites |
| $M_f$ | : | Mass of fibre |
| $M_m$ | : | Mass of matrix |
| $v_f$ | : | Volume of fibre |
| $\rho_f$ | : | Density of fibre |
| $v_m$ | : | Volume of matrix |
| $\rho_m$ | : | Density of matrix |
| $v_c$ | : | Volume of composites |
| $\rho_c$ | : | Density of composites |
| $V_f$ | : | Fibre volume fraction |
| $V_m$ | : | Matrix volume fraction |
| $\sigma_c$ | : | Compressive stress |
| F | : | Applied load |
| $A_0$ | : | Initial area of the specimen |
| $\varepsilon_c$ | : | Compressive strain |
| $l_0$ | : | Initial extension of the specimen |
| l | : | Extension of the specimen |
| L | : | Length of the specimen |
| b | : | Width of the specimen |
| d | : | Depth or thickness of the specimen |
| D | : | Deflection of the specimen |
| m | : | Slope value at the initial straight line of the stress-strain curve |
| $\sigma_f$ | : | Flexural stress |
| $\varepsilon_f$ | : | Flexural strain |
| $E_f$ | : | Flexural modulus |

# CHAPTER 1

# INTRODUCTION

## 1.1 General overview of sandwich composite

The usage and application of composite material have been widely recognised by various kinds of industry such as aerospace, marine, automotive and even sports. The popularity of the composite which are still increasing nowadays is due to its high performance properties which are stronger, but lighter compare to the traditional material. Composite is a combination of two or more material that has different physical and chemical properties to produce a material with better characteristics from its individual component. There are two main categories of constituent material which is matrix and reinforcement. Matrix supports the reinforcement by surrounding it to maintain their relative positions. The reinforcements has a special mechanical and physical properties that can enhance the matrix properties once they are combine.

In manufacturing composites, there are many aspects that needs to be taken account into to make sure that the required properties of the composites can be achieve. The aspects include the physical conditions of the constituents needed to manufacture the composites such as the fibre orientation, type of matrix, and many more. These physical conditions affects greatly to the performance of the composites to be manufacture. Therefore, it is important to make sure that all the constituents required are in good condition before and during the manufacturing process.

The history of composite materials goes way back even before centuries. The early application of composite materials was to form bricks for building or shelter which were made out of straws and muds. Since then, many developments have been made to enhance and increase the properties of composites which also increasing the application of composites material in daily life routine. In the application of engineering industry, complex shape is necessary to meets the engineering requirement. Thus, composite materials is widely used as it can be shape to our needs. With the rapid increase of technologies, researches and developments, more advance composite materials have been produced and its usage is expanding still.

## 1.2 Sandwich structured composites

One of the advance composite material is a sandwich composite. Sandwich composite is a composite material that consists of two thin skins with high stiffness attached to both side of a thick core which is a low strength but high bending stiffness material. The most commonly used core materials are a cell structured foams such as polystyrene, balsa and honeycomb. Metal foam can also be used as core materials. As for the skin materials, laminates of glass or carbon fibre-reinforced thermoplastics or mainly thermoset polymers are widely used. Sandwich composites can be manufactured as a panel with the desired shape. Sandwich panels are widely used in aircraft manufacturing, where mechanical performance and weight-saving are essential. Other applications of sandwich panels are high performance automobiles, boats and wind turbines. The strength of the sandwich composite material depends mainly on two factors; the outer skins and the adhesive bond between the core and the skin of the sandwich composite material.

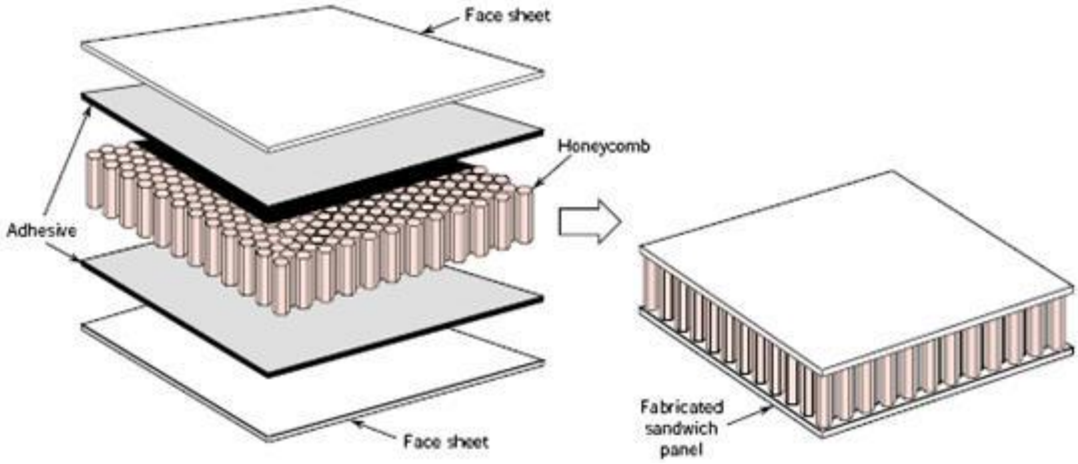


Figure 1.1: Sandwich structured composite

## 1.3 Effects of fibre orientation on sandwich composites

The mechanical properties of the sandwich composites is not solely depends on materials itself. Manufacturing method can also affect the mechanical properties as it implies on the final product of the composites been manufactured. Every factor is to be taken into account during the manufacturing process in order to produce a composites that have a satisfactory value for all their parameters and properties. One of the most important factor in manufacturing the composites is the fibre orientation. Fibre orientation affects greatly on the performance of the composites since the fibre provide stiffness to the composites according to the direction of the fibre. Even a slightest misalignment of the fibre during the process could lead to several changes in the mechanical properties of the composites. By improving the conditions of the production procedure, more effective and advanced manufacturing method can be develop. This is for the continuity of producing the sandwich panels as a mere structural fault in the aircraft for example, could lead to failure in flying and worse, could lead to a catastrophic incident. Therefore, it is important to consider the effects of the fibre orientation as a defects to make sure that the mechanical performance of the sandwich composites is not compromises.

## 1.4 Sandwich composite in aerospace application

During the early days, composites materials only been used for secondary structure. As the knowledge and developments of the material has improved, their uses are expanding to the primary structure such as wing and fuselage of an aircraft. The use of composite materials in aviation is popular because a reduced airframe weight enables a better fuel economy and therefore lowers the operating costs. The first significant use of composite materials is by Airbus in 1983. They use a composite material for the rudder of A300 and A310. After that, the use of composite materials in aviation expands significantly with the improvement of knowledge and developments in composites.

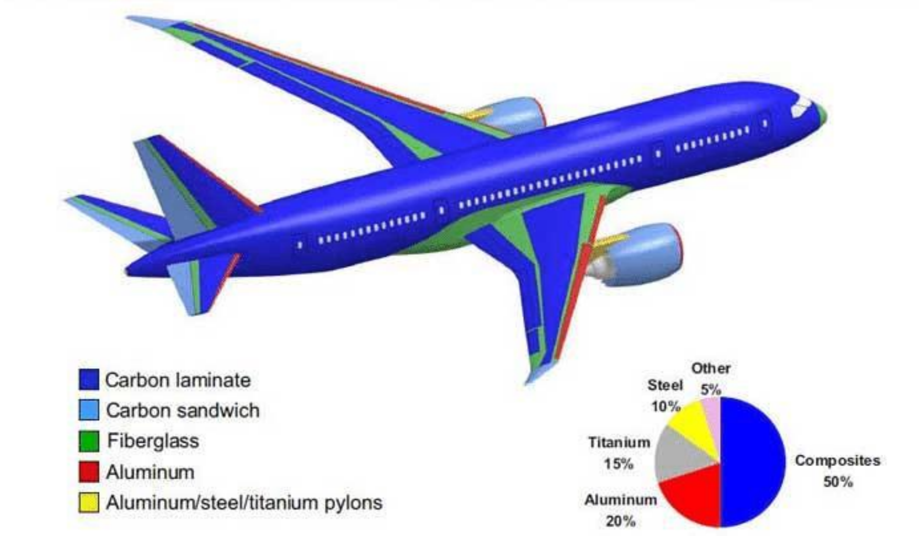


Figure 1.2: Percentage of materials in Boeing 787

Sandwich-structured composites are also one from the class of composites that has been greatly used in aviation and aerospace industry. The application of sandwich-structured composites in large structures aircraft was for the elevator of the A310. Later on, the applications expands as most parts of the aircraft implies a sandwich-structured composites as their materials.

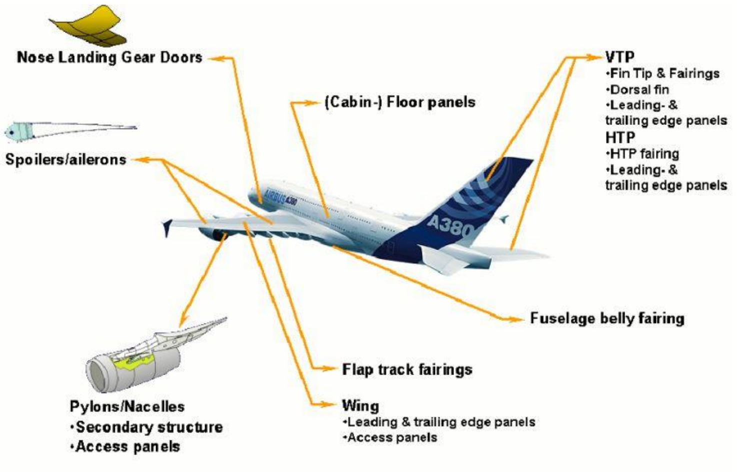


Figure 1.3: Example of sandwich applications in A380

## 1.5 Advantage and disadvantage of sandwich composite

The attention received by composites materials is due to its advanced properties that cannot be achieved in other materials. As mentioned, one of advantages of sandwich composites is the core material properties, which is a low strength but high bending stiffness material. By adding two fibre reinforced plastic skins on both side of the core, sandwich composites has more stiffness since the properties of the skins are high stiffness. Thus, it produces a very high stiffness-to-weight ratio and high bending strength-to-weight material. Significantly, it reduces the weight of the aircraft, reduced the fuel consumption and also reduced the operating cost. Sandwich panels have low thermal conductivity and low coefficient of thermal expansion. Even if the composite is expose to high temperature condition, it can withstand the heat. That is why the sandwich composites is apply in the interior design of the aircraft for safety purpose. Sandwich composites also offers a high resistance to corrosion and good resistance in fatigue. This implies for the aircraft as an aircraft cannot be use if it is corrode or undergoes fatigue in their parts.

Although the benefits are more promising, there are some disadvantages that should also be taken into account. One of the disadvantages is that the cost for the raw materials of the composites and also the fabricating process is relatively high which makes the cost a major issue in aviation industry. Also, the repairing procedure of the composite is complicated as the structural failure is more on the inside of the composite and cannot be detected. At certain points, the whole parts have to be remove even though the damage is just small and could lead to wastage of material since most composites cannot be recycle. In order to come deal with these issue, research and development in composite material is done to make composites more sustainable.

## 1.6 Motivation and Problem Statements

Composites has been studied and analysed for over a century. Along the time, many types of composites has been developed with its physical and mechanical properties been upgraded from the previous development. One of the most advance type of composites is a sandwich composite. There are many kind of factors that could affect the mechanical and physical properties of sandwich composites. One of the factors is the fibre orientation of the skin of a sandwich composites. Skins of a sandwich composites plays an important role in providing stiffness to the composites. Many researches has been performed regarding the effect of fibre orientation on the mechanical and physical properties of a sandwich composite. The researches include manufacturing the composite and performing tests to know the mechanical behaviour of the composite. Nowadays, sandwich composite becomes a trend as the most common composite type used in aviation, marine and automotive industries due to its effective and enhanced properties such as high strength-to-weight ratio, high stiffness and other advantageous properties. Therefore, by studying and manufacturing the sandwich composites with different fibre orientation, the misalignment defect of the sandwich composites can be observed and analysed for future improvement of sandwich composites usage in the industry.

## 1.7 Objectives of Research

The research work described in this thesis is performed based on the following objectives:

i. To manufacture a set of sandwich composite with different fibre orientation with 0°, 9° and 15° fibre orientation.
ii. To perform the mechanical testing such as compression test and bending test on the manufactured sandwich composites.
iii. To analyse the mechanical test results and compare it for different misalignment angle of the skins of sandwich composites.

## 1.8 Thesis Layout

This thesis comprises of five chapters. Chapter 1 is an introduction to composites and its historical background. The main part would be the introduction to sandwich composites. The general structure and basic manufacturing method is discussed in this part. This chapter also includes the general application of sandwich composites in aerospace industry. The advantages and disadvantages of using sandwich composites will also be discussed in this chapter. Apart from that, the problem statement and the objectives of this research is also stated in this part of the thesis.

Chapter 2 will be an explanation and review of related literatures such as journals, papers and articles of this research. The literature review will be focusing on the sandwich structures, its properties and mechanical behaviour, manufacturing method and effect of fibre orientation of sandwich composites.

Chapter 3 demonstrates all the method and a step by step procedure of all activities that is being used to complete this research. It comprises the method used in fabricating the sandwich composites and also the procedure of performing the mechanical tests. This section also provides detail information about material being used throughout the process of fabrication until the final testing.

Chapter 4 includes the results of the mechanical test acted on the manufactured composites. The data and information from the test is analysed to determine the mechanical properties of sandwich composites for different misalign angle. This section will be focusing more on the stress and strain results, also the Young's modulus of the composites.

Lastly, chapter 5 summarised all the information and results that has been point out throughout this research with the number of improvements that could be made to enhance the availability and sustainability of the research. All the suggestions and recommendations regarding the fibre orientation of the skins is being reviewed to make sure the misalign angle can be taken into account as a defect in manufacturing process in the future.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Composite materials and its application

Recent development of knowledge and technologies regarding the composites world has achieved a higher level and still increasing for the future. The demand on the composite materials are expanding in every industry especially in the aerospace sector. This is because the materials has an advances properties that has very strong even though its weight is relatively small. Composite materials is a combination of two or more constituents with different physical and chemical characteristic to form a material with an advanced properties. Several examples of composites material can be seen in nature itself, attained simply through the principle of natural selection. For example, wood is formed by cellulose fibres bound by a lignin matrix which makes wood as a composite material [1]. As the demands for the composite materials increases, many researches and investigations have been conducted to improve the properties of the composite materials. By providing the light weight yet a high performance properties, composites has become the most applied materials in the transportation industry, since it can decrease the fuel consumption, which will eventually reduce the carbon emissions and also saving the costs for the consumer and the manufacturer. Thus, it is an advantage to gain the knowledge and improve the composite material properties in order to achieve sustainable advancement in technologies also to save the environment from all the carbon emissions that are produced nowadays [2].

## 2.2 Classification of composites

Composite materials is named by its type of reinforcement and matrix materials. For example, a combination of an E-glass fibre reinforcement with an epoxy resin is called an “E-glass fibre epoxy composite material” [2]. Composites is classified in accordance to the type of materials used. On the basis of matrix type, composites can be classified into ceramic matrix composites (CMCs), organic matrix composites (OMCs) and metal matrix composites (MMCs). As for the reinforcement base, composites can be classified as fibrous composites, particulate composites and structural composites [3].

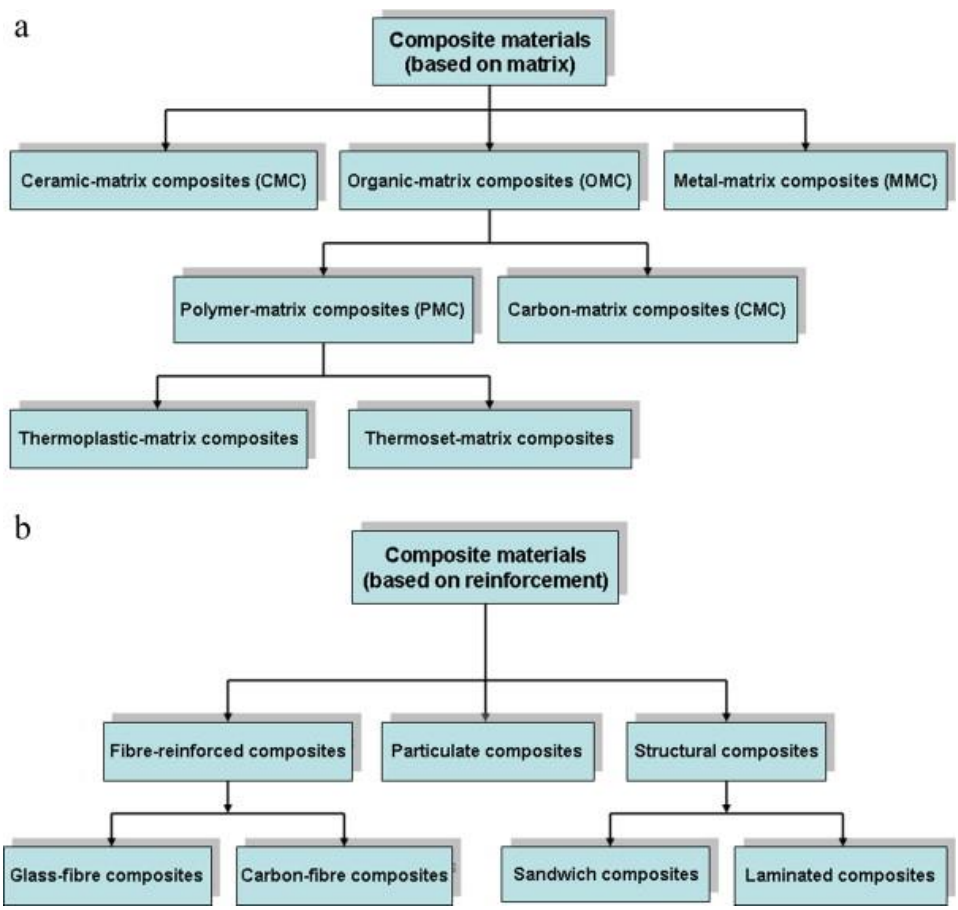


Figure 2.1: Classification of composites. (a) Matrix base. (b) Reinforcement base.

### 2.2.1 Reinforcement

The reinforcement for the composite materials are responsible for the stiffness and strength properties of the composites. The most used reinforcement type in the industry is a continuous reinforced fibres. There are many types of fibres been used such as glass, graphite and aramid. The origin of the fibre's material only has a high tensile and compressive strength properties but extremely brittle causing each material to fail below its theoretical 'breaking point'. To solve this problem, these materials is produced in a fibre form. A bundle of fibres will reflect more accurately to the performance of the material. However fibres alone can only exhibit tensile properties along the fibre's length. This is because the reinforcing fibres have their highest mechanical properties along their lengths rather than their width [4].

Figure 2.2: A bundle of glass fibre

### 2.2.2 Matrix

Matrix is a material that bonds with the reinforcement to produce a composite materials. Matrix is produced in the form of resin solution. The matrix properties determine the resistance of the PMCs to most of the damages that eventually causes failure to the structure. These damages are, impact damage, delamination, water absorption, chemical attack and high temperature creep. The matrix phase of commercial composites can be classified into two categories which is thermoset and thermoplastics [5].

Thermoset resin undergoes a chemical reactions that crosslink the polymer chains and thus connect the entire matrix together in a three-dimensional network. This process is called curing. Thermosets have high dimensional stability, high temperature resistance and good resistance to solvents. Examples of thermosets are polyesters, vinyl-esters, epoxies and polyamides. The most commonly used thermosets in fibre-reinforced plastics is the epoxies [5].

Thermoplastics is a plastic materials that melts at certain specific temperature and solidifies when cooled. The molecular structure of thermoplastics is long and discrete molecules. The process of melting the plastic is so that it ca be formed to a certain shape and then cooled to produce an amorphous, semi-crystalline or crystalline solid. The degree of crystallinity has a strong effect on the final matrix properties. Examples of thermoplastics are polyesters, polyetherimide, polyamide imide, polyphenylene sulfide, polyether-etherketone (PEEK), and liquid crystal polymers. The recent developed high-performance thermoplastics, such as PEEK, which have a semi-crystalline microstructure, exhibit excellent high temperature strength and solvent resistance.

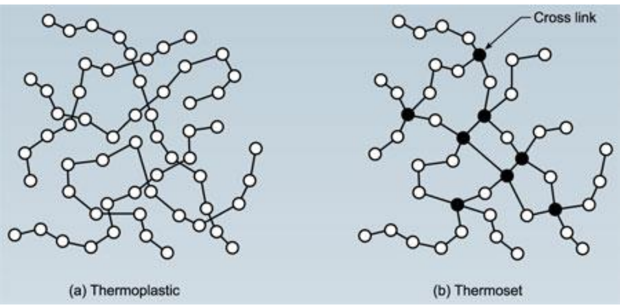


Figure 2.3: Molecular structure of (a) thermoplastic and (b) thermoset

## 2.3 Sandwich composites

Sandwich composites is one of the special class composites under structural composites. A sandwich structured composites have been applied extensively in the aerospace and the civil infrastructure industries. The popularity of the sandwich structured composites is due to their extremely low weight but high stiffness properties that leads to weight reduction and reduced fuel consumption. Sandwich composites consists of a strong and stiff skins which covers the low density core material [6]. The main concept of the sandwich panel is that exterior surfaces transfer loads caused by bending (flexural load and compression), while the core transfers load caused by shearing. Sandwich composites materials belong to the group of anistropic materials. It means that their strength properties changes depending on the applied load [7]. Sandwich structures allow optimization of structures that are weight-critical such as part of aircraft, spacecraft structures, sports equipment, marine structures and blades for wind turbines.

### 2.3.1 Face sheets

The face sheets or the skins of a sandwich composites has a very high stiffness. The E-glass fibre with epoxy resin laminates was manufactured to apply it as the skins for the sandwich composites to be test to achieve this research objective. In structural sandwich composites, face sheets are mostly identical in material and thickness and they primarily resists the in-plane and bending loads. The concept of sandwich composites is similar to the I-beam concept. When the sandwich is supported at both sides and a downward force is applied in the middle, the bending moment will introduce shear force to the material which causes the bottom skin to be in tension while the top skin to be in compression [6, 7].

### 2.3.2 Core

The core materials has low density but has a high thickness. Thus, the core structure provides stiffness due to its thickness although it is low strength material. The core materials are classified in four types which is foam or solid core, honeycomb core, web core and corrugated or truss core. For this research, a cell structured foam which is honeycomb core is used as the core material. The primary purpose of the core is to keep the face sheets separated in order to maintain a high section modulus (a high 'moment of inertia' or 'second moment of inertia') [6]. The core transfer the load caused by shearing. The interface between the core and the skins are also important. If the adhesive bond between the two layers of the skin is too weak, the most probable result will be a delamination of the composites as the shear stresses in the composite materials change rapidly between the core and the skin making the adhesive layer experiences some of the shear forces.

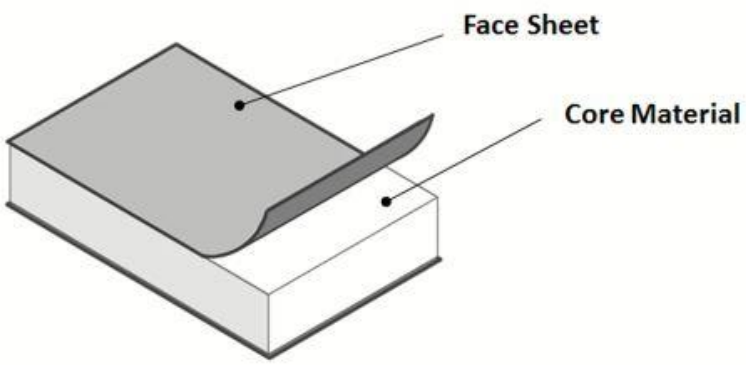


Figure 2.4: Structure of sandwich composites

## 2.4 Fibre orientation

The mechanical properties of a composite depends highly on several factors such as fibre length, fibre orientation and the bond between the fibres and the matrices [8-12]. For this research, the focused factor is the fibre orientation of the composites. Fibre orientation represents the direction of the fibre been placed for each fibre layer. For this research, the fibres is placed with the same directions for the two layers of one skin of the sandwich composites. In fibre-reinforced composites, damping energy is the energy that withstand the vibration of the composites structure. The damping loss factor of PMC materials is about 10 to 100 times greater than that of structural metallic materials. One of the reason that result in loss of damping energy is the layer orientations [13]. The orientations not only could lead to damping energy loss, but also other defects that could damage the composites. Many attempts have mainly focused on the effects of the fibre volume fraction and the interfacial adhesion between the fibre and matrix. However, it was pointed out that the mechanical properties of composites also depended strongly on the fibre orientation and fibre aspect ratio [14, 15]. It is also stated that core or face sheets discontinuities could lead to the decrease of mechanical performance of the structure [15-18]. Anjang et al. studied the influence of fibre orientation on tensile properties of sandwich composites in fire. Form this research, it is stated that as the fibre orientation angle increase, the tensile properties of the composites decreases [19].

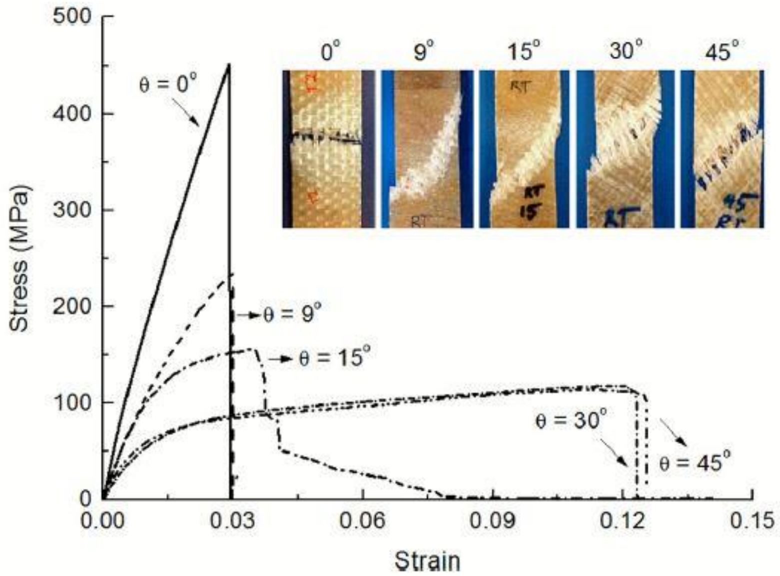


Figure 2.5: Stress-strain curve for different fibre orientation [19].

## 2.5 Mechanical test

Sandwich composites has a high strength-to-weight ratio and has high stiffness properties. Many researches includes performing a mechanical test in order to proof the advance properties of sandwich composites. The purpose of this research is to determine the effect of fibre orientation on mechanical properties of the sandwich composites. By performing the mechanical test on manufactured sandwich composites with different fibre orientations, the properties of the composites can be analyse to see the differences and proof the theory of decreasing mechanical performance on the increase of misalign angle. The most frequently tested mechanical properties of sandwich composites are the measurements of compressive strength, three-point bending test and impact test of a panel [7]. For this research, only compressive strength and three-point bending test is considered.

### 2.5.1 Compression test

A compression test is a test which a material or specimen experiences pushing forces from both sides of each end inward. In other terms, the specimens are either squashed, crushed or flattens. The post test would results in the specimen getting shortened in directions of the applied loads and expands in the direction perpendicular to the load. The parameters that can be obtain from this test is compressive stress, compressive strain and Young's modulus. The illustration of compression test is shown below. The test is done by using the universal testing machine Instron.

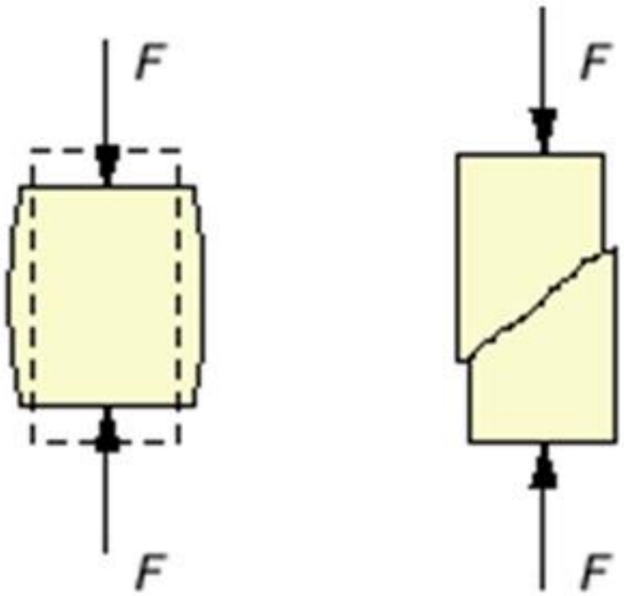


Figure 2.6: Illustrations of compression test

From this test, the compressive strength of the sandwich composites with different fibre orientation can be analyse. The compressive strength of composite is greatly reduced by the local instabilities initiated by fibre orientation defects according to Gillespie J.W. et al [20].

### 2.5.2 Three-point bending test

The stiffness of a material or specimen can tested using the three-point bending test procedures. From this test, the material will experienced a downward force at the centre whilst being supported at both ends. Three-point bending test are performed to obtain the mechanical properties, including bending stiffness, strength and energy absorption of the sandwich composites [11, 21]. Basically, the flexural properties of the sandwich composites for different fibre orientation can be obtain and analyse. The parameters that can be obtain form this test is flexural stress, flexural strain and flexural modulus. The test is also done using the universal testing machine Instron. Below are the illustration of the three-point bending test.

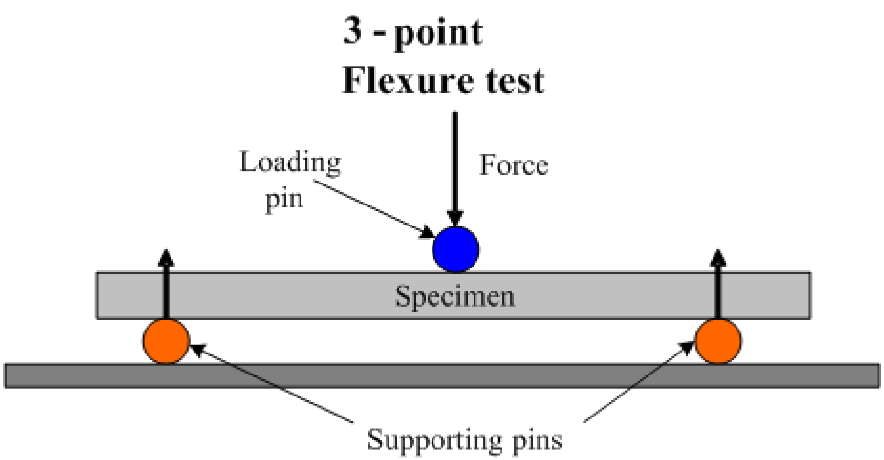


Figure 2.7: Illustrations of three-point bending test.

# CHAPTER 3

# METHODOLOGY

In order to complete this whole project, there are several stages involve starting from fundamental study up to testing the composites. The first stage will be involving the fundamental studies in reading article, journal, research papers and also books. Next stage will be the fabricating process of the specimen using a proper method. The method to be use is a wet hand lay-up with vacuum bag aided. After the fabrication is done, the final stage will be the testing procedures. The overall flow chart of all the processes included are stated below:

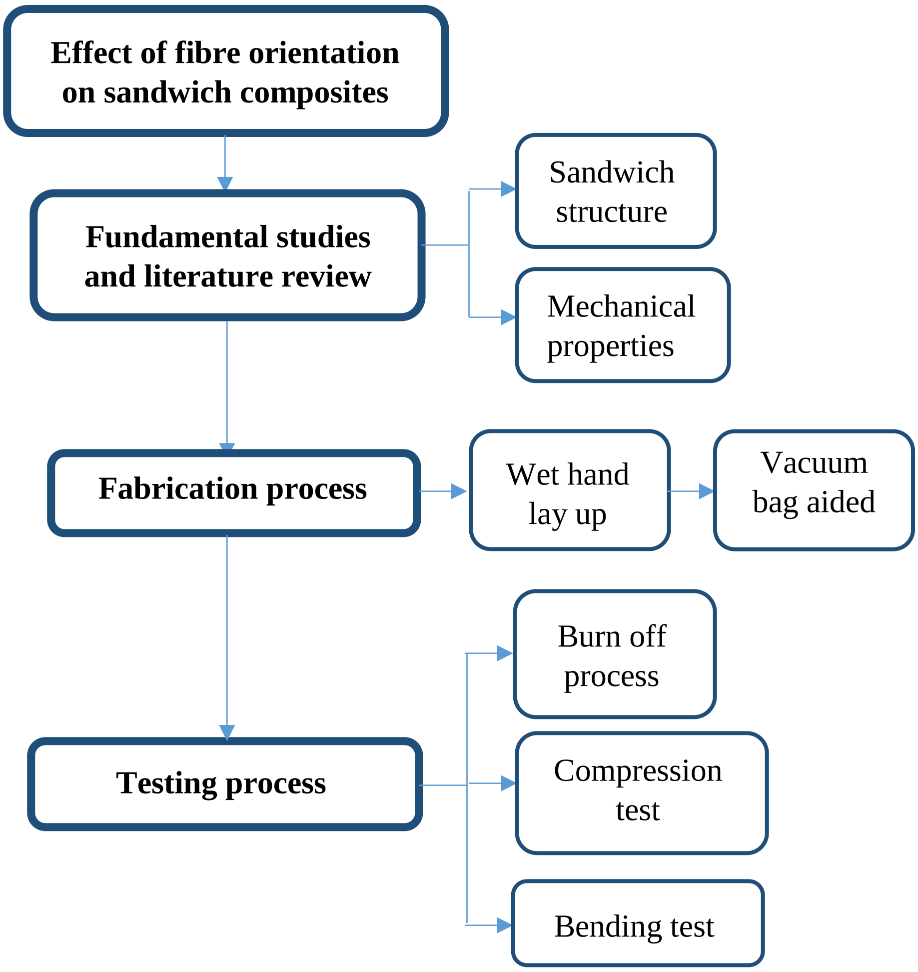


Figure 3.1: Flow chart of overall process

## 3.1 Material selection

In order to fabricate a composite, there are some important details need to be determine from the first stage of methodology before moving into the fabrication process. From the studies, the first and foremost things to be decided is the materials to be used as matrix and reinforcement of the composites. Sandwich composites consists of two skins attach to one core material on both sides.

### 3.1.1 Skin

The skins is fabricated by using a wet hand lay-up process and it consists of two layers of E-glass woven roving fibre (800g/$m^2$) as its reinforcement and an epoxy as resin for one surface of the sandwich composite. The amount of resin to be use is determine by the weight ratio of fibre to resin which is 1:1. First, the fibre was cut into a square shape with dimension of 350mm x 350mm. Then, the weight of the fibre was measured in order to determine the weight of the resin to be used. The bottom and top surface of the sandwich composites was done separately.

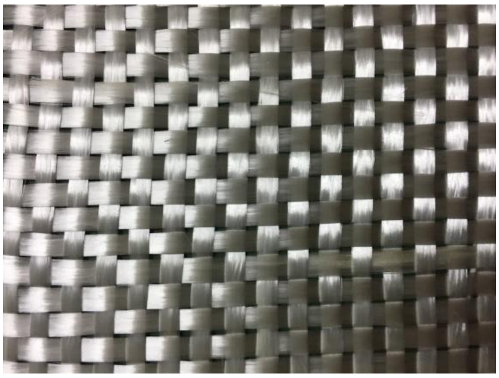

Figure 3.2: E-glass woven fibre

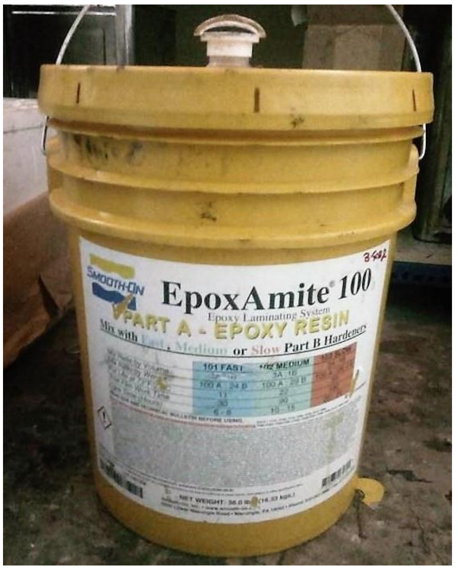


Figure 3.3: Epoxy resin

For fibre orientation, a printed protractor on transparent plastic sheet is used as a guidance to cut the fibre with 9° and 15° misalign angle. The fibre was also cut in the shape of a square but with different fibre orientation.

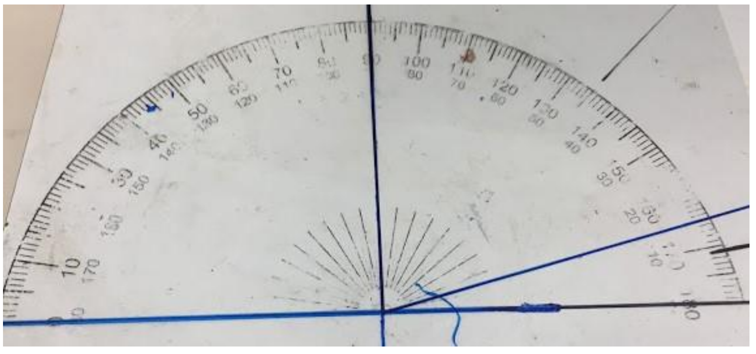

Figure 3.4: Printed protractor

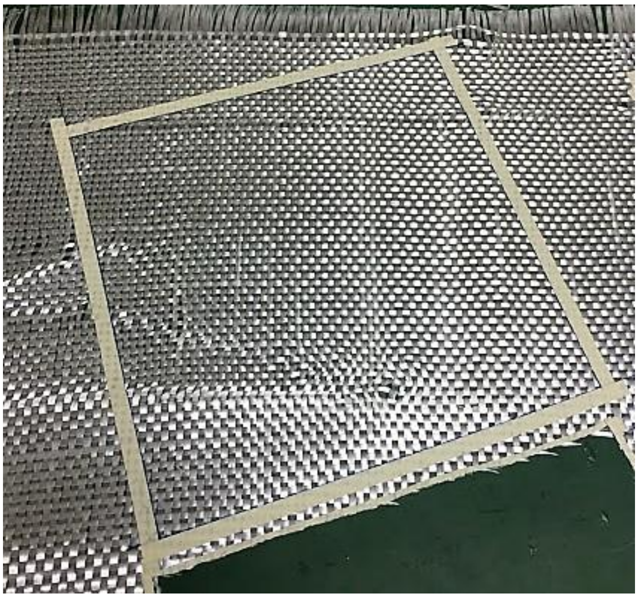

Figure 3.5: E-glass fibre being cut at 15° misalign angle

### 3.1.2 Core

The core chosen for the sandwich composite specimens is a plastic honeycomb structure with the thickness of 10mm. The dimension of the honeycomb core would be the same as the fibre which is 350mm x 350mm.

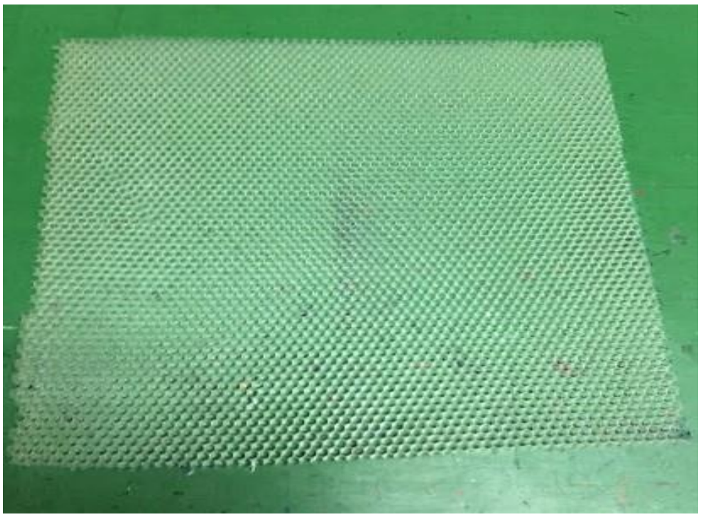

Figure 3.6: Plastic honeycomb structured core

## 3.2 Method of Fabrication

For this research, a wet hand lay-up method is used to produce the sandwich composites. To make sure that the sandwich composites has smooth surface and the resin distributes evenly throughout the specimen, a vacuum process is used as an aid system for the overall fabrication process.

### 3.2.1 Wet hand lay-up method

This method start off with preparing the materials included in the fabrication process. This method was done on a square metal plate as a working base with its dimension is a little bit larger than the desired fibre dimension. The metal plate was cleaned with a wax. This is to make sure that the composites are easy to detach from the working base and has a smooth surface after the curing process. It also acted as a carrier for the composites as it can be lifted and moved to another place easily.

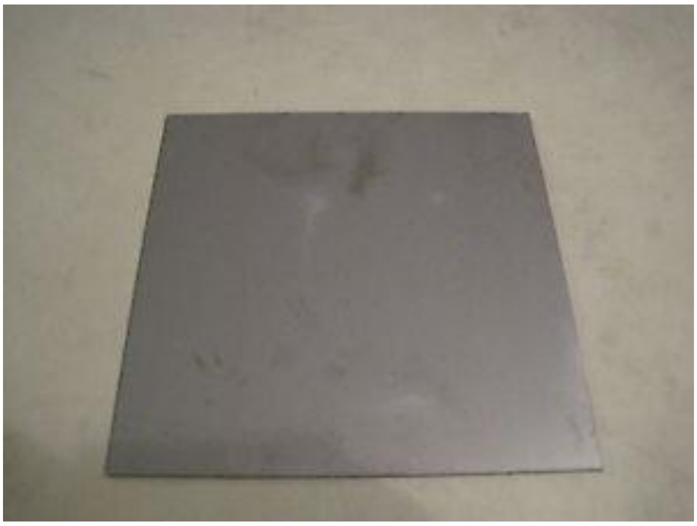

Figure 3.7: Metal plate