LOW-VELOCITY IMPACT RESPONSE OF THERMOPLASTIC HONEYCOMB CORE SANDWICH STRUCTURE WITH ALUMINIUM FACE SHEET

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by

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Master of Science

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DECLARATION

I hereby declare that I have conducted, completed the research work and written the dissertation entitled "Low-Velocity Impact Response of Thermoplastic Honeycomb Core Sandwich Structure with Aluminum Face Sheet". I also declare that it has not been previously submitted for the award of any degree or diploma or other similar title for any other examining body or University.

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LIST OF ABBREVIATIONS

UV	Ultraviolet
vs.	versus

LIST OF SYMBOLS

J	Joule
N	Newton
^{o}	Degree
E_f	Flexural modulus
P	Force
k	Contact stiffness
α	Indentation
E	Young Modulus
R	Impactor radius
C	Contact parameter
n	Contact parameter
m	mass
v	velocity
L	Span length
D	Flexural rigidity
G	Shear modulus
δ	Sigma
^{o}C	Degree Celsius
^{o}F	Degree Fahrenheit
t	time
s	second

KESAN RESPON IMPAK HENTAMAN HALAJU RENDAH STRUKTUR TERMOPLASTIK INDUNG MADU TERAS TERAPIT BERSAMA KEPINGAN ALUMINIUM

ABSTRAK

Kesan respon impak hentaman halaju rendah struktur termoplastik indung madu teras terapit yang dilapik bersama dengan kepingan aluminium dikaji dengan menjalankan beberapa siri ujian impak hentaman halaju rendah pada suatu julat suhu dan geometri yang dipertimbangkan. Dengan menggunakan mesin impak penerjunan-pemberat, tenaga impak dapat dibezakan dengan melakukan variasi terhadap ketinggian aras pemberat. Dalam kajian ini, model imbangan-tenaga diaplikasikan untuk menentukan tenaga penyerapan bagi deformasi lenturan, ricih dan sentuhan. Bagi setiap ujian, kesan daya maksimum impact hentaman telah digunakan sebagai titik utama untuk menentukan kesan respon struktur terapit dimana nilai yang diperolehi dari eksperimen dibandingkan dengan nilai yang dikira dari model. Daya impak maksimum bagi setiap tenaga impak menunjukkan ketinggian terhadap kenaikan ketebalan struktur teras dan kepingan aluminium tetapi menunjukkan penurunan terhadap peningkatan suhu. Ujian mekanik seperti ujian lentur dan dan mampatan turut dilakukan dalam kajian ini untuk menentukan sifat lentur dan mampatan struktur terapit. Keputusan kajian mendapati bahawa kedua-dua modulus lentur dan kekuatan tidak terpengaruh dengan kesan kadar. Dengan menggunakan model imbangan-tenaga, nilai eksperimen dan teori menunjukkan persetujuan yang baik walaupun terdapat sedikit taburan pada data daya impak maksimum yang diperoleh. Kerosakan dan mod kegagalan yang terdapat pada struktur terapit diperhatikan menggunakan mata kasar dan mikroskop optik bagi menentukan jenis kegagalan dan luas impak kegagalan di dalam struktur terapit.

LOW-VELOCITY IMPACT RESPONSE OF THERMOPLASTIC HONEYCOMB CORE SANDWICH STRUCTURE WITH ALUMINIUM FACE SHEET

ABSTRACT

The low-velocity impact response of thermoplastic honeycomb core sandwich structure with aluminium face sheet was investigated by conducting a series of drop-weight impact tests on a range of temperatures and thickness considered. By using an instrumented drop-weight impact tower, the impact energy were varied according to variation of drop heights. In this study, a simple energy-balance model was used to predict the impact response of the sandwich structure which accounts for energy absorption in bending, shear and contact deformations. For each test, the resulting impact force was used as an indicator to determine the impact response of the sandwich structure which the value obtained from the experiment were compared to those calculated from the model. The maximum impact force for a given impact energy was found to be increase with core and face sheet thickness but decreases with increasing temperature.Mechanical tests such as flexural and compression tests were also conducted in this study in order to determine the flexural and compression properties of the sandwich structure. The results found that both flexural modulus and strength were rate-insensitive over the range of crosshead displacement rate. By using the energy-balance model, the agreement between the experimental value and theoretical value was found to be good with a small scatter of data in the maximum impact force values. Damage and failure modes from the test were observed by using naked eye and optical microscope in order to determine the types of damage occured and the impact damage area of the structure.

CHAPTER 1

INTRODUCTION

1.1 Introduction

There is a growing interest in the use of structural sandwich composite panels, ranging from automotive and marine applications to aircraft structures. Furthermore, building and consumer industries are now showing interest in studying possible uses because of its excellent properties, such as superior bending stiffness, low weight, improved stability, excellent thermal insulation, good acoustic damping, fire retardant capabilities, ease in machining and ease in forming, among others (Hosur et al., 2004; Hosur et al., 2008). In addition, its ability to provide increased bending rigidity, without a significant change in structural weight, is its main advantage to sandwich construction.

Sandwich panels consist of two thin face sheets and a lightweight thicker core. Commonly used materials for facings are composite laminates and metals. Cores are made of metallic and non-metallic honeycombs, cellular foams, balsa wood and trusses. The facings carry almost all the bending and in-plane loads. The core helps stabilize the facings and defines the flexural stiffness and out-of-plane shear and compressive behaviour (Daniel et al., 2009). The behavior of the sandwich structure are depends on the properties of the core material used, especially under impact loading. In addition, the impact damage resistance of the sandwich structure is greatly influenced by the type of face sheet and thickness of the core (Park et al., 2008).

1.2 Background

Lately, sandwich structures are being widely used in material studies. The use of sandwich materials allows for weight savings and an improvement in stiffness design criteria. As a type of layered structure, sandwich plates often fail, similar to the other layered structures such as composite laminates. The basic design concept is to space strong, thin facings far enough apart to achieve a high ratio of stiffness to weight. The lightweight core provides the required resistance to shear, and is strong enough to stabilize the facings to the desired configuration through a bonding medium such as an adhesive layer, braze, or weld. The core also provides most of the shear rigidity of the sandwich construction. By choosing proper materials for the facings and the core, constructions with high ratios of stiffness to weight are achieved.

Materials used in a single form are relatively weak and flexible compared to materials working together, such as sandwich structures. These structures undeniably are superior in terms of strength, rigidity, stiffness and are more lightweight. In sandwich designs, elements work together and the face sheet captures the bending load (one surface provides tension and the other is compressed) while the thick core handles the shear load. All the stresses transform into several types of load with each element providing resistance toward the stresses. The stress distribution of the structure is not expected to be uniform; most stresses are obtained by introducing a theory or a model. Stress distributions and deformations are determined using a theory, which help to reach the optimal properties for each sandwich design.

In a composite sandwich structure, the skin is responsible for eroding and breaking projectiles, carrying bending load, and protecting the core; the core is responsible for separating and fixing the skins, resisting transverse shear, carrying in-plane load, and providing other functionalities like absorbing impact energy, shielding radiation, and insulating heat transfer. Therefore, the versatility of sandwich construction comes from the core (Li and Muthyala, 2008). In order for the sandwich core to be lightweight, it is usually made of low-density materials, such as types of cellular construction (honeycomb-like core formed of thin sheet material), or of corrugated sheet materials. As a consequence of employing a lightweight core, design methods account for core shear deformation because of the low effective shear modulus of the core. The main difference in design procedures for sandwich structural elements as compared to design procedures for homogeneous material is the inclusion of the effects of core shear properties on deflection, buckling, and stress for the sandwich.

Most sandwich structures are exposed to a variety of threatening environments, including extreme temperatures, humidity, moisture, excessive UV light and environmental disasters. Hence, these factors are important to consider as they affect the performance of the structure by decreasing the stiffness and the strength of the materials. In addition, stress conditions play a key role in determining a material's likelihood to fail in different environments. Impact failure for laminated composites at high or low temperatures is more complicated than at room temperature (Salehi-khojin et al., 2006).

1.3 Problem statement

Sandwich structure is susceptible to impact damage and failure. The impact damage is considered potentially dangerous because the damage might be left undetected, as the surface appear to be undamaged. There are many practical situations that induce considerable damage to sandwich structural composites, including hailstones, bird strikes and debris lifted from the undercarriage of planes during take-off and landing (Alcock et al., 2008 and Salehi-khojin et al., 2006). Apart from that, the reduction in properties of sandwich structure is mainly because they are inherently weak in transverse direction (Bitzer, 1997). In spite of that, the damage can also reduce its structure stiffness caused by through-thickness damage. Hence, in order to solve this problem the understanding about the formation of such damage in sandwich structure is very important. Furthermore, lack of knowledge about the impact damage mechanism in sandwich structure during the impact has brought an unwanted failure to arise.

In sandwich structure, low-velocity impact damage can also arise caused by nature. When these structures are exposed to certain temperature and environment, damages such as core-skin debonding, delaminations, and through-thickness penetration can also occur. Such problems arise, with the structure's poor resistance toward localized impact damage under critical condition which limits the usage of the structure. For this problem, the solution to overcome it is to evaluate the impact response experimentally and numerically so that the effect of nature can be taken into account.

Lack of understanding of deformation distribution in sandwich structure has caused an unpredicted damage to occur in the structure during the impact. Even though experimental tests under impact conditions provide considerable information about the tested specimen and their characteristic parameters, the dynamic properties and failure behavior of such sandwich structure is complex. To overcome this problem, testing methodology that can simulate the behavior of sandwich structure during impact is needed in order to find a good combination of materials and design which can relate to the respective applications. In this case, by using modeling solution such as energy-balance model, the deformation behavior under certain condition (temperature, geometry and humidity) can be determine so that it will allow for better resistance toward localized impact loading.

1.4 Objectives of the study

- To determine the mechanical properties of thermoplastic honeycomb core sandwich structure with aluminum skin.
- To investigate the impact performance of thermoplastic honeycomb core sandwich structure with aluminum skin under various temperatures.
- To determine the effect of core and face sheet thickness on impact response of thermoplastic honeycomb core sandwich structure.
- To predict the low velocity impact response of the sandwich structure using the simple Energy-Balance Model.

CHAPTER 2

LITERATURE REVIEW

In this section, the factors that influence the impact response of sandwich structures are introduced and discussed. The following section will concentrate on the applications and factors that affect the impact performance of sandwich composite materials. This includes the effects of constituent materials, the specimen thickness, evaluation of properties and applications of sandwich structure.

2.1 Applications of sandwich structure

Sandwich structures are used in a wide range of engineering applications including the automative, marine, aeropsace and construction industries. This is because sandwich structures are extremely efficient in stiffness-to-weight and strength-to-weight situations. In addition, their improved stability, excellent thermal insulation, good acoustic damping and fire retardant properties make them very favourable for use in many industries. The summary of applications for sandwich structure is given in Table 2.1. In all applications, sandwich panels can cut down body weight, increase speed, and save energy while providing strength and lessening shakiness.

Table 2.1 Applications of thermoplastic honeycomb core

Application	Specification
Marine	Hull, deck, bulkhead, tank, and canopies
Chemical	Provide protection for tanks, pits, pipes, grates and filtration media
Construction	Dome, wind turbine (blades, canopy, housing and rotor hoods)
Transportation	Floor bus, exterior body panels
Tooling	Fabricating tooling and moulds
Sports	Provide safety production for sportsman (elbow protector, kneepad, chest protector, helm, crash helmet)

2.2 The influence of constituent materials on the properties of sandwich structure

Advanced materials are now being used around the world due to modern technologies. The technologies require advances in the materials, leading to higher performance, lower cost and lower-weight structures which will assure the construction of the new materials continue to be in demand. Modern technologies involve many materials with unusual combinations of properties, from conventional materials such as metals, ceramics and polymeric materials. These advanced materials are needed in construction and load bearing areas, such as aerospace, marine, and transportation applications. These applications necessitate using materials with a low density, strong, stiff, abrasion and impact resistance, and that are not easily corroded. Strong materials are relatively dense, and increasing the strength or stiffness generally results in a decrease in impact strength.

Material property combinations and ranges have been extended by the development of composite materials. Basically, a composite is any multiphase material that exhibits a significant proportion of the properties of both constituent phases, so that a better combination of properties is realized. According to the combined action principle, better property combinations are fashioned by the judicious combination of two or more distinct materials. Property trade-offs are also made for many composites.

2.2.1 Composite

A composite is defined as a combination of two or more chemically distinct and insoluble phases with a recognizable interface, in such a manner that its properties and structural performance are superior to those of those of the constituents acting independently (Kalpakjian and Schmid, 2006). A composite is a multiphase material that is artificially made, as opposed to one that occurs or forms naturally. In addition, the constituent phases must be chemically dissimilar and separated by a distinct interface. In the most general sense, composites can also be thought of as a wide variety of materials, such as cermets, two-phase alloys, natural materials such as wood and bone, and general reinforced and combined materials such as kevlar and steel-wire reinforced automobile tires. The demands made on materials for better overall performance are so great and diverse that no one material can satisfy them. This naturally led to a resurgence of the ancient concept of combining different materials in an integral-composite material to satisfy the user requirements. Such composite material systems result in a performance unattainable by the individual constituents, and they offer the great advantage of a flexible design; that is in principle, tailor-make the material as per specifications of an optimum design (Chawla, 1998).

The term composite has come to mean a material made by dispersing particles, of one or more materials in another material, which forms a substantially continuous network around them. The properties of the composite may bear little relation to those of the components, even though the components retain their integrity within the composite. The components can be randomly arranged, or organized in some sort of pattern. Generally, the arrangement will have a large effect on the properties. Further, they can have roughly spherical shapes, such as stones in concrete, or can have some very distinctive shape, such as the iron carbide laminate found in some steels, or long thin fibers, such as the cellulose fibers in wood. The particle shape also has a very profound effect on the properties of the composite. There are many composite materials that have been designed, including on combination of various metals, ceramics, and polymers to build new materials. Most composites have been produced to improve mechanical characteristics such as stiffness, toughness, and ambient and high temperature strength (Callister, 2003). Many composite materials are composed of three phases; fiber, matrix (dispersed), and interface. In general, composites are classified according to their matrix material. The main classes of composites are polymer-matrix, metal-matrix and ceramic-matrix composites (Chung, 2010). The properties of composites are a function of the properties of the constituent phases, their relative amounts, and the geometry of the dispersed phase. The dispersed phase geometry indicates the shape of the particles and the particle size, distribution, and orientation. One basic classification scheme for the various composite types is shown in Figure 2.1. A structural composite typically consists of both homogeneous and composite materials, the properties of which depend not only on the properties of the constituent materials but also on the geometrical design of the various structural elements. There are two common types of structural composites; laminar composites and sandwich panels. This study focuses only on sandwich structure composites.

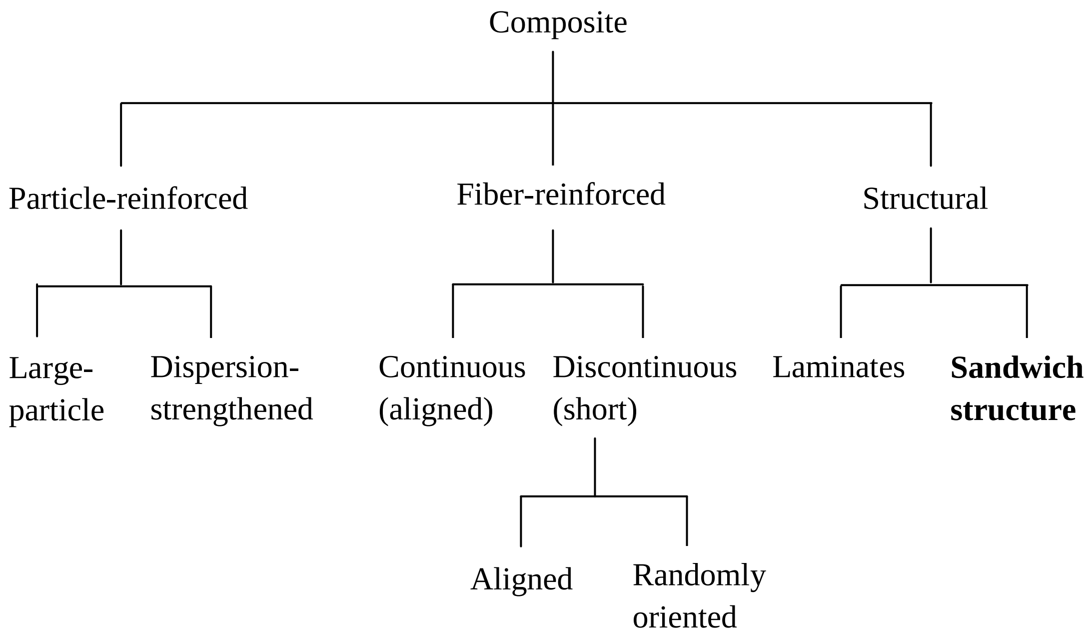

Figure 2.1 Classification scheme for the various composite types (Callister, 2003).

2.2.2 Sandwich structure

The basic concept of sandwich composite structures was described in the previous chapter. It consists of three important elements; the core, the adhesive, and the strong outer face sheet or skin. These elements play a vital role in influencing and determining the properties of the sandwich composite structure.

2.2.2.1 Definition and basic concept of sandwich structures

Sandwich structures are successfully being used for a variety of applications, such as for the needs of spacecrafts, aircrafts, trains, car structures, wind turbine blades, boat/ship superstructures, boat/ship hulls and many others. Traditionally, these sandwiches consisted mainly of a polymer composite configuration, but there is now a growing interest in metallic composite configurations, including metallic cores and face sheets (Shenoi et al., 2005). The ability of sandwich construction to provide increased bending rigidity, without significant increment in structural weight, is its main advantage. Structural sandwich composites are a special type of composite laminate where two thin, stiff, strong and relatively dense face sheets, which are often by themselves composite laminate, are separated by and bonded to a thick, lightweight and compliant core material. Such sandwich structures have gained widespread acceptance as an excellent way to obtain extremely lightweight components and structures with very high bending stiffness, high strength and high buckling resistance (Daniel et al., 2009).

Basically, sandwich structures consist of three important elements; the core, the adhesive, and the strong outer face sheets or skins (Icten et al., 2009). The structure of a sandwich composite material is illustrated in Figure 2.2. These elements play a vital role in influencing and determining the properties of the sandwich composite structure. For example, the distribution of adhesive between the core and the face sheet must be uniform in order to bond these two constituents, as it is greatly influences the performance of the sandwich structure. Commonly used materials for facings are composite laminates and metals, while cores are made of metallic and non-metallic honeycombs, cellular foams, balsa wood or trusses.

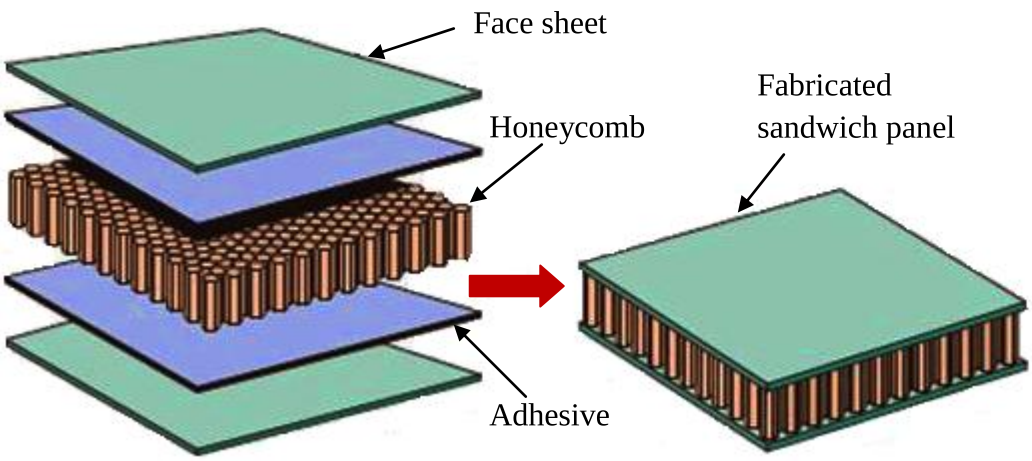

Figure 2.2 Honeycomb core sandwich structure (Callister, 2003).

The concept of sandwich structures generally mimics an I-beam, but in two dimensions. The face sheet of the sandwich is equivalent to the flanges of the I-beam, which carry the bending loads. The core of the sandwich plays the part of the web of the I-beam, carrying the shear load (Carlsson and Kardomateas, 2011). Hence, the bond between the face sheet and the core needs to be strong enough to resist the tensile and shear stresses set up between them. This is where the majority of strength is created in a sandwich structure. In addition, this concept has been used extensively in building structures as the weight is usually not a critical concern. Figure 2.3 illustrates a simple I-beam configuration.

Figure 2.3 A simple I-beam configuration

(http://www.sandwichpanels.org/articles/article_whatmakessandwich.html).

2.2.2.2 Behavior of sandwich structure

Over the last decade, various improvements have been made in the manufacturing of sandwich structures. Different combinations of core and face sheet materials have been developed in order to meet the increased requirement for the mechanical strength. Sandwich materials generally exhibit some favourable properties such as high load bearing capacity at low weight, excellent thermal insulation, relatively long life at low maintenance cost, and excellent acoustic damping and thermal resistance properties. There are, however, some features of a sandwich structure that need to be carefully monitored, such as quality control in production and operation, damage tolerance and toughness (especially in relation to the skin-core interface), susceptibility to fire (especially in polymer sandwich configurations) and low creep resistance (with some PVC cores) (Shenoi et al., 2005).

Generally, structural sandwich consist of two thin face sheets surrounding a thick core. Each of the elements plays a certain role in protecting the structure. The core provides shear rigidity for the sandwich while the top and bottom face sheets resist nearly all of the applied in-plane loads and flatwise bending moments, which mark the overall bending rigidity to the sandwich (Staal et al., 2009). Furthermore, the lightweight core transfers the load between the two face sheets, which provide the load carrying capability of the panel and induce a high second area moment of inertia (I-beam theory). Unlike conventional monolithic materials, their high strength-to-weight ratio makes them very favourable for a wide range of applications (Hosur et al., 2004). In addition, their ability to provide increased bending rigidity, without significant increases in structural weight, is the main advantage of sandwich construction. The major problem that limits the usage of sandwich composites is their susceptibility to damage due to impact loading (Staal et al., 2009). There are many practical situations that induce considerable damage to sandwich structural composites, including hailstones, bird strikes and debris lifted from the undercarriage of planes during take-off and landing (Bhuiyan et al., 2009). Low-velocity impact is considered potentially dangerous mainly because the damage might be left undetected, as the surface may appear to be undamaged. Hence, in order to improve the damage resistance of sandwich structures, understanding about the formation of such damage in sandwich composite materials is very important. A low-velocity foreign object impact on sandwich structures can cause damage to the face sheet, the core material and the core-facing interface. Damage initiation thresholds and damage size depend on the properties of the core materials and face sheets; the relationship between the properties of the cores and those of the face sheets; and the size and shape of the structures.

2.2.2.3 Design principle of sandwich structure

A sandwich structure is not a material having unique mechanical properties but rather a structure with a design for a particular purpose to which it will be subjected. In order to design a sandwich structure, a certain rule needs to be considered; the sandwich is a composite, with anisotropic materials, and the shear modulus of the core must be low. In sandwich construction, the basic concept is to use thin, dense, strong facing materials bonded to a thick, lightweight core (Bitzer, 1997). At first, each element or component of the sandwich structure is relatively weak and flexible but they can provide an extremely stiff, strong and lightweight structure if it is combined and working together as a unit. In sandwich design, it is assumed that the facings take the bending load (one facing in tension and the other in compression) and the core carries the shear load. It is usually assumed that the facing stresses are uniformly distributed and the cores offer no resistance in bending. In other words, the core bending modulus equals to zero. This assumption also leads to a uniform shear stress throughout the core thickness.

As mention in 2.2.2.1, the sandwich structure concept is similar to those wide-flange or I-beam concepts. This concept is extensively used in building construction, as weight is not a critical factor to the subject. However, in aircraft, marine and transportation applications, weight has become an important topic. To cut down the weight, the thickness of the flange needs to be reduced. Heavy weights can cause a buckling problem to the flange tips. Thus, the entire flange does not carry the full material yield stress. In order to improve the design, honeycombs have been used to completely support the facing so that the thin facing will not buckle. Furthermore, the facing can also handle the full material yield stress.

2.2.3 Core materials

One of the important elements in sandwich construction is the core. Cores have a significant effect on the properties of the sandwich structure. There are two functions of the core. First, it separates the face sheet and resists deformations perpendicular to the face plane. Second, it serves to provide a certain degree of shear rigidity along planes that are perpendicular to the faces. In addition, the purpose of the core is also to hold the skins together so that the panel does not buckle, snap, deform, or break. Moreover, the core keeps the skins fixed and relative to each other. Typically, the core experiences a shear stress as the two skins attempt to slide past each other. Furthermore, the stiffness of the core is determined by the shear properties of core materials. The stiffness of the panel is mainly determined by the core material properties and the thickness of the core.

Flexible cores are known to have a low shear modulus while very stiff cores have a high shear modulus. If the core is bent enough, eventually tension will cause the side to crack and fail. The top layer of the sandwich skin will tear when the tensile strength of the skin is exceeded by the bending force. A solution to this would be to bond another material to the surface, creating a skin with a higher tensile/compressive strength. This skin works in conjunction with the core. By doing this, a composite sandwich panel is constructed. Moreover, to minimize the change in stiffness and then the interlaminar stress concentration at the interface, the core should have smooth property variations across the thickness, that at this position are similar to those of the faces (Icardi et al., 2009).

The failure characteristics of sandwich structures are significantly different from conventional laminated structures and are strongly dependent on the core and skin materials and their thickness. The core material is much softer than the skin and will experience a much larger deformation. The localized damage is usually confined to the top facing, the core-top facing interface, and the core material (Meo et al., 2005). Furthermore, damage of the core proves to be very important as it occurs at the weakest energies and without any visible damage on the laminated skins. Most of the damage initiation threshold and damage size depends on the properties of the core materials, face sheets, and the relationship between the properties of the cores and those of the facings (Hosur et al., 2004).

Core materials are expected to substantially affect the damage initiation characteristics of sandwich panels because they generally have lower mechanical properties than skins due to their lower density. Hence, core damage, which is characterized by a substantial change in the load-deflection curve, has been identified as the first failure mode in low velocity impacts of honeycomb sandwich structures with a high skin-to-core stiffness ratio (Foo et al., 2008). However, one of the problems in the honeycomb is the low surface area of core for bonding. There are a number of materials and structures employed for cores. Among them is honeycomb, foam, balsa wood, and corrugated cores (Hosur et al., 2004). Comparisons between the core materials are shown in Table 2.2. This study focuses only on honeycomb structures as the core in sandwich structures.

Table 2.2 Comparisons of properties for variation types of core

Material	Compressive Strength (MPa)	Young's Moduli (GPa)	Recoverable	Reference
Polymeric foam core	2.05	0.28	No	Hazizan and Cantwell, Yen et al
Metallic foam core	13.5	0.5	No	Kiratisavee and Cantwell, Koza et al
Aluminium honeycomb core	5.91	70	Yes (but takes time)	Hazizan and Cantwell, Foo et al.
Thermoplastic honeycomb core	1.5	1.02	Yes	Griskevicius et al.
Nomex honeycomb	212	0.127	No	Foo et al

2.2.3.1 Honeycomb core

Honeycomb core materials have been extensively used in sandwich construction. The most common adhesively bonded honeycomb cores are aluminium or made out of composite materials; Nomex, fiberglass, glass thermoplastic, glass-phenolic or paper (Bitzer, 1997). Stainless steel is the most widely produced corrugated core. The basic reason behind the use of honeycomb is to save weight; however, smooth skins and excellent fatigue resistance are also attributes of a honeycomb panel. The honeycomb mechanical properties that are generally determined are compressive strength and modulus, shear strength and modulus, fatigue, and Poisson's ratio. For energy absorption applications, crush strength is needed, which is approximately 50% of the compressive strength. In a study by Aminanda et al.(2009), honeycomb is represented by a grid of vertical springs in which behaviour law in compression experiments.

Figure 2.4 Honeycomb core-cell (http://www.alustrong.com).

The basic cell shape for the honeycomb is hexagon, square and flex-core, as shown in Figure 2.4. The hexagon cell is a common adhesively bonded honeycomb, while most resistance welded and brazed cores have square cells (vary narrow nodes). The honeycomb core properties depend on the size of cells and the thickness and strength of the web material. They result in stiff and very light sandwich laminates with composite skins and high-performance resin systems, such as epoxy, provided that the necessary adhesion to the laminate skins can be achieved (Aktay et al., 2005). Sandwich construction with honeycomb is also excellent for absorbing mechanical and sound energy. It has high crush strength-to-weight ratio. It can also be used to be an insulative barrier (Vinson, 1999). Among the options of many kinds of cores, polypropylene (PP) honeycomb is the most attractive for transportation applications due to its excellent properties, such as light weight, rot resistance, impact resistance, excellent bonding, and recycling ability (Ning et al., 2007).

A thorough and detailed review of the characteristics of cores has been investigated. Certainly, understanding and modelling the crushing phenomenon is the main point of impact on sandwich structures with honeycomb. Core crushing is a complex mechanical phenomenon characterized by the appearance of various folds and failures in the hexagonal structures. This phenomenon is known for its energy-absorbing capacities and has been analysed since 1963 by R.K. Jr. McFarland. The authors also showed that much of the incident energy of the projectile is absorbed in crushing the core material within a localized region immediate to the point of impact. The crushing of aluminium core has been extensively studied by Wierzbicki et al.(1983). Constitutive equivalent models have been developed and have been applied successfully to experiments on large structures subjected to blast loads. All the approaches presented have a common feature which is to consider the honeycomb as a homogeneous material.

There are many types of honeycomb that have been used extensively in sandwich manufacturing. These include Nomex honeycomb, aluminium honeycomb and thermoplastic honeycomb. A number of studies have been carried out to investigate the honeycomb core properties for sandwich structure fabrication. Horrigan et al. (2000) conducted impact tests on a Nomex honeycomb sandwich structure with glass fibre reinforced epoxy facings. Their results indicate that a soft projectile generates shallow crushing in the core whereas rigid impactors generate deeper damage that conforms to the shape of the projectile. It also appears that Nomex honeycomb has a more complex micromechanical behaviour. Matrix cracking at the surface and local detachment and tears are observed (Tsotsis and Lee, 1996). Griskevicius et al. (2010) characterise the deformation behaviour of thermoplastic honeycomb core sandwich structures. According to the results, the dynamic properties of the structure, as well as deformation behaviour, depend upon its geometry. With buckling failure dominating the deformation mode, the shear strains increased, which led to more effective view point of energy absorption to dominate. They also recommend that this system is very suitable for application in safety important structures.

Honeycomb cores are not continuous, since they are made of webs arranged in cells which are joined together to form periodic structures. In compression, linear elastic behaviour is observed until a peak load is reached. As load is introduced in a compressed manner, steady crushing under constant load is observed (Abrate, 1998). During this time, the cell walls deform elastically with linear elastic deformation up to the bare compressive strength. Beyond that, the cell walls will start to be crushed by elastic buckling and plastic yielding or brittle fractures, depending on the honeycomb material. Once the honeycomb is fully compacted, the load will start to rise rapidly again. This point is called the densification point. The densification level of the honeycomb during compression depends on the cell wall thickness, length and thickness-length ratio (Wang and Wang, 2009). Unloading after steady crushing of the honeycomb produces minimal elastic recovery, which is again dependent on the type of material for the honeycomb. A typical curve for honeycomb load compression is shown in Figure 2.5.

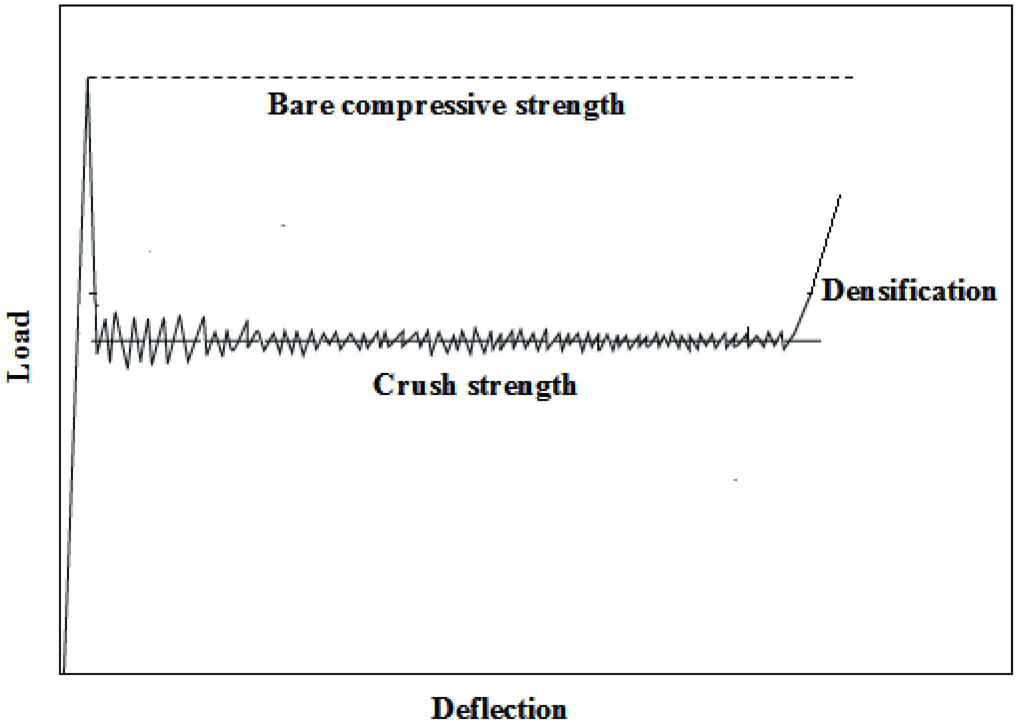

Figure 2.5 Honeycomb core crush curve (HexWeb® Honeycomb Energy Absorption Systems).

Due to its excellent properties, PP honeycomb was used as the main core in this study. PP honeycomb cores hold excellent characteristics which are suitable for many applications. These include being lightweight with a good stiffness strength ratio, good energy absorption, resistance to corrosion, fungi, rot, chemical and moisture resistant, sound and vibration dampening, recyclable, and easy to be assembled. This type of honeycomb core can be easily combined with different surface panels such as wood, plywood, fiberglass, stainless steel, steel, paper, marble, PU foam, and aluminium. The combination methods are by hand, vacuum, pre-immerged resin, and insert to frame.

2.2.4 Face sheet material

Face sheets play an important role in determining the overall stiffness of the sandwich structure. The sandwich structure consists of thin and stiff face-sheets, made from either metal (aluminium alloys) or composites (such as carbon/epoxy, glass/epoxy, etc.), separated by light weight cores. One of the function of the face sheets is to protect the core. Almost any material can be used for sandwich facings from plywood to carbon tape fiber composites. Other examples of face sheet materials include alumina, carbon fiber reinforced aluminium, titanium, aluminium, high strength steel, and SiC/Al. The selection of the face sheet material is dependent on the panel requirements such as strength, stiffness, damage tolerance, environmental conditions, appearance and cost (Bitzer, 1997).

In many applications a thin skin would work structurally to handle the loads and deflection requirements but would not withstand the damage to which it would be subjected. For damage tolerant sandwich panels, the face sheet materials and thickness also depend on the type and density of the honeycomb (core). Within the principle of sandwich structure construction, the face sheet carries the tangential and bending loads, whereas the core keeps the face sheets at their desired distance and transmits the transverse normal and shear loads. Furthermore, when a sandwich panel is bent, one skin experiences tension, and the other skin experiences compression. This is where the majority of strength is created in a sandwich structure. Although the skin and core stretch and compress evenly at the location of the bond, the core and the skins have different material properties, and will in turn act differently to this bending. As the face sheet becomes the first target of the projectile during the impact, it is important to consider the influence it will have on the overall structure. To protect the core, the face sheet needs to be a strong and stiff material. Basically, the most important aspects in the selection of a face sheet are determined by its stiffness. In this case, the stiffness of the face sheet is not only dependent on the material properties themselves, but also on the thickness of the laminate, the design, its size and the boundary conditions. The stiffness of the thickness has a significant effect on the value of the maximum force, which leads to the extent of the damage induced.

To date, several researchers have reported their studies on the effect of face sheet materials on the stiffness and strength of the laminates and sandwich structures. Mohan et al. (2007) studied the effect of face sheet on the indentation response of the metallic foams. As loads increase, the indentation depth also increases since the initial elastic response is very shallow. The failure mode is essentially due to local indentation beneath the spherical punch. The face sheet material has to stretch to accommodate the punch profile. Park et al. (2008) studied the impact damage resistance of sandwich structures composed of Nomex honeycomb cores and two kinds of face sheets (carbon/epoxy and glass/epoxy laminates). The results show that most of the impact damages are greatly influenced by the face sheet type as the main delamination in the face sheets consists of a peanut-shape with a major axis along the lower fiber orientation. Furthermore, the damage resistance of sandwich structures appears to be dependent on both the face sheet materials and core thickness, as the lower the stiffness of face sheets becomes, the greater the core thickness affects the impact resistance. Wen et al. (1998) conducted experiments on composite sandwich panels consisting of woven E-glass/polyester laminates and foam cores, and also found that there was an increase in the failure load of the composite sandwich under impact loading when compared to static load indentation. They attributed the load increase to the enhanced strength and stiffness of the glass/polyester face sheet and foam core at high strain rates, as well as the inertia of the projectile and composite sandwich.

One of the materials that has been gaining interest as a face sheet in sandwich construction is metallic skins. The purpose of using a metallic skin in sandwich structure is to avoid the complex mechanisms of laminate skins damage. A limited number of studies has focused on the impact behaviour of sandwich structures with metallic face sheets. Castanie et al. (2008) conducted a low-velocity impact test on metallic skin sandwich structures, but only focused on developing a method to model the low-velocity/low-energy impact on metal skinned sandwich composites. Aminanda et al. (2009) investigated the compression after impact of sandwich structures with metallic skins, but also focused only in modelling the structure.

2.2.5 Adhesive systems

Adhesives play a major role in bonding a sandwich structure. The main purpose of the adhesive is to bond the face sheet to the core. Sandwich structures are normally used because they are lightweight; therefore, the panel should be made as light as possible. Most film adhesives used for this purpose weigh about 0.29 kg/m. On thin panels, the adhesive can be a very large percentage of the total sandwich weight. However, on thicker panels it is not as important.

A brief discussion on adhesive joints is appropriate. There are five critical factors to any adhesive joint; the two adherend (the materials to be bonded), the adhesive and the boundary layers between the adhesive and the adherend. These are shown in Figure 2.6. The adherend physical properties are tensile and shear modulus, coefficients of thermal expansion and so on. The properties of adherend are important in determining which adhesive to use. The most important principle in this case is the boundary layer interaction between the adhesive and adherend. Metals from oxides on the surface and the adhesive must be compatible with this surface energy to ensure that an adequate bond is developed.

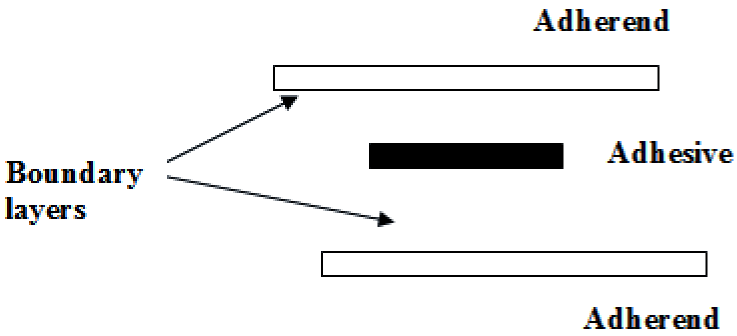

Figure 2.6 Adhesive joint (Bitzer, 1997).

The basic ways an adhesive is loaded are in tension, shear, peel and cleavage. Tension and shear stresses are taken by the entire bond area and provide the strongest mode. Peel and cleavage forces concentrate the stress along one side or at a very thin line at the edge of the bond. These act to concentrate the stresses rather than distribute them, such that very little of the bond contributes to the load bearing. The joint should be designed to eliminate these latter modes. This is also a very important consideration in designing panel closeouts. A tough adhesive should be used if the sandwich panel skin is going to be subjected to peeling or cleavage loadings. The major problem in this case is that tough adhesives are usually not good or suitable for high temperature applications, and most high temperature adhesives are brittle. For example, when a honeycomb sandwich panel is loaded for a long time or at high temperatures, creep can occur at the boundary layers. As shown in Figure 2.7, added deflection over time is caused by the deformation of the core-to-skin adhesive.