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TAJUK PROJEK : PERIODIC TWO-DIMENSIONAL SELF REINFORCED POLYPROPYLENE HONEYCOMB CORE FOR SANDWICH STRUCTURES

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PERIODIC TWO-DIMENSIONAL SELFREINFORCED POLYPROPYLENE HONEYCOMB CORES FOR SANDWICH STRUCTURES

UNIVERSITI MALAYSIA PAHANG

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ABSTRACT

Hexagonal honeycomb cores have found extensive applications particularly in the aerospace and naval industries. In view of the recent interest in novel strong and lightweight core architectures, square honeycomb cores were manufactured and tested under uniform lateral compression. A slotting technique has been used to manufacture the square honeycomb self-reinforced polypropylene (SRPP). The compressive responses of the sandwich structures were measured as a function of relative density. In this research, particular focus is placed on examining the compression strength and energy absorption characteristics of the square honeycombs with different types of model. Comparisons in terms of specific strength and specific energy absorption have shown that the Sandwich Star core offers excellent properties in term of compressive strength. The SRPP core could potentially be used as an alternative lightweight core material for recyclable sandwich structures.

ABSTRAK

Teras sarang lebah heksagon mendapat aplikasi yang meluas terutamanya dalam industri aeroangkasa dan tentera laut. Memandangkan kajian baru-baru ini dalam seni bina teras novel kuat dan ringan, teras sarang lebah persegi telah dibuat dan diuji di bawah mampatan sisi seragam. Satu teknik slotting telah digunakan untuk menghasilkan sarang lebah persegi polipropilena bertetulang sendiri (SRPP). Maklum balas mampatan struktur sandwich diukur sebagai fungsi ketumpatan relatif. Dalam penyelidikan ini, tumpuan khusus diberikan terhadap memeriksa kekuatan mampatan dan penyerapan tenaga dengan ciri-ciri honeycombs persegi dengan pelbagai jenis model. Perbandingan dari segi kekuatan tertentu dan penyerapan tenaga tertentu telah menunjukkan bahawa teras Sandwich Star menawarkan ciri-ciri yang sangat baik dari segi kekuatan mampatan. SRPP teras serta berpotensi digunakan sebagai bahan teras ringan alternatif dalam struktur sandwich dikitar semula.

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H	Height
σ	Stress
F	Force
A	Area
E	Elastic modulus
ε	Strain
e	Energy
ρ	Density
M	Mass
L	Length

LIST OF ABBREVIATIONS

SRPP	Self-reinforced polypropylene
PP	Polypropylene
CAE	Computer-aided engineering
ANSYS	Analysis system software
FEA	Finite element analysis
CFRP	Carbon fibre reinforce plastic
TTU	Through-transmission ultrasonic
C-scan	Computer scan
FRP	Fibre reinforce plastic
PVC	Polyvinyl chloride
3D	3 Dimension
ASTM	American Society for Testing and Materials
SEA	Specific energy absorbtion

CHAPTER 1

INTRODUCTION

1.1 GENERAL INTRODUCTION

Nowadays, the designers faced a challenge of protection of impact which is to absorb the maximum amount of energy within a minimum amount of space. Energy absorbing honeycomb provides the solution for the situation. Honeycomb structures that have a minimum amount of material used to achieve minimum weight and material cost. Honeycomb main advantages are light weight, low density, high stiffness to weight ratio, high energy absorption and great anti-shock properties study by Shen et., al (2013) and Asprone et al., (2013).

In the automotive industry, honeycomb energy absorbers are widely used for impact protection and crash test barriers. The properties of honeycomb structure of energy absorbing are also used in the aerospace and nuclear industries besides of automotive industries. The advances buffer structure found in honeycomb structures. Honeycomb structures are used as shock-absorbent layer in an automobile because of the anti-shock properties and high energy absorption to reduce the impact effect (Li, m. et al., 2014). The partially pre-crushed honeycomb is used to eliminate peak loading, helps in reducing the risk of structural damage during collision or impact.

In this project the square honeycomb structure is chosen because of the high energy absorption properties with minimum peak stress values. Besides that, the polypropylene material is chosen because of the high strength to weight ratio, high specific properties and the most relevant to use this material because its characteristic plus recyclability. The main objective of this project is to develop the square honeycomb composite structure by using recyclable material (selfreinforced polypropylene)

Compression properties of square and triangular honeycomb plus specific energy absorption of reinforce polypropylene (SRPP). Finally, the structural model will be constructed using CAE software (ANSYS). Finite element models are develop to accurately predict the strength, energy absorption characteristic, buckling behavior and failure mode on this structural.

1.2 PROBLEM STATEMENT

In recent year, road accidents in Malaysia showing an increasing trend. In order to reduce the road accidents, transportation vehicle manufactures are searching for advanced buffer that has low weight and volume to design the vehicles. Honeycomb structure used as ideal structure in vehicle design due to its high energy absorption, lightweight, high relative stiffness and strength. A honeycomb structure is an ideal snub structure due to its low density, low stiffness, large pressure-deformation and deformation control (Li, Deng, Guo, Liu & Ding, 2014). One practical application for metal honeycomb structures is as energy absorbers, which are frequently adopted in the automotive industry. The present invention relates to automobile bumpers. In particular, bumper of impact absorber comprising a metallic, plastic or paper honeycomb core covered by a metal, plastic shell or rubber are used to reduce damage to body and fenders of an automobile during slow speed crashes. Previous studies showed that energy absorption capacity of honeycombs relies not only of the base materials, foil thickness and cell length but also on the topological properties of the honeycombs. Besides hexagonal honeycomb structure, these honeycombs can be fabricated using triangular and square structures (Li, Deng, Guo, Liu & Ding, 2014).

Recyclable material have been used in the honeycomb structure such as fibre. Furthermore some material does not user friendly such as fibre glass even the materials has the better maximum stress and stiffness. Moreover, traditional sandwich structure mostly used glue and hot press technique. Therefore, a new design that have a good strength to weight ratio using simple slotting technique will increase the mechanical performance without avoiding the energy absorbtion. This study will be focusing on square and triangular honeycomb structure. Research was completed by finding the maximum strength and minimize the density where the design and length of the structural model were used as values.

1.3 OBJECTIVES OF RESEARCH

This research mainly focuses on applying the slotting method with variable design and length in order to examine the most optimized square honeycomb structure that has the maximum energy absorption and lightweight capacity. This research highlight three main objectives to be achieved.

The objectives of this research are:

1. To develop the square honeycomb composite structure by using recyclable material (self-reinforced polypropylene)
2. To investigate the compression characteristics and specific energy absorption of the structures
3. To model the structural behavior, and predict the failure location and mechanism of both the composite core structures

1.4 SCOPE OF RESEARCH

The scopes of this research are as follows:

i. Literature review of general properties of honeycomb structures.
ii. Determine parameters settings and include the parameters into a test matrix.
iii. Using CATIA software to design the square honeycomb structural model.

iv. The structural models will be constructed using the CAE software and will be analysed by utilising the ANSYS software

v. Fabricate square and triangular honeycomb structure by using end mill machine and slotting technique.

vi. Validate crushing behaviour of composite square honeycomb structure using Instron universal compression test. vii. Analyzing typical stress-strain curve of elastic-plastic deformation and compare with ANSYS FEA software.

1.5 THESIS ORGANIZATION

The thesis is organized in five chapters. Chapter 1 mainly reviewed about the general introduction of honeycomb structure and some main objective of this project. Chapter 2 reviewed the different material plus assemble design of honeycomb structure that proposed by other researcher and the latest approach. This chapter also contain the type mechanism of the other design and material used that give the ultimate strength and what cause the tendency to happen.

Chapter 3 basically illustrates the methodology of using the CATIA and ANSYS software to predict the strength. Besides that, it also contains experiment setup to run the compression test. This chapter also describe on how to assemble the rectangular and triangular honeycombs. Chapter 4 focuses on result of the compression tests and the discussion based on the result obtained. It shows the two types of analysis that are experimental result compare to ANSYS analysis software.

Lastly, in chapter 5, it’s concluded the overall objectives of this project about how this project runs and what one the outcomes from this project. Recommendations also included in this chapter in order to improve this project for future research.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter review all the other research has been done before. There are many proposed and description of the composite material will be discussed. In addition, this chapter will focus on properties of honeycomb structures, crushing behavior, scaling effect, failure mechanisms and energy absorption. The necessary and application of square honeycomb structure at several sector also discussed. The type and material used for honeycomb structure will be discussed further in this chapter that has been proposed from time to time. However, there are some argument on how precise the method used and how simple that method. So, in this chapter it will review all the methods proposed and how to handle the methods.

2.2 SANDWICH MECHANISM AND STRUCTURE

Sandwich structures are broadly utilized as a part of aviation and astronautic building for a better weight-particular compare to monolithic solid sheet due to the separation of two thin skin layers by cellular core materials. The lattice truss materials, including pyramidal, lattice block, tetrahedral and Kagome, have drawn attention as a new generation of cellular core materials because of their higher weight efficiency and multifunctional potential. The truss members in lattice truss materials deform predominately by local stretching unlike bending of cell walls in stochastic foams under all macroscopic stress states. (Deshpande et al. 2001and Queheillalt Douglas T 2009). For the purpose of exploring the mechanical properties of lattices, the corresponding techniques have been developed for manufacturing metal lattice truss core sandwich structures, including perforated sheet folding, wire assembly and investment casting methods. (Wadley et al., 2006). Kooistra have manufactured aluminium tetrahedral lattice truss sandwich structures with cell core relative densities between 0.02 and 0.08 by folding perforated aluminium alloy sheets, indicating that the compressive strength of this structure outperforms other cellular aluminium topologies and the impact energy absorption competes well with other concepts under high intensity loading conditions (Kooistra et al., 2008).

In general, comparisons with other cellular core materials such as metal foam, prismatic corrugations and honeycombs, have shown that the created metal grid truss center materials are stiffness/strength-to-weight ratio and energy absorption performance, particularly in multifunctional applications of their large interconnected void space. The mechanical behavior of cross section truss center materials is defined by the inherent properties of their constituent material and relative thickness. So that, the mechanical properties of grids can be enhanced by utilizing high specific/firmness material. CFRP has been utilized to manufacture grid materials because of high specific quality/firmness by the base is composite pyramid lattice truss centers.

Curved panels with sandwich construction are used successfully in a variety of applications such as spacecraft, aircraft, train/car, and boat/ship structures. However, traditional sandwich shells made from foam corrugated and honeycomb cores with close-cells cannot accommodate free fluid movement through them (Ballere l et al., 2009; Baba et al., 2009; Kazemahvazi et al., 2009; Shen et al., 2010; Yan et al., 2013). According to the study (Wadley et al., 2006) fabrication of sandwich panels with open-cell core constructions with interconnected void spaces can extend the usage of sandwich panels to functional applications.

Fiber reinforced composite sandwich panels with lattice core construction are already of increasing interest in aerospace and marine applications. The effort to fabricate low density lattice core construction has been considerably accelerated by the utilization of several manufacturing techniques including Kirigami techniques (Saito K. Kirigami et al., 2013, and Hou Y et al., 2014). Significant amount of literatures exist about the bending behavior of flat sandwich panels with lattice cores. (Xue et al., 2007) proposed a general Homogenization method for modeling the response of low density core constructions capable of simulating the response of sandwich panels up to large deformations with high fidelity.

In this study, investigate the bending behavior of hybrid structures with bended metallic lattice core and composite face sheets utilizing a mix of three point bending tests on in-house manufactured specimens, scientific modelling and computational simulation. From the other point, composites generally have higher quality/weight and solidness/weight contrasted with metals. Moreover, manufacture techniques for curved composite sandwich boards are still in their initial stages, particularly considering challenges connected with improvement of composite lattice core center developments.

A range of sandwich cores have been produced with the objective of developing a lightweight structure, which is both strong and stiff. From balsa wood of the 'mosquito aircraft' to polymer foams and honeycomb cores, and recently more researchers are investigating ideal lightweight cellular core candidates for sandwich structures (Rejab and Hassan., 2014). The mechanical properties of sandwich core materials are governed by three factors; the topology of the cellular materials, the properties of the parent and the relative density, ρ* defined by the volume fraction of solid material.

The manufacture of strong and stiff cellular materials requires the correct selection of materials and topologies. An appropriate combination can delay the onset of failure modes such as yielding or plastic buckling in metals, and delamination or fibre fracture in fibre reinforced composites. Since the majority of studies in the field of sandwich structures are on polymeric and honeycomb core materials, there is very little information in the open literature on honeycomb square core. Therefore, this project aims to undertake finite element investigation on square honeycomb sandwich structures subjected to compress loading condition. Optimization of shape design will be conducted and honeycomb core sandwich structure will be performed, and the simulation results will be validated against the experimental data.

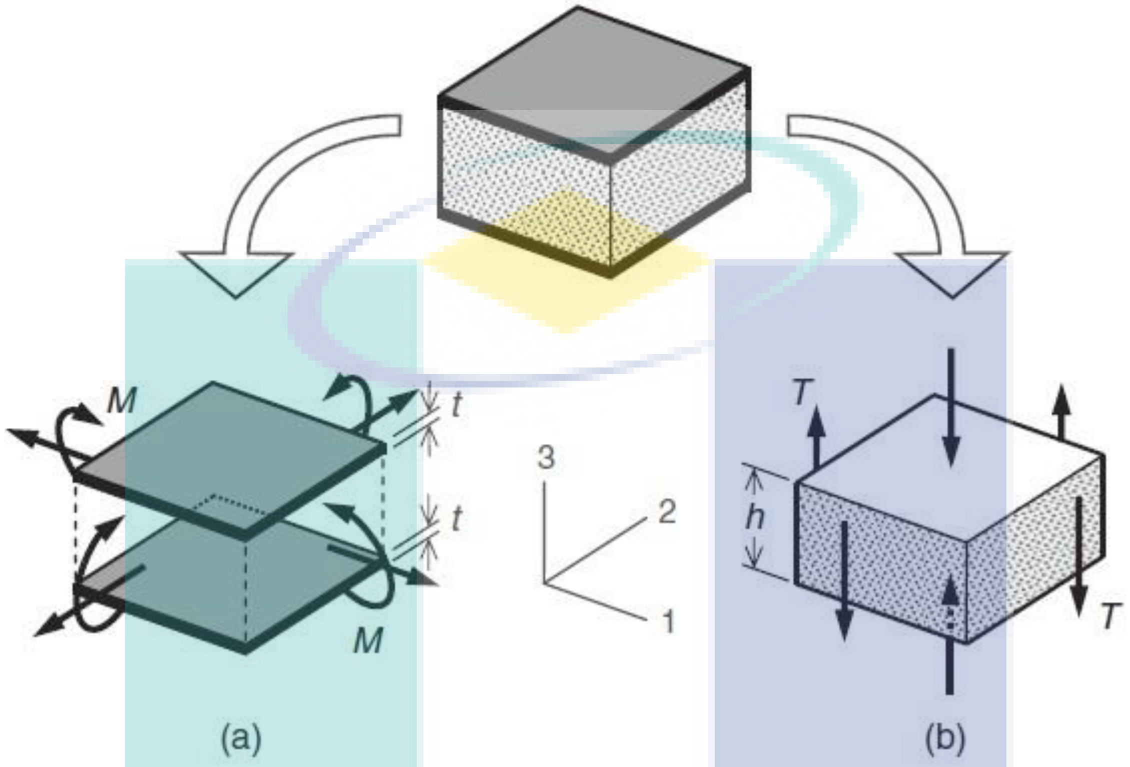


Figure 2.1 Load sharing between faces (a) and core (b) in a sandwich structure.

Source: Eugenio Dragoni et al., 2013

The weight optimization of the entire panel must take into account the weight of the faces and the weight of the core, both of which depend primarily on the corresponding thicknesses. From an engineering standpoint, the overall mass of the sandwich (core mass plus faces mass) is rightly regarded as the objective function to be minimized. By way of example, shows that the thickness *h* of the core is a key parameter in this global optimization process for a sandwich panel under coplanar bending and shear (M and T in Figure 2.1). For any particular thickness *h*, demonstrates that the total mass of the sandwich is minimized by minimizing the apparent density of the core under the ensuing constraints on its mechanical properties. In order to minimize the panel weight globally, thickness *h* needs to be inserted in the optimization procedure as a loop variable. In short, the process assumes an initial value for *h*, the core density is minimized (Eugenio Dragoni et al., 2013).

Minimization of the core density is central to minimizing the overall sandwich weight. To this aim, the next section presents the fundamental properties of the tetrahedral truss core which are necessary for its density minimization. Sandwich-structured is a structural composite material that is fabricated by attaching two thin but stiff skins to a lightweight but thick core. The core material is normally low strength material, but its higher thickness provides the sandwich composite with high bending stiffness with overall low density. Open- and closedcell-structured foams like polyvinylchloride, polyurethane, polyethylene or polystyrene foams, balsa wood, syntactic foams, and honeycombs are commonly used core materials. Open- and closed-cell metal foam can also be used as core materials. Laminates of glass or carbon fiber-reinforced thermoplastics or mainly thermoset polymers are widely used as skin materials. Sheet metal is also used as skin material in some cases. The core is bonded to the skins with an adhesive or with metal components by brazing together (Zenkert et al.,1995).

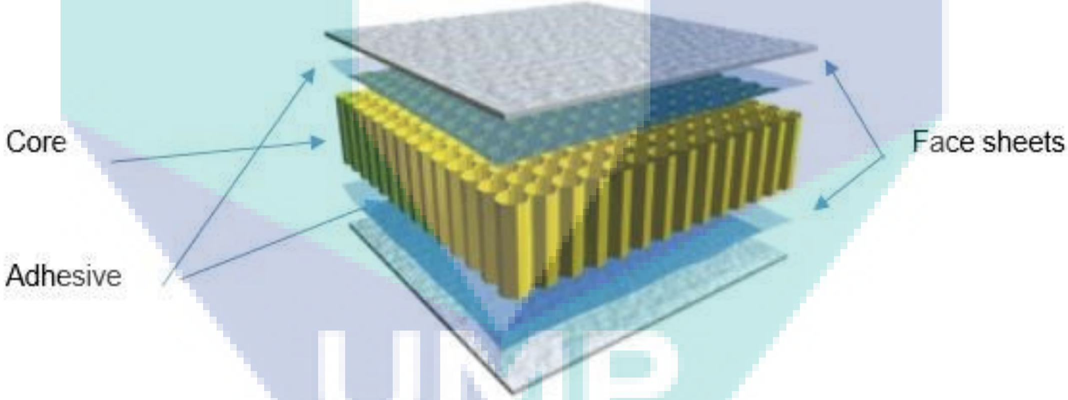


Figure 2.2 Main component of sandwich structure

Source: Zenkert et al.,1995

2.2.1 The face sheet

The face sheet carries most of the tensile stress. When the local pressure is high, the faces should be dimensioned for the shear forces connected to it compressive stresses in the sandwich. The local flexural rigidity is often so small test it can be ignored. Conventional materials such as steel, stainless steel and aluminum are often used as face sheet material. It is also suitable and common to choose fiber or glass-reinforced plastics as face materials.

2.2.2 Core

The core's main function is to support the thin skins so they do not buckle (deform) inwardly or outwardly, and to keep them in relative position to each other. To accomplish this, the core must have several important characteristics. It has to be stiff enough to keep the distance between the faces constant. It must also be so rigid in shear that the faces do not slide over each other. The shear rigidity forces the faces to cooperate with each other. If the core is weak in shear, the faces do not cooperate and the sandwich will lose its stiffness. It is the sandwich structure as a whole that gives the positive effects. However, the core has to fulfill the most complex demands. Strength in different directions and low density are not the only properties the core must have. Often there are special demands for buckling, insulation, absorption of moisture, aging resistance. The core can be made of a variety of materials, such as wood, aluminum, and a variety of foams (Kehrle R et al., 2004).

2.2.3 Adhesive (Bonding layer)

To keep the faces and the core cooperating with each other, the adhesive between the faces and the core must be able to transfer the shear forces between them. The adhesive must be able to carry shear and tensile stresses. It is hard to specify the demands on the joints (Zenkert et al.,1995). A simple rule is that the adhesive should be able to take up the same shear stress as the core. It is of utmost importance that the face sheet properly adhered to the core to give the expected structural behavior.

2.3 SANDWICH PRINCIPLE

A sandwich structure operates in the same way with the traditional I-beam, which has two flanges and a web connecting the flanges. The connecting web makes it possible for the flanges to act together and resist shear stresses.

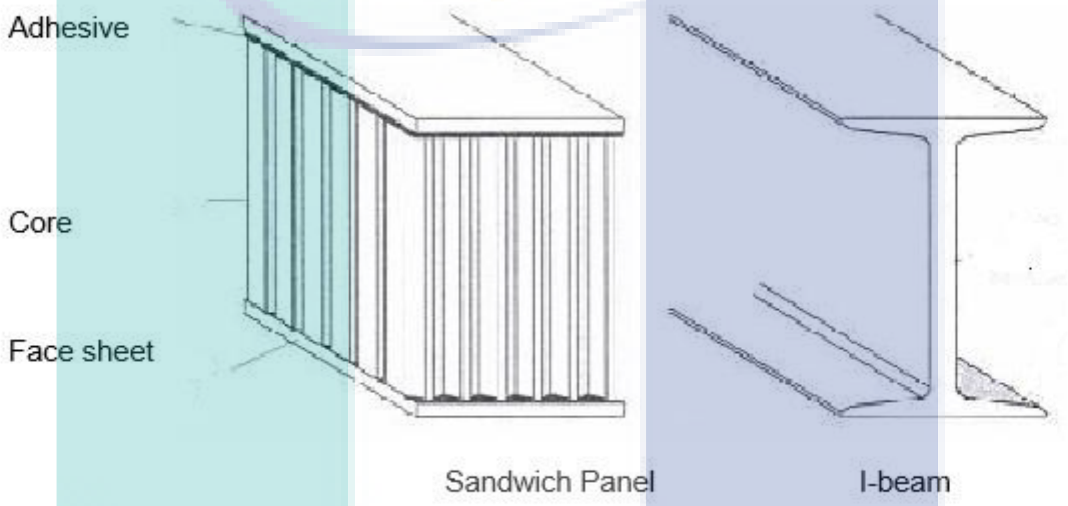


Figure 2.3 Sandwich structure in comparison with an I-Beam.

Source: (Vaziri et al.,2007).

Sandwich structure and an I-beam differ from each other that, in a sandwich structure the core and laminates are different materials and the core provides continuous support for the laminates rather than being concentrated in a narrow web. When the structure subjected to bending the laminates act together, resisting the external bending moment so that one laminate is loaded in compression and the other in tension. The core resists transverse forces, at the same time, supports the laminates and stabilizes them against buckling and wrinkling (local buckling)(vaclav 2013).

Sandwich structures should be designed to meet the basic structural criteria such as the face sheets should be thick enough to withstand the tensile, compressive and shear stresses and the core should have sufficient strength to withstand the shear stresses induced by the design loads. Adhesive must have sufficient strength to carry shear stress into core. The core should be thick enough and have sufficient shear modulus to prevent overall buckling of the sandwich under load to prevent crimping. Compressive modulus of the core and the face sheets should be sufficient to prevent wrinkling of the face sheets under design load. The core cells should be small enough to prevent the face sheet (Vaziri et al.,2007).

2.4 DESIGN CONSIDERATIONS

A sandwich structure is designed to make sure that it is capable of taking structural loads throughout its design life. In addition, it should maintain its structural integrity in the in-service environments. The structure should satisfy the following criteria (Petras., 1998):

- The face sheets should have sufficient stiffness to withstand the tensile, compressive, and shear stresses produced by applied loads.
- The core should have sufficient stiffness to withstand the shear stresses produced by applied loads.
- The core should have sufficient shear modulus to prevent overall buckling of the sandwich structure under loads.
- Stiffness of the core and compressive strength of the face sheets should be sufficient to prevent the wrinkling of the face sheets under applied loads.
- The core cells should be small enough to prevent inter-cell buckling of the face sheets under design loads.
- The core shall have sufficient compressive strength to prevent crushing due to applied loads acting normal to the face sheets or by compressive stresses produced by flexure.
- The sandwich structure should have sufficient flexural and shear rigidities to prevent excessive deflections under applied loads.

2.4.1 Failure Types of Sandwich Structures

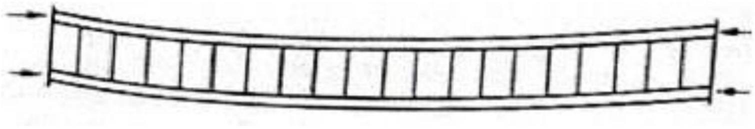


Figure 2.4.1. (a)

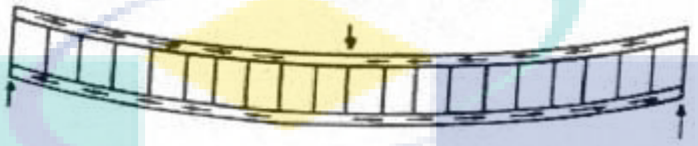


Figure 2.4.1. (b)

Figure 2.4.1(a)(b): Faceplates should be thick enough to withstand the tensile, compressive and shear stresses induced by the design load

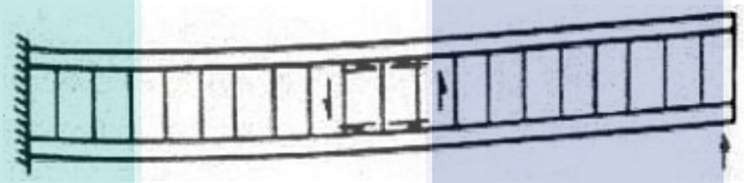


Figure 2.4.2: The core should have sufficient strength to withstand the shear stresses induced by the design loads. The adhesive must have sufficient strength to carry shear stress into the core.

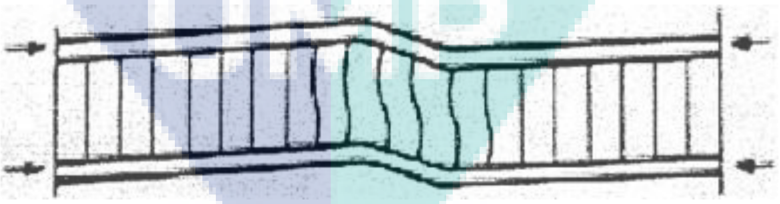


Figure 2.4.3: The core should be thick enough and have sufficient shear modulus to prevent overall buckling of the sandwich under load, and to prevent crimping.

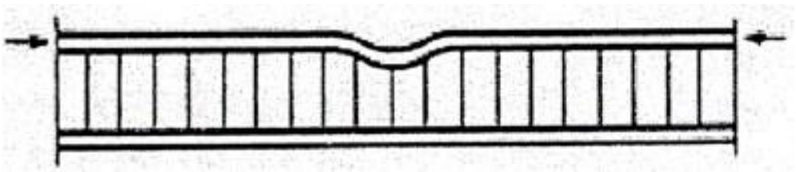


Figure 2.4.4: Compressive modulus of the core and facings should be sufficient to prevent wrinkling of the faces under design load.

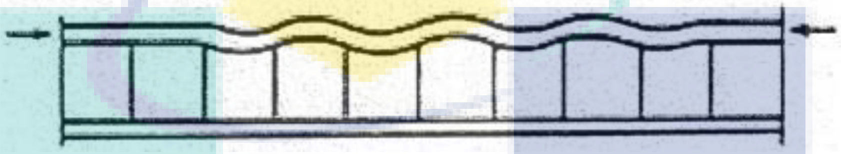


Figure 2.4.5: The core cells should be small enough to prevent intracell dimpling of the faceplates under design load.

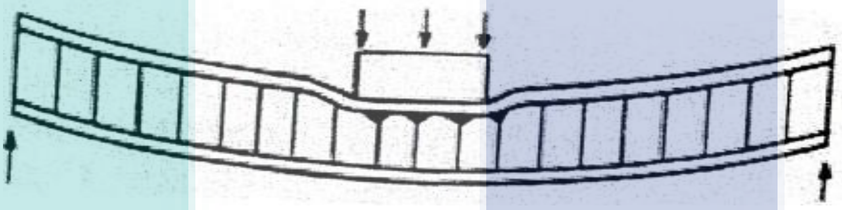


Figure 2.4.6: The core should have sufficient compressive strength to resist crushing by design loads acting normal to the panel facings or by compressive stresses induced through flexure.

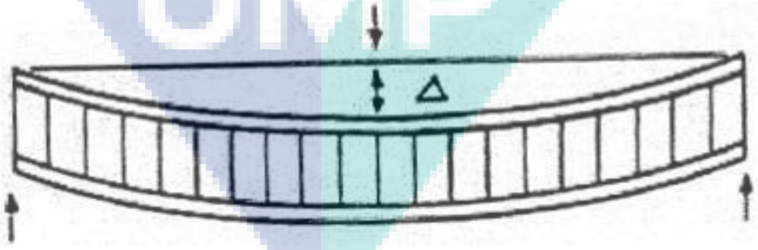


Figure 2.4.7: The overall structure should have sufficient flexural and shear rigidity to avoid excessive deflections under design load.

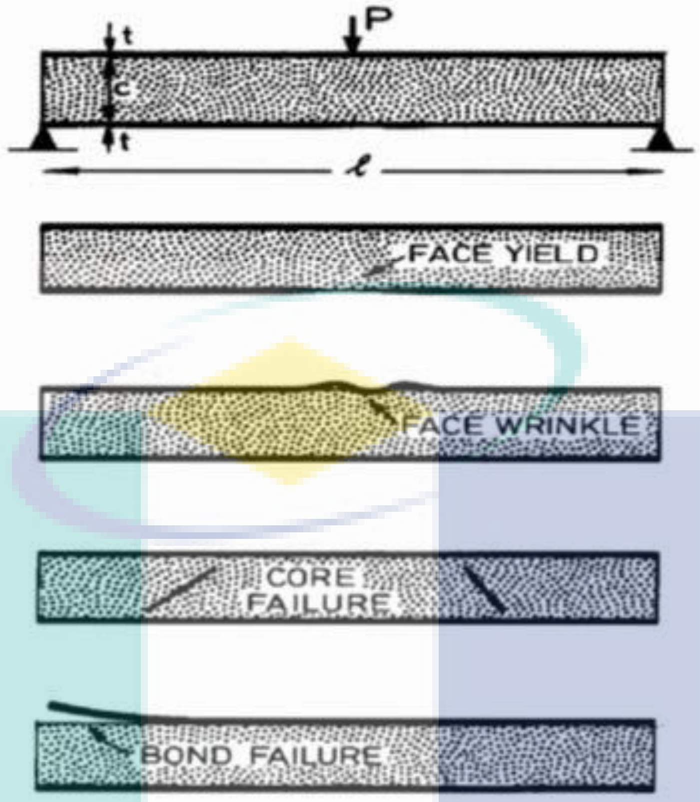


Figure 2.4.8: Damage in sandwich composites, whether foam or honeycomb, is a complex phenomenon due to the numerous competing failure mechanisms (Baba et al., 2009).

2.4.2 Effect of compression towards sandwich structure

The damage states in sandwich panels can be broadly classified as material damage states and geometric damage states. The material damage states include face sheet damage, core damage, and face sheet-core interface disbands (Mitrevski et al. 2005). The face sheet damage states encompass delamination, matrix cracks, and face sheet/ply fractures. The core damage states may comprise of core crushing (foam cores), cell wall buckling (honeycomb cores), and core fractures. The geometric damage state in sandwich panels manifests as a residual indentation distribution around the point of impact. The various damage states may occur simultaneously with the relative proportions being dictated by the intrinsic and extrinsic variables. In this section, the damage states observed during the experimental program are enumerated.

2.4.3 Face Sheet Damage

The facesheet damage states may be comprised of facesheet delaminations, matrix cracking, and ply/facesheet fractures. The initiation of facesheet damage was observed to be dependent on the impactor size (diameter). A limited number of sandwich panels ($[(90/45)_2/CORE]_s$) with fiberglass facesheets and honeycomb cores (Plascore PN2-3/16-3.0; 0.75″ thick) were impacted to study the facesheet damage states in sandwich panels. The translucency of the fiberglass face sheets was exploited to observe the face sheet damage states, since the underlying core damage masks the face sheet damage during the through-transmission ultrasonic Cscan (TTU C-scan) measurements (Poon et al., 1990).

The face sheet damage was observed to initiate in the form of delamination between the plies adjacent to the face sheet-core interface, and this delamination occurred above the honeycomb cell walls (Khaliulin et al., 2007). A network of delamination was observed at higher-impact energy levels. The area over which delamination networks occurred was found to increase with impact energy up to the point when face sheet fracture was initiated. The typical delamination network in sandwich panels impacted with the 3.00″ diameter impactor. It was observed that the damage area measured by the TTU C-scan method was consistently higher than the area corresponding to the face sheet delamination. This implies that, in practice, the face sheet damage may go undetected in the absence of a conspicuous face sheet fracture. Further, the presence of a layer of paint or a non translucent face sheet will make it difficult to detect these face sheet damage states (Sanders .,2001).

2.4.4 Core damage

The core damage in honeycomb core sandwich panels was observed to be predominantly cell wall buckling, core crushing, and cell wall fracture. The incipient failure mode in all cases was observed to be cell wall buckling, which propagated across the planar dimensions of the panel. The damage metrics associated with the core damage in sandwich panels (honeycomb core). The TTU

C-scan method measures the planar damage size 2R$_{damage}$ of the core reasonably well. The damaged core increases the impedance of the honeycomb core to the ultrasonic waves and thus can be detected. The through thickness distribution of the core damage may be characterized by the maximum crush depth of the core Δ_{crush} . This damage metric is of particular importance in analytical models for predicting residual strength of impact damaged sandwich panels. The damaged core within the crushed region will offer no support to the face sheet under subsequent in-plane loads, until the indentation depth increases by Δ_{crush}. The ratio of planar damage size (2R$_{damage}$) to the maximum crush depth (Δ_{crush}) will, in general, 4 depend on the impactor size, face sheet stiffness, and the transverse compressive behavior of the core. Additional destructive sectioning of impact damaged sandwich panels will be necessary to characterize the effects of face sheet stiffness and core properties on the core crush depths associated with planar damage size (R.E. Sanders,2001).

2.5 HONEYCOMB CORES

Honeycomb cores are available in a variety of materials for sandwich structures. These range from paper and card for low strength and stiffness, low load applications (such as domestic internal doors) to high strength and stiffness, extremely lightweight components for aircraft structures. Honeycombs can be processed into both flat and curved composite structures, and can be made to conform to compound curves without excessive mechanical force or heating (Gutierrez .,2004).

2.5.1 Thermoplastic Honeycombs

Thermoplastic honeycombs are usually produced by extrusion, followed by slicing to thickness. Other honeycombs (such as those made of paper and aluminium) are made by a multi-stage process. In these cases, large thin sheets of the material (usually 1.2x2.4m) are printed with alternating, parallel, thin stripes of adhesive and the sheets are then stacked in a heated press while the adhesive cures. In the case of aluminium honeycomb the stack of sheets is then sliced through its thickness. The slices (known as 'block form') are later gently stretched and expanded to form the sheet of continuous hexagonal cell shapes. In the case of paper honeycombs, the stack of bonded paper sheets is gently expanded to form a large block of honeycomb, several feet thick. Held in its expanded form, this fragile paper honeycomb block is then dipped in a tank of resin, drained and cured in an oven. Once this dipping resin has cured, the block has sufficient strength to be sliced into the final thicknesses required. In both cases, by varying the degree of pull in the expansion process, regular hexagon-shaped cells or over-expanded (elongated) cells can be produced, each with different mechanical and handling/drape properties. Due to this bonded method of construction, a honeycomb will have different mechanical properties in the 0° and 90° directions of the sheet (Cripps, 2013).

While skins are usually of FRP, they may be almost any sheet material with the appropriate properties, including wood, thermoplastics (e.g. melamine) and sheet metals, such as aluminum or steel. The cells of the honeycomb structure can also be filled with a rigid foam. This provides a greater bond area for the skins, increases the mechanical properties of the core by stabilizing the cell walls and increases thermal and acoustic insulation properties. Properties of honeycomb materials depend on the size (and therefore frequency) of the cells and the thickness and strength of the web material. Sheets can range from typically 3-50 mm in thickness and panel dimensions are typically 1200 x 2400mm, although it is possible to produce sheets up to 3m x 3m. Honeycomb cores can give stiff and very light laminates but due to their very small bonding area they are almost exclusively used with high-performance resin systems such as epoxies so that the necessary adhesion to the laminate skins can be achieved.

2.5.2 Aluminium honeycomb

Aluminium honeycomb produces one of the highest strength/weight ratios of any structural material. There are various configurations of the adhesive bonding of the aluminium foil which can lead to a variety of geometric cell shapes (usually hexagonal). Properties can also be controlled by varying the foil thickness and cell size. The honeycomb is usually supplied in the unexpanded block form and is stretched out into a sheet on-site. Despite its good mechanical properties and relatively low price, aluminium 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. In this situation care also has to be exercised to ensure that the honeycomb does not come into direct contact with carbon skins since the conductivity can aggravate galvanic corrosion (Gutierrez., 2004). Aluminium honeycomb also has the problem that it has no 'mechanical memory'. On impact of a cored laminate, the honeycomb will deform irreversibly whereas the FRP skins, being resilient, will move back to their original position. This can result in an area with an unbounded skin with much reduced mechanical properties.

2.5.3 Nomex honeycomb

Nomex honeycomb is made from Nomex paper - a form of paper based on Kevlar, rather than cellulose fibres. The initial paper honeycomb is usually dipped in a phenolic resin to produce a honeycomb core with high strength and very good fire resistance. It is widely used for lightweight interior panels for aircraft in conjunction with phenolic resins in the skins. Special grades for use in fire retardant applications (e.g. public transport interiors) can also be made which have the honeycomb cells filled with phenolic foam for added bond area and insulation (Gutierrez., 2004). Nomex honeycomb is becoming increasingly used in highperformance non-aerospace components due to its high mechanical properties, low density and good long-term stability. However, it is considerably more expensive than other core materials. Table 2.1 shows characteristic and benefits of the materials.

Table 2.1: The core usually using in Sandwich Structure (Gutierrez., 2004).

Core Materials	Characteristics and Benefits
Balsa wood (end grain)	Good shear strength, high fatigue endurance, low cost, high bond ability, easily finished, good temperature range.

PVC foam (crosslinked)	High strength, high stiffness, low cost, easily bonded.
PVC foam (linear)	Low cost, easily bonded, good impact resistance.
Polyimide-paper honeycomb	High strength to weight, corrosion resistant, good thermal insulation, fire resistant, easily shaped, excellent dielectric properties, high bondable.
Polyolefin honeycomb	Rigid and elastic, high toughness, sound and vibration dampening, explosion containment vessels, scrim cloth available, high strength to weight, corrosion resistant, fungi resistant, thermoform able, recyclable.
Engineering plastic honeycomb	Tough, relatively high temperature tolerant, excellent dielectric properties, good thermal insulator, fire resistant, fungi resistant, highly variable cell sizes and densities.
High performance honeycomb	Carbon fiber reinforced, carbon-carbon, aramid, quartz, superior strength, and superior thermal resistance.
Metal honeycomb	Aluminum, titanium, stainless, nickel available, no outgassing, high temperature tolerant, fire resistant, fungi resistant, high thermal conductivity.
PEI foam	Low water absorption, high thermal stability, high strength, fire resistant, good dielectrics

2.6 APPLICATION OF SANDWICH STRUCTURE

The use of sandwich structure in automotive, aeronautical, aerospace, marine and civil engineering application is growing. This is because these structures have excellent stiffness to weight ratios, leading to weight reduction and decrease fuel consumption. Besides, they have high structural crashworthiness, because they are capable of absorbing large amount of energy in a sudden collision (Fischer. and Drechsler. et al., 2008).

In automotive industry, fuel efficiency of the vehicle depends on the weight of the vehicle. Sandwich structure is further lighter than steel structure of the same size and provides superior crash protection, improved stiffness, and good thermal and acoustic properties. Reports from the United States and Canada predicted that plastic and composites include sandwich structure would be widely used in body panels, bumper system, flexible component and transport parts of cars (Kehrle R. and Drechsler. et al., 2008). Furthermore, sandwich structure often used in truck structure, for the low weight with high thermal insulation for the transportation of cold goods for examples fruit or other types of food.

In aerospace application, various honeycomb sandwich structure was used for space shuttle constructions. It's because their ability to substantially decrease weight while maintaining mechanical performance. This weight reduction results in a number of benefits, including increased range, higher payloads and decreased fuel consumption (Khaliulin et al. 2007). All have a positive impact on cost as well as a decreased impact on the environment. They are also used for both military and commercial aircraft.

For more 20 years, both the U.S Navy and the Royal Swedish navy have used honeycomb sandwich bulkheads to reduce ship weight, to withstand underwater explosions. Moreover, in marine environments or in places with moisture or condensation, polymer core materials are excellent (Khaliulin et al. 2007). The reason for this is, once again, the closed cell structure. This prevents water or moisture from entering the core and increasing weight or ruining mechanical performance. In comparison, most closed cell polymer materials have extremely low water vapor permeability or water absorption over their lifetime. Table 2.2 below shows the application of usage a sandwich structures.

Table 2.2: Design according to application.

Application	Specification	Properties
Automotive	• Body panel • Bumper system • Interior part	• Light • Stiffness • Good thermal
Aircraft	• Fairings • Flight control surfaces • Landing gear doors	• Light • Stiffness
Marine	• Hull • Deck	• Stiffness • Closed cell structure

Aerospace	• Space shuttle	• Light • Stiffness • Good thermal
Sports	• Snow board • Skate board	• Light • Stiffness

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

In this Chapter 3 will discuss about the methodology of the project. Methodology shows the flow on how this project was conducted. Project methodology is a guideline in conducting the project by selecting the suitable technique from the information that can be used to conduct the project. The project methodology also will give clear steps on conducting the project. This section focused on the experimental setup used in this study to investigate the mechanical properties of the corrugated sandwich structure. The purpose of these materials was chosen for experiment will be explained further in the next section. Before experimental testing is conducted, the self-reinforcement polypropylene (SRPP) need to be fabricated. Fabrication technique and parameters of composite and experimental testing will be discussed thoroughly. End mill machine will be used to create slotting part at the SRPP. The structures will have various parameters to be manipulated. The completed SRPP will be assembled through slots to form square structure. A compression test will be conducted to observe the crushing behavior, failure mechanism and energy absorption of the square honeycomb structure.

3.2 OVERVIEW METHODOLOGY

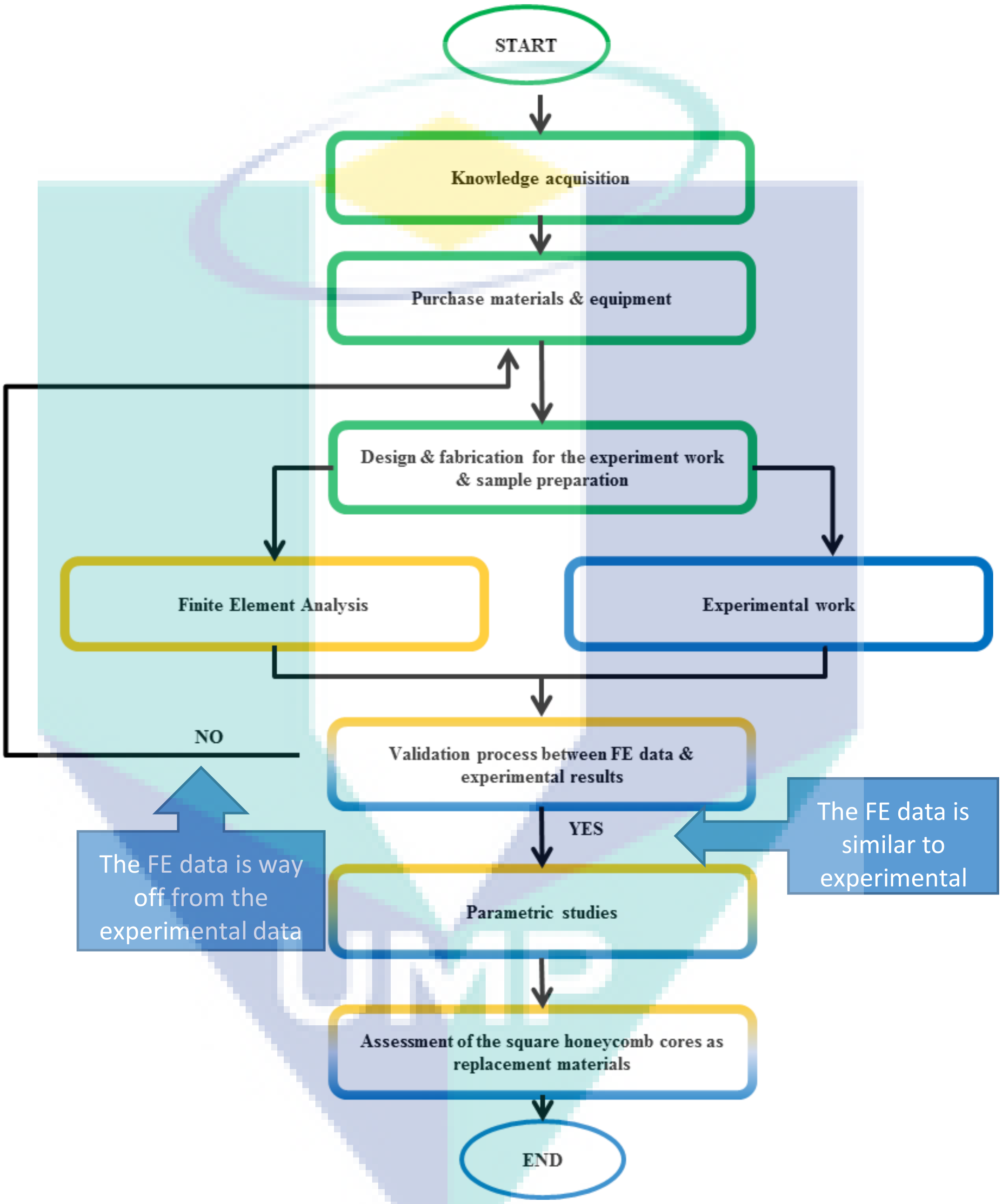


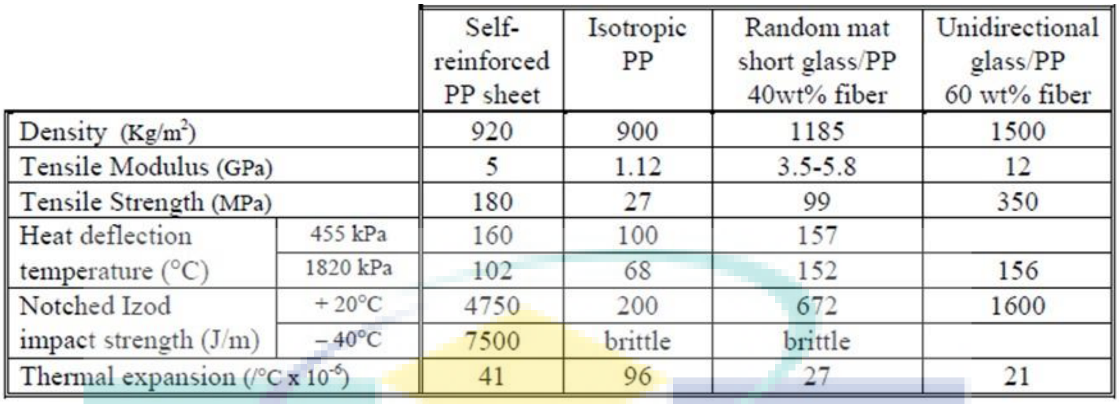
Figure 3.1: Methodology of Research

3.3 MATERIAL SELECTION

3.3.1 Self-reinforced Polypropylene

A novel 100% polypropylene material was developed which creates a new class of thermoplastic composites. In a patent process, high modulus polypropylene tapes are compacted to form a self-reinforced, thermoformable polypropylene sheet. The recently commercialized material exhibits a unique set of properties including: low density, good tensile strength, outstanding impact strength (even at low temperatures), and recyclability. This performance positions the composite between isotropic thermoplastics and highly structured glass reinforced composites (Yan et al., 2013). Polypropylene (PP) has long been favored by the automotive industry because of its relative low cost. Light weight and inert nature. However, PP is resulting composites are often difficult to thermoform into component shapes, they can still relatively heavy, their impact and abrasion resistance are no match for metal (particularly at low temperature), and glass fibers can be a source of great irritation the workplace. This self-reinforced, or single polymer, composite is formed by compacting high modulus PP tapes or fibers under carefully controlled temperature and pressure (Drechsler et al., 2004). A small portion of the tape or fiber surface is melted during the process and recrystallized upon cooling to bind the structure together. The rest of the tape or fiber maintain high molecular orientation. The sheet is therefore able to retain a high proportion of the original tape or fibers' physical properties. It is believe that the compaction process of homopolymer PP result in degree of molecular continuity between the oriented portion and the matrix. This, in turn, leads to higher stiffness than would be found using alternative approaches such as bicomponent fiber (Russell et al., 2008).

Table 3.1: Mechanical properties, PP-based materials



		Self-reinforced PP sheet	Isotropic PP	Random mat short glass/PP 40wt% fiber	Unidirectional glass/PP 60 wt% fiber
Density (Kg/m^3)		920	900	1185	1500
Tensile Modulus (GPa)		5	1.12	3.5-5.8	12
Tensile Strength (MPa)		180	27	99	350
Heat deflection temperature (°C)	455 kPa	160	100	157	
	1820 kPa	102	68	152	156
Notched Izod impact strength (J/m)	+ 20°C	4750	200	672	1600
	– 40°C	7500	brittle	brittle	
Thermal expansion (/°C x 10^{-6})		41	96	27	21

Source : Comparative data www.matweb.com averages of all commercially available materials of that type.

Mechanical properties of the self-reinforced PP composite were compared to performance of other PP based material as shown in Table 3.1. Several results are particularly noteworthy:

- Low density of the all PP composite translate to weight saving at the same part thickness relative to glass/ PP composites.
- Desirable stress-strain properties result in good impact strength. The self-reinforced composite possesses a unique combination of high strain-to-failure and high tensile strength. Due to unique oriented structure, this impact performance is retained at low temperatures.
- High level of abrasion resistance also have been demonstrates since, unlike glass and natural fibers, the PP reinforcement is always ductile and cannot fracture.

Because of the lower pressure required to process the self-reinforced composite, thermoforming is a very attractive processing alternative. Capital cost and lead times can be reduced through use aluminum matches tooling and smaller process. The self- reinforce PP sheet energy management properties are beneficial in other exterior application such as skid plates and bumper beam components. In conjunction with foam or honeycomb, it can also be considered for uses such as tonneau covers. From tooling and handling standpoint, the all PP composites also offers advantages over glass-reinforced materials (Wang et al., 2010). Tool life is improved because the all PP composite is non-abrasive, and the processor does not encounter the handling issue associated with glass fiber. A shear edge is not required since the composite remain as a sheet throughout the forming process. The tool may be either used cold or heated, depending upon the specific part design. Self-reinforced PP composites bridge the gap between isotropic polymer and glass reinforced materials by providing some unique set properties. These materials are best suited for application in which several characteristics of the process and performance are value (Wadley et al., 2006).

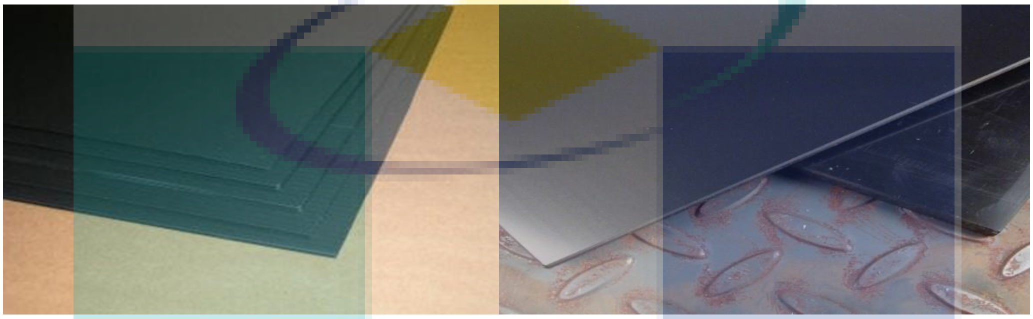


Figure 3.2: Polypropylene sheet

3.4 DESIGN AND FABRICATION

3.4.1 Design Using Software CATIA

Before proceed to fabrication stage, a drawing of composite square honeycomb need to be drawn by using software. In this case, the composite is drawn into shape by using CATIA software.

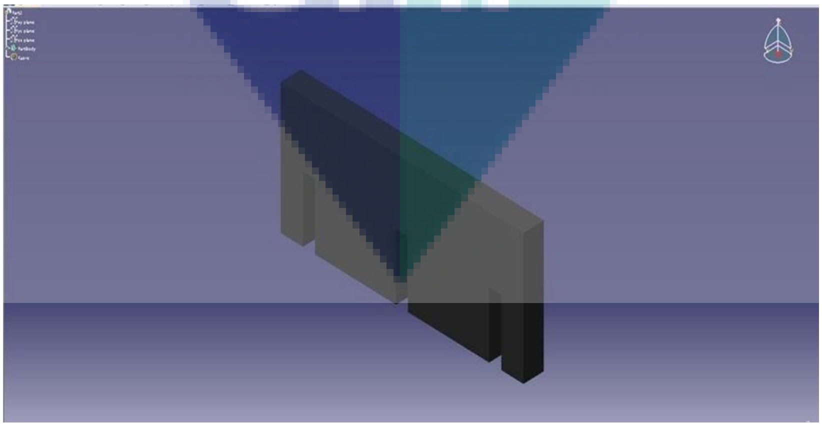


Figure 3.3: Single slotting design by CATIA

The single unit of composite was drawn with respective dimension. Then, multiple units of composites are assembled together to form a square structure of 2x2 unit cells. Below is the three-dimensional (3D) drawing of the square honeycomb structure. The drawing have dimensions of thickness, t= ±3mm; total length, *l*= ±70mm; height, H= ±30mm, and length of slots of ±3mm each. The parameters of the experimental work will be discussed further in next subtopic.

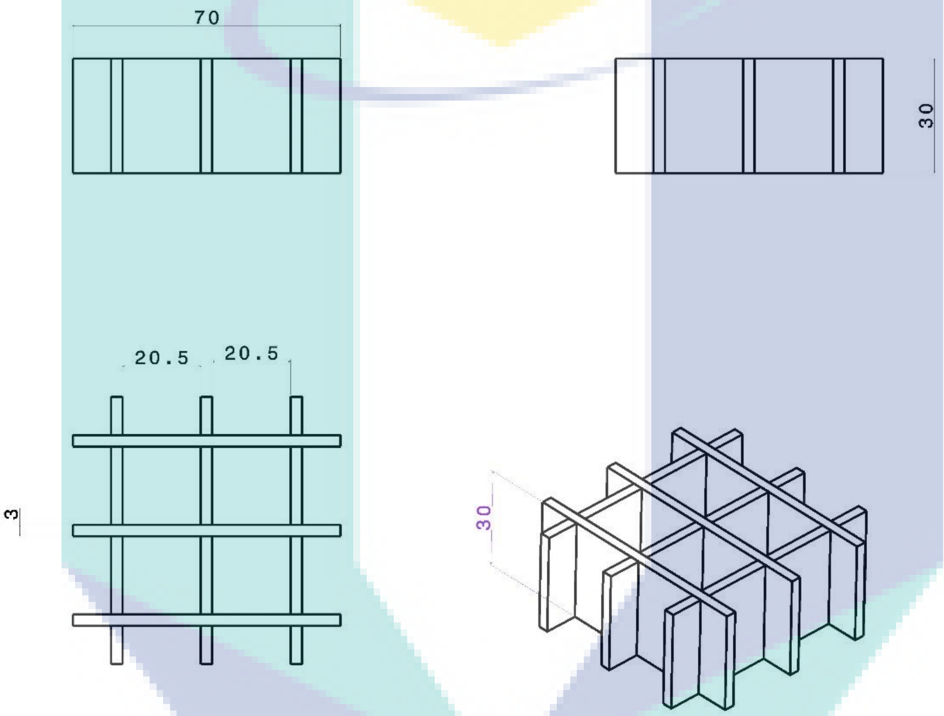


Figure 3.4: 3-dimension view of hashtag concept design

For the first concept, the design of the structure has been added on as shown in Figure 3.4 to determine the performance.

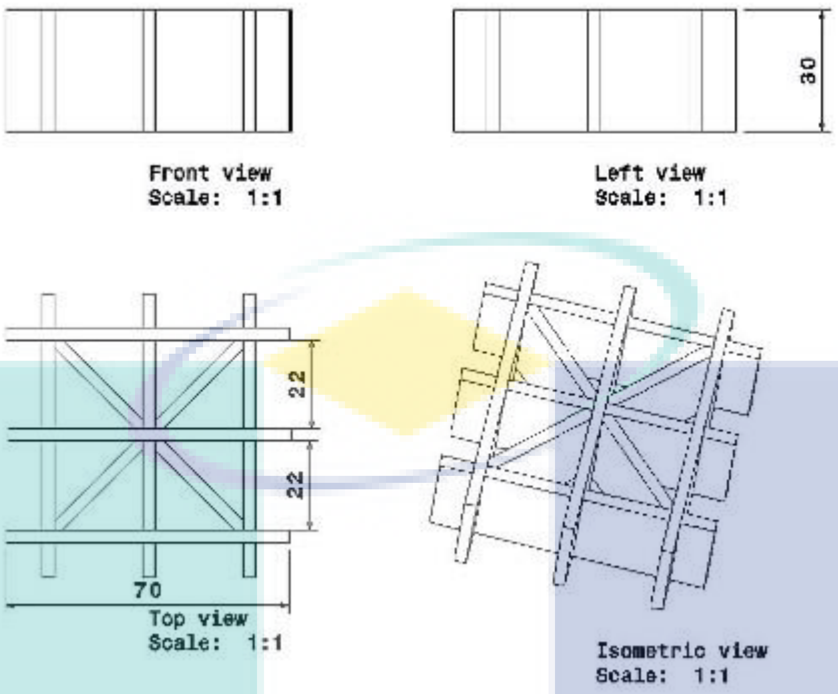
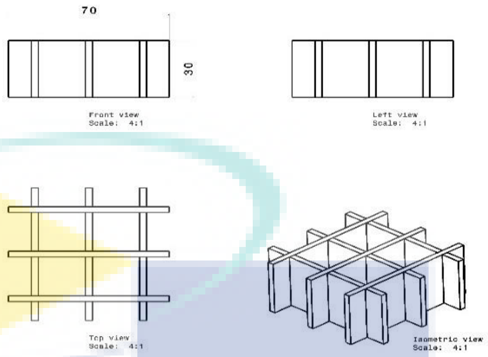
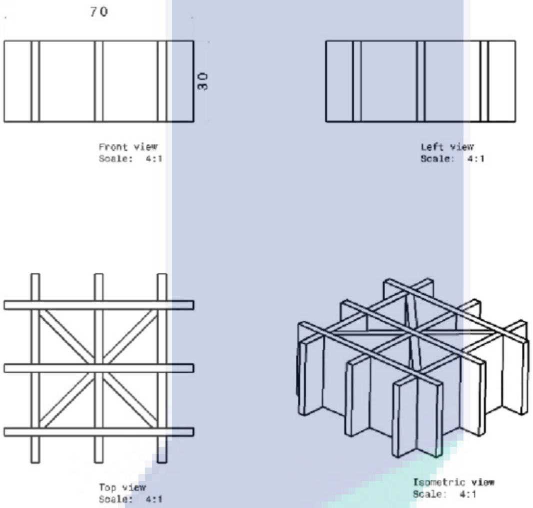
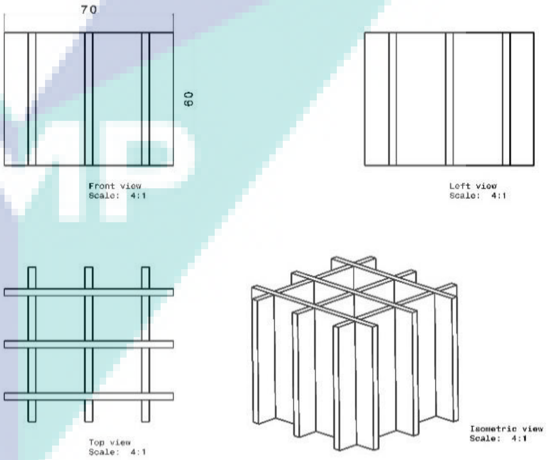
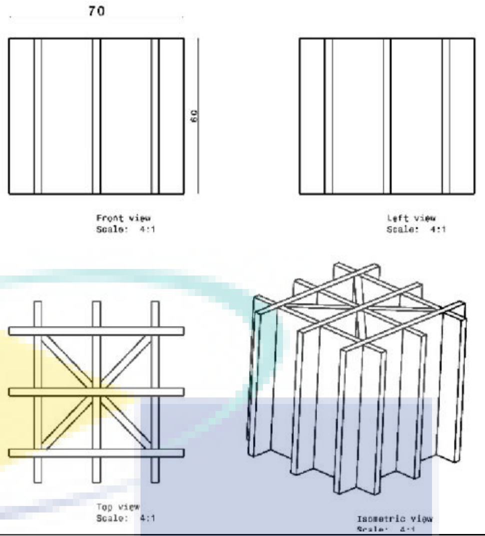
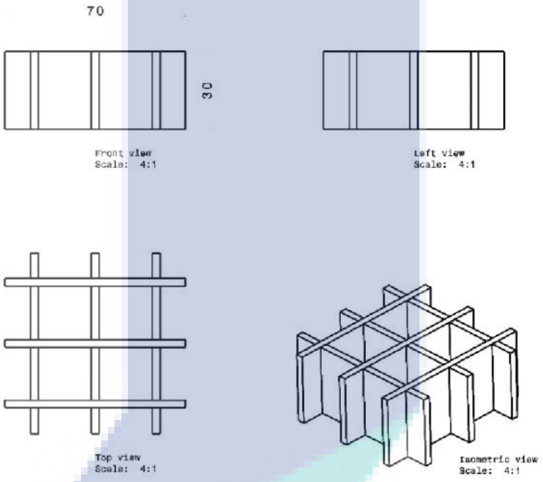
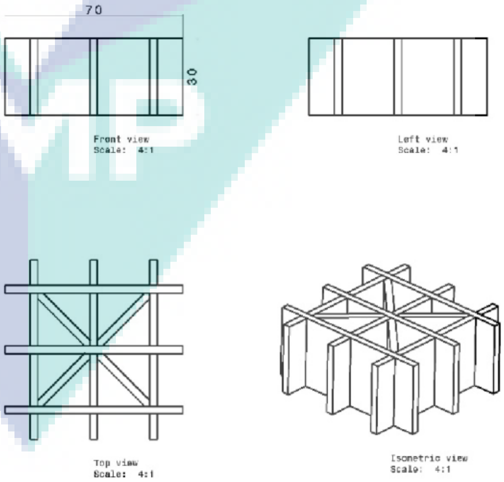


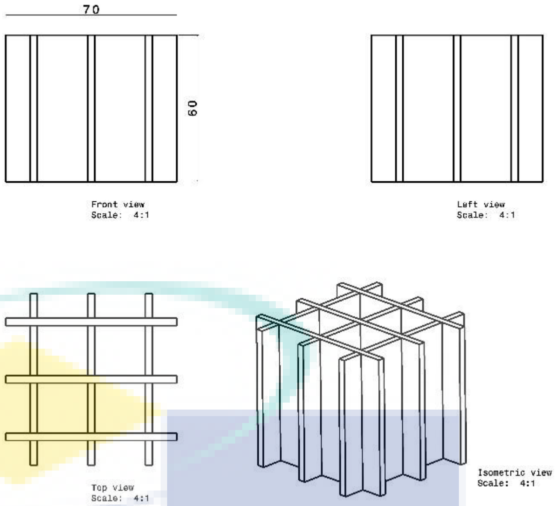
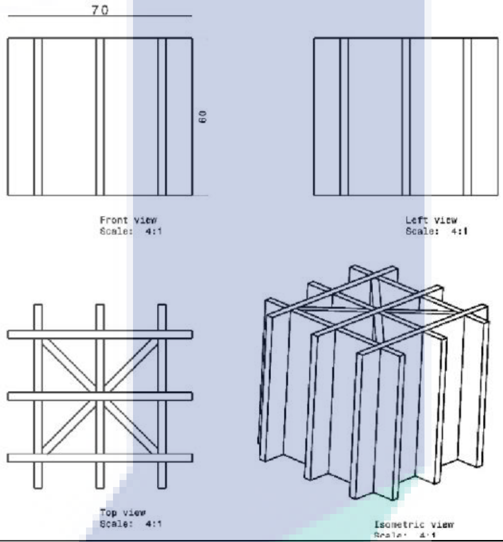
Figure 3.5: 3-dimension of star concept

For the second concept, the design was modify from the first concept with more complex with add more cross section part. There are many parameter that will be used in this experimental with different dimension. Moreover, all the specimen will be tested universal testing machine Instron 3369 for compression test to determine the performance. The different design and dimension of the structures as shown in Table 3.2 below:

Table 3.2: Type of SRPP model structures

No.	Type	Size (mm)	Drawing Sample
1.	Hashtag with height (30mm)	70 x 30	
2.	Star with height (30mm)	70 x 30	
3.	Hashtag with height (60mm)	70 x 60	

4	Star with height (60mm)	70 x 60	
5	Sandwich Hashtag with height (30mm)	70 x 30	
6.	Sandwich Star with height (30mm)	70 x 30	

7.	Sandwich Hashtag with height (60mm)	70 x 60	
8.	Sandwich Star with height (60 mm)	70 x 60	

3.4.2 Self-Reinforced Polypropylene fabrication

The polypropylene sheet (1500 x 1400 mm) thickness 3 mm were cut by using LVD metal sheet cutter with different parameter (Figure 3.6). There are 3 parameters to cut:

- 70 x 30 mm thickness 3 mm
- 70 x 60 mm thickness 3 mm

Figure 3.6 : LVD metal sheet cutter

Milling machine is use to fabricate the slotting design on polypropylene piece. Firstly, edge finder is use to find the center point of the specimen between the end mill table vice. The device is use to accurately determine edges or markings and therefore the center of a workpiece or a previously machine feature during the setup phase of a machining operation (Figure 3.7).

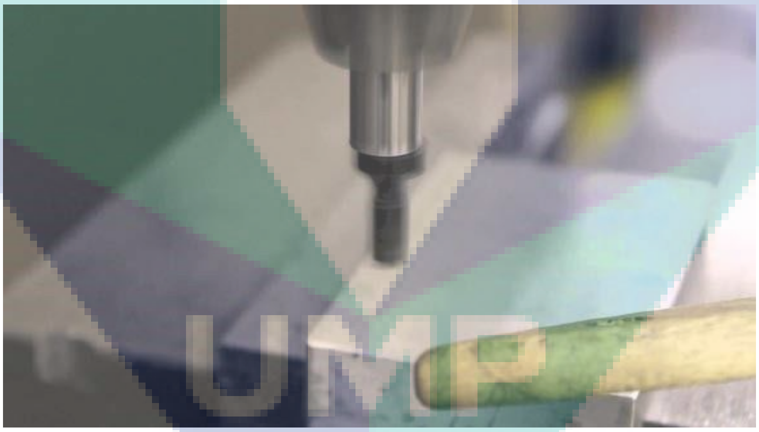


Figure 3.7: Setting a work zero using edge finder

After that, the drill cutter with diameter 3 mm was used to make the slotting on polypropylene piece that has been cut in the earlier process of fabrication (Figure 3.8).

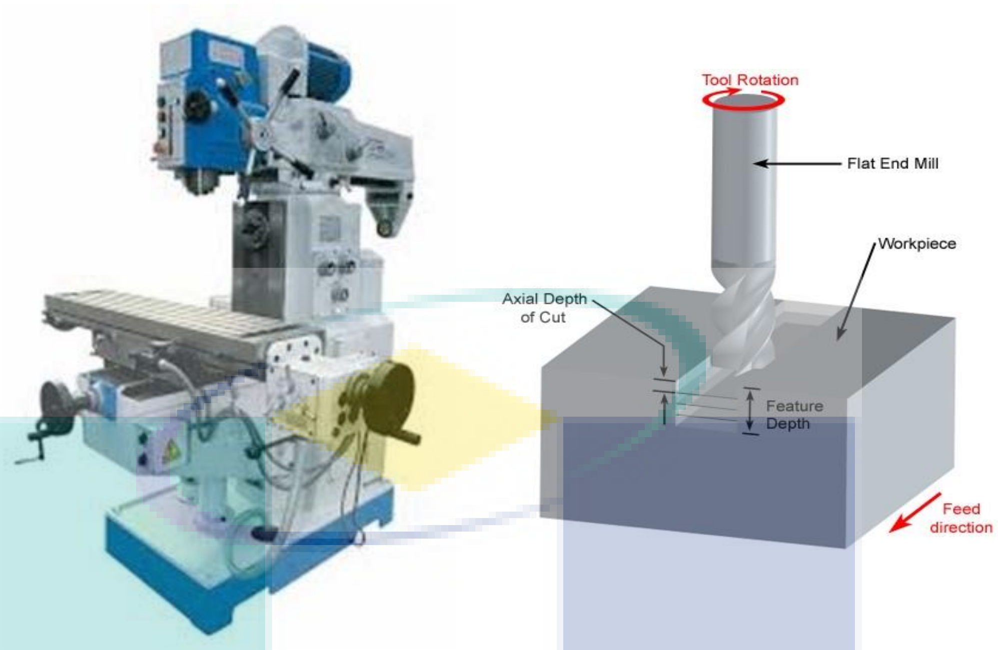


Figure 3.8: Milling machine and workpiece been cut

After done the cutting process. Assemble the polypropylene piece to form a square and triangular design (Figure 3.9).

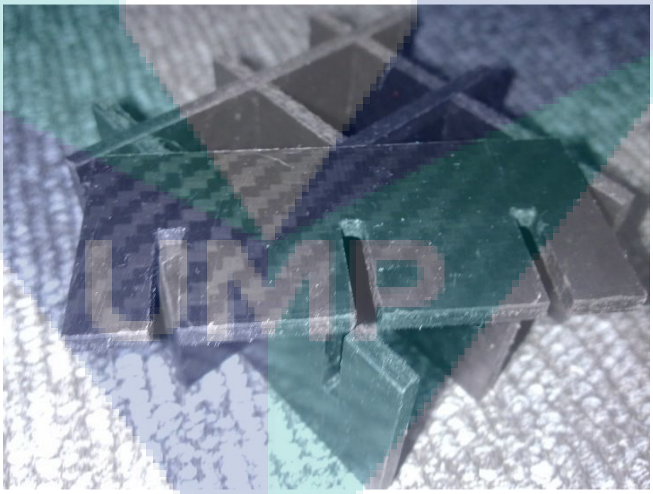


Figure 3.9: Self-Reinforced Polypropylene assemble

3.5 COMPRESSION TEST

Method for determining behavior of materials under crushing loads. Specimen is compressed, and deformation at various loads is recorded. Compressive stress and strain are calculated and plotted as a stress-strain diagram which is used to determine elastic limit, proportional limit, yield point, yield strength and (for some materials) compressive strength. Electromechanical, or universal testing machines, are most commonly used for static testing in a tensile or compression mode within a single frame. They are also referred to as pull testers. Additional test types include tension, compression, shear, flexure, peel, tear, cyclic, and bend tests (Instron US, 2014).

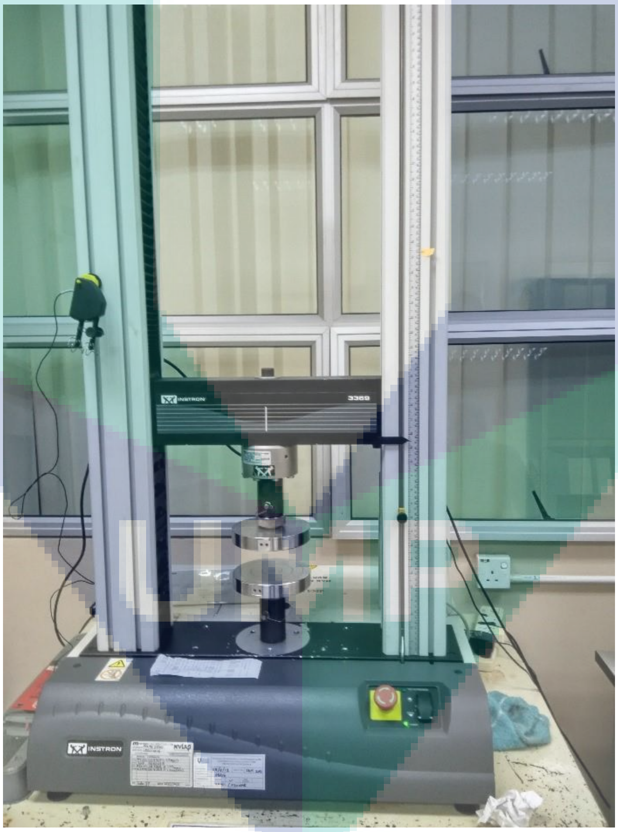
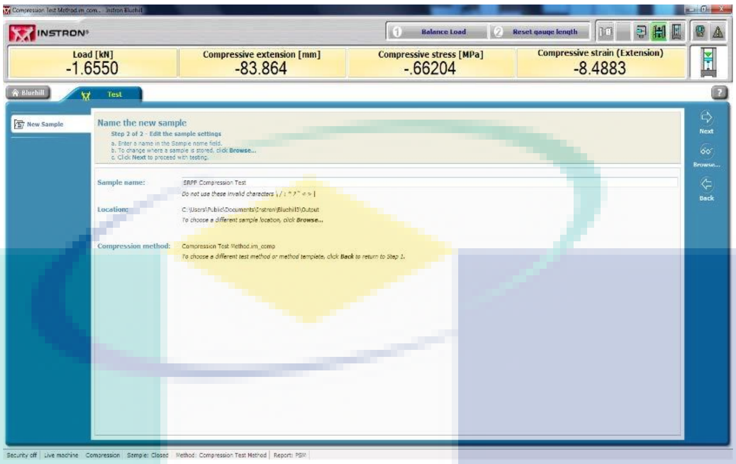


Figure 3.10: Instron 3369 compression test

For the first step, click on Bluehill 3 to start the Instron. Universal Instron compression (Figure 3.10) test comes with Bluehill 3 software in order to operate this compression machine. From this software, the data obtain from the compression test will be analyze and shown in graph (compressive Stress MPa vs compressive Strain).



Load [kN] -1.6550

Compressive extension [mm] -83.864

Compressive stress [MPa] -.66204

Compressive strain (Extension) -8.4883

Name the new sample

Step 2 of 2 - Edit the sample settings

a. Enter a name in the Sample name field.
b. To change where a sample is stored, click **Browse...**
c. Click **Next** to proceed with testing.

Sample name: SRPP Compression Test

*Do not use these invalid characters \ / : * ? " < > |*

Location: C:\Users\Public\Documents\Instron\Bluehill3\Output

To choose a different sample location, click ***Browse...***

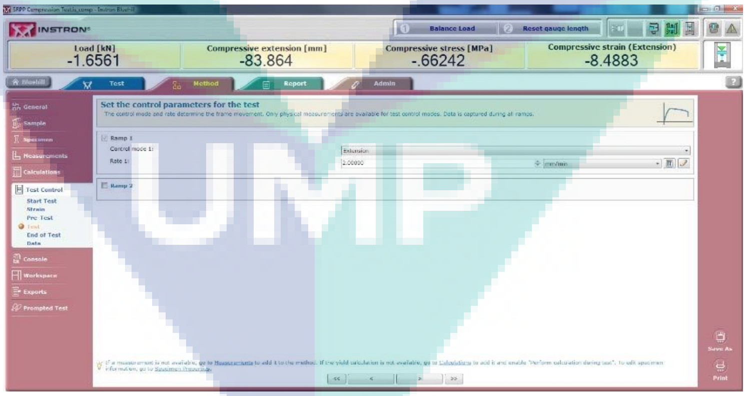
Compression method: Compression Test Method.im_comp

To choose a different test method or method template, click ***Back*** *to return to Step 1.*

Security off | Live machine | Compression | Sample: Closed | Method: Compression Test Method | Report: PSM

Figure 3.11: Bluehill 3 sample test.

For the second step, on this screen select the ‘test’ option to open a prepared test or ‘method’ to create a new test (Figure 3.11). Select which test you wish to run from a list of premade procedures. This is available after selecting ‘Test’ on the previous screen.



Load [kN] -1.6561

Compressive extension [mm] -83.864

Compressive stress [MPa] -.66242

Compressive strain (Extension) -8.4883

Set the control parameters for the test

The control mode and rate determine the frame movement. Only physical measurements are available for test control modes. Data is captured during all ramps.

☑ Ramp 1

Control mode 1: Extension

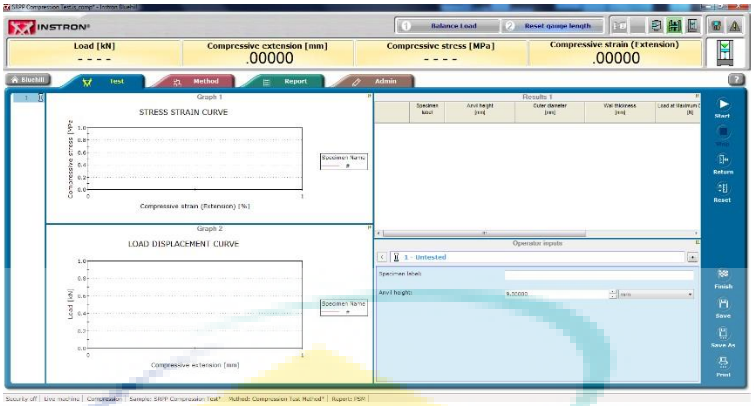
Rate 1: 2.00000 mm/min

☐ Ramp 2

If a measurement is not available, go to Measurements to add it to the method. If the yield calculation is not available, go to Calculations to add it and enable "Perform calculation during test". To edit specimen information, go to Specimen Properties.

Figure 3.12: Bluehill 3 control parameter

Then, click on method to control the parameter speed and percentage of the specimen will be compress (Figure 3.12). According to the ASTM D-5467 compression speed for the SRPP which is 2mm/min.



Load [kN]: - - - -
Compressive extension [mm]: .00000
Compressive stress [MPa]: - - - -
Compressive strain (Extension): .00000

Specimen label:
Anvil height: 9.00000 mm

Security off | Live machine | Compression | Sample: SRPP Compression Test* | Method: Compression Test Method* | Report: PSM

Figure 3.13: Bluehill 3 analyzed result

Finally, select to play button right on top to begin the compress test. During the testing, the results will be appeared in graph (compressive Stress MPa versus compressive strain) (Figure 3.13). The machine will be stop consequently until 80% of the structure compress/fracture.

Figure 3.14: Before and after compression testing square honeycomb for length between slots, structure complex width + length (30 x 70) mm.

ASTM D-5467 standard was used for compression test procedure for self reinforced polypropylene. Test Method D5467/D5467M where compressive force is transmitted by subjecting a honeycomb core sandwich beam with thin skins to four-point bending. The composite material forms are limited to continuous-fiber or discontinuous-fiber reinforced composites for which the elastic properties are specially orthotropic with respect to the test direction. Factors that influence the compressive response and should therefore be reported include the following: material, methods of material and specimen preparation, specimen conditioning, environment of testing, specimen alignment, speed of testing, time at reinforcement. Properties, in the test direction, that may be obtained from this test method include:

- Ultimate compressive strength
- Ultimate compressive strain
- Compressive (linear or chord) modulus of elasticity

Where the tensile strength (σ) values were calculated by following equation;

$$\sigma = \frac{F}{A} \tag{3.1}$$

Where F is the ultimate load, and A is the cross sectional area of the specimen.

Elastic modulus was obtained from the initial slope (σ) – strain (ε) curves based on the equation below;

$$E = \frac{\sigma}{\varepsilon} \tag{3.2}$$

From testing of compression using this machine, results including force, displacement, stress, strain and energy absorption could be obtained. The relationship between the stress and strain that a specific material presentations is known as that specific material's stress–strain curve. It is unique for each material and is found by recording the amount of deformation (strain) at distinct intervals of compressive loading (stress). These curves uncover large portions of the properties of a material (including data to establish the Modulus of Elasticity, E). Stress–strain curves of various materials vary widely, and different tests conducted on the same material yield different results, depending upon the design of the specimen and the speed of the loading.

3.5.1 Specific Energy Absorption

Progressive crushing is now well-established as a means of absorbing energy in composite structures. Extensive localized micro fracture of the composite occurs in a crush zone which propagates through the structure. Numerous micro fracture processes are active in the crush zone, all of which contribute to the energy absorption, and additional factors, such as friction, are also involved. A large number of material, structural and testing parameters influence the crushing behavior and the energy absorbed (H.hamada et al.1992). The specific energy absorption, e, is defined as:

$$SEA = \frac{aaaaaa}{M} \tag{3.3}$$

Where $aaaaaa$ is area under curve of the load and displacement curves in J(joule) and M is mass of the specimen structure in Kg(Kilogram). Specific energy is an intensive property, whereas energy and mass are extensive properties. The SI unit for specific energy is the joule per kilogram (J/kg).

3.6 FINITE ELEMENT ANALYSIS AND SIMULATION PROCEDURE

ANSYS/CAE is very useful finite element analysis software as shown in Figure 3.15 which are now widely use in industries field like automotive and aerospace as well as in academic and also research institution due to capability in solving nonlinear problems. In this project, a Standard model is created in ANSYS in order to carry out the modelling and numerical simulation.

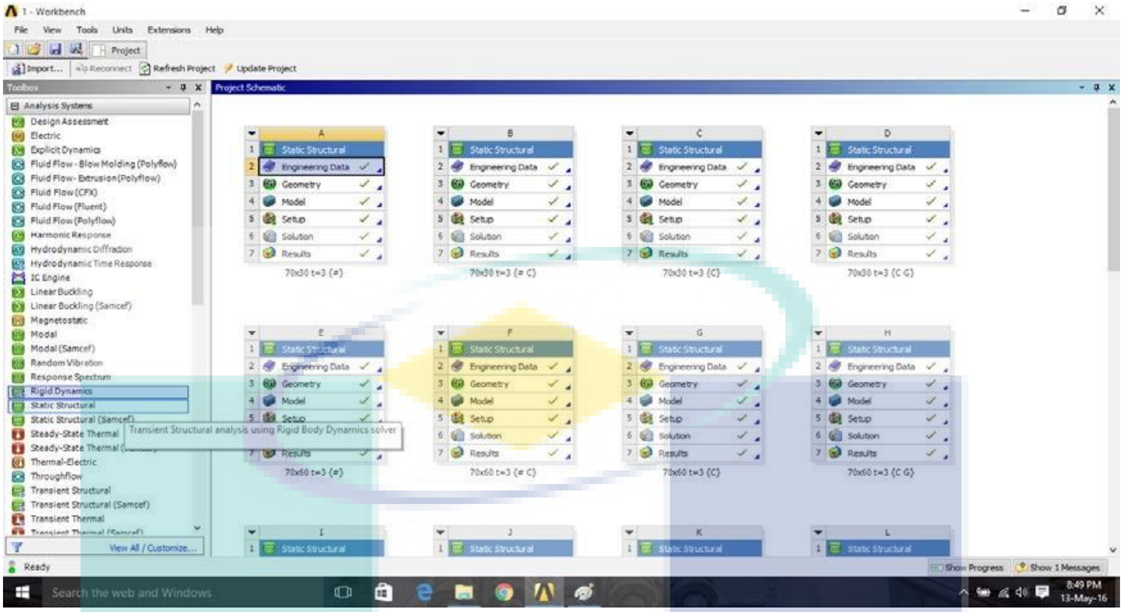
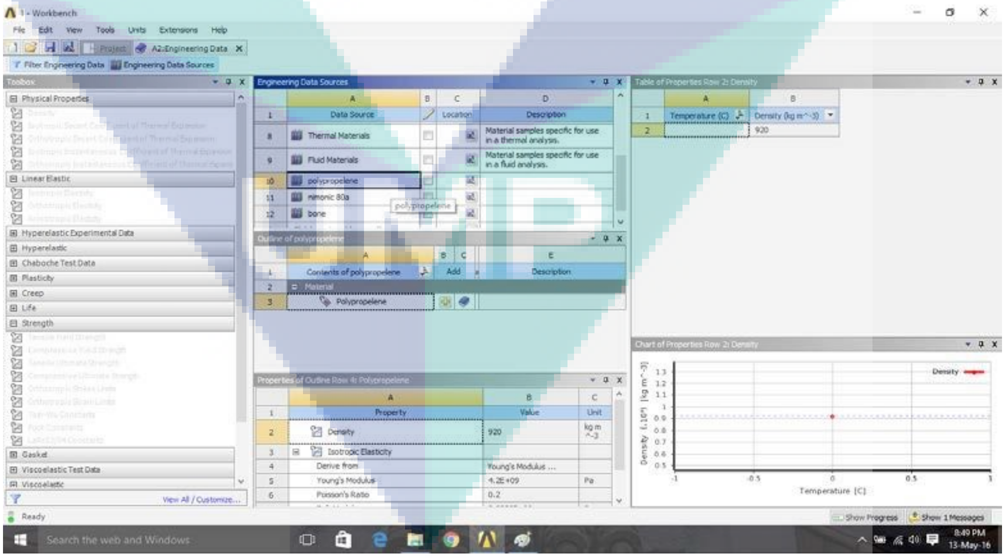


Figure 3.15: Creating part on ANSYS simulation

In the ANSYS/CAE model tree, select the static structural to create a new part section. Then, the table of the modelling will appear on the right side of the view. Select on the engineering data to add the composite properties.



Property	Value	Unit
Density	920	kg m^-3
Isotropic Elasticity		
Derive from	Young's Modulus ...	
Young's Modulus	4.2E+09	Pa
Poisson's Ratio	0.2	

Figure 3.16: Polypropylene material properties

From the Figure 3.16 show that the polypropylene materials properties. Select the propylene type then the new table of material properties will appear below as shown in figure. Then add the value of the self-reinforce polypropylene such as tensile modulus, tensile strength, and poisson’s ratio.

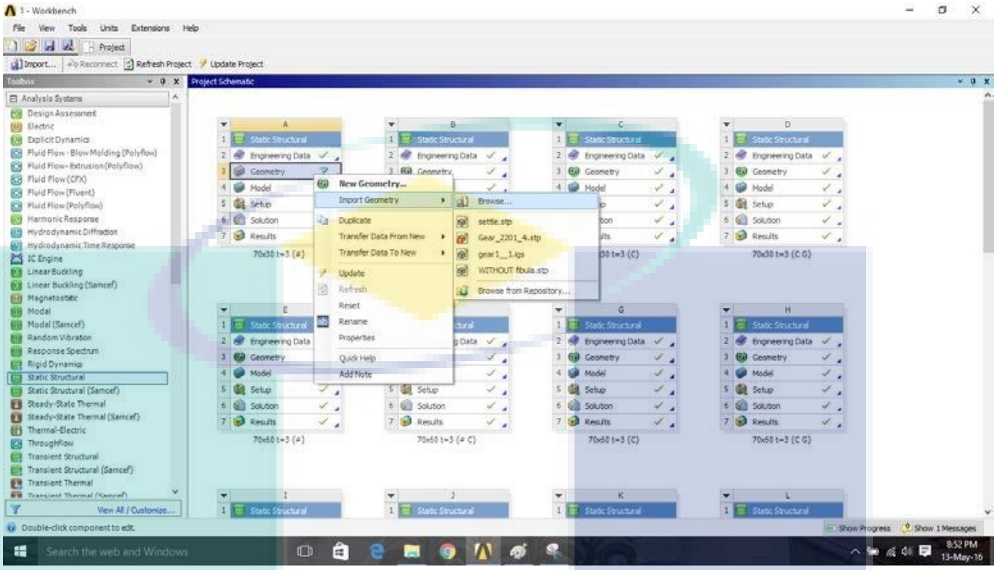


Figure 3.17: Geometry selection

From the table tree as shown in Figure 3.17 select the import geometry to add the new design of the structure that have been design in the CAD software previously. After that, select on model in the tree table to start the simulation as shown in Figure 3.18 below.

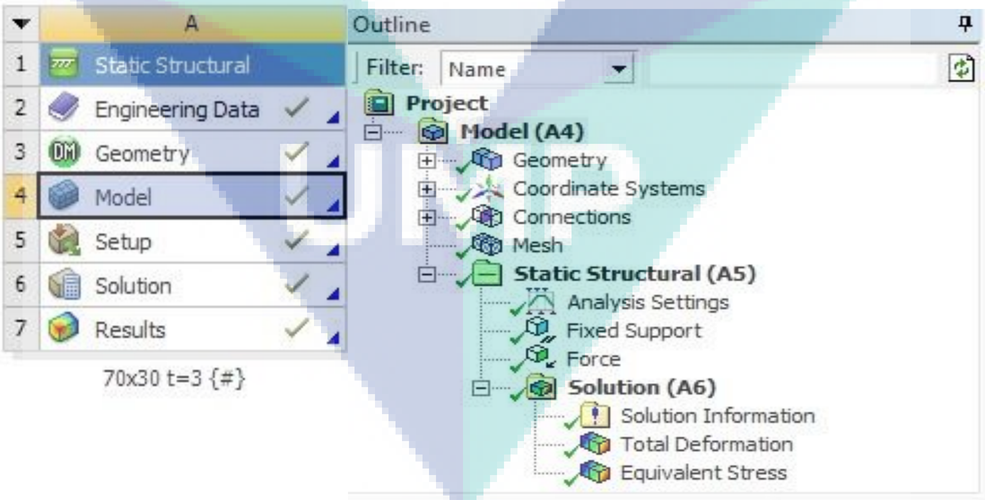
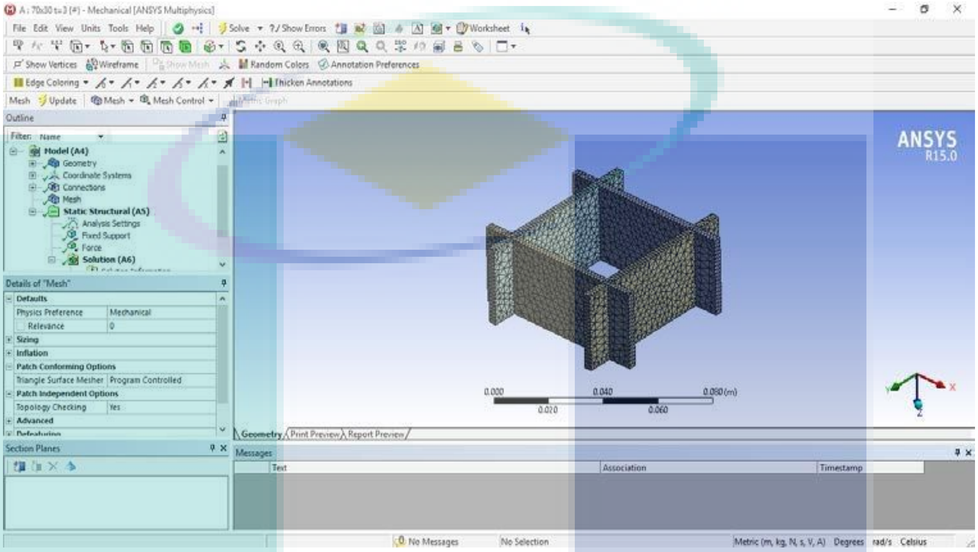


Figure 3.18: Model selection

After select the model, a new project will appear in a new window. From the project tree above there are 3 main sub before the simulation to be done. In the model subtopic, i can define the connection within the slot and create the meshing for the design. Then i can define the fixed support and load force for the design in this simulation. For the solution we can select total deformation and equivalent stress.

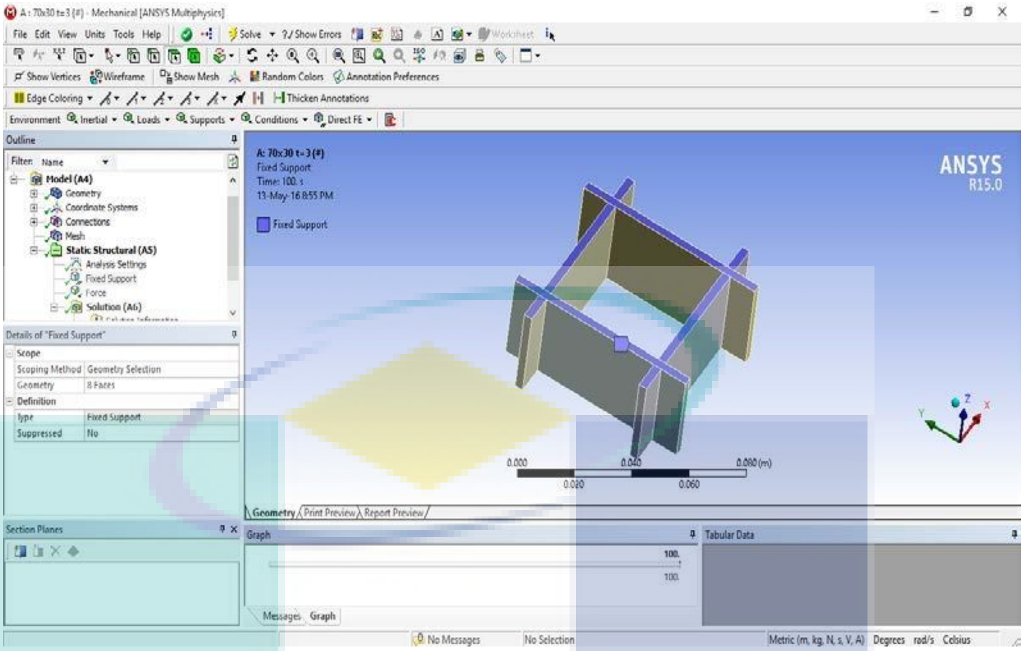


Details of "Mesh"

Defaults
Physics Preference Mechanical
Relevance 0
Sizing
Inflation
Patch Conforming Options
Triangle Surface Mesher Program Controlled
Patch Independent Options
Topology Checking Yes
Advanced
Defeaturing

Figure 3.19: Design meshing

From the Figure 3.19 it show that the design have been meshing. In the meshing part it can define the meshing sizing to small, medium or large. For the better simulation result used the small meshing. Meshing is a discrete representation of the geometry that is involved in the problem. Essentially, it partitions space into elements (or cells or zones) over which the equations can be approximated. Zone boundaries can be free to create computationally best shaped zones, or they can be fixed to represent internal or external boundaries within a model. Region boundaries are used to define a coarse polygonal mesh which is quadrangulated to obtain a parameterization domain.



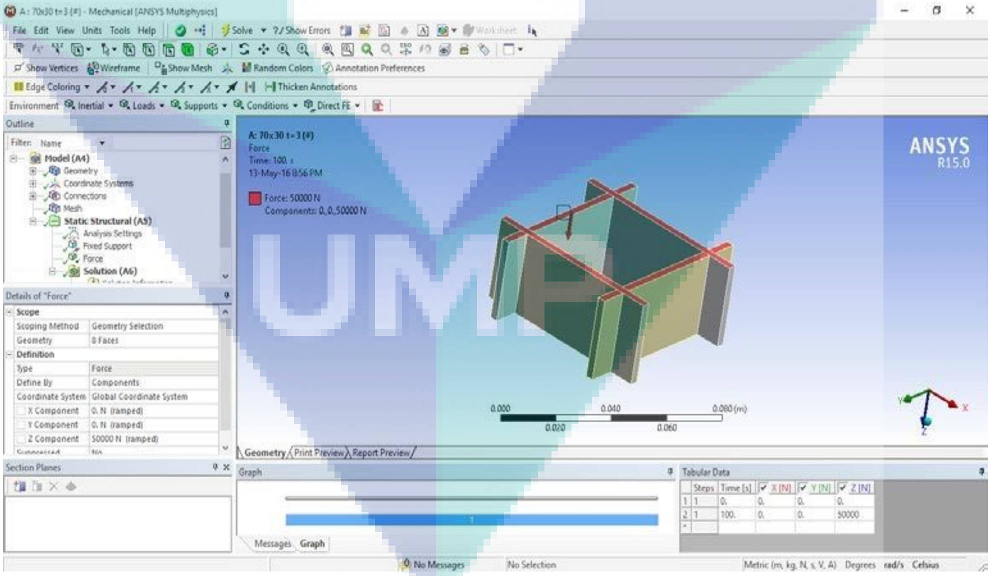
A: 70x30 t=3 (#)
Fixed Support
Time: 100. s
13-May-16 8:55 PM

Fixed Support

Scope	
Scoping Method	Geometry Selection
Geometry	8 Faces
Definition	
Type	Fixed Support
Suppressed	No

Figure 3.20: Select the fixed support

From the Figure 3.20, select the fixed support on the x-axis of the design. Fixed support is define as support that can hold the design before the load is varied.



A: 70x30 t=3 (#)
Force
Time: 100. s
13-May-16 8:56 PM

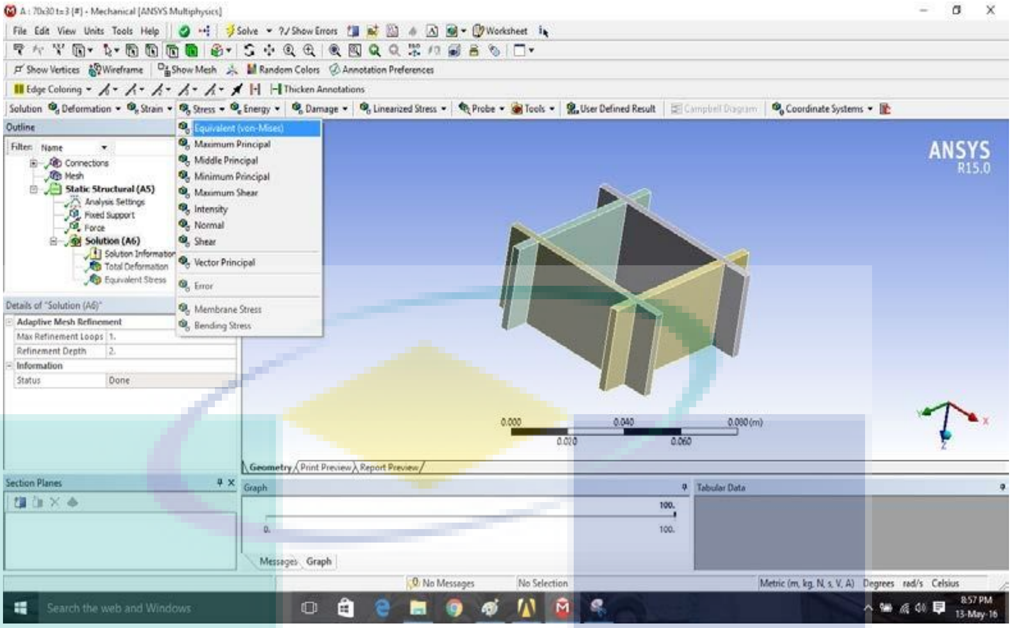
Force: 50000 N
Components: 0.,0.,50000 N

Scope	
Scoping Method	Geometry Selection
Geometry	8 Faces
Definition	
Type	Force
Define By	Components
Coordinate System	Global Coordinate System
☐ X Component	0. N (ramped)
☐ Y Component	0. N (ramped)
☐ Z Component	50000 N (ramped)
Suppressed	No

	Steps	Time [s]	☑ X [N]	☑ Y [N]	☑ Z [N]
1	1	0.	0.	0.	0.
2	1	100.	0.	0.	50000
*					

Figure 3.21: Force selection

Figure 3.21 shows that the force selection on the z-axis. By doing this, select to applied a varied force in this segment.



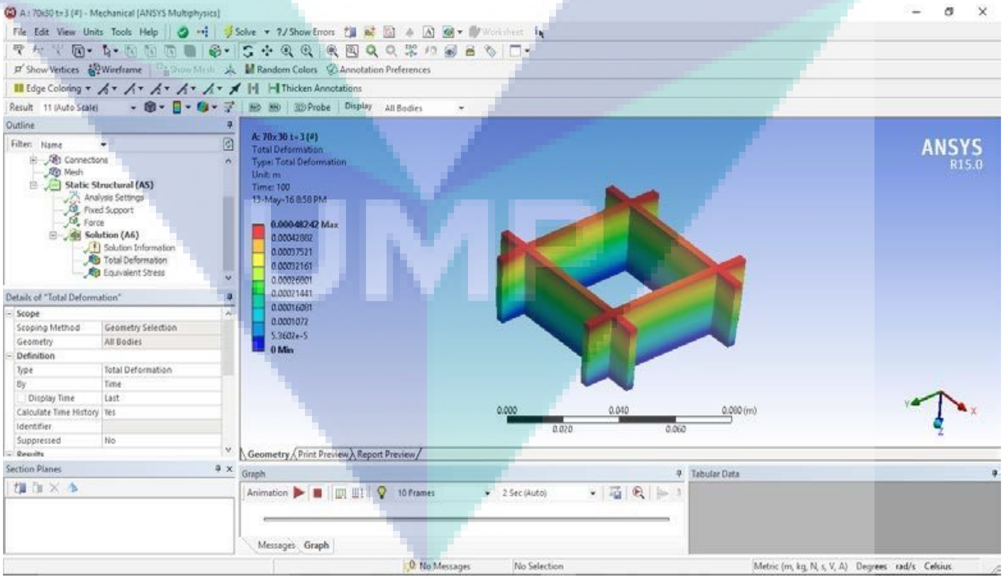
Details of "Solution (A6)"

Adaptive Mesh Refinement
Max Refinement Loops 1.
Refinement Depth 2.
Information
Status Done

No Messages
No Selection
Metric (m, kg, N, s, V, A) Degrees rad/s Celsius

Figure 3.22: Select the suitable solution

Figure 3.22 shows that selection of the solution for this design. After select the solution that wants to determine, update the process and ANSYS will automatically run the simulation as shown in Figure 3.23



Details of "Total Deformation"

Scope
Scoping Method Geometry Selection
Geometry All Bodies
Definition
Type Total Deformation
By Time
Display Time Last
Calculate Time History Yes
Identifier
Suppressed No
Results

No Messages
No Selection
Metric (m, kg, N, s, V, A) Degrees rad/s Celsius

Figure 3.23: ANSYS simulation result

CHAPTER 4

RESULTS AND DISCUSSION

4.1 INTRODUCTION

This chapter present the mechanical properties of the fabricated SRPP square honeycomb by conducted a compression test on the control specimen. The numerical simulation for the square honeycomb structure is modelled by CATIA V5 software and using ANSYS for a finite element analysis. The result obtain from this simulation will be discussed further in this chapter. Lastly, the result obtained from the experimental is compared with the analytical result.

4.2 COMPRESSIVE RESPONSE OF THE HONEYCOMBS

Compressive tests were conducted on the composite square honeycombs to investigate the compressive test specimen. The compression tests were conducted in a test machine INSTRON Universal Testing machine model 3369 with maximum load capacity of 50 kN. The compressive stresses were inferred from the load cell output of the test machine. For each different length between slots (L) parameters of square honeycombs, the tests were repeated and the data that were collected will be further discussed below. Typical stress–strain traces following compression tests on the square honeycomb SRPP structures. It should be noted that the stress is based on the total area of the structure including the cells. The traces rise rapidly during the elastic loading phase before reaching a maximum and dropping rapidly as the walls in the core buckled. The relationship between the stress and strain that a particular material displays is known as that particular material's stress–strain curve. It is unique for each material and is found by recording the amount of deformation (strain) at distinct intervals of tensile or compressive loading (stress). These curves reveal many of the properties of a material (including data to establish the Modulus of Elasticity, *E*).

Stress–strain curves of various materials vary widely, and different tensile tests conducted on the same material yield different results, depending upon the temperature of the specimen and the speed of the loading. It is possible, however, to distinguish some common characteristics among the stress–strain curves of various groups of materials and, on this basis, to divide materials into two broad categories; namely, the ductile materials and the brittle materials.

Consider a bar of cross sectional area A being subjected to equal and opposite forces *F* pulling at the ends so the bar is under tension. The material is experiencing a stress defined to be the ratio of the force to the cross sectional area of the bar: This stress is called the tensile stress because every part of the object is subjected to tension. The SI unit of stress is the newton per square meter, which is calledthe pascal.1 pascal = 1 Pa = 1 N/m2.

4.3 LOAD VS DISPLACEMENT FOR CORE MODEL DESIGN

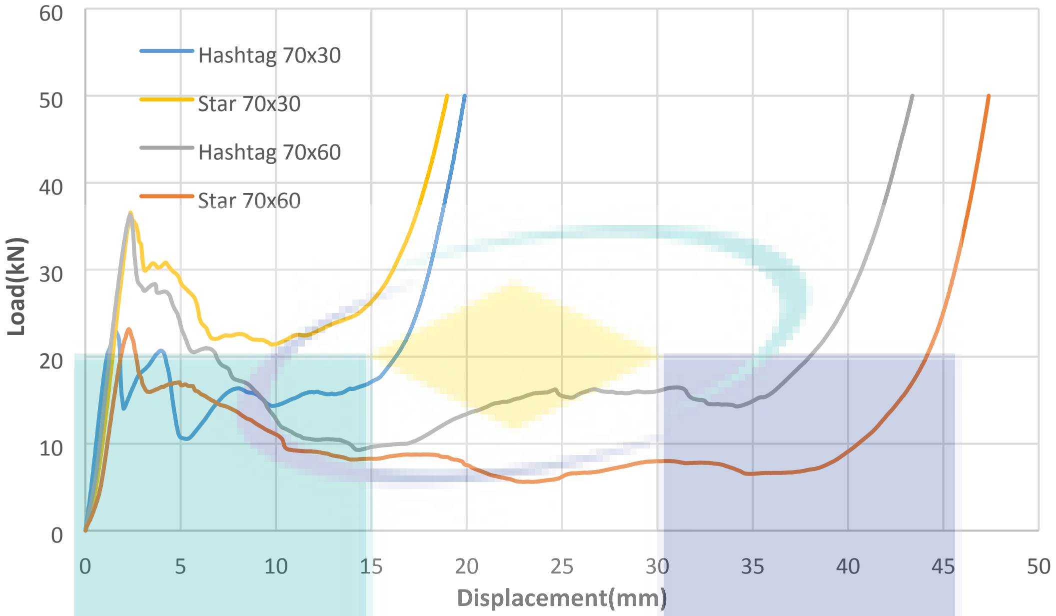


Figure 4.1: Graph of Load (N) against Displacement (mm) for core model sandwich.

4.4 LOAD VS DISPLACEMENT FOR SANDWICH MODEL DESIGN

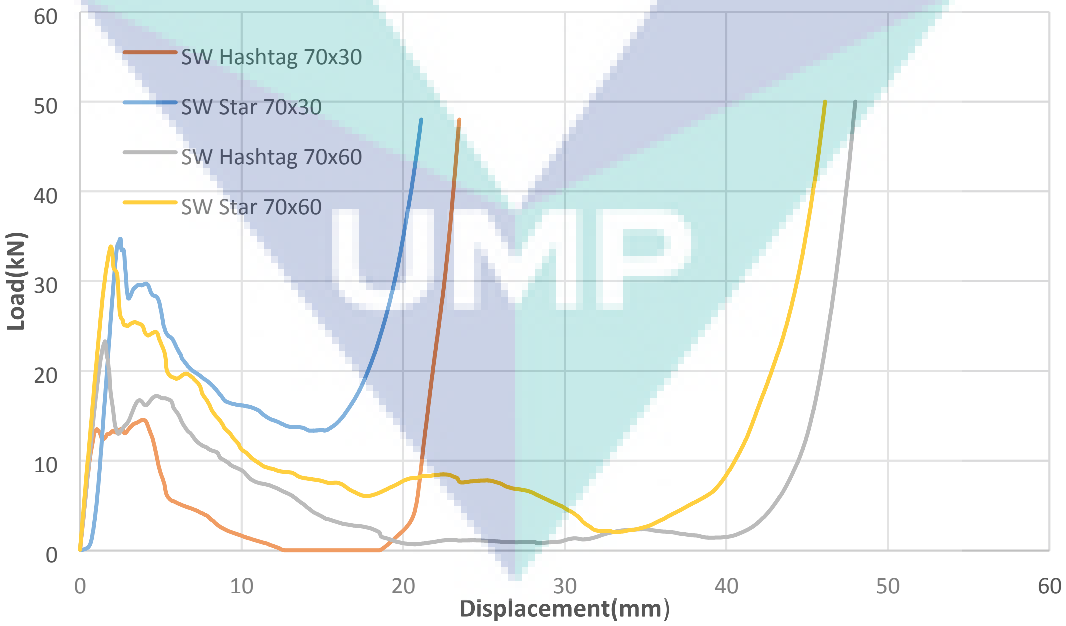


Figure 4.2: Graph of Load (N) against Displacement (mm) for sandwich model sandwich.

From the observation above, Figure 4.1 to Figure 4.2 shows a typical force-displacement curve for each model square honeycomb structure of SRPP with different length between 30 mm and 60 mm. Each specimen shows an initial elastic behavior, reached a maximum force followed by a decrease in slope. The curves then show a constant region of force with the increase of the specimens' displacement. For the compression testing, the specimens were set to be compressed to half and quarter of its original length which is up to 80%. From Figure 4.1, curve of maximum force of star 70x30 shows the highest force of 36.45 kN with displacement of 2.47 mm. Meanwhile, Figure 4.2 with curve SW Star 70x30 shows maximum force of 33.61 kN with displacement of 1.96 mm. These maximum forces are achieved when the displacement of square honeycomb structure model reached its maximum elastic limit before undergoes constant force. However, comparing these results, square honeycomb structure with length between 30 mm have a slightly higher compressive force but have a short displacement compared to those of 70 mm. This may due to the imperfection model during fabrication of the composites. Some of the slots were not equal to the depthness of a slot and some of it does not fit well into each other. Therefore, these imperfections do affect the results of the compression testing slightly.

4.5 COMPRESSIVE RESPONSE OF CORE MODEL DESIGN

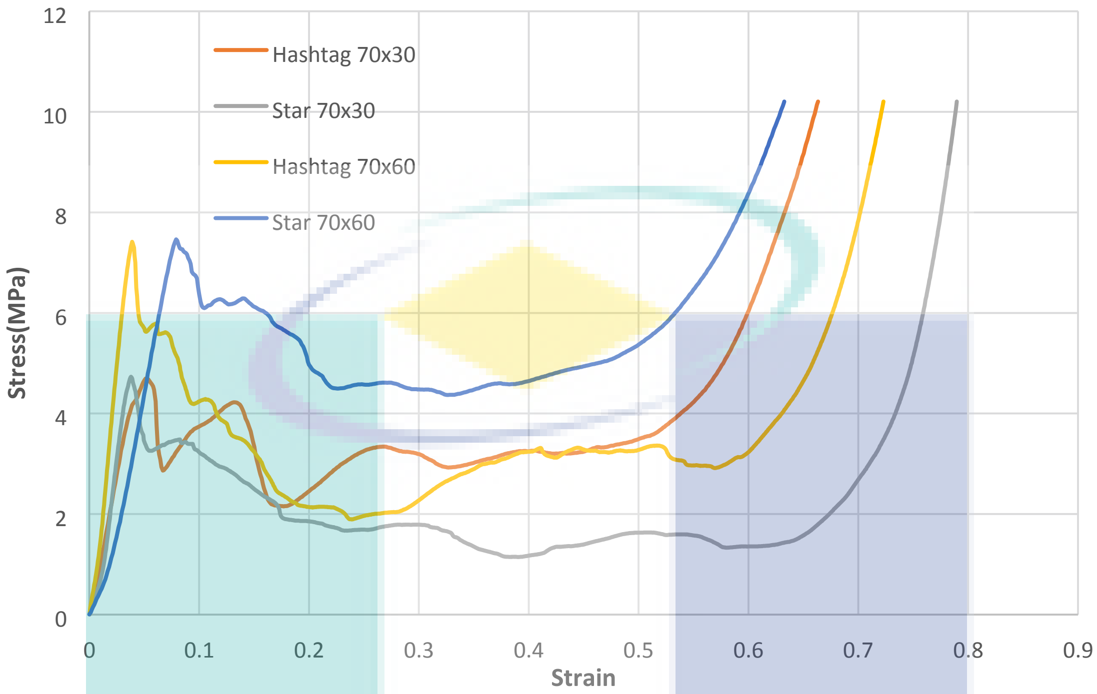


Figure 4.3: Typical compression stress-strain curves for core structure.

From the Figure 4.3, the specimen was tested in room temperature and exhibits an initial non-linear response, the specimen subsequently responds in a non-linear fashion up to the first peak in the trace. The highest elastic deformation (compression strength) is Star 70x60 with 7.46327 MPa, second Hashtag 70x60 with 7.41429 MPa, third Star 70x30 with 4.7326 MPa and the lowest Hashtag 70x30 with 4.73MPa. After reaching the peak stress, one of the cross section in the model was partially bent and as a consequence, the overall stiffness of the specimen decreased. The small non-linear regime degraded stiffness due to structure starts to buckle and deform of segment onset of compression test. The load required to further deform the sample gradually decreases due to the propagation of localised buckling across the width of the honeycomb. The response then becomes progressively linear, where the force drops rapidly as the panel loses stability due to elastic buckling. The honeycomb structure shape continue applied load and starts to increase again due to interactions between the surfaces of the cell. Finally, the all design has been completely densified.

4.6 COMPRESSIVE RESPONSE OF SANDWICH MODEL DESIGN

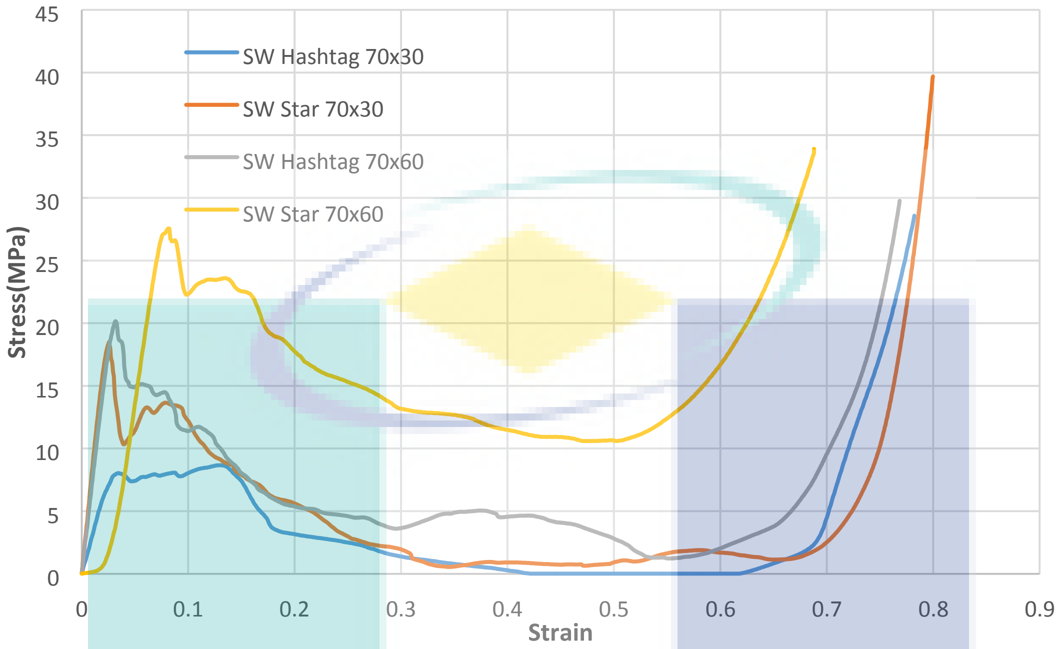


Figure 4.4: Typical compression stress-strain curves for sandwich structure.

From the Figure 4.4, the specimen was test in room temperature and exhibits an initial non-linear response, the specimen subsequently responds in a non-linear fashion up to the first peak in the trace. The highest elastic deformation (compression strength) is SW Star 70x60 with 27.55556 MPa, second SW Hashtag

70x60 with 20.16071 MPa, third SW Star 70x30 with 18.5 MPa and the lowest SW Hashtag 70x30 with 8.041667 MPa. The compression test about 2 times higher than core because by adding skin between structure (sandwich) improve the bonding of the segments in the model plus this sandwich structure absorb and hold the force before the actual force reach the inner segments structure. After reaching the peak stress, one of the cross section in the model was partially bent and as a consequence, the overall stiffness of the specimen decreased. For the design SW Star 70x30 shows the uniform decrease before its starts to continue the fracture. The small nonlinear regime degraded stiffness due to delamination of cross section onset of compression test. The load required to further deform the sample gradually decreases due to the propagation of localised buckling across the width of the honeycomb. The response then becomes progressively linear, where the force drops rapidly as the panel loses stability due to plastic buckling. The honeycomb structure shape continue applied load and starts to increase again due to interactions between the surfaces of the cell. Finally, the all design has been completely densified. The evidence from these tests on the core model indicates that elastic buckling, plastic deformation and the formation of plastic hinges are the dominant failure mode in this design.

4.7 COMPARISON BETWEEN SIMULATION AND EXPERIMENTAL

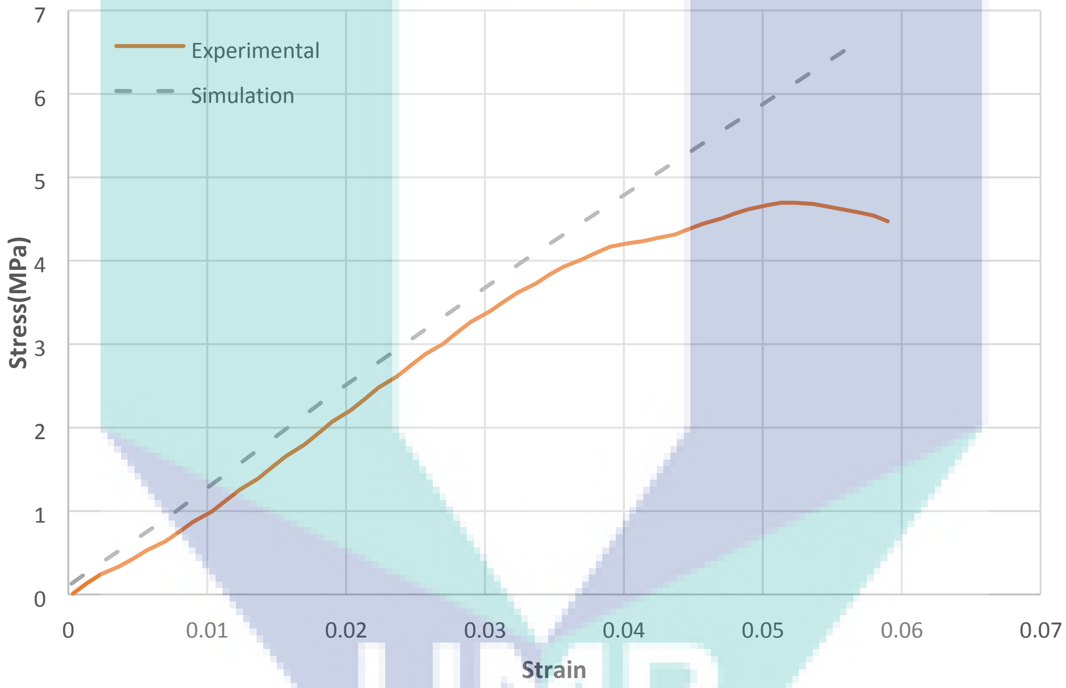


Figure 4.5: Comparison for Hashtag 70x30 model structure

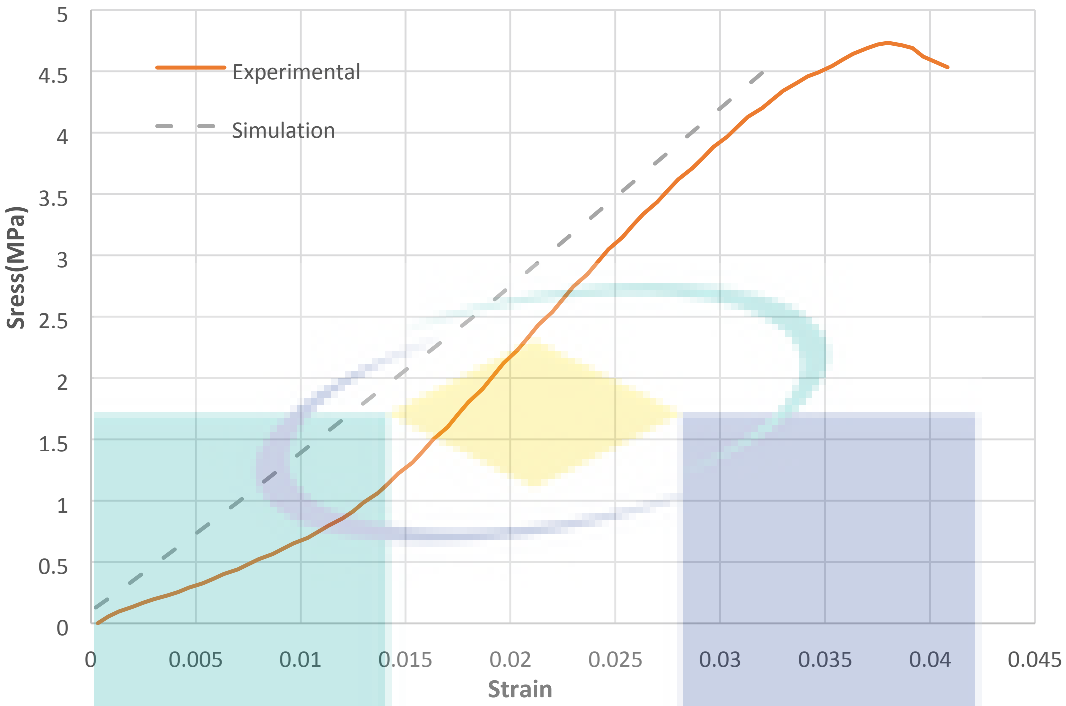


Figure 4.6: Comparison for Star 70x30 model structure

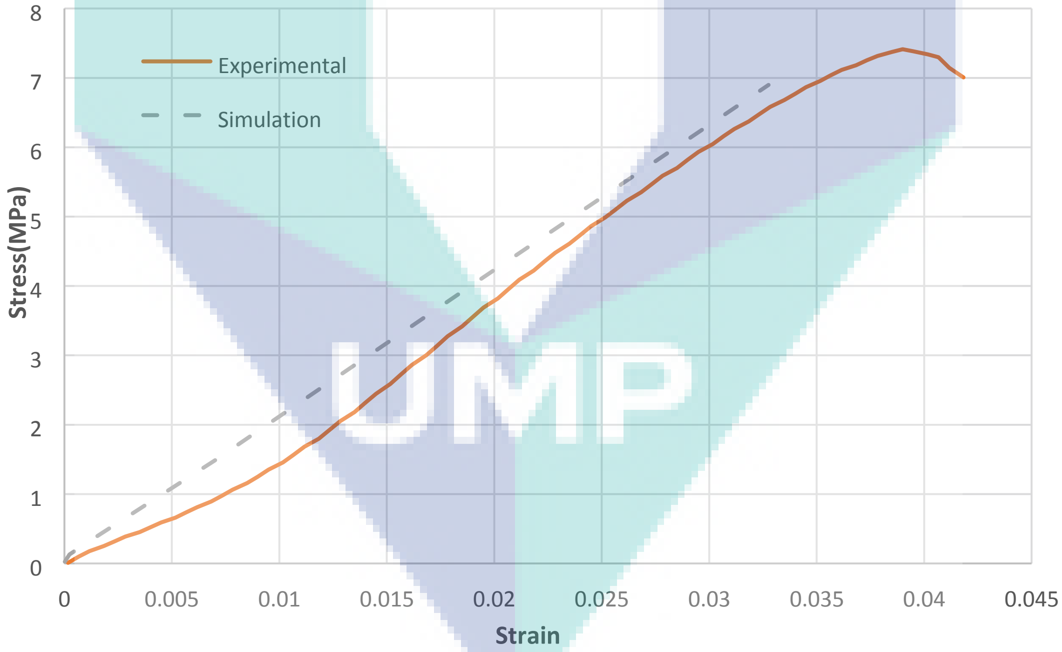


Figure 4.7: Comparison for Hashtag 70x60 model structure

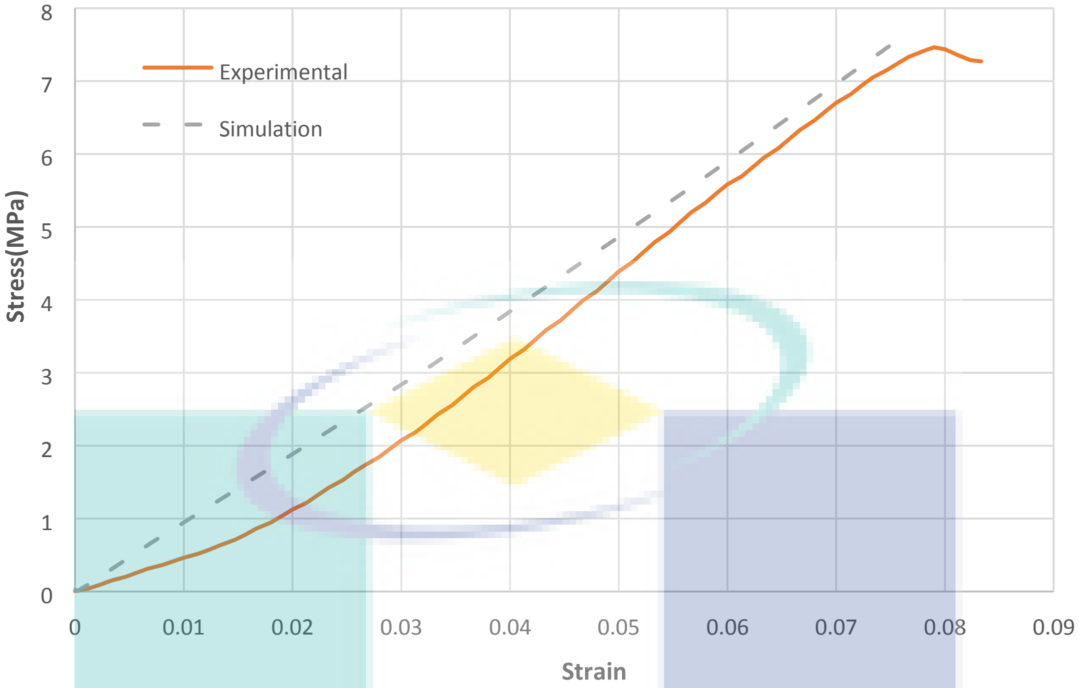


Figure 4.8: Comparison for Star 70x60 model structure

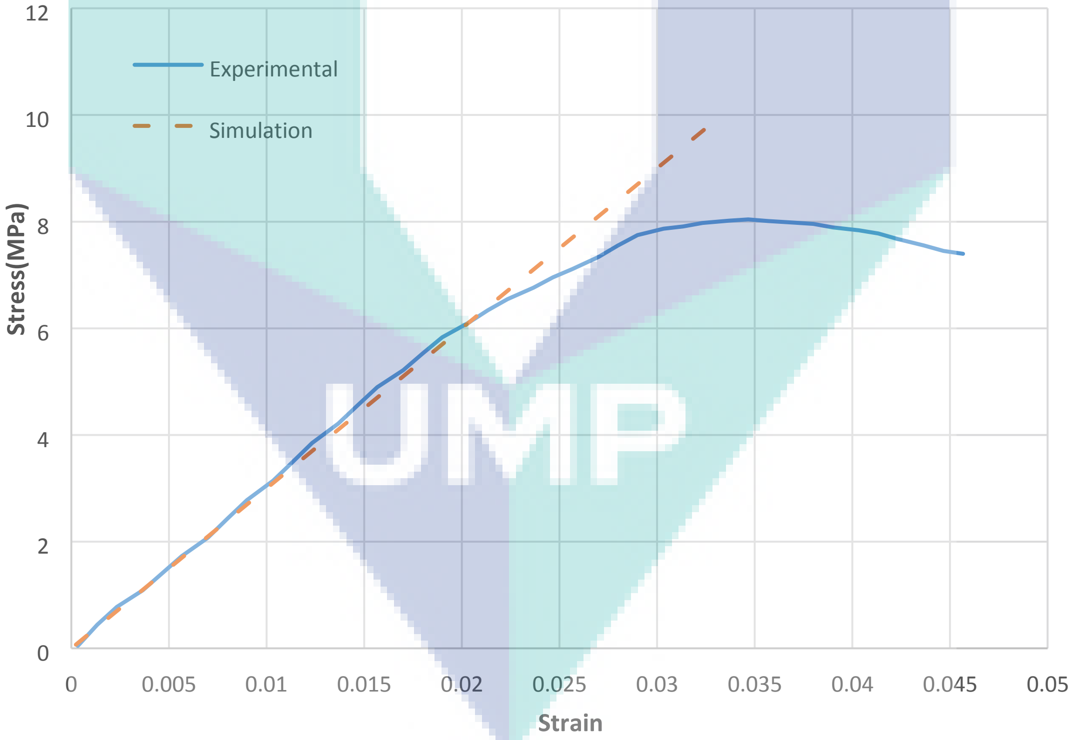


Figure 4.9: Comparison for Sandwich Hashtag 70x30 model structure

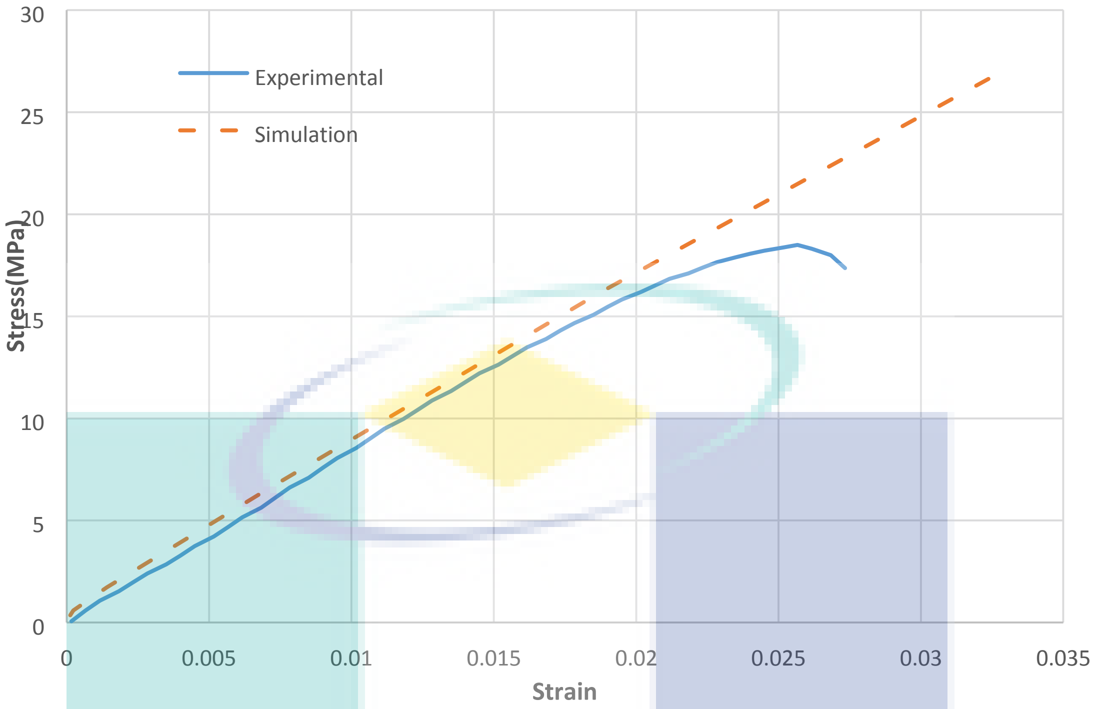


Figure 4.10: Comparison for Sandwich Star 70x30 model structure

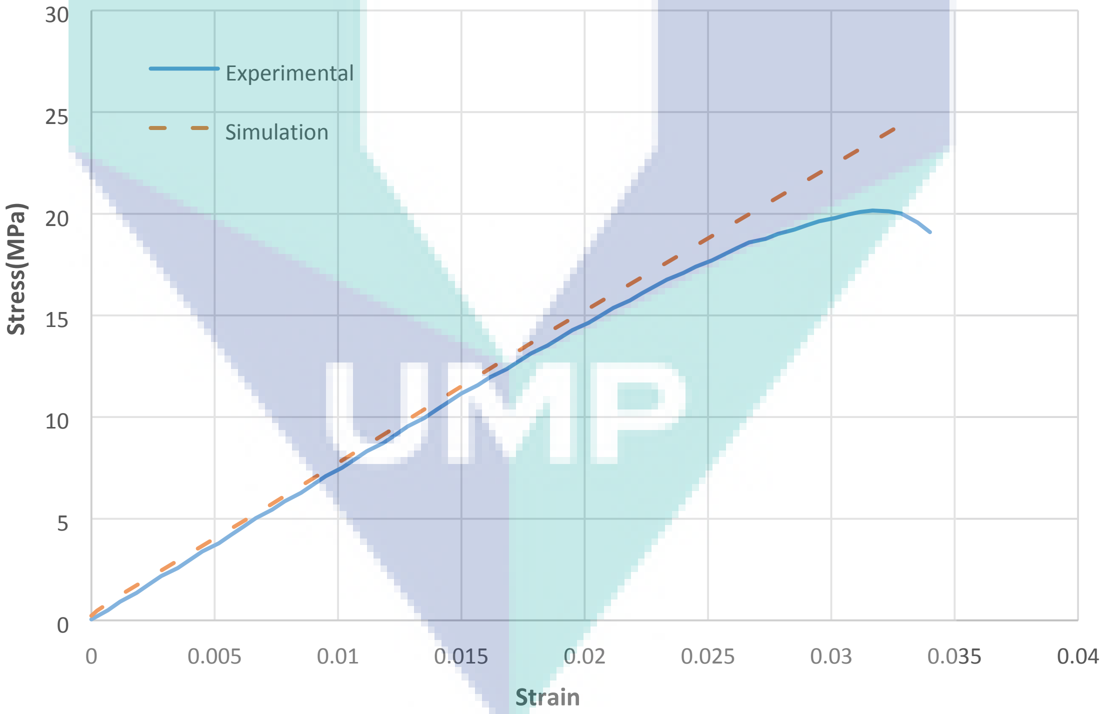


Figure 4.11: Comparison for Sandwich Hashtag 70x60 model structure

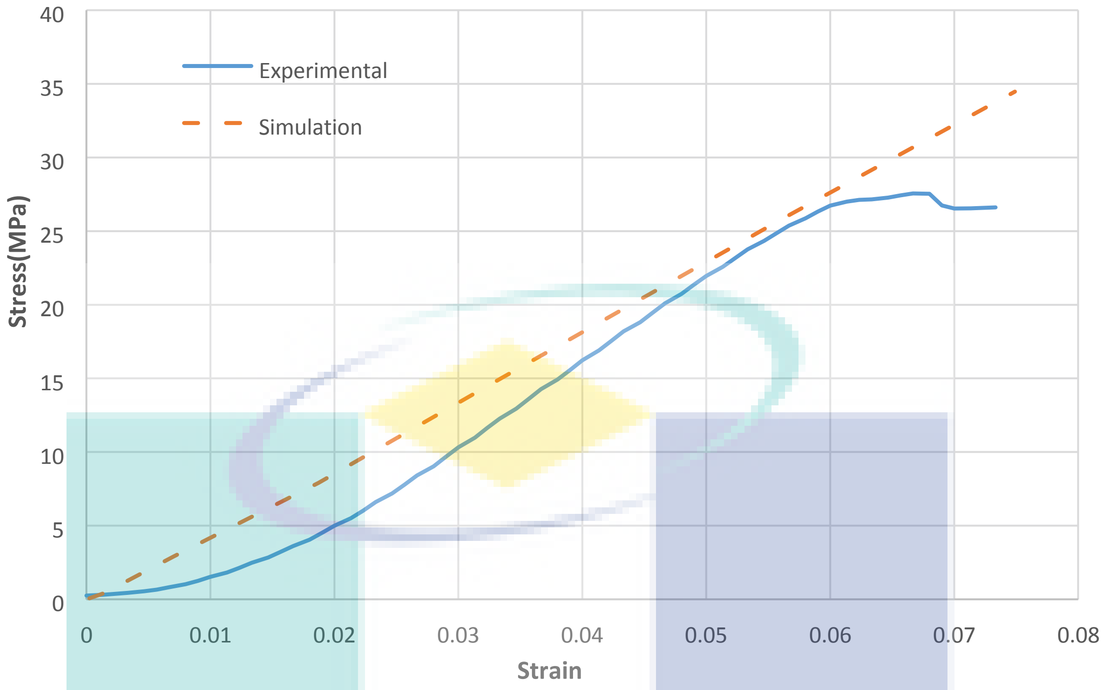


Figure 4.12: Comparison for Sandwich Star 70x60 model structure

For none sandwich and sandwich square honeycomb structure of SRPP with different length between 30 mm and 70 mm, figure 4.5 to figure 4.12 shows comparison between simulation and the elastic region of typical stress-strain curve. From the observation show that simulation have the linear results compare to experimental that after reach the peak(elastic region) where the honeycomb structures cell walls start to bend as stress increases, then the curves starts to decreasing until the structure total deformation. The simulation and experimental data is slightly different because of the lack of properties input in simulation, which is homogenous structure cannot be define while the actual structure using in experimental is homogenous.

The maximum stress is the greatest stress that a model structure is capable of sustaining without any deviation from proportionality of stress to strain. The highest stress for core is model Star 70x30 in figure 4.8, with experimental result 7.438 MPa and for simulation is 7.842. Meanwhile, the highest stress for sandwich is Sandwich Star model structure with experimental result 27.53 MPa and for the simulation is 34.465 MPa. From this observation, we can define that the sandwich structure have a high strength because the sandwich structure plate between the model hold the inner structure before its start to fracture. In general, the correlation between the experimental and simulation result is excellent with for the elastic region. The peak load for both almost identical and they achieved a good agreement in the compression stress-strain graph.

Figure 4.13: Comparison for compression stress for core and Sandwich model structure

From the Figure 4.13 shows that the sandwich comparison between eight different models square honeycomb of model structure. From the graph the pattern that the SRPP of star sandwich design with parameter 70x60 mm gives 3 times higher compression stress compare to core model for model hashtag 70x30mm. This is because of the Sandwich star 70x60 mm have complex cross section in the model structure plus with the larger length increase the strength of the structure, thus increase the compressive stress strength. In other words, the more segments in the structures, the stronger the structure of the model due to the segment helps to hold the structure tightly compare to hollow structure.

4.8 FAILURE MECHANISM OF THE DESIGN

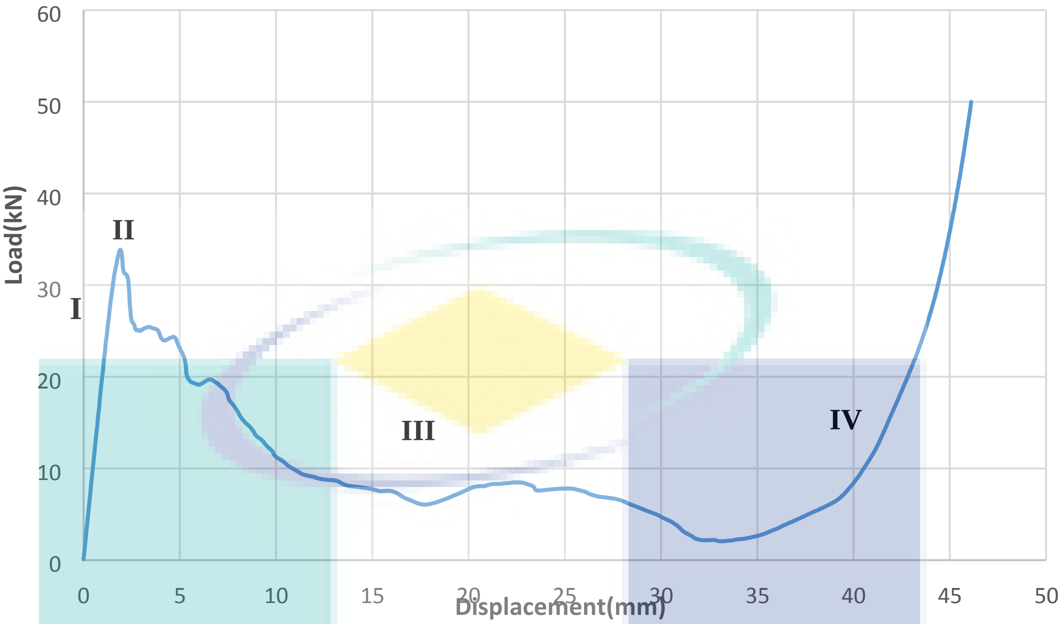


Figure 4.14: Graph of Load (kN) against Displacement (mm) for Hashtag model structure 70x60 mm

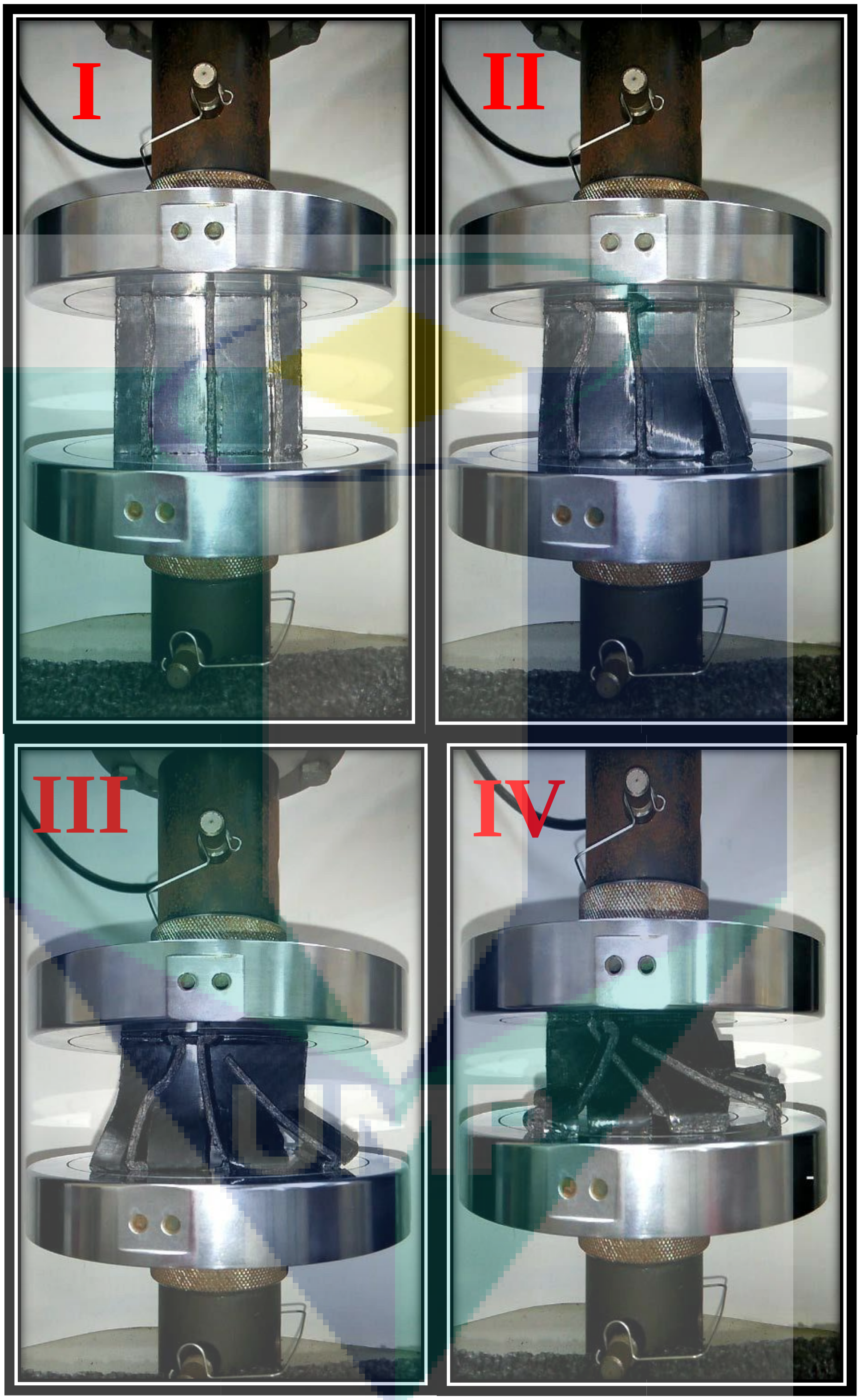


Figure 4.15: Compression of SRPP square honeycomb for hashtag 70x60 mm structure model

For the structural behavior and failure mechanism, specimen hashtag 70x60 mm is chosen to be analyzed as it has the greatest maximum stress compared to other specimens. Based on Figure 4.14, in the first region (I), the structure undergoes an initial elastic deformation with a constant load compressing the square honeycomb structure. Figure 4.15 shows at small strain (linear elastic region), the cell walls are bent. The linear elastic region ends at 2.5 mm strain. As the load increases along the displacement, it is then reaches a maximum load at 32.87 KN at the second region (II). Figure 4.15 shows that as load increases, the elastic buckling of the columns or plates that make up the cell edges or walls occurs. This causes the plateau region, in which the overall modulus is dominated by the lateral cell walls. At third region (III), there is a plateau of deformation at almost constant stress. The plateau region can be beneficial to energy absorption as more work is done within this range. The cell walls also collapse through plastic behavior. The plastic collapse occurs when the moment exerted on the horizontal cell walls exceeds its fully plastic moment, creating plastic hinges. The compression process continues at this point with speed of 2 mm/min. After certain deformation, at the fourth stage (IV), a region of densification occurs as the cell walls crush together.

4.9 SPECIFIC ENERGY ABSORBTION

In general, the failure modes observed during compression tests were unstable local buckling and mid length buckling and affected by the geometry of the SRPP square honeycomb structures in term of lengths between the slots of the composite honeycomb. The value of specific energy absorption capability of a structure is depended on the area under the load–displacement curve. Specific energy absorption characteristics of SRPP composite square honeycomb structures obtained from load–displacement curves according to the length of the displacement. Consequently square honeycombs with higher value of average crushing load showed higher value of energy absorption.

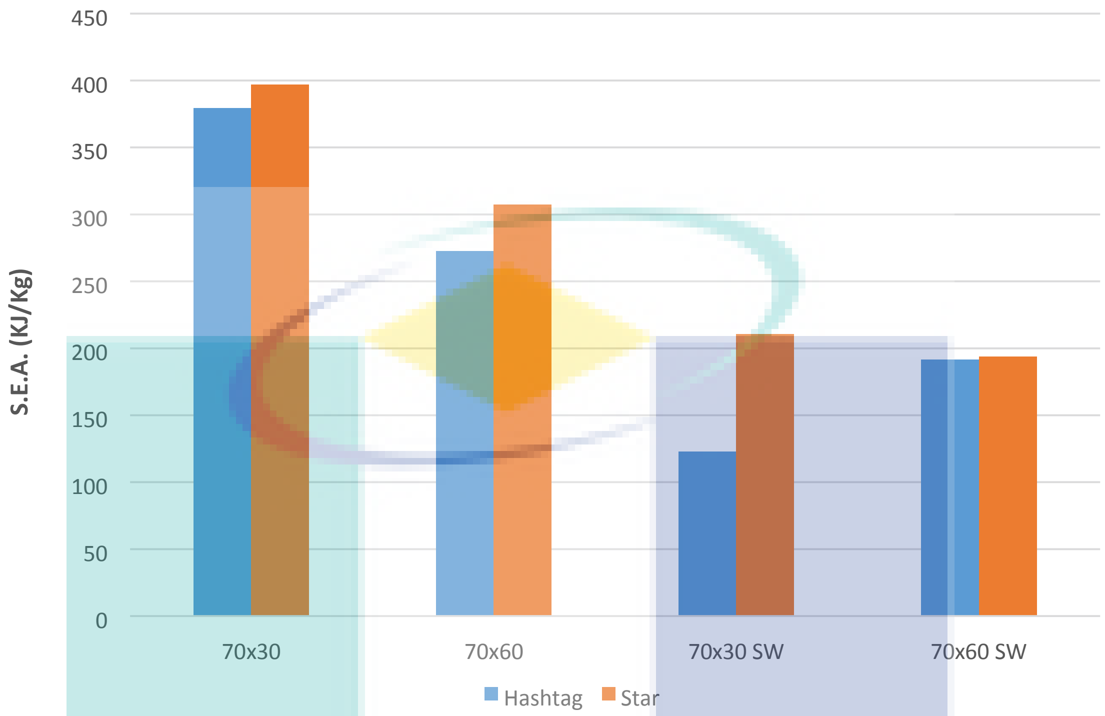


Figure 4.16: *SEA* of the square honeycomb SRPP structures

From the Figure 4.16, as can see the pattern and make observation that the energy absorption of all the square honeycomb cores were divided by weight of the core, and specific energy absorption (SEA) at a strain ε = 0.3 are compared using this intrinsic property. From the graph can observe that model structure none sandwich 70x30 mm have the higher S.E.A plus the Star model show the best results S.E.A from this experimental.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 INTRODUCTION

This chapter summarizes the important and significant outcomes from the work carried out in this research. It also embraces some recommendations for future work related to this research.

5.2 CONCLUSION

As the world is rapidly growing, advanced materials especially composites are being developed to be applied in human daily life. Finding alternatives to reduce the cost, ensuring the sustainability in the future and environmental effect of these materials are necessary to be considered for future generation. The aim of this project is to determine the compression characteristics and the of self-reinforced polypropylene (SRPP) composite square honeycomb structure. Eight types of different model structures have were tested, where are the main model are the Hashtag model and Star Model by using slotting technique. These specimens were evaluated and the results were discussed in Chapter 4.

Comparing the results of compression testing between none sandwich and sandwich square honeycomb structure, it can be conclude that SRPP with length 60 mm of Sandwich Star has the best properties to withstand high force. As the number of unit cells cross section for this specimen is more than those with length, the force acting on the honeycomb are equally distributed among these unit cells. In other words, the higher the number of unit cells, the higher the force/stress produced. For specific energy absorbtion, the specimen with length 30 mm for none sandwich star shows the highest specific energy absorption value of 396.91 J/Kg. This is the length of the structure 70x30 mm is more stable then 70x60 mm. As a conclusion, SRPP with Sandwich structure shows it is the best compressive strength meanwhile, core model structure give the higher specific energy absorbtion. The square honeycomb cores were made from slotting technique and they have outstanding properties in terms of the σ and *SEA*. From the experimental observations, it found that initial failure in the structures was dominated by the instability of the cross section when the cell wall starts to buckle. No evidence was found to show that adding a sandwich surface plate will increase the stability of the overall structure. However the surface plate helps to absorb more energy compared to none sandwich structure. The experiments indicate that the response was very sensitive to the density of the specimens, which led to change the deformation behaviour of the structure. For the scalling effect of this experiment, increasing the sizing of the structure manipulate the compressive strength and specific energy absorbtion in term bigger the size structure model improve the performance of the strength and the density of structure meanwhile by this it will effect the specific energy absorbtion because to calculate *SEA* equal to area under curve over mass. From the equation, higher the density of the structure, smaller the *SEA* of structure. The SRPP square honeycomb sandwich structure and none sandwich made by 100% recyclable sandwich structure. This potential core type design and material is a suitable candidate for automotive and aerospace applications in a near future.

5.3 RECOMMENDATION

There is something that been found to be useful for the next researcher that found this research useful and need to be brought forward more. The compression tests conducted were considered successful because the data obtained was relevant to previous studies of composite square honeycomb structures. For future research, in order to further the studies of these structures, there are few steps that could be taken to improve the result and data analyzing process. The advancement of materials nowadays has led to a development of material that is not only superior in properties, but can abundantly use in many kind of applications. A structural sandwich is a special form of a laminated composite comprising a combination of different materials that are bonded to each other so as to utilize the properties of each separate component to the structural advantage of the whole assembly. So due to the importance of sandwich structure nowadays, the recommendations is make further research on the ability of sandwich composite as well as experiments because this was a composite stunning beside its strength is not as severe. In addition it can save more cost such as if it is unable to replace materials used in car bodies, directly decrease the car load. When the load can be reduced, automatically fuel consumption can be reduced by more. The steps are listed below:

- Improve the process that will only result to one finished or “appearance” surface with the quality of the specimen depends mostly on the operator skills.
- As this experimental work requires a square geometry, the process is not too complicated to be executed. On the other hand, the cycle time per specimen is long and only small series can be produced while rigid properties of final product that requires undercut (slots) and straight cut need to be considered as composite material in sheet form.

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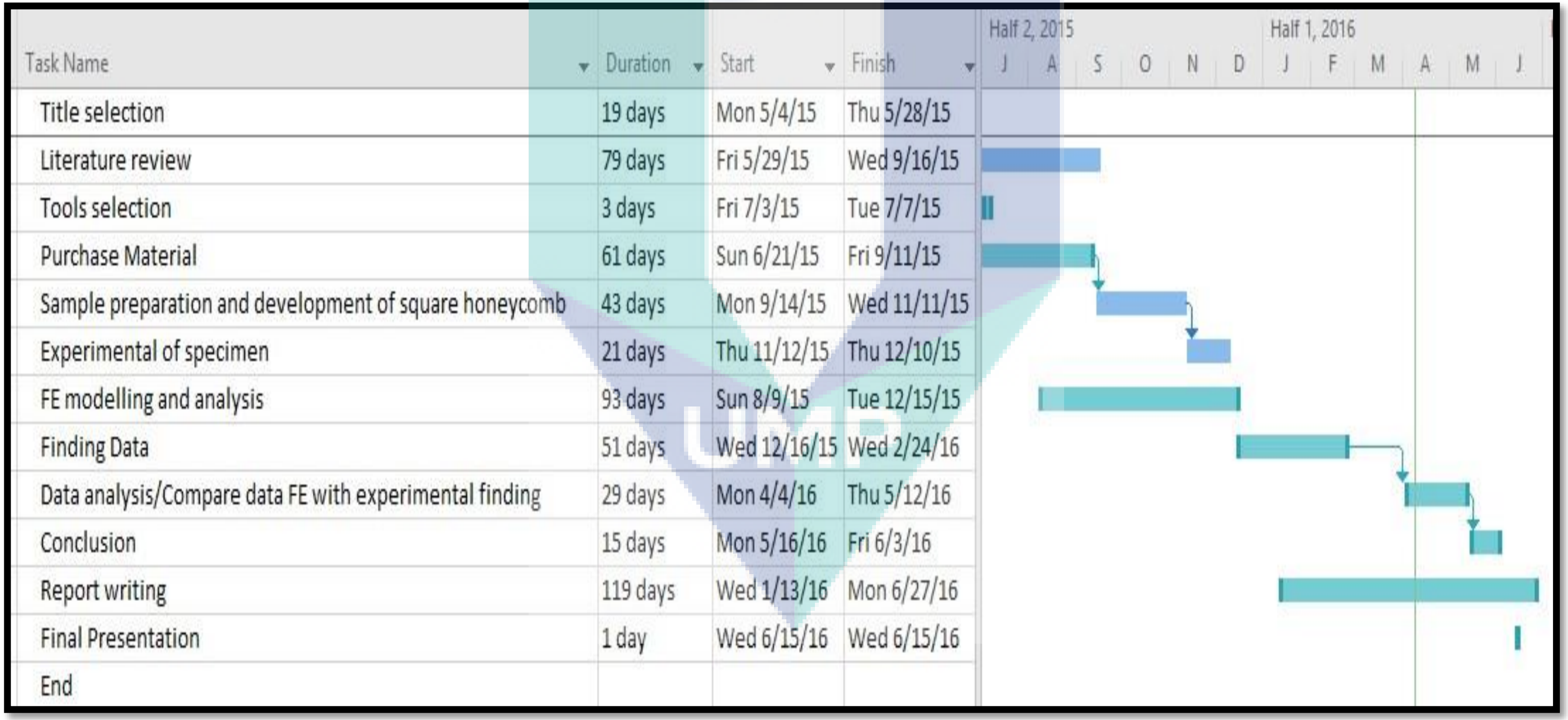
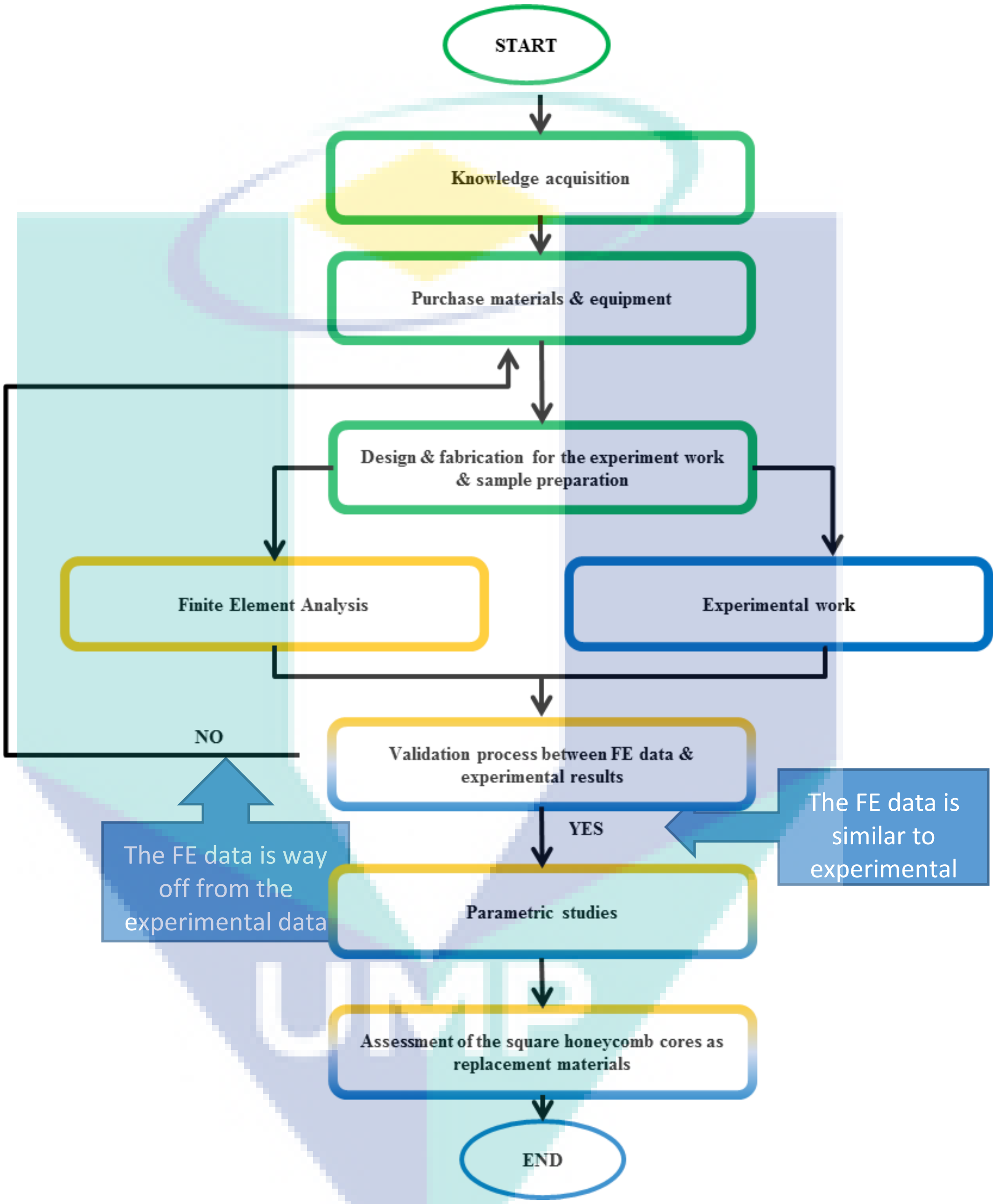
APPENDICES

Appendix A



Task Name	Duration	Start	Finish
Title selection	19 days	Mon 5/4/15	Thu 5/28/15
Literature review	79 days	Fri 5/29/15	Wed 9/16/15
Tools selection	3 days	Fri 7/3/15	Tue 7/7/15
Purchase Material	61 days	Sun 6/21/15	Fri 9/11/15
Sample preparation and development of square honeycomb	43 days	Mon 9/14/15	Wed 11/11/15
Experimental of specimen	21 days	Thu 11/12/15	Thu 12/10/15
FE modelling and analysis	93 days	Sun 8/9/15	Tue 12/15/15
Finding Data	51 days	Wed 12/16/15	Wed 2/24/16
Data analysis/Compare data FE with experimental finding	29 days	Mon 4/4/16	Thu 5/12/16
Conclusion	15 days	Mon 5/16/16	Fri 6/3/16
Report writing	119 days	Wed 1/13/16	Mon 6/27/16
Final Presentation	1 day	Wed 6/15/16	Wed 6/15/16
End			

Appendix B


START
Knowledge acquisition
Purchase materials & equipment
Design & fabrication for the experiment work & sample preparation
Finite Element Analysis
Experimental work
Validation process between FE data & experimental results
NO
The FE data is way off from the experimental data
YES
The FE data is similar to experimental
Parametric studies
Assessment of the square honeycomb cores as replacement materials
END