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NUMERICAL INVESTIGATION OF STRUCTURAL BEHAVIOR OF FIBER REINFORCED POLYMERS FILLED SANDIWCH PANELS

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Abubaker Sami DHEYAB

ABSTRACT

NUMERICAL INVESTIGATION OF STRUCTURAL BEHAVIOR OF FIBER REINFORCED POLYMERS FILLED SANDWICH PANELS

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This thesis deals with numerical investigation of structural behavior of fiber reinforced polymers filled sandwich panels. The skin of the panel is glass fiber reinforced polymer, carbon fiber reinforced plastic or aluminum. The core material is a polyurethane foam or honeycomb formed a glass fiber reinforced polymer. The sandwich panels are investigated with or without U channel profile ends. The numerical model is developed using the ANSYS APDL program for analysis of sandwich panels. This model is verified with experimental results which are available in the literature for sandwich panel subject to 4-point load test and made of glass fiber reinforced polymer skins, and polyurethane foam core. The verification study shows that there is good agreement between numerical and experimental results. The approved numerical model is used for the parametric study. The type of skin material, type of core material, the thickness of the skin and U profile ends are considered for the parametric study. The results of the parametric study are reported for the use of design engineers.

Keywords: Sandwich panels, Glass fiber reinforced polymer, Carbon fiber reinforced plastic, Finite element, Composite materials, Polyurethane foam core, Honeycomb core.

ÖZET

FİBER TAKVİYELİ POLİMERLER İLE DOLDURULMUŞ SANDVİÇ PANELLERİN YAPISAL DAVRANIŞLARININ SAYISAL OLARAK İNCELENMESİ

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65 sayfa

Bu tez, fiber takviyeli polimerler dolgulu sandviç panellerin yapısal davranışlarının sayısal incelenmesi ile ilgilidir. Panelin dış yüzeyi cam elyaf takviyeli polimer, karbon fiber takviyeli plastik veya alüminyumdur. Çekirdek malzeme cam elyaf takviyeli polimerden oluşan petek veya poliüretan köpük şeklindedir. Sandviç paneller, mesnet uçlari profilsiz veya U kanal profilli olarak araştırılmıştır. Sayısal model, sandviç panellerin analizi için ANSYS APDL programı kullanılarak geliştirilmiştir. Bu model, 4 noktalı yük testine tabi tutulan ve cam elyaf takviyeli polimer dış yüzey ve poliüretan köpük çekirdekten yapılmış sandviç panel için literatürde bulunan deney sonuçları ile doğrulanmıştır. Doğrulama çalışması, sayısal ve deney sonuçları arasında iyi bir benzerlik olduğunu göstermektedir. Parametrik çalışma için test edilmiş sayısal model kullanılmistir. Parametrik çalışma için dış yüzey malzemesinin türü, çekirdek malzemesinin türü, dış yüzeyin kalınlığı ve U profil uçları dikkate alınmıştır. Parametrik çalışmanın sonuçları tasarım mühendislerinin kullanımı için rapör edilmiştir.

Anahtar Kelimeler: Sandviç paneller, Cam elyaf takviyeli polimer, Karbon fiber takviyeli plastik, Sonlu elemanlar, Kompozit malzemeler, Poliüretan köpük çekirdek, Petek çekirdek.

To My Family

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LIST OF SYMBOLS/ABBREVIATIONS

3D	Three Dimensional
2D	Two Dimensional
ASTM	American Society for Testing and Materials
CFRP	Carbon Fiber Reinforced Plastic
D	Bending stiffness
E	Elastic modulus
FE	Finite Element
FHWA	Federal Highway Administrator
FRP	Fiber Reinforced Polymers
G	Shear modules
GFRP	Glass Fiber Reinforced Polymers
K	Initial stiff-ness
L	Space between the supports
M	Bending moment
PET	Polyethylene Terephthalate
PU	Polyurethane
P_u	Ultimate load
PVC	Polyvinylchloride
S	Shear stiffness
SiC	Solid silicon carbide

W	Weight
δ_u	Maximum deflection
ε	Strain
ε_u	Maximum longitudinal strain
σ	Normal stress
σ_u	Maximum flexural stress
τ	Shearing stress
τ_u	Maximum average shear stress
υ	Poisson ratio

CHAPTER 1

INTRODUCTION

1.1 General

Composite materials are not new. The Babylonians are credited with discovering that chopped straw added to wet earth extended the life of a wall and enabled it to support more weight. The Egyptians used plaster of paris laced with hair to prepare their tombs walls. What these ancients discovered was that a mixture of materials is often stronger than any of the individual components. This concept is now well established in many technologies [1].

Sandwich panels are meeting the requirements of modern civil infrastructures because their many benefits such as high stiffness to weight ratio, good fatigue resistance, high durability, corrosion resistance and light weight. The main benefit of sandwich construction in the applications for civil engineering is its ability to provide increased flexural strength without a significant increase in weight [2]. In World War II the sandwich plate was first used using plywood [3]. Since then, there is huge improvement in production, material and design of sandwich panels. In general, the sandwich plate as shown in Figure 1.1 consists of two thin skin, one at the top and the other at the bottom, separated by a low-density core.

In the manufacturing of sandwich panels used different materials as well as different forms to meet the new civil engineering applications requirements. In recent times, new materials are used to increase the benefit of sandwich panel such as (fiber-reinforced composite laminated material) for skin, solid foams for core [4]. Sandwich panels has high mechanical strength, low weight, thermal insulation and the low cost, therefor they are employing in several and modern application: civil structures, vehicles, airplanes, sporting tools and marine [5,6].

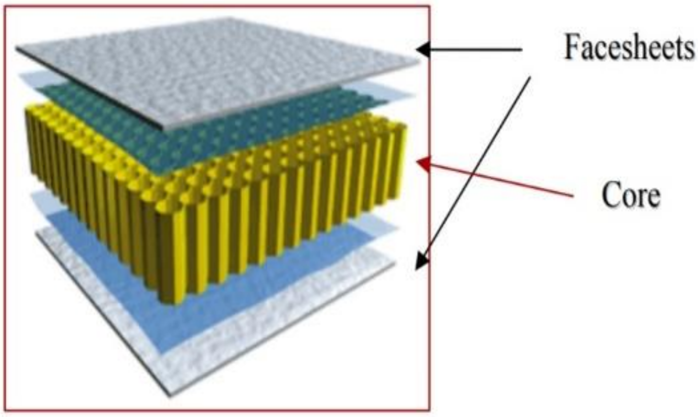


Figure 1.1 Main components of sandwich structure

1.2 Type of Sandwich Panels

The sandwich plate consists of two main parts (skin and core). Sandwich panels are classified according to the shape of the core as illustrated in Figure 1.2. There are different type of core;

- continuous corrugated-core,
- top-hat core, zed-core,
- channel-core and
- truss-core.

These types have a good mechanical property and many advantages; some of which are [4]:

- decreasing the problems for the connection.
- less cost for construction, handling, transportation.
- these shapes provide the flexibility to the designer to create curved shapes.

In addition, there are other types of sandwich panels core as shown in Figure 1.3. These are:

- honeycomb,
- solid foam (polyurethane, polystyrene, phenolic foam),
- solid plastic material (polyethylene) [5].

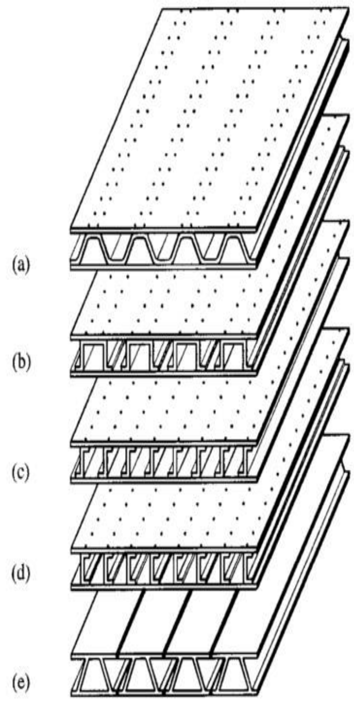


Figure 1.2 Type of sandwich panel with (a) continuous corrugated-core, (b) top-hat core, (c) zed-core, (d) channel-core and (e) truss-core.

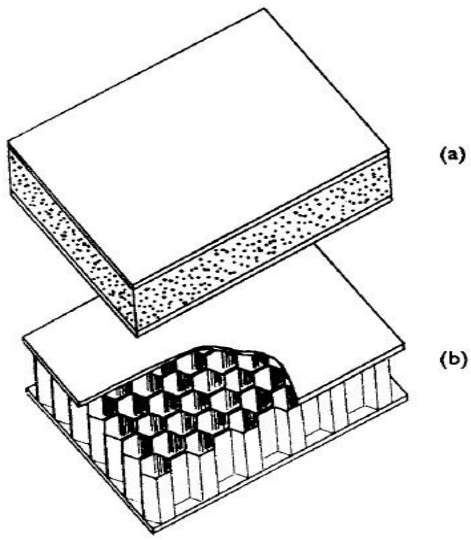


Figure 1.3 Types of sandwich panel core with (a) expanded plastic core, (b) honeycomb core.

Different methods and techniques used in sandwich panels manufacturing (wet / hand lay-up, vacuum bagging, adhesive bonding). The factors affecting the method of manufacture are economic [6].

1.3 Type of Material Used in Sandwich Panel Construction

The modern structures need many requirements, so a single material cannot meet that. The best solutions are composite materials like sandwich panels. For selection of the materials type for sandwich panel must have been systematic assessment of the possibilities available. The main task is to choose the most efficient material [1].

1.3.1 Face sheets materials

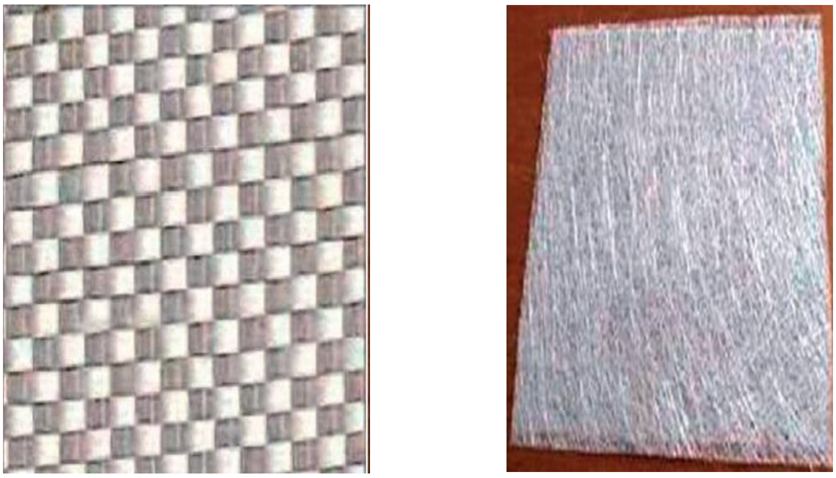
Face sheets or skins for sandwich panels have many properties, high-strength, high hardness, heat insulation and corrosion resistance. So these must meet the needs of manufacturing and new applications [6]. Materials used in skins of the sandwich panel (face sheets) are:

1.3.1.1 Glass fiber reinforced polymers

Glass Fiber Reinforced Polymer materials (GFRP) are have been developed appropriately for using in formation a sandwich panel skin. This material has many good properties; higher durability, higher mechanical performance, good insulation, lower maintenance and cost competitive solutions. That is making it suitable for use in sandwich panel skin [7]. GFRP is the most widely used composite material. The matrix comprised organic, polyester, thermostable, vinylester, phenolic and epoxy resins. Their mechanical behavior changes depending on the order shape of the fiber and arrangement of the fiber matrix as well as the method of bonding between them and the chemical stability. Figure 1.4 shown woven and random glass fiber mat [8].

1.3.1.1 Carbon fiber reinforced plastic

Carbon Fiber Reinforced Plastic (CFRP) is widely used in different applications due to it has unique properties according that it is desirable in the composition of the sandwich plate to use in aircraft parts, it is used in airplane to decrease the weight of structural and improved fuel economy [9].



(a) (b)

Figure 1.4 (a) Woven glass fiber mat, (b) Random glass fiber mat

CFRP are characterized by their high resistance, low density, strength and rigidity. CFRP material consists of a polymer (usually duroplastics, thermoplastics) used as a matrix material. The mechanical properties depend on matrix formation [10]. CFRP composite has a very poor thermal conductivity compared with general metals [11]. The typical structure of CFRP is illustrated in Figure 1.5 [12].

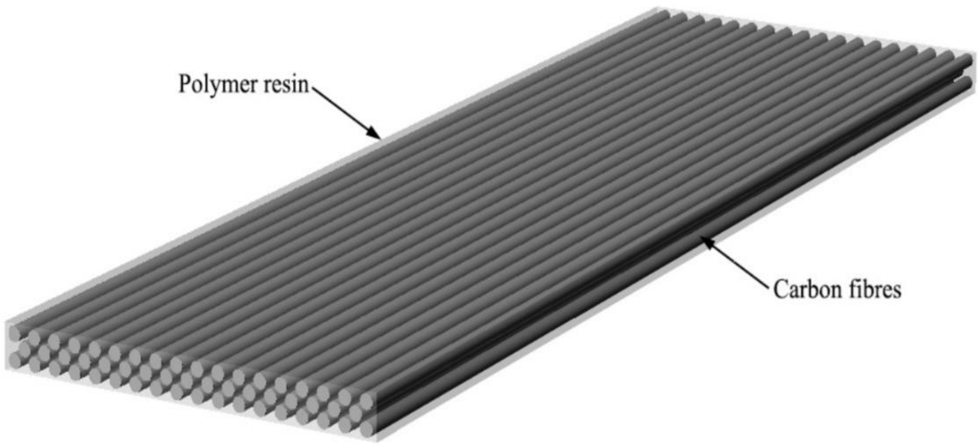


Figure 1.5 Typical structure of CFRP

1.3.1.2 Aluminum

Aluminum face sheet has been used in many fields and is one of the most proven materials in the aerospace industry since it is lightweight and very durable. Although its weight heavy compared to some materials but it is used in some applications to achieve the requirements. It plays a major role in the composition of the sandwich panel especially in aircraft industry [13].

1.3.2 Foam core materials

It is the second main part of the composition of the plate sandwich, as it is usually the thickness of the largest and one homogenous material and be tasked with carrying the second part of the loads. The core mainly carries transverse shear loads [14]. Materials used in the core of sandwich panel are:

1.3.2.1 Polyurethane foam

Polyurethane (PU) is commonly used in sandwich panels. PU foam is available in different rigidity, ranging from flexible to rigid or from tough to stiff elastomers according to the applications requirements. Density and rigidity are important parameters that effect on the efficiency of PU foam [15]. It has many advantages, so it is widely used in construction, flotation in boats, household refrigerators, aircraft, industrial insulation, and other marine structures [16].

1.3.2.2 Polyvinylchloride foam

PolyVinylChloride (PVC) foam is the first used in the 70's. PVC was developed to meet the requirements of marine applications. PVC foam generally used in marine application, because it has many properties such as resistant for high moisture content, low-density, consistent. PVC foam proved efficiency for employing it in a marine application. PVC foam is formed from closed cells that makes it resistant to moisture [17].

1.3.2.3 Aluminum foam

It is a common foam that is produced in various technologies, including make air in the molten bath of aluminum contains fine and solid particles of solid silicon carbide (SiC). One of the main functions of these molecules is to make the component more stable. It has also been used to suit the needs and requirements of modern industries. [18]. When the aluminum foam is subjected to pressure, it exhibits very high stiffness, although it is characterized by light weight, The failure of aluminum foam occur due to progressive collapse in the closed cells as illustrated in Fig 1.6 [19].

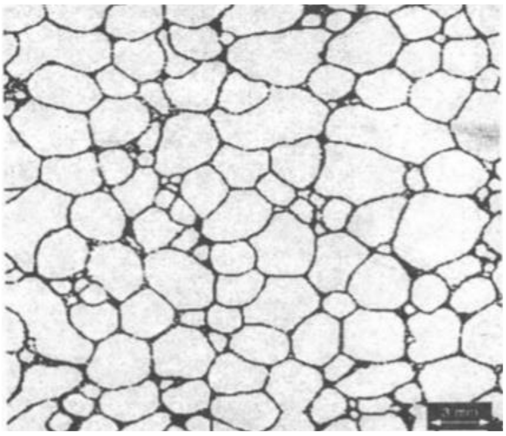


Figure 1. 6 Formation of cells enclosed in aluminum foam

1.4 Adhesive Materials

Adhesives used to connect the components of the sandwich panel, so it must be characterized by important properties of them such as bonding pressure, shear resistance. The adhesives materials used in the sandwich panel are: [20]:

- Phenolic blended with vinyl rubbers or epoxy
- Epoxies modified with nylon or other polyamide polymers
- Nitrile rubber modified epoxies
- Urethanes
- Other polyimides, thermoplastics and highly specialized adhesives.

1.5 Advantages of Sandwich Panels

Important features that make the sandwich panel of efficient applications are [20]:

- Ease of manufacturing process: In the manufacture of sandwich panel and accompanying operations, intersections are less, welding process is less.
- Effects of details: The sandwich panel design is less sensitive to poor design details and inadequate workmanship during construction or repair.
- Weight: Sandwich panels are very suitable for modern applications as they are lightweight compared to other structures.
- Cost: Using the sandwich panel reduces overall costs in all applications.

1.6 Objectives and Aims of the Thesis

The main aim of this thesis is to develop a method for reliable and validated numerical model for sandwich panels to meet the requirements for new applications. Finite Element (FE) software ANSYS APDL is presented in this study the possibility of determining and predicting the behavior of different types of sandwich panel and how will behave in the four-point load test required by the rules.

First focuses on the understanding and development of numerical model for sandwich panels, as well as comparing the numerical results with available experimental results to verify the extent of their approach. Besides that, parametric study taken to investigate in the effect of thickness and materials of skins, results for this phase important for future work to develop the sandwich structure.

1.7 Layout of the Thesis

The contents and arrangement of this thesis are expressed as:

Chapter 1 includes general introduction, types of sandwich panels, types of skins, types of cores, advantage of sandwich panels and objective of the present study.

Chapter 2 contains the literature review about structural behavior of sandwich panel and application of sandwich panels.

Chapter 3 describes the FE modeling and verification.

Chapter 4 presents parametric study and discussion of results.

Chapter 5 Conclusions based on the present results are given at the end.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The sandwich composite consists of two thin materials, the “skin”, separated by a much thicker lightweight material which is called “core”. The principle is to increase the structure’s stiffness and strength without compromising on weight or cost. According to American Society for Testing and Materials (ASTM) sub-committee D30-9, concerning common test methods for sandwich constructions, the ratio of the skin to core thickness should be equal to or less than 1/10th (e.g. ASTM C393). There are numerous benefits to a material like this. The main advantage, that it is characterized by high stiffness compared to the faces made of one material. The efficiency of a lightweight sandwich composite can be demonstrated by comparing it to a steel beam in bending. To have the same constraint on a deflection, a standard sandwich panel can save almost 90% in weight compared to a steel beam although the sandwich is over three times thicker [21].

2.2 Behavior of Sandwich Structures

To understand the mechanical behavior of the sandwich panels and to know the deformation under loads, the simply supported sandwich panel was loaded in its faces. The corresponding behavior would be as described in Figures 2.1. For the purposes of this discussion, it can be observed or assumed that shear strength is resisted by the uniform shear stress in core and skins resisted bending moment by axial stresses as indicated in Figure 2.1. The connection area between the skins and the core exposed to a shear stress equal to that in the core.

The basic function of the sandwich panel and adhesives is to prevent sliding faces. Figure 2.1(d) shows, If used adhesive material has low shear strength, the slipping of skins will occur. Figure 2.1(e) explains how failure occurs when using core materials have weak properties for shear strength or stiffness. In order to avoid this failure, the core materials must be chosen with a high shear modulus with high shear strength. These properties are required when designing the sandwich panel.

The second task for the adhesive and core materials is to resist the local buckling in upper skin in compression case. This behavior is illustrated in Fig. 2.1(f). Wrinkling, it phenomenon occur if upper skin subjected to compression. Wrinkling failure takes place is dependent on the stiffness of the core. The mechanical properties of the core play a major role in reducing this failure. The final mode of failure, which is shown in Fig. 2.1(g), is the tensile yielding of the lower face. This is generally the least likely of the alternative modes shown in Fig. 2.1 [6].

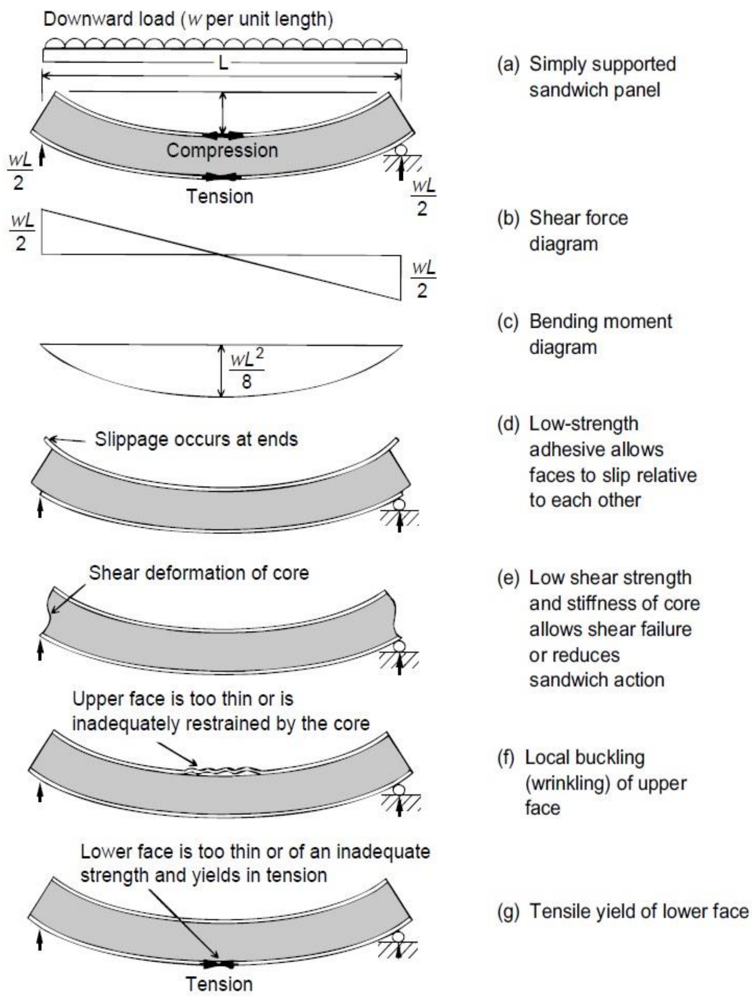


Figure 2.1 Structural behavior of a simply supported sandwich panel

Mamalis et al [22] studied the mechanical behavior of eight samples of a sandwich panel made of different materials under edgewise compression load. Two of samples are made of GFRP skins laminates. As results, three modes of collapse were recorded in this study. These are unstable sandwich column buckling with foam core shear failure, unstable sandwich disintegration with buckling of faceplates to opposite directions, and progressive end crushing of the sandwich panels. the type of failure is depending on the main properties of core.

Mostafa & Shankar [23] developed alternative system to reduce the effect of shear in bonding area between skins and core by adding new shape (shear keys). GFRP shear keys has semi-circular shape with different thicknesses. The shear keys carried a some of shear loads under testing. This system improved the shear strength with approximately 10% higher than ordinary model.

Awad et al. [24] studied the mechanical properties of GFRP sandwich floor panels and focused on the vibration facing the sandwich panels. Also, the effect of type of support (one-way, tow-way) and fiber orientation have been studied. It has been found that the direction of fiber effect with the type of support have affected for the behavior of sandwich panels.

2.3 Sandwich Panel Applications

The sandwich panel has many features that met the requirements in several fields. Some of them are:

2.3.1 Floors

One of the most recent large-scale applications of GFRP sandwich panels is currently under construction, corresponding to the roofs of the stations in the Haramain high speed railway project, in Saudi Arabia shown in Figure 2.2. A modular arrangement is being used for the station roofs, composed of a steel main structure supporting structural GFRP roof panels with a Polyethylene Terephthalate foam PET core. These will have span lengths of up to nine meters, and a total of over 160,000 m² of GFRP sandwich panels will be used across the project's four stations. The modularity of these panels allows for significant reductions in their production costs, while construction time associated with the roof structures is relatively low.

The example shown here illustrate the potential of lightweight sandwich panels for civil engineering structural applications. So far, this potential has been mostly used to create lightweight roof structures and bridge decks. Their application in building floors is still mostly unexplored in the construction industry. This segment is constituting a research and industrialization opportunity with a high potential for the civil engineering domain [25].

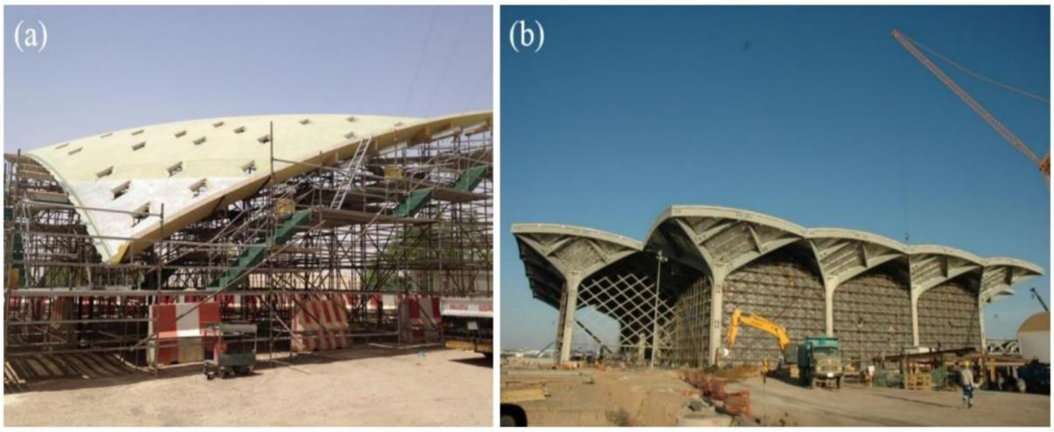
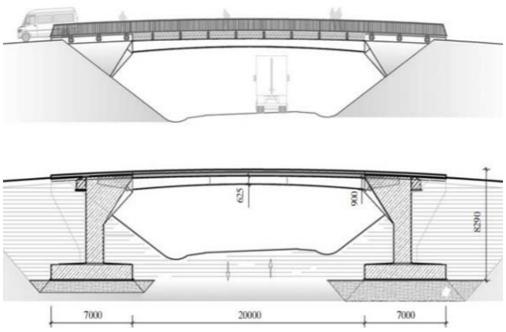
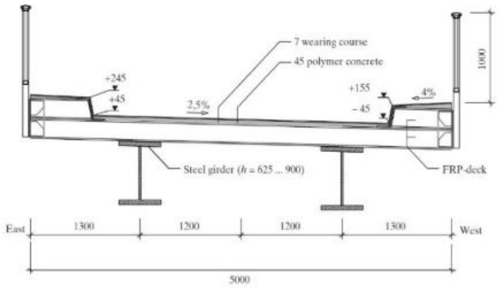


Figure 2.2 Roofs of the Haramain high speed railway station: (a) mock-up installation, and (b) construction phase

2.3.2 Bridges

The first bridge was implemented in Germany in 2008 where it was used GFRP deck in Friedberg/Hessen shown in Figure 2.3. The span of this bridge is 27 m over across the federal road B3. The most important features of this new type of bridges are the ease of assembly, high durability, light weight, it's helpful for the construction of bridges fast installation. In these years, many light bridges have been built in Japan, America and Europe. Through these projects, valuable experience was gathered regarding construction, and the use and performance of composites could be demonstrated [26].





(a) (b)

(c) (d)

Figure 2.3 Bridge structure (a) FRP bridge in Friedberg (Hessen—Germany); (a) Elevation and longitudinal section, (b) Standard cross section of composite superstructure, (c) Mounting of superstructure on construction site, (d) Front face of superstructure

Tuwair et al. [27] were worked on the investigation of PU foam-infill bridge deck panels (PU sandwich panels) after being exposed to various environmental conditions. These panels were constructed with woven E-glass fiber/PU face sheets that were separated by a trapezoidal-shaped, low-density PU foam. Corrugated web layers were introduced into the core to enhance the panel's structural characteristics. An experimental work was designed to simulate there in situ environments. The environmental conditions used included different conditioning regimens to examine the behavior of both GFRP laminates and PU sandwich panels. The GFRP laminates, which were made from the same materials as the PU sandwich panels, were exposed to ultraviolet radiation, a de-icing solution at both room temperature and elevated temperature, and thermal cycling. The PU sandwich panels were exposed to thermal cycling (a series of freeze–thaw, mid–high temperatures, and mid– high relative humidity cycles). The thermal cycling exposure was conducted in a computer-controlled environmental chamber to duplicate seasonal effects in Midwestern states. Following the exposure regimens, tensile strength tests and four-point loading tests were performed on the GFRP laminates and the PU sandwich panels, respectively. The evaluation was based on visual inspection, strength, stiffness, and failure modes, as compared to those that were not conditioned (the control). The results of this study revealed that degradation did exist due to the effects of thermal cycling and the de-icing solution. The ultraviolet radiation, however, did not cause any degradation. These results were within the recommended environmental durability design factors of the Federal Highway Administrator FHWA guidelines.

2.3.3 Ships and submarine

The using of composites in ships increased significantly in the mid-1980s as those were used in military areas to improve structural performance as well as reduce weight and reduce the cost of maintenance. And its use has become widespread in marine applications, including their current and potential use in the superstructures, decks, bulkheads, advanced mast systems, propellers, propulsion shafts, rudders, pipes, pumps, valves, machinery and other equipment on large warships such as frigates, destroyers and aircraft carriers. Potential applications of composites to submarines are: their possible use in propulsors, control surfaces, machinery and fittings. The growing use of composites in the complete construction of fast patrol boats. Figure 2.4 shows the applications of composite structures to naval ships and submarines

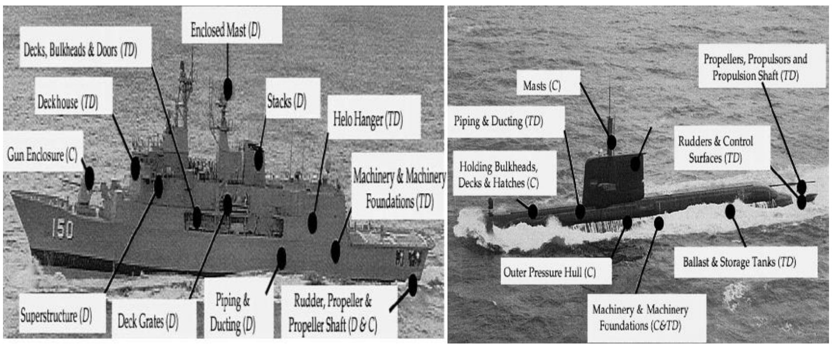


Figure 2.4 Applications of composite structures to naval ships and submarines [28].

The mechanical properties of the sandwich panel were studied and investigated in case of surface cracks and damage to the pressure under effect of bending or shear by Thomson et al. [29]. The sandwich panel is made of GFRP skins and PVC foam core, and this sandwich material is used in some naval mine hunting ships. It was found that determining the edgewise compression properties of a large sandwich structure (such as a mine hunting ship) using small specimens is difficult because the strength and failure mechanism are dependent on the gauge length. The compression strength decreases rapidly with increasing gauge length, and the failure mechanism changes suddenly from compressive fracture of the skins to shear crimping of the core when the specimen length reaches -100 mm. Because of this sensitivity, size effects become an important factor when scaling-up the results from small coupon tests to a much larger structure such as a minehunter. Edgewise compression loading causes the failure mechanism to change from core shear crimping to skin buckling while shear loading changes the mechanism from localized skin buckling to core shear cracking.

2.3.4 Aerospace

To achieve the main tasks of the airframe the sandwich panels were used in the manufacture of parts of the aircraft. The sandwich panel is increasingly used in the formation of aircraft structures, characterized by many properties of these applications Example-Jaguar, Light Combat Aircraft, Advanced Light Helicopter) includes fuselages, wings, ailerons, floor panels and storage and pressure tanks as shown in Figure 2.5 [30].

Ding [53] worked on the optimum design of sandwich construction by using FE methods. Where he studied the effect of thickness on three parts. These are beam clamped at both ends, wing box, and wing of the ultralight aircraft. shown in Figure 2.6.

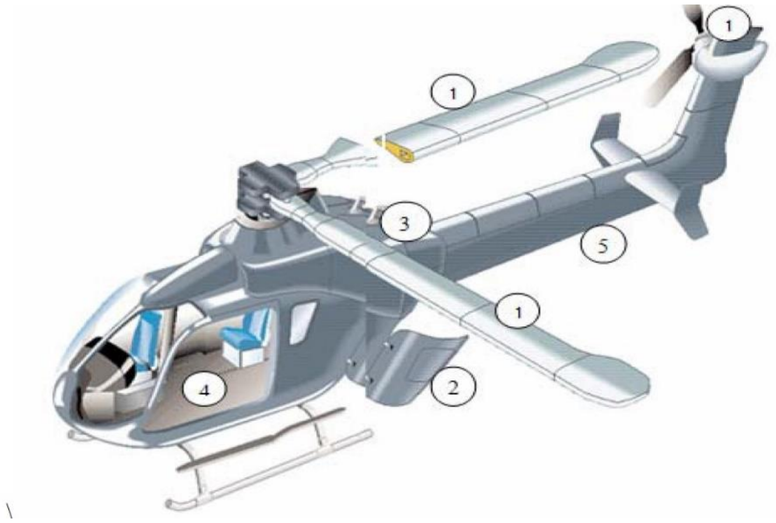


Figure 2.5 Application of sandwich structure in helicopter. (1. Rotor Blades, 2. Main and Cargo Doors, 3. Fuselage Panels, 4. Fuselage, 5. Boom and Tail section) [30].

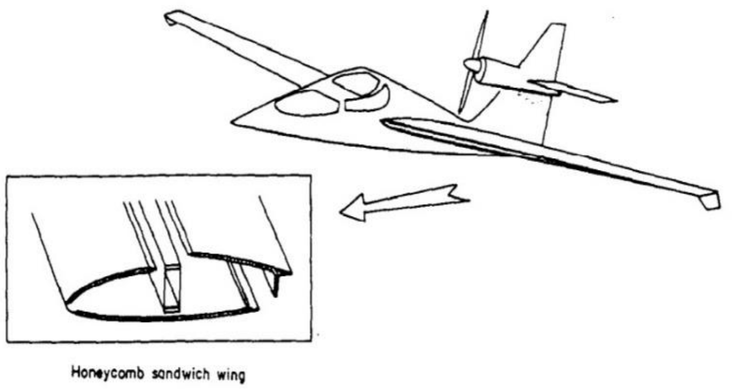


Figure 2.6 Application of sandwich structure in aircraft [31].

2.4 Analysis of Sandwich Panels

Many researchers used numerical methods to find the mechanical properties and behavior of the sandwich panel. Some of them are summarized below.

Ha [32] presented overview of the state-of-the-art FE analysis of sandwich plate structures. Transverse shear deformities were discussed and found transverse shear deformations occur to a certain extent in any plate subjected to transverse loading, but they are more significant in thick isotropic or laminated composite plates. The sandwich plates with soft cores is necessary to make sure whether the effects of transverse shear deformations are significant enough to warrant the extra analysis effort. A rule of thumb for preliminary design is that such effects can be neglected if equation (2.1) is satisfied.

$$\frac{\boldsymbol{SL^2}}{\boldsymbol{D}} > 100 \qquad (2.1)$$

where $\boldsymbol{S}$ and $\boldsymbol{D}$ are the shear and bending stiffness, respectively, and L is the length of the beam or plate.

It has been clarified that the material can be represented for the sandwich panel skin and core as isotropic, orthotropic or anisotropic.

Stress distribution in skin section can be modelled using one of the following theorem:

a) Thin facing theory: the face is treated as a solid membrane, i.e. constant σ_x, σ_y, τ_{xy}.
b) Thick facing theory: Thin facing theory: the face is treated as a solid membrane, i.e. constant a,,σ_x, σ_y, τ_{xy}.
c) All five stress components σ_x, σ_y, τ_{xy}, τ_{xz}, τ_{yz} are defined, and are often allowed to vary across the layer thickness.

For core section stress distribution may be assumed as

a) Flexible core: constant transverse shear stresses τ_{xz}, τ_{yz}
b) Stiff core: similar to skin model (c) above.

Displacement variation. The approximations so far are concerned with individual layer behavior. Since the layers are bonded together, certain quantities such as interlaminar shear stresses and displacements are continuous across layers. This, combined with the need to enforce strain compatibility within the layers (as required in the displacement FE formulation), necessitates an assumed kinematic deformation mode for the plate section. The following approach can be used

a) Linear variation (Fig. 2.7): the normal remains straight across the entire cross-section of the plate, but not necessarily perpendicular to the middle plane.
b) Piece-wise linear variation with partial continuity (Fig. 2.8).
c) Piece-wise linear variation with full continuity (Fig. 2.9).
d) Quadratic or cubic variation to allow for warping of the cross-section.

The discontinuity of the in panel displacements at the layer interface shown in Fig. 2.9 arises from the neglect of transverse shear deformations in the stiff layers.

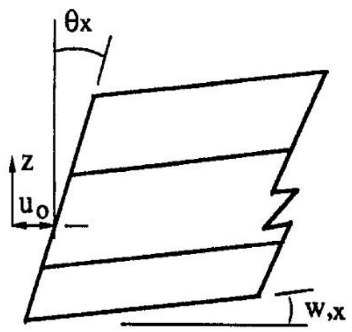


Figure 2.7 Linear displacement variation [32]

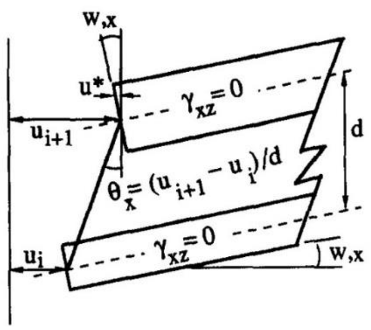


Figure 2.8 Piece-wise linear displacement with partial continuity [32]

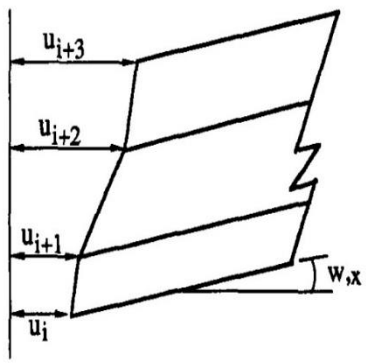


Figure 2.9 Piece-wise linear displacement with full continuity [32]

Mudassir et al. [33] were studied on the mechanical behavior in 4-point bending of two different composite sandwiches laminate foam with two different orientations of fiber. The skin face consisted of balance symmetry [0/90/90/0]2 and Quasi-isotropic [0/45/90/-45]2 orientations. The simulations of all the experimental tests have been carried out by using the ANSYS software.

The calculation of core and facing flexural stiffness are given below.

$$EI_{core} = \frac{bc^3}{12}\, E_C \qquad 2.2$$

Where:

EI_{core} : flexural stiffness of core material, EI_{face} : about the parallel axis and equal to $E_f I_{face}$. I_{face} can be calculated from the parallel axis theorem as

$$I_{face} = 2\left[I_{faces} + Area.\left({}^{d}/_{2}\right)^2\right]$$

$$EI_{faces} = E_f\left[{}^{bt^3}/_{12} + {}^{btd^2}/_{2}\right] \qquad 2.3$$

The standard formulas for flexural stiffness was calculated using ASTM standards EI [33]:

$$EI = \left[\frac{bt^3}{6} + \frac{btd^2}{2}\right]E_s + \frac{bc^3}{12}E_c \qquad 2.4$$

Where: $EI$is flexural stiffness, b is width of the specimen, t is skin thickness, c is core thickness, d is specimen thickness and E_s, E_c: skin and core Young's modulus.

The deflection of the beam was then calculated using ASTM D 7250/D 7250M-06 standard [33]:

$$\delta = \frac{P(2S^2 - 3SL^2 + L^3)}{96EI} + \frac{P(S - L)}{4U} \qquad 2.5$$

Where, P is load applied on the specimen, L is load span length, U is transverse shear rigidity and S support span length.

The flexural behavior of a composite sandwich beam has been studied experimentally, analytically and numerically. The behavior of different foam cores with the different fiber orientations of sandwich composite panels was also investigated.

CHAPTER 3

FE MODELING AND VERFICATION

3.1 Finite Element Modeling

The sandwich panel is designed to study mechanical characteristics and behavior by using the ANSYS APDL software program. The sandwich panel is consisting of upper and lower GFRP skin and PU foam core between the two skins as shown in the Figure 3.1.

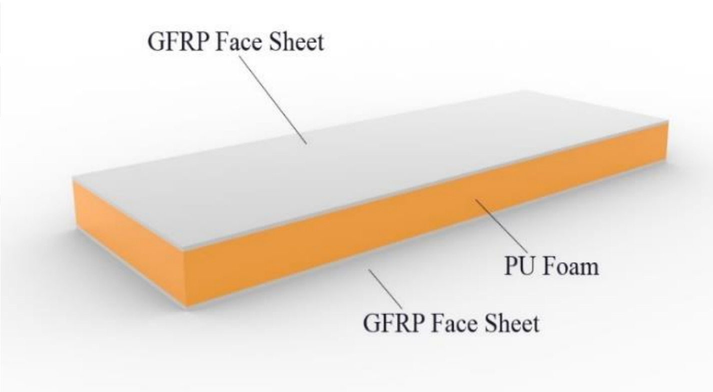


Figure 3.1 Schematic illustration for sandwich panels

Another sandwich panel was modeled, it is also made up of two skins and core but with GFRP U profile in two edges as shown in the Figure 3.2.

In this chapter we will investigate how the sandwich panel is designed, what elements are used and how they are represented.

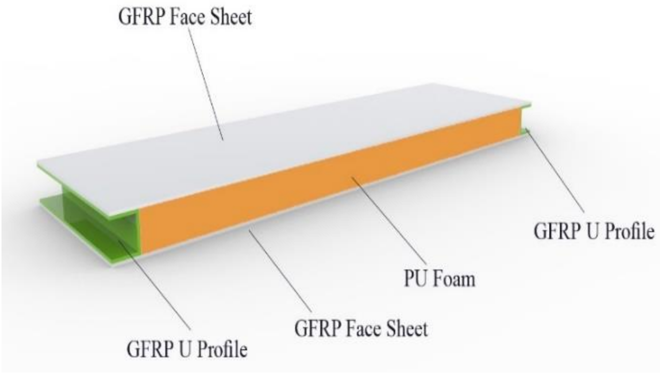


Figure 3.2 Schematic illustration for sandwich panels with U profile

3.1.1 Types of elements used in finite element model

Various ANSYS FEs were used to represent the parts of the sandwich panels, as listed in Table 3.1 below.

Table 3.1 ANSYS Element to represent sandwich panels parts

Part of sandwich panels	Element used in ANSYS
GFRP Skins	SOLID185
PU Foam core	SOLID45
GFRP U profile	SOLID185
Contact	CONT175 TAGRE170
GFRP Honeycomb core	SOLSH190

3.1.2 FE modeling of GFRP skin and GFRP U profile

GFRP skins and GFRP U profile were represented using 3D solid element SOLID185. It has eight nodes having three degrees of freedom at each node translations in the nodal *x, y,* and *z* directions. The element has plasticity, hyper elasticity, stress stiffening, creep, large deflection, and large strain capabilities**.** SOLID185 structural solid is suitable for modeling general 3D solid structures. It allows for prism, tetrahedral, and pyramid degenerations when used in irregular regions. Various element technologies such as B-bar, uniformly reduced integration, and enhanced strains are supported by element as shown in Figure 3.3 [34].

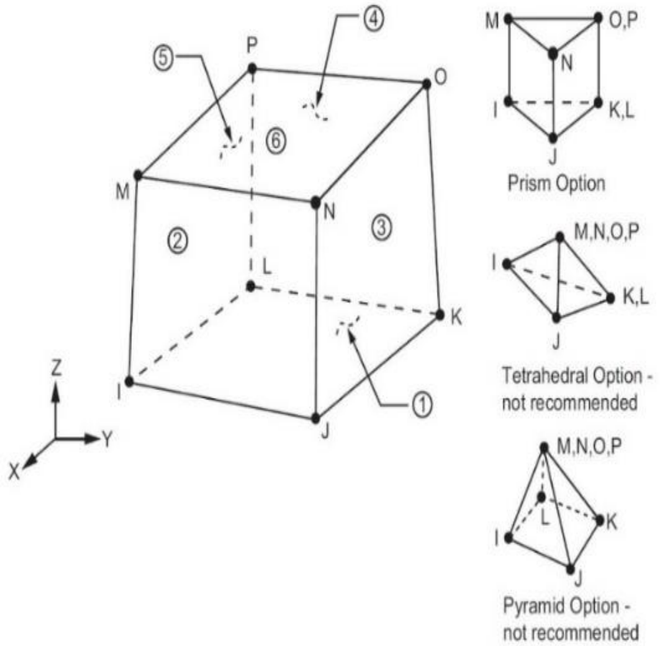


Figure 3.3 SOLID185 3-D Structural Solid

3.1.3 FE modeling of PU foam core

PU foam core was represented using 3D solid element SOLID45 which is defined by eight nodes having three degrees of freedom at each node: translations the nodal x, y and z directions. The element SOLID45 has plasticity, creep, swelling, stress stiffening, large deflection and large strain capabilities [35]. SOLID45 3D structural solid element shown in Figure 3.4.

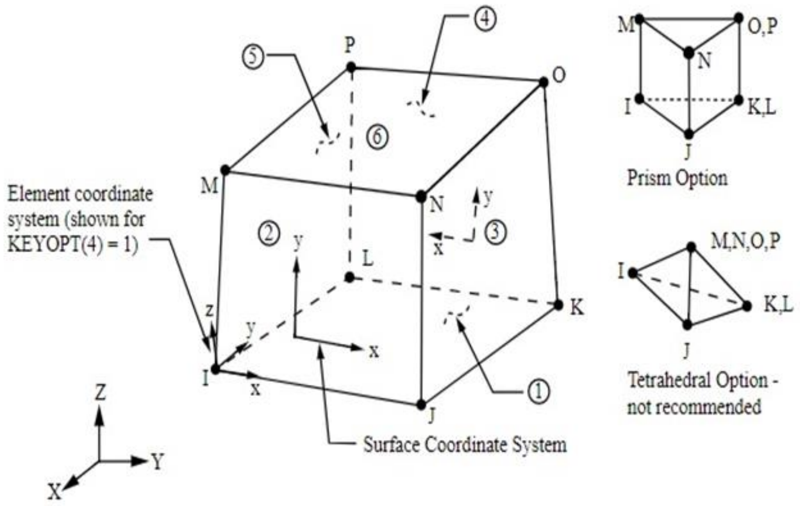


Figure 3.4 SOLID45 3-D Structural Solid

3.1.4 FE modeling of contact

The sandwich panels consist of different materials (skins and core) so the bonding process between them, so it required to be used contact element CONTACT175. The element is applicable to 2D or 3D structural and coupled field contact analyses. CONTA175 geometry is shown in Figure 3.5.

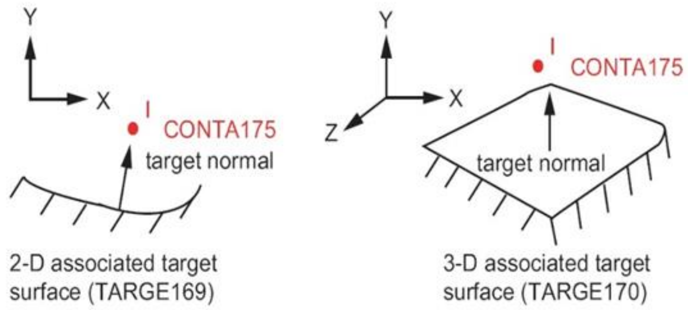


Figure 3.5 CONTA175 geometry

This element is located on the surfaces of solid, beam, and shell elements. The contact elements TAGRE170 themselves overlay the solid, shell, or line elements describing the boundary of a deformable body and are potentially in contact with the target surface [34].

3.1.5 FE modeling of GFRP honeycomb core

GFRP honeycomb core were represented by using 3D solid shell element SOLSH190. It has eight-node connectivity with three degrees of freedom at each node: translations in the nodal *x, y,* and *z* directions. The element has plasticity, hyper elasticity, stress stiffening, creep, large deflection, and large strain capabilities. It also has mixed displacement versus load formulation capability for simulating deformations of nearly incompressible elastoplastic materials, and fully incompressible hyper elastic materials. SOLSH190 Structural shown in Figure 3.6 [34].

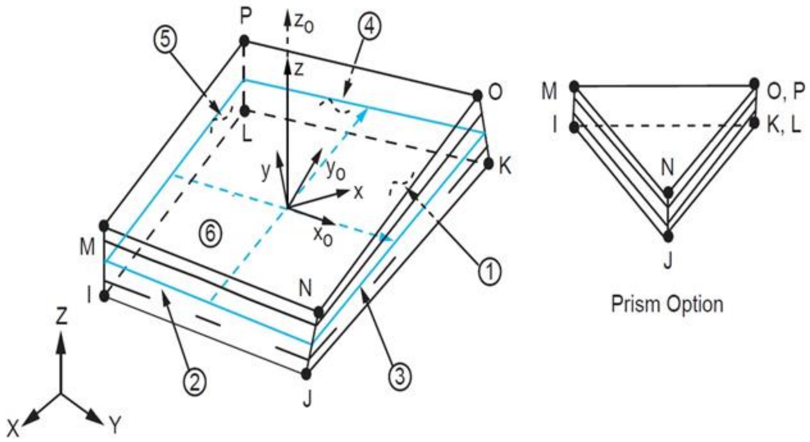


Figure 3.6 SOLSH190 structural FE

3.2 Material Properties

The mechanical properties of the materials were investigated by Abdolpour et al. [36] through laboratory experiments where they were relied upon in the modeling of the materials for the small scale of sandwich panel without GFRP U profile and small scale of sandwich panel with GFRP U profile. GFRP skins were defined as linear-elastic orthotropic material: elastic modulus E_x, E_y, and E_z, Poisson ratio, ultimate stress, and shear modules G_{xy}, G_{yz}, and G_{xz}. For PU foam material for the core was defined as isotropic material: elastic modulus E, Poisson ratio and yield stress. GFRP U profile has been defined as linear-elastic orthotropic material. It carries the following properties: elastic modulus E_x, E_y, and E_z, Poisson ratio, ultimate stress, and shear modules G_{xy}, G_{yz}, and G_{xz}. A summary of the properties of the materials is given in Table 3.2.

Table 3.2 A summary of the properties of the materials

Material Properties	GFRP skin	GFRP U profile	PU foam
E_x (GPa)	9.6	28	0.0091
E_y (GPa)	10.3	13	-
E_z (GPa)	10.3	13	-
υ_{xy}	0.3	0.3	0.15
υ_{yz}, υ_{xz}	0.3	0.3	-
G_{xy} (GPa)	5	5	-
G_{yz} (GPa)	5	5	-
G_{xz} (GPa)	5	5	-
σ_u (MPa)	117	415	-
σ_y (MPa)	-	-	0.3

3.3 Verification of FE model

Two types of sandwich panel were studied in this phase, depending on the experimental work carried out by Abdolpour et al [36] dealt with two types of sandwich plate:

- small scale of sandwich panel without GFRP U profile
- small scale of sandwich panel with GFRP U profile,

Both of them examined under four point loads.

3.3.1 FE analysis of small scale of sandwich panels without GFRP U profile

The small scale of sandwich panel without GFRP U profile which is named as (PG5) was modeled by using the ANSYS APDL software, which consists of two GFRP skins and PU foam core. The sandwich panel was modelled to simulates the sandwich panel. One-way static behavior of sandwich panels up to failure was investigated according to ASTM C393 standard by Abdolpour et al. [36] as shown in the Figure 3.7.

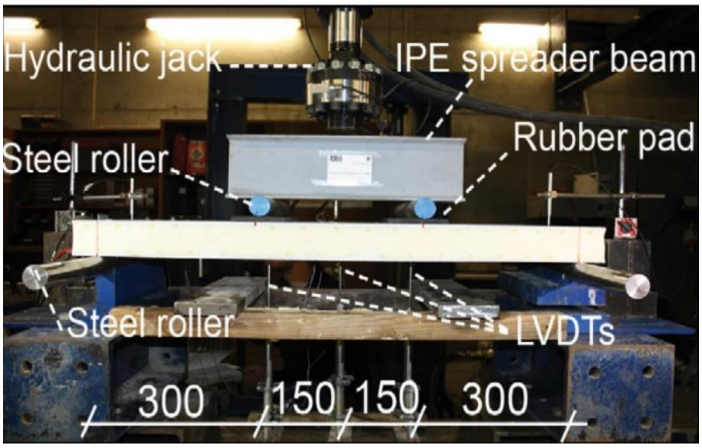


Figure 3.7 Test setup for four-point bending tests of PG5 sandwich panel [36]

The dimensions of the sandwich panel are shown in Figure 3.8. Each with a thickness of 5 mm for skin and a length of 950 mm and a width of 350 mm. Between two skins, there is a core of foam material 60 mm thickness. The clear span was 900 mm and shear span was 300 mm.

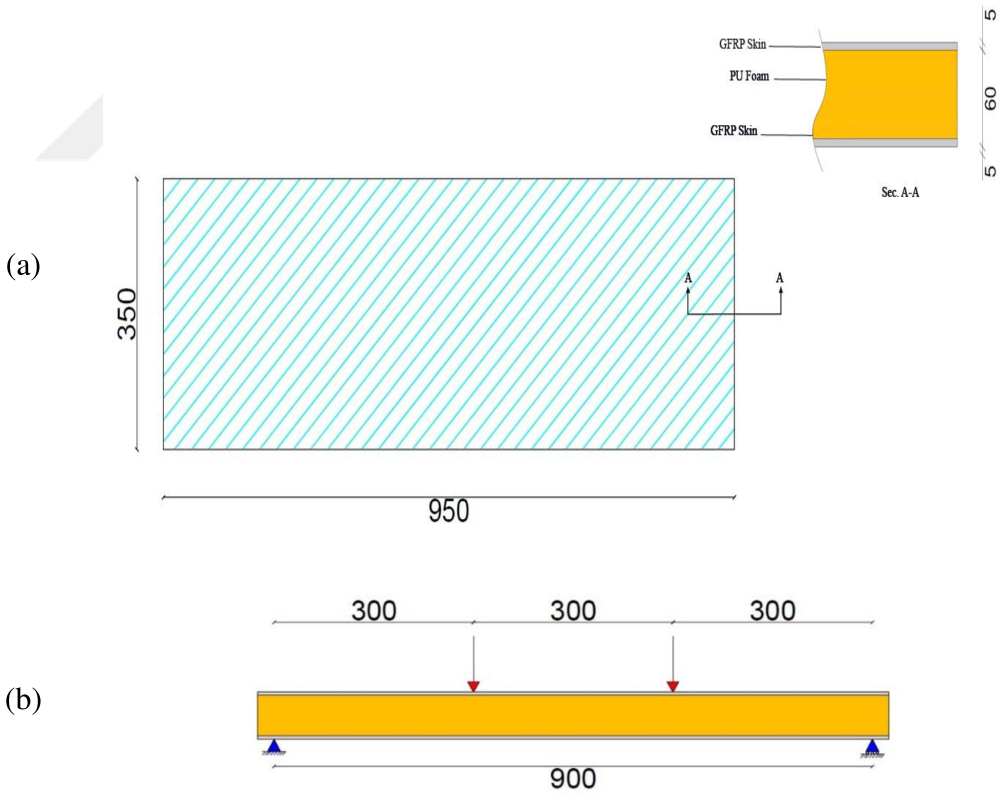


Figure 3.8 PG5 geometry (a) small scale of sandwich panel description. (b) description for loads and Supports. (all units in millimeter)

The element SOLID185 was used to represent skins and SOLID45 used to represent PU foam. For contact surface CONTACT175 and TAGRET170 used as shown in the Figure 3.9.

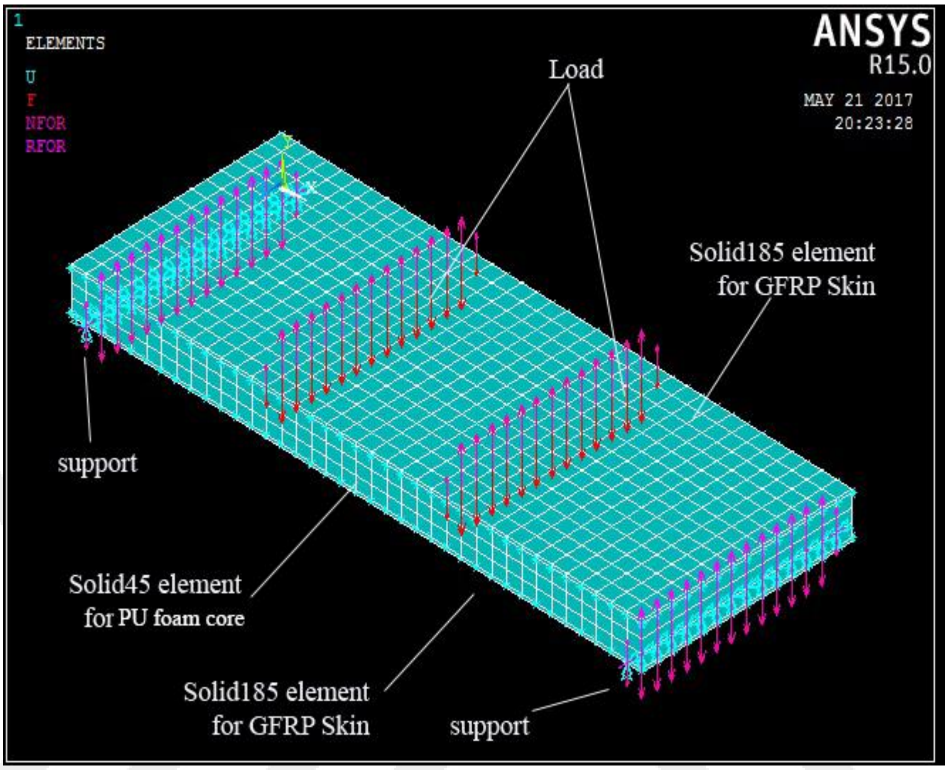


Figure 3.9 FE model of PG5 sandwich panel

Meshing was design by used volume mesh option divide each element by 5 mm. Applied loads were defined as force on nodes at the top surface of skin. The simply supports have been defined and corresponding displacement of nodes set on bottom skin.

3.3.2 FE analysis of small scale of sandwich panels with GFRP U profile

The numerical modeling of a new shape of the sandwich panels with GFRP U profile which is named as PGU5 is carried out. Model PGU5 is similar to that of the experimental study as shown in Figure 3.10 [36]. The sandwich panels with GFRP U profile consisted of two layers of GFRP skins, PU foam core and GFRP U profile which was added to the sides of the sandwich panel.

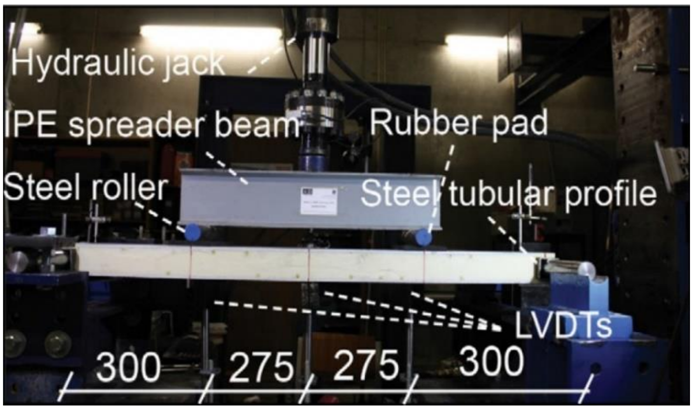


Figure 3. 10 Test setup for four-point bending tests of PGU5 sandwich panel [36]

The upper and lower GFRP skin thickness was 5 mm and between the skins was PU foam core. The thickness for core was 60 mm. As for the edges, GFRP U profile U60*55*5 was added. the dimension and detail for sandwich panel (PGU5) explained in Figure 3.11.

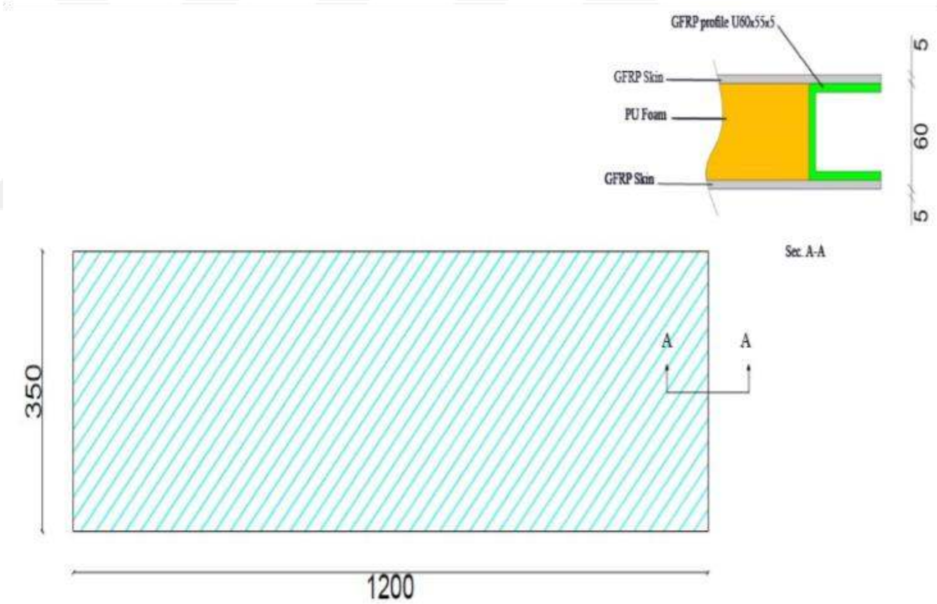


Figure 3.11 PGU5 sandwich panel description. (All units in millimeter)

The length for PGU5 sandwich panel 1200 mm and a width of 350 mm. The clear span between the supports is 1150 mm. The description of loads and supports are shown in Figure 3.12.

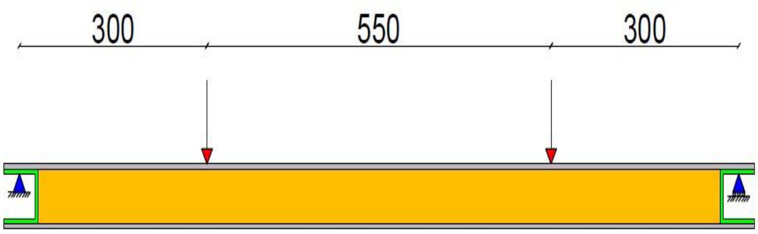


Figure 3.12 Description for loads and supports

PGU5 was simulated by use several elements. GFRP skins represented by SOLID185 element. SOLID45 element used to represent PU foam core and SOLID185 element used for GFRP U profile. Loads were defined as force on nodes at the upper surface of skin. The GFRP U profile is simply supported. Figure 3.13 illustrates FE mesh, supports and loading.

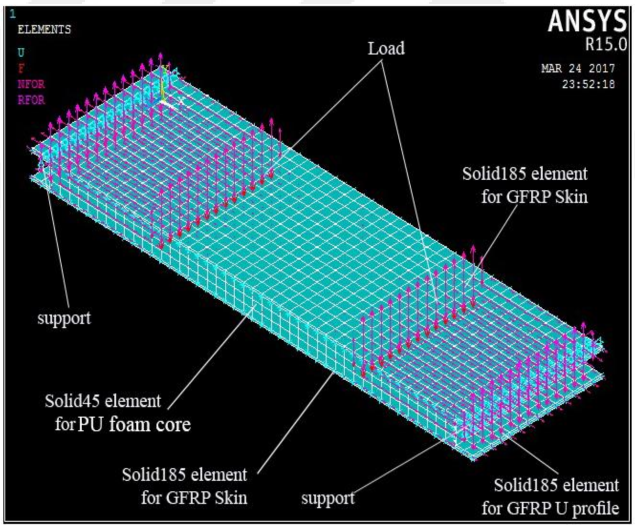


Figure 3.13 FE Model of PGU5 sandwich panels.

3.3.3 Results for verification phase

In this section will present the results of FE analysis for PG5 and PGU5. FE results will be compared with available experimental results was reached by Abdolpour et al [36]. In experimental work, the failure was investigated according to ASTM C393 standard. Four-point bending tests were carried out with the following two groups of specimens: (a) without an end GFRP 'U' profile, and (b) with that profile.

The ultimate load (P_u), the maximum deflection (δ_u), and the initial stiffness (K) defined as the slope of the force and deflection in the linear part. The maximum longitudinal strain on the top and bottom skins (ε_{ut} and ε_{ub}, respectively), the maximum flexural stress (σ_u), and the maximum average shear stress in the core (τ_u) obtained according to equations (3.1) and (3.2), based on equilibrium analysis [37].

$$\sigma = \frac{M}{b.d.h_f} \tag{3.1}$$

$$\tau = \frac{\partial M}{\partial x}\frac{1}{b.d} \tag{3.2}$$

Where d is the distance between the centroids of the skins, $d = h_c + h_f$, where h_c and h_f are the core and skin thicknesses respectively, and b is the width of the panel, as shown in Figure 3.14.

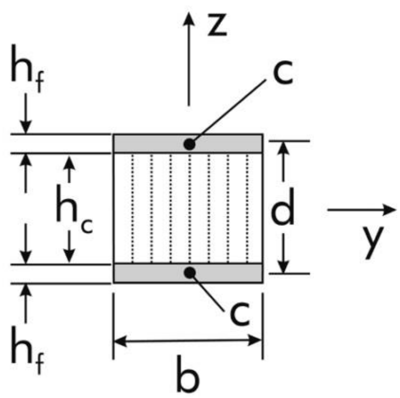


Figure 3.14 Cross-sectional view of a symmetric sandwich beam. “C” represents the centroid location for each of the face sheets, and y the neutral axis of the beam

3.3.3.1 FE results for small scale of PG5 sandwich panel

By comparing the numerical results obtained by using the ANSYS program and the experimental results, they were found that are very close and acceptable as shown in Table 3.3. The vertical displacement in midspan was 14.53 mm in Y axis direction obtained from the FE analysis as shown in Figure 3.15, where that was at ultimate load 7.7938 kN.

Table 3.3 Comparison between experimental and numerical FEM results for small scale of sandwich panels without U profile (PG5)

	FE Result		Experimental Result [36]	% Error
Ultimate Load (kN)	7.7938		7.27	6.72
Ultimate Deflection in midspan (mm)	14.5376		13.59	6.51
Ultimate Stress (MPa)	10.84		9.58	11.62
Ultimate Strain (μstrain)	ε_{ut}	-1107.88	-807	27
	ε_{ub}	1168.77	804	31

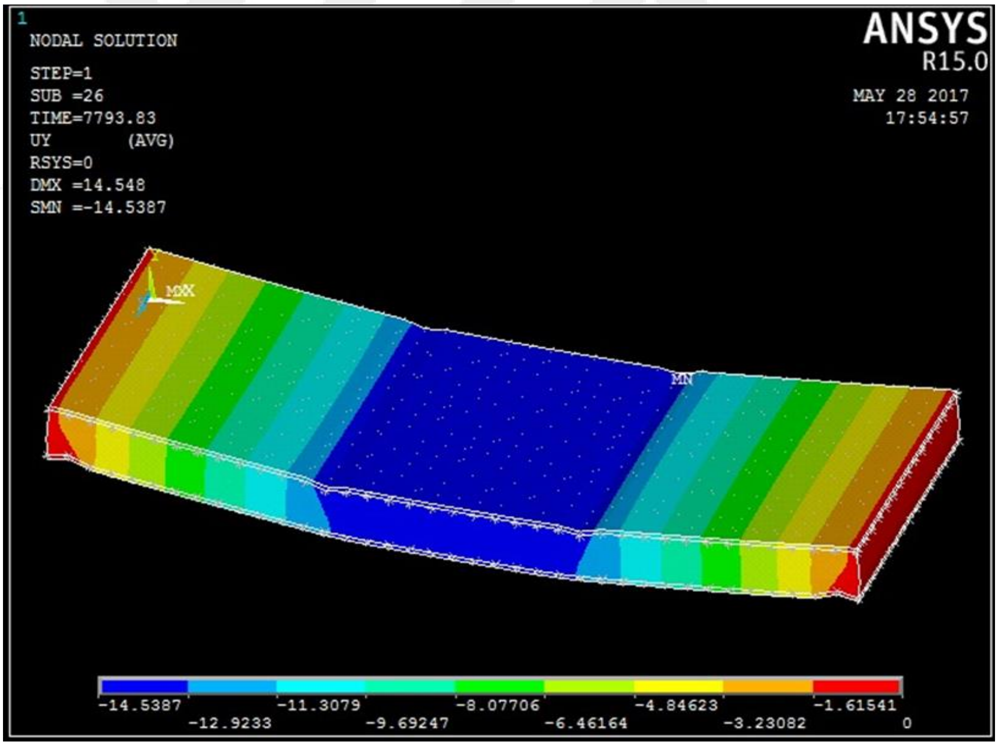


Figure 3.15 Deformed shape for the FE model for sandwich panels without U (PG5)

Figure 3.16 shows the corresponding load–deflection curve in mid-span. It is shown that a good agreement between numerical and experimental results.

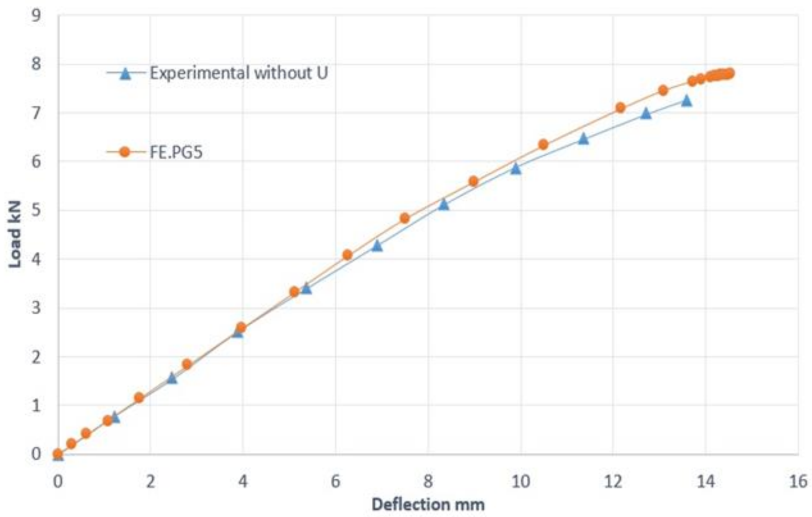


Figure 3.16 The comparison between numerical and experimental studies–mid-span deflection curves

Bending strain–stress relation at top and lower skins for PG5 is depicted in Figure 3.17. The strain values in experimental work were those registered in the strain gauges applied on the top and bottom surfaces of the panels, while the stresses were calculated based on the equilibrium of tension and compression forces on the skins, according to Eq. 3.1.

FE strain–stress values were taken directly from the program at ultimate stress for the upper and lower skin.

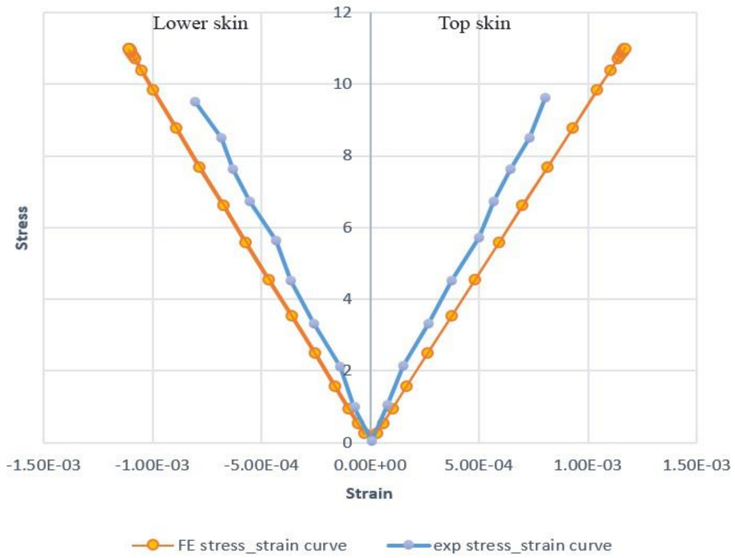


Figure 3.17 The comparison between numerical and experimental stress-strain curves

3.3.3.2 FE results for small scale of PGU5 sandwich panel

FE result for PGU sandwich panel listed in Table 3.4. the results were, that are very close and acceptable for experimental results. The vertical displacement 20.93 mm in y direction as shown in Figure 3.18 at ultimate load 7.473 kN.

Table 3.4 Comparison between experimental and numerical FEM results for small scale of sandwich panels with U profile (PGU5).

		FE Result	Experimental Result [36]	% Error
Ultimate Load (kN)		7.473	7.18	3.9
Ultimate Deflection in midspan (mm)		20.9311	20.01	4.39
Ultimate Stress (MPa)		11.8	9.58	18.8
Ultimate Strain (µstrain)	ε_{ut}	-1147.84	-714	37.7
	ε_{ub}	1228.25	859	30

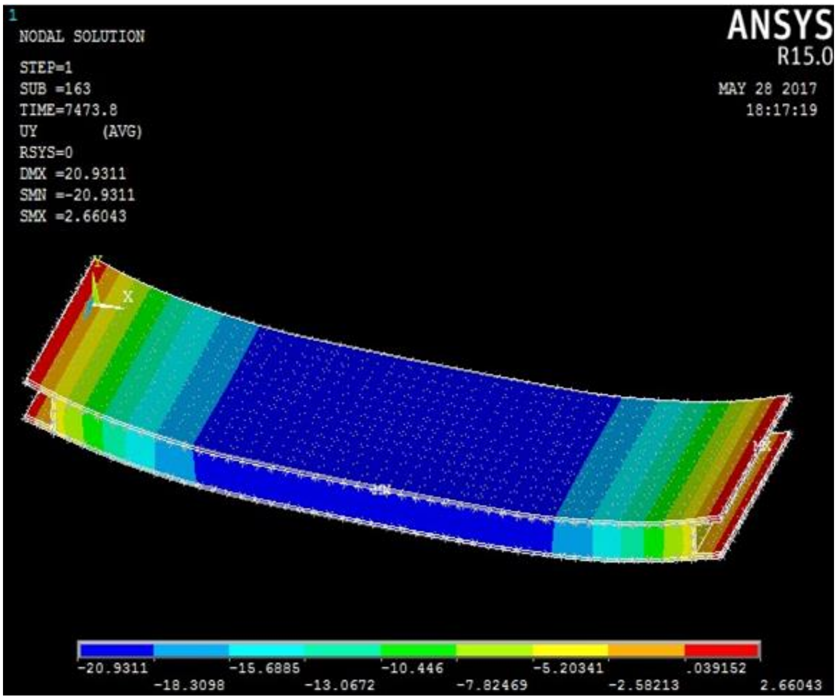


Figure 3.18 Deformed shape for the FE model for sandwich panels with GFRP U profile (PGU5)

The relationship between the load and deflection illustrated in Figure 3.19. Bending strain–stress relation at top and lower skins for the specimens tested is depicted in Figure 3.20.

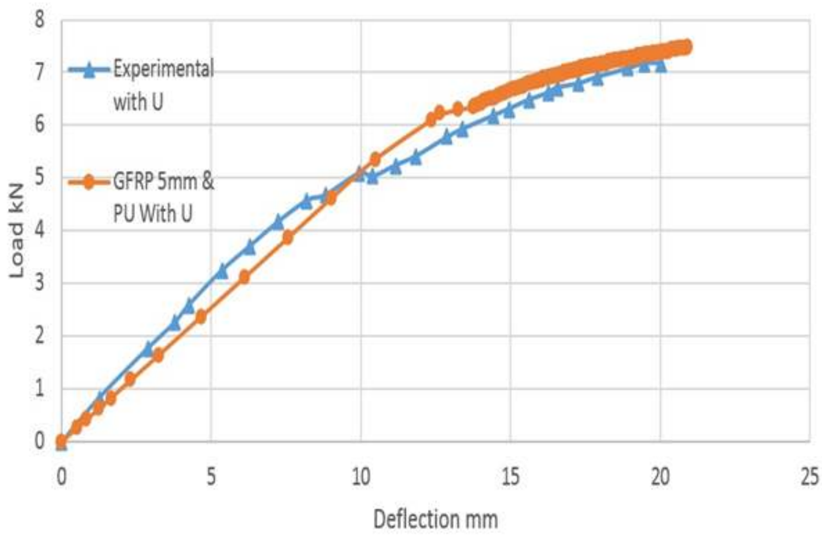


Figure 3.19 The comparison between numerical and experimental load–midspan deflection curves

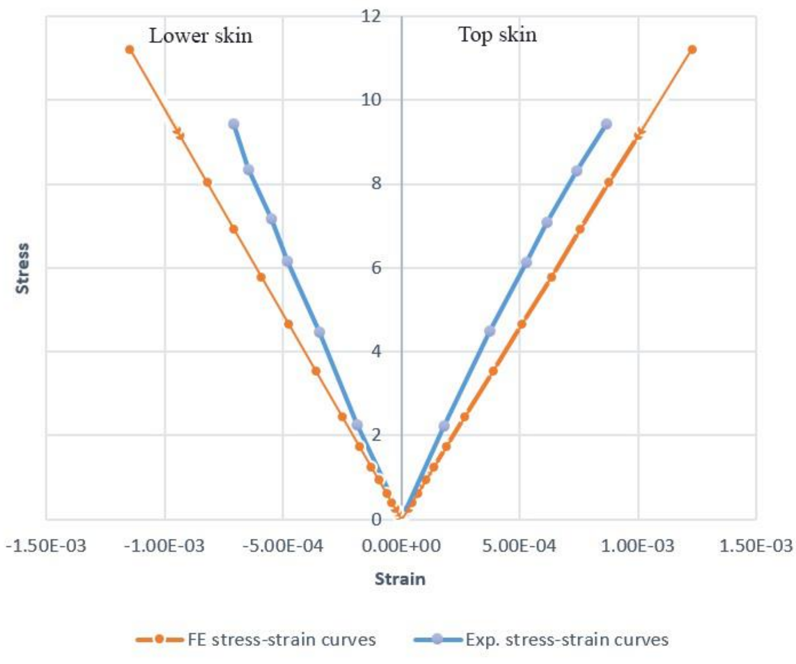


Figure 3.19 The comparison between numerical and experimental stress-strain curves

CHAPTER 4

PARAMETRIC STUDY

4.1 General

Sandwich panel is a composite material. A parametric study will have carried out to explore the potentiality of the proposed material and structural concept for sandwich panel. It is studying the effect of the thickness, materials of the skin and materials of core on the behaviour and efficiency of the sandwich panels, it was made simulation to 30 model.

4.2 Material Properties

In parametric study used a various of materials. So it must explain what the characteristics of materials and how represent in ANSYS APDL software.

The mechanical properties of GFRP skins and PU foam were taken from Abdolpour et al. [36]. In this phase will studied another material such as:

- Aluminum skins
- CFRP skins

The mechanical properties of aluminum, CFRP were given by Rejab and Cantwell [38].

GFRP, CFRP, and GFRP honeycomb were defined as linear-elastic orthotropic material: elastic modulus E_x, E_y, and E_z, Poisson ratio, ultimate stress, and shear modules G_{xy}, G_{yz}, and G_{xz}. Aluminum skins, and PU foam core were defined as isotropic material: elastic modulus E, Poisson ratio, yield stress.

GFRP U profile has been defined as linear-elastic orthotropic material. It carries the following properties: elastic modulus E_x, E_y, and E_z, Poisson ratio, ultimate stress, and shear modules G_{xy}, G_{yz}, and G_{xz}. A summary of the properties of the materials is given in Table 4.1.

Table 4.1 The mechanical properties of the materials

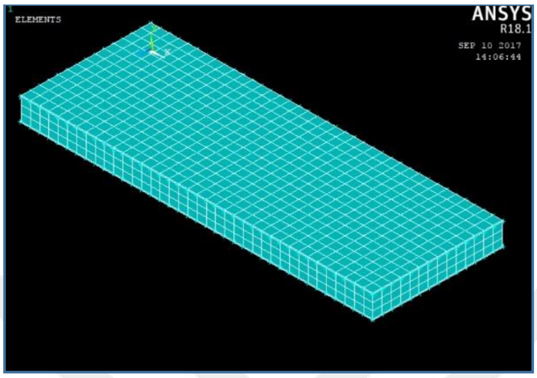
Material Properties	**GFRP skin and honeycomb core**	**GFRP U profile**	**PU foam**	**CFRP skin**	**Aluminum skin**
E_x (GPa)	9.6	28	9.1	48	70.6
E_y (GPa)	10.3	13	-	48	-
E_z (GPa)	10.3	13	-	1	-
υ_{xy}	0.3	0.3	0.15	0.1	0.3
υ_{yz}, υ_{xz}	0.3	0.3	-	0.1	-
G_{xy} (GPa)	5	5	-	9	-
G_{yz} (GPa)	5	5	-	9	-
G_{xz} (GPa)	5	5	-	-	-
σ_u (MPa)	117	415	-	550	-
σ_y (MPa)	-	-	0.3	-	164.7

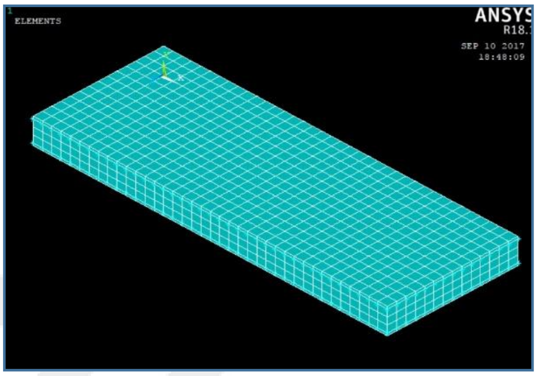
4.3 Effect of Thickness for GFRP Skins with PU Foam Core for Sandwich Panel

The first group of parametric study will deal with effect of thickness of GFRP skins, while keeping the thickness of the PU foam and all dimensions. Two types of panel ends with and without U profile is also investigated.

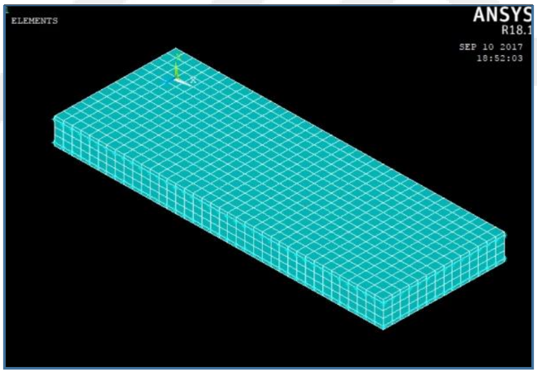
To study the effect of thickness for GFRP skins was simulated three models have same dimensions for length and width, boundary condition, type of loads, and thickness for core but the thickness for skin is changed.

The thickness of skin was changed in the following dimensions (3, 7 and 9 mm) (PG3, PG7 and PG9) for small scale of sandwich panels without U profile shown in Figure 4.1. And the same procedure carried for small scale of sandwich with U profile skin, that were (3, 7, and 9 mm) (PGU3, PGU7, PGU9) shown in Figure 4.2.



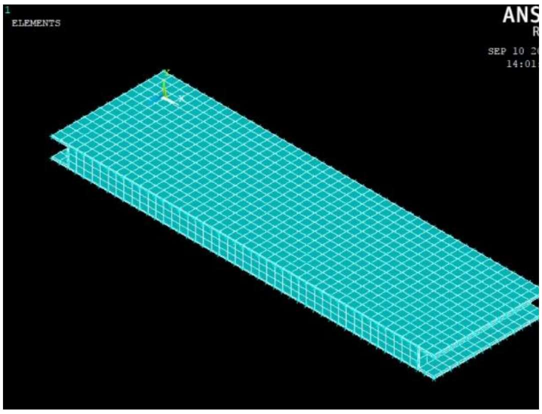


(a) (b)

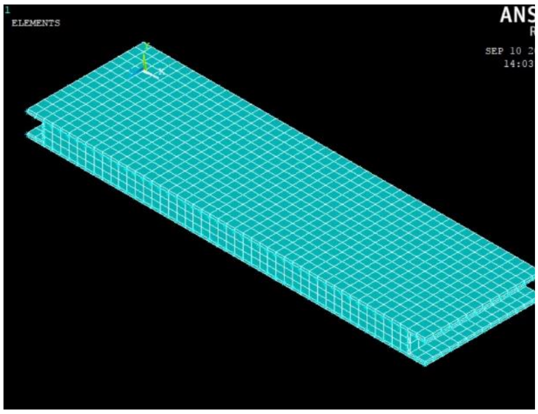


(c)

Figure 4.1 FE Models for small scale of sandwich panels without GFRP U profile (a) PG3 (b) PG7 (c) PG9



(a)



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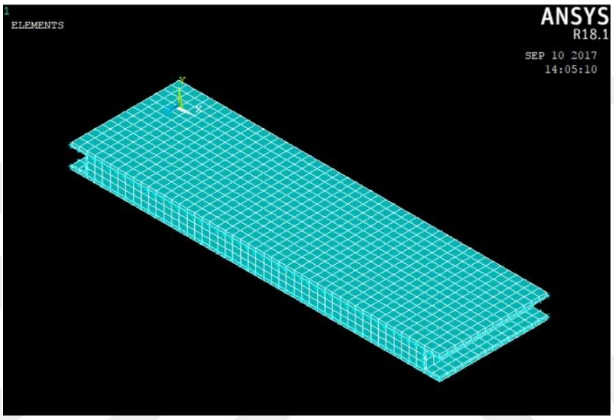


(c)

Figure 4.2 FE Models for small scale of sandwich panels with GFRP U profile (a) PGU3 (b) PGU7 (c) PGU9

The FE results for first group are listed in Table 4.2. The maximum deflection, ultimate stress and failure load result of models show the effect of thickness. And the relationship between the load and deflection for all models illustrated in Figures 4.3 and 4.4. The vertical displacement shown in Figures 4.5 and 4.6 can be seen in the direction of the Y axis obtained from the FE models.

Table 4.2 FE result for the model with various thickness

	Ultimate Load (kN)	**Ultimate Deflection in midspan** (mm)	**Ultimate Stress** (MPa)
PG3	7	72	26.26
PG5	*7.7938*	*14.5376*	*10.84*
PG7	15.54	30.97	14.77
PG9	16.77	42.51	16.57
PGU3	6.99	21.59	17.9
PGU5	*7.473*	*20.9311*	*11.8*
PGU7	9.87	22	11.19
PGU9	10.38	19.5	9.88

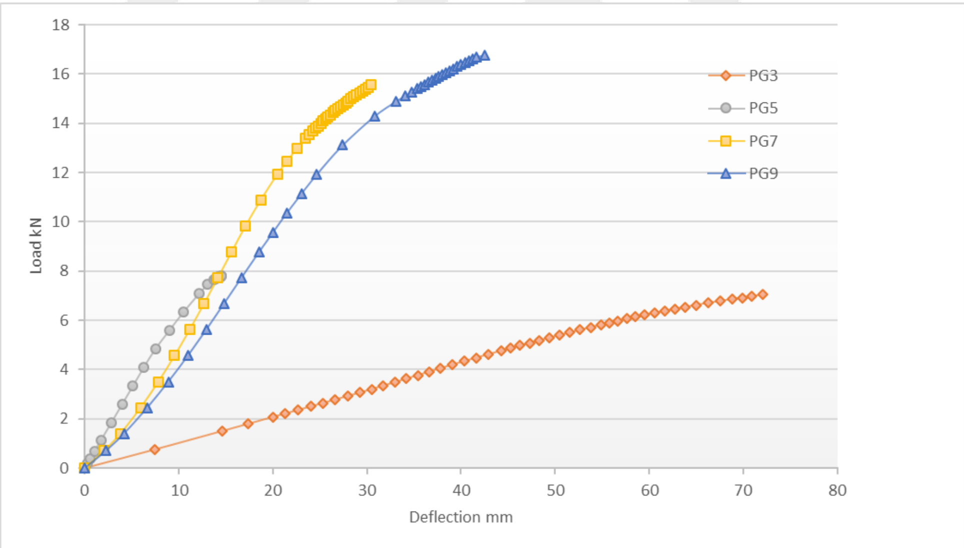


Figure 4.3 Load–midspan deflection curves for small scale models without U profile

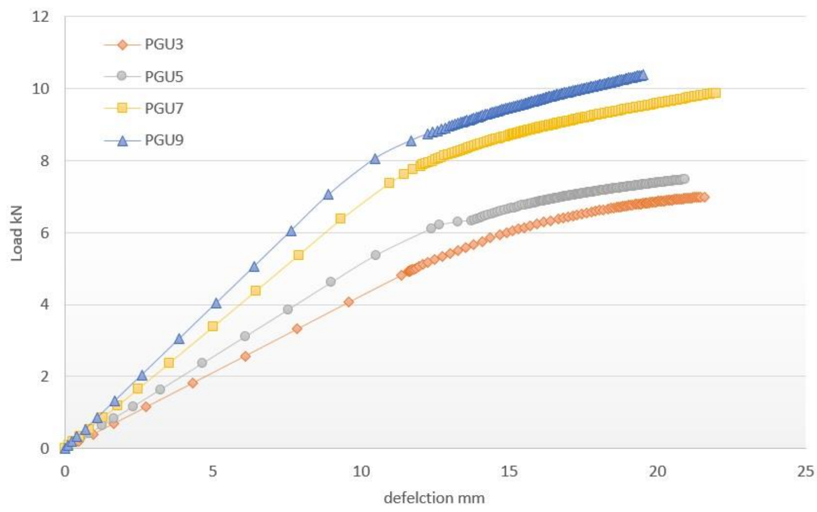
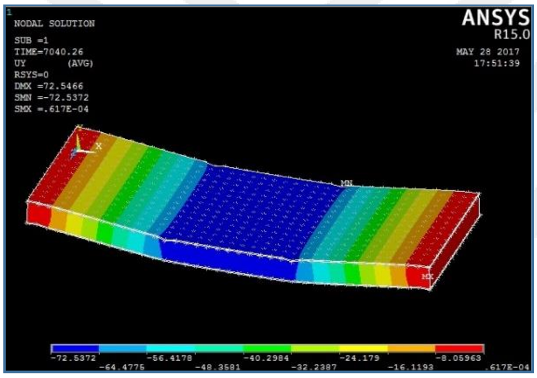
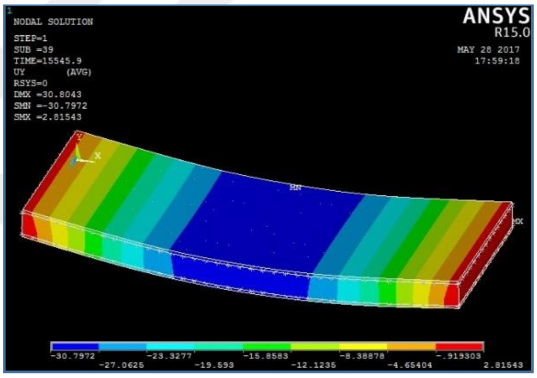


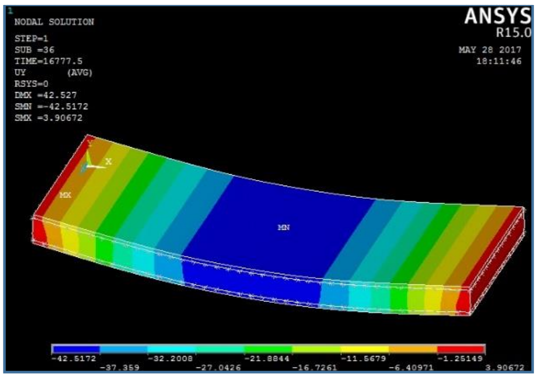
Figure 4.4 Load–midspan deflection curves for small scale models with U profile



(a)

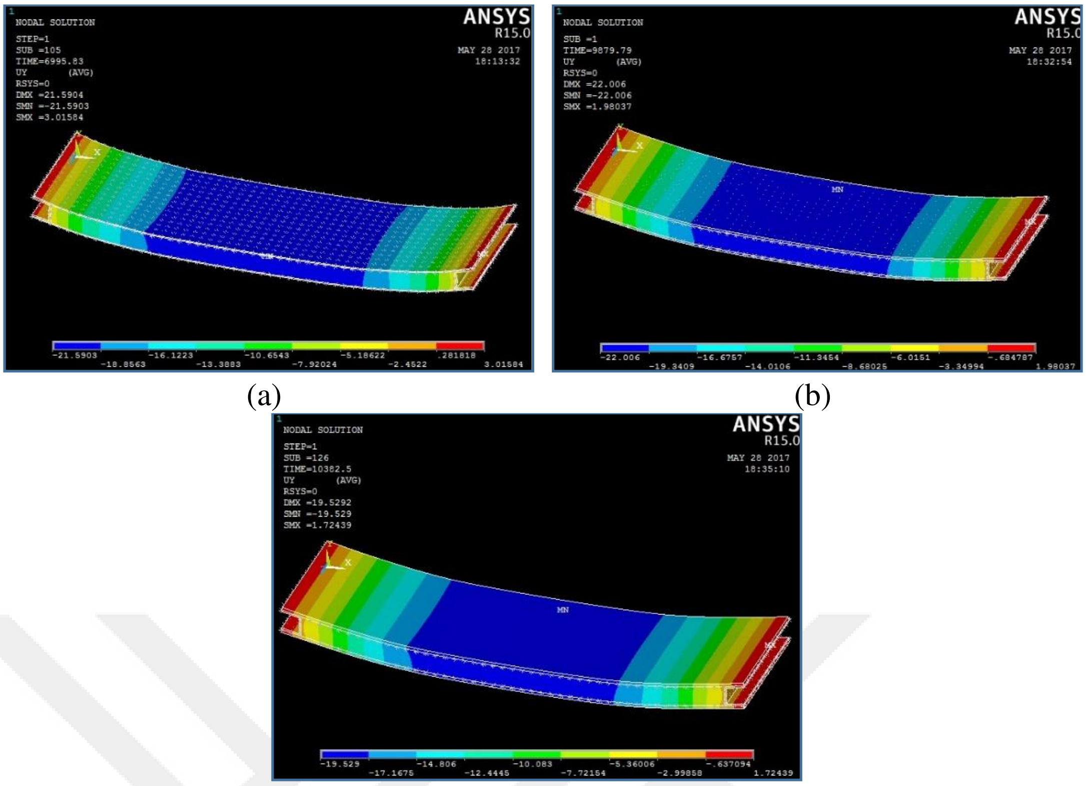


(b)



(c)

Figure 4.5 Deformed shape for the FE model for sandwich panels without U profile: (a) PG3 (b) PG7 (c) PG9



(a) (b) (c)

Figure 4.6 Deformed shape for the FE model for sandwich panels with U profile: (a) PGU3 (b) PGU7 (c) PGU9

4.4 Effect of Thickness for CFRP Skins with PU Foam Core for Sandwich Panel

In second group of parametric study was involved new material, it was CFRP skins with PU foam core. The dimensions for small scale of sandwich panel without U profile and with U profile was same to the models in verification phase. But the skins thicknesses were (3,5,7, and 9) mm (PC3, PC5, PC7 and PC9), (PCU3, PCU5, PCU7, PCU9).

FE results listed in Table 4.3 for second group and the deformation shape shown in Figures 4.7 and 4.8. The relationship between the load and deflection for all models illustrated in Figures 4.9 and 4.10.

The results for CFRP sandwich panels without U profile (PC3, PC5, PC7, and PC9) were: ultimate load (7.25, 7.9, 8.69, and 9.52 kN), ultimate stresses (60, 14.88, 37.4, and 20.8 MPa) and deflection in midspan (55.79, 11.5, 29.4, and 8.4 mm).

The results for CFRP skins of sandwich panels with U profile (PCU3, PCU5, PCU7, and PCU9) is given in Table 4.3. Ultimate load (7, 7.3, 7.8, and 8.3 kN), ultimate stresses (37.9, 29.6, 14.7, and 13.23 MPa) and deflection in midspan (18.4, 14.56, 13.94, and 12.58 mm).

Table 4.3 FE result for CFRP skin

	Ultimate Load (kN)	**Ultimate Deflection in midspan (mm)**	**Ultimate Stress (MPa)**
PC3	7.25	55.79	60
PC5	7.9	11.5	14.88
PC7	8.69	29.4	37.4
PC9	9.52	8.4	20.8
PCU3	7	18.4	37.9
PCU5	7.3	14.56	29.6
PCU7	7.8	13.94	14.7
PCU9	8.3	12.58	13.23

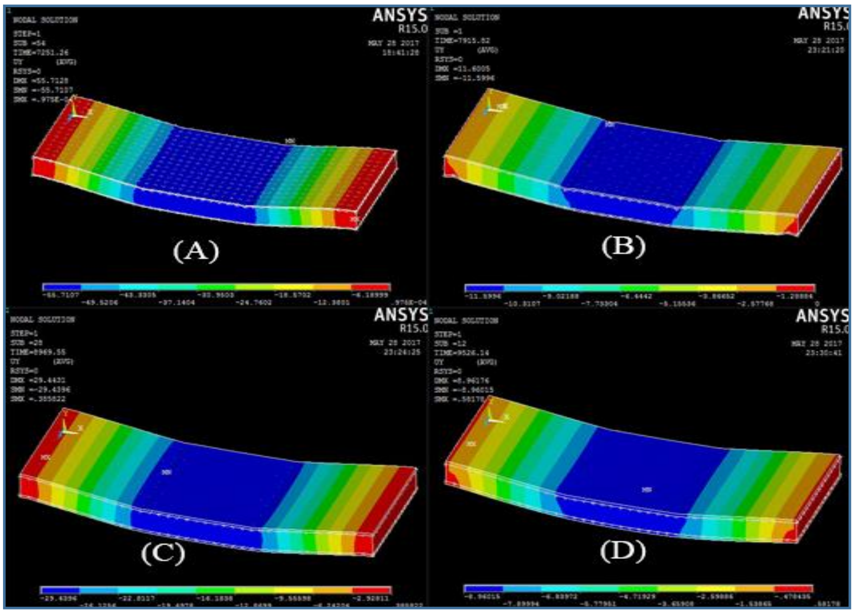


Figure 4.7 Deformed shape for the FE model for CFRP skins of sandwich panels without U profile: (a) PC3 (b) PC5 (c) PC7 (d) PC9

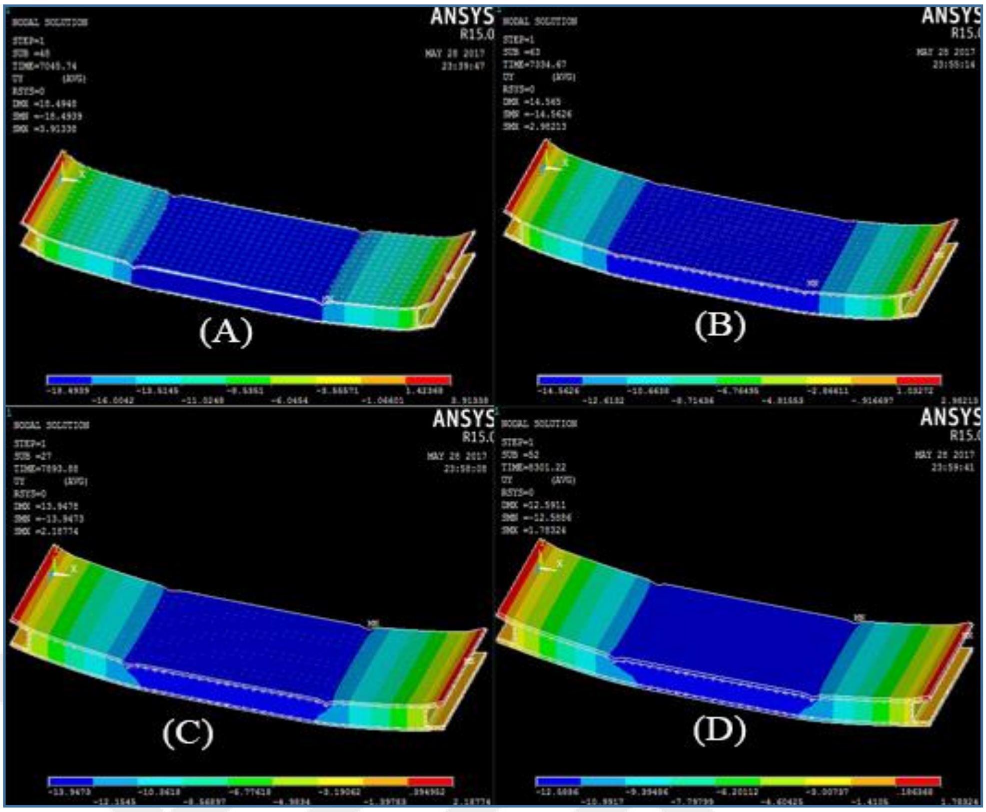


Figure 4.8 Deformed shape for the FE model for CFRP skins of sandwich panels with U profile: (a) PCU3 (b) PCU5 (c) PCU7 (d) PCU9

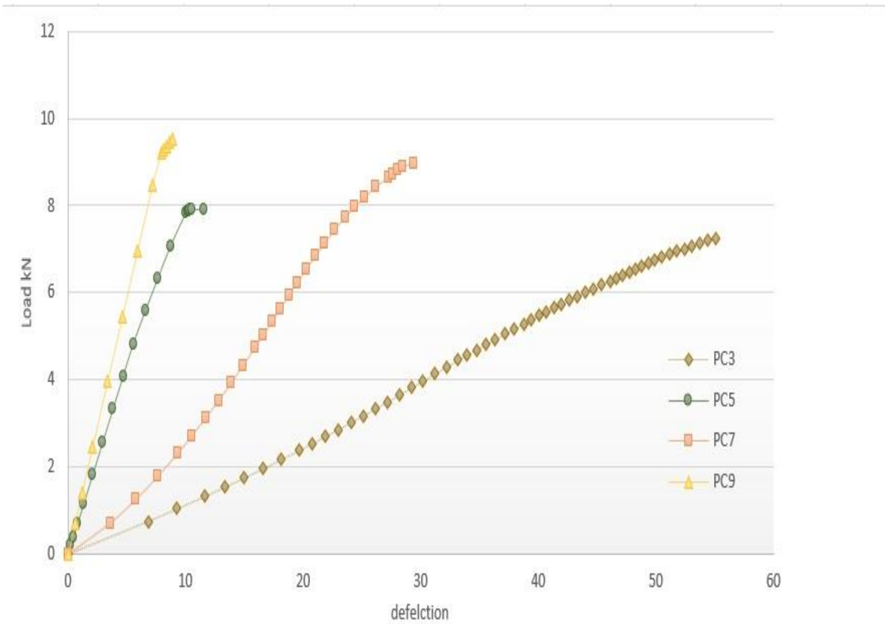


Figure 4.9 Load–midspan deflection curves for CFRP skins of small scale models without U profile

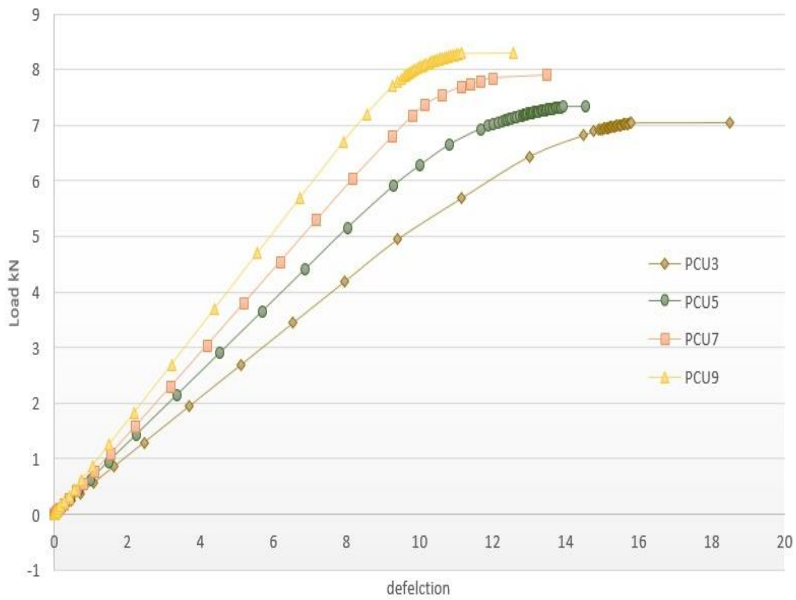


Figure 4.10 Load–midspan deflection curves for CFRP skins of small scale models with U profile

4.5 Effect of Thickness for Aluminum Skins with PU Foam Core for Sandwich Panel

In third group. That is studied the effect of aluminum skins. Aluminum skins were defined as isotropic material. In this group was simulated 8 models, four models are without U profile and their skins is consisting of the aluminum material with a different thickness of the skins (3, 5, 7, and 9 mm) (PA3, PA5, PA7, PA9). Another four models were small scale of sandwich panels with U profile with a different thickness of the skins (3, 5, 7, and 9 mm) (PAU3, PAU5, PAU7, PAU9).

The FE results for this group listing in Table 4.4. Ultimate load for aluminum skins without U profile (PA3, PA5, PA7, and PA9) (16.83, 24.82, 32, and 39.79 kN), ultimate stresses (42.2, 55, 66.56, and 73 MPa) and deflection in midspan (35.91, 42.3, 42.5, and 42.67 mm). For aluminum skins of sandwich panels with U profile (PAU3, PAU5, PAU7, and PAU9). Ultimate load (16, 24.1, 31.9, and 39.26 kN), ultimate stresses (40.5, 53.48, 63.59, and 72.9 MPa) and deflection in midspan (46.33, 62.7, 64.47, and 64.72 mm). The deformed shape shown in Figures 4.11 and 4.12. The relationship between the load and deflection for all models illustrated in Figures 4.13 and 4.14.

Table 4.4 FE result for aluminum skin

	Ultimate Load (kN)	Ultimate Deflection in midspan (mm)	Ultimate Stress (MPa)
PA3	16.83	35.91	42.2
PA5	24.82	42.3	55
PA7	32	42.5	66.56
PA9	39.79	42.67	73
PAU3	16	46.33	40.5
PAU5	24.1	62.7	53.48
PAU7	31.9	64.47	63.59
PAU9	39.26	64.72	72.9

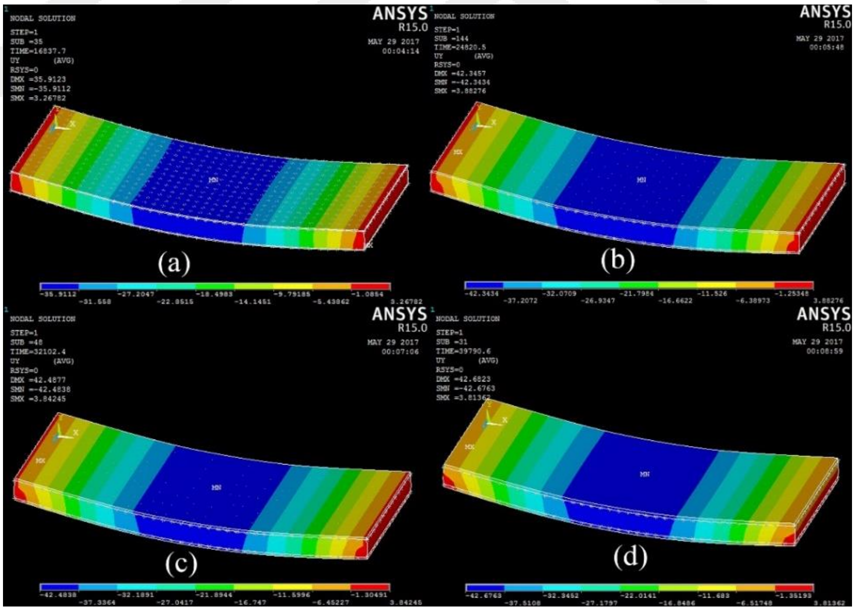


Figure 4.11 Deformed shape for the FE model for aluminum skins of sandwich panels without U profile: (a) PA3 (b) PA5 (c) PA7 (d) PA9

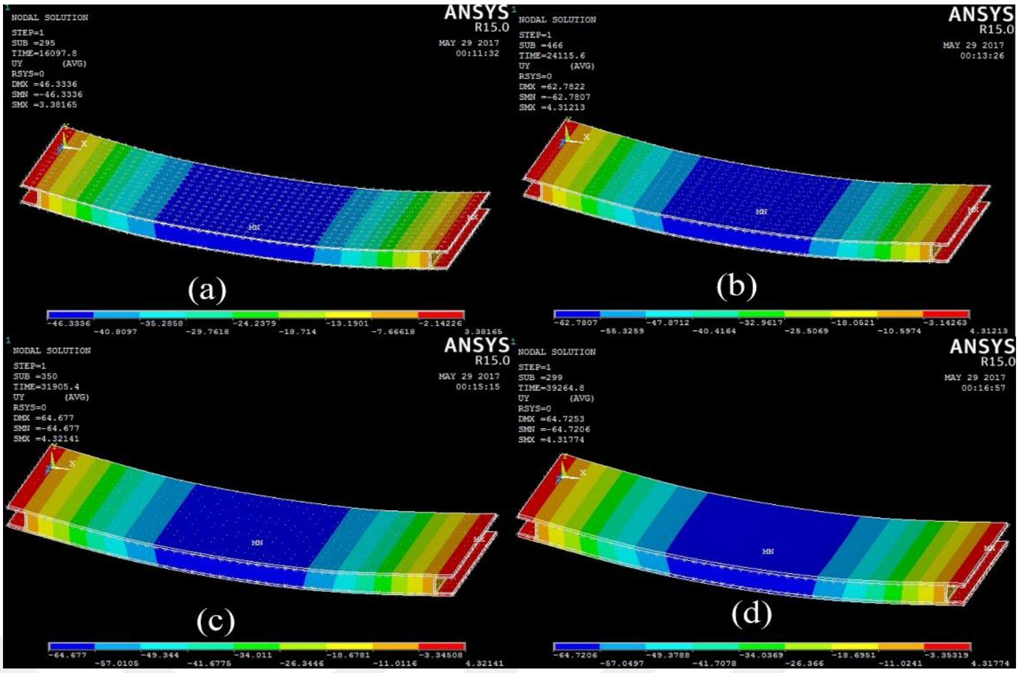


Figure 4.12 Deformed shape for the FE model for aluminum skins of sandwich panels with U profile: (a) PAU3 (b) PAU5 (c) PAU7 (d) PAU9

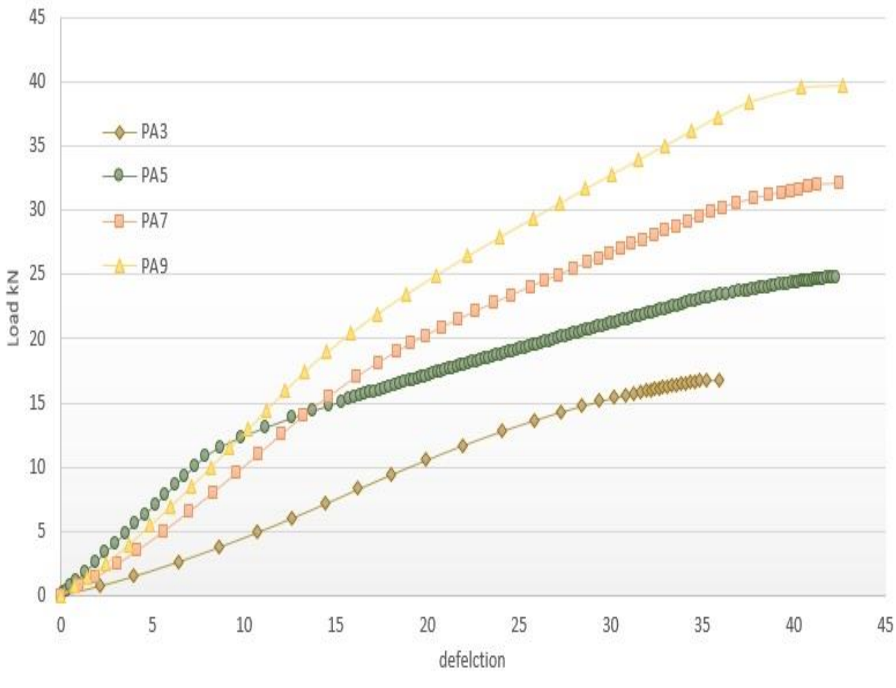


Figure 4.13 Load–midspan deflection curves for aluminum skins of small scale models without U profile

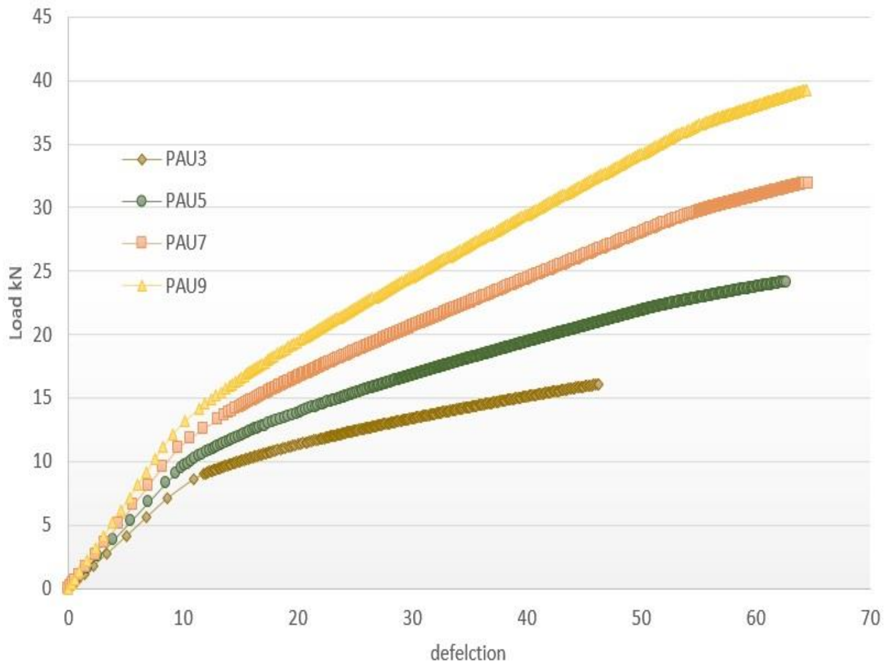


Figure 4.14 Load–midspan deflection curves for aluminum skins of small scale models with U profile

4.6 Effect of Thickness for GFRP Skins with Honeycomb Core for Sandwich Panel

In this section studied the effect of type of core and skin thickness. Honeycomb core one of modern solutions to develop the sandwich panel, that it has lot of properties such as light weight and thermal insulation. This type of sandwich panel using in variety fields and modern applications.

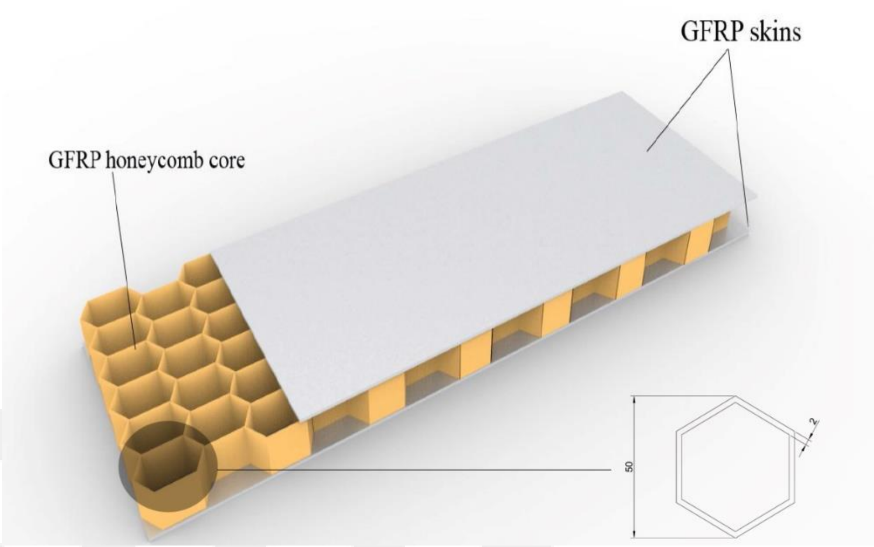
GFRP honeycomb was modeled by using SOLSH190 element in ANSYS software. The shape of this core and model shown in Figure 4.15.

The thickness of GFRP skins without U profile (PH3, PH5, PH7, and PH9) and with U profile (PHU3, PHU5, PHU7, and PHU9) were 3, 5, 7, and 9mm.

All results listed in Table 4.5 for without U profile (PH3, PH5, PH7, and PH9) Ultimate load (21.75, 22.86, 24.77, and 25.52 kN), stresses (46, 29.8, 27.9, and 26.4 MPa) and deflection in midspan (15, 10.14, 8.67, and 7 mm).

For with U profile (PHU3, PHU5, PHU7, and PHU9) result was found ultimate load (21.36, 26.37, 28.66, and 32.3 kN), stresses (46, 35.8, 25, and 36 MPa) and deflection in midspan (16.99, 12.93, 9.62, and 12.62 mm). the shape of deformation shown in Figures 4.16 and 4.17. The relationship between load-deflection curves are shown in Figures 4.18 and 4.19.

(a)



(b)

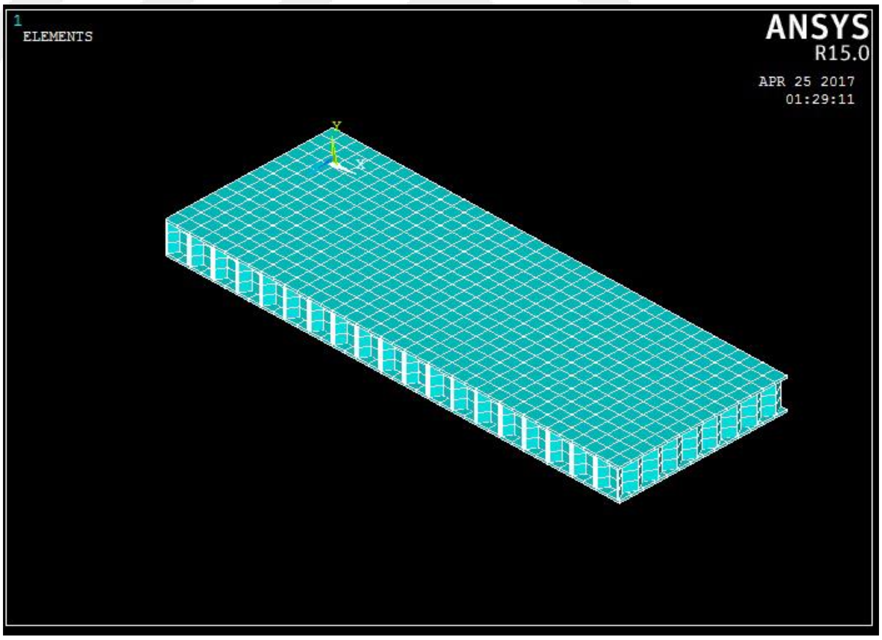


Figure 4.15 Small scale of sandwich panels with GFRP honeycomb core,(a) geometry, (b) FE Model for Small scale of sandwich panels with GFRP honeycomb core

Table 4.5 The FE result for honeycomb core

	Ultimate Load (kN)	Ultimate Deflection in midspan (mm)	Ultimate Stress (MPa)
PH3	21.75	15	46
PH5	22.86	10.14	29.8
PH7	24.77	8.67	27.9
PH9	25.52	7	26.4
PHU3	21.36	16.99	46
PHU5	26.37	12.93	35.8
PHU7	28.66	9.62	25
PHU9	32.3	12.62	36

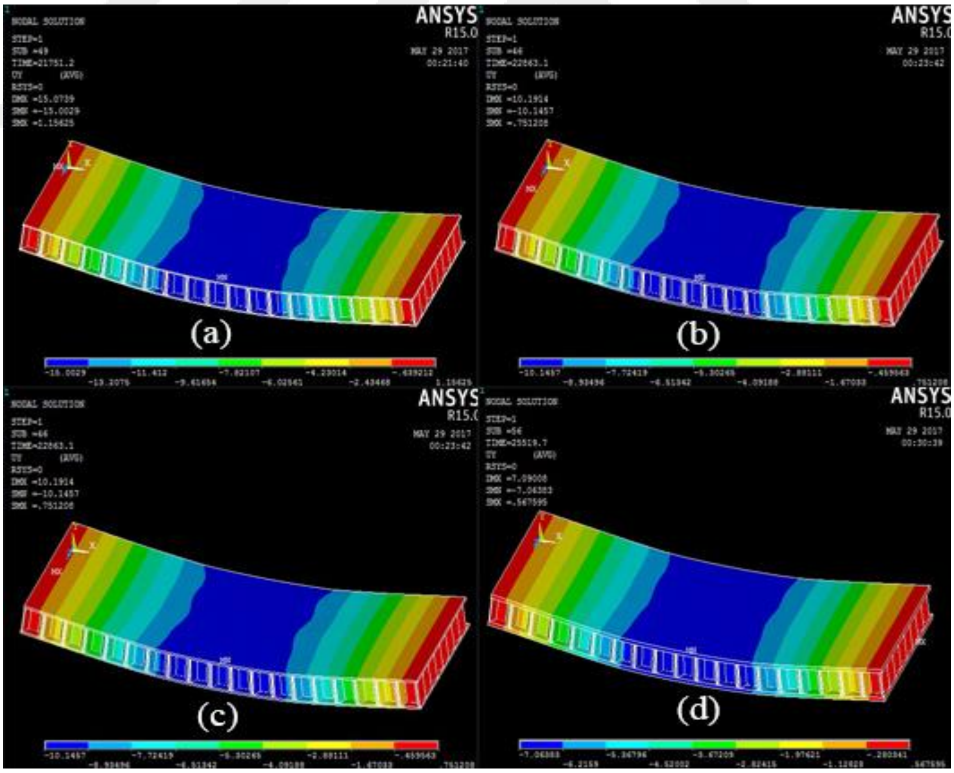


Figure 4.16 Deformed shape for the FE model for GFRP skins with honeycomb core of sandwich panels without U profile: (a) PH3 (b) PH5 (c) PH7 (d) PH9

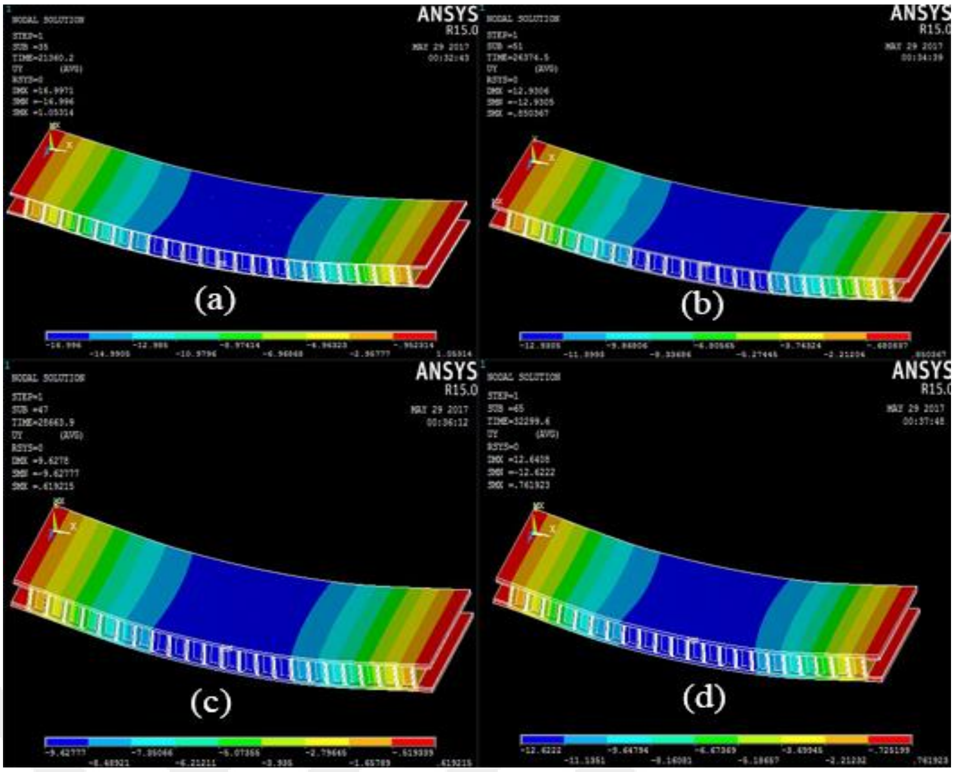


Figure 4.17 Deformed shape for the FE model for GFRP skins with honeycomb core of sandwich panels with U profile: (a) PHU3 (b) PHU5 (c) PHU7 (d) PHU9

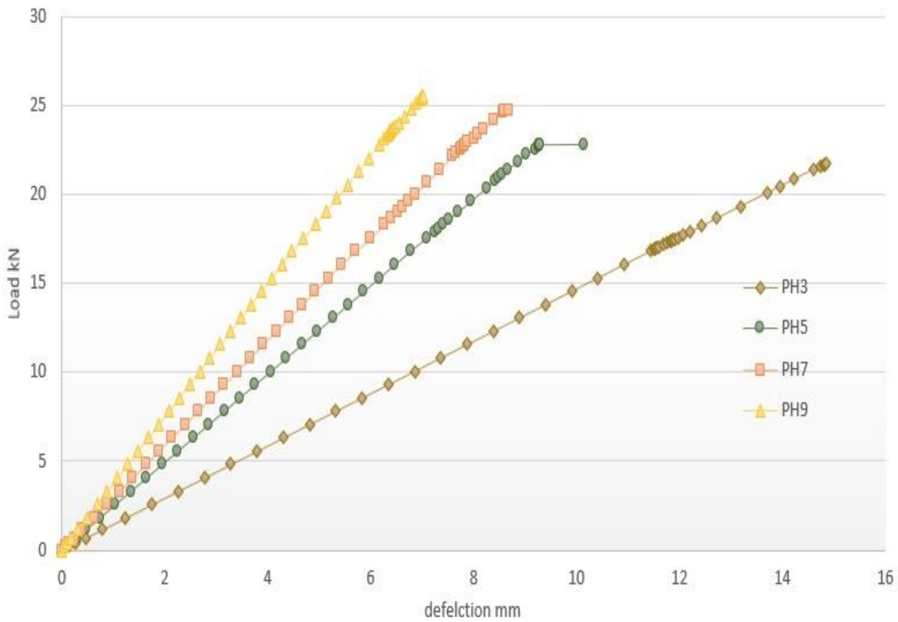


Figure 4.18 Load–midspan deflection curves for GFRP skins with honeycomb core of small scale models without U profile

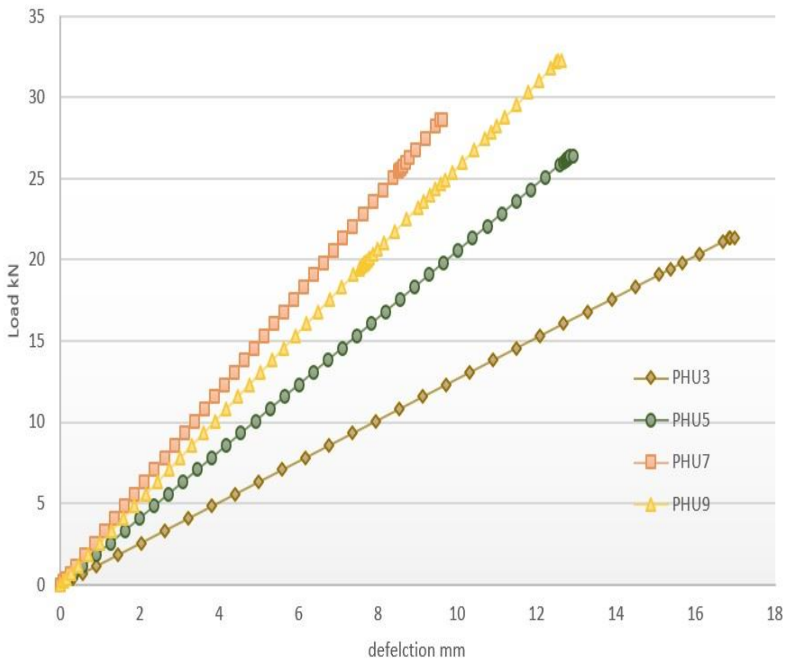


Figure 4.19 Load–midspan deflection curves for GFRP skins with honeycomb core of small scale models with U profile

4.7 Summery and Discussion

In parametric study was made four group, that was explained in this chapter. This section will discuss the results for each group and make compression between them.

In first group was modeled the small scale of sandwich panel (GFRP & PU foam core) first one with U profile, second one without U profile. We can have noticed from the numerical results in Table 4.2.

Through those results it was found that the relationship between the ultimate load and thickness skins positive relation. Figure 4.20 illustrating the relationship between the thickness of skins and ultimate load.

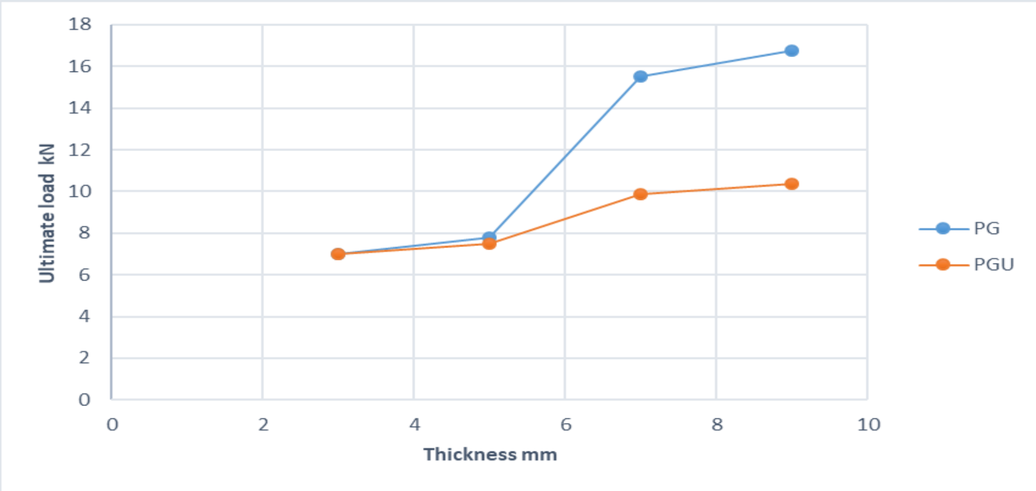


Figure 4.20 Relationship between the thickness of skins and ultimate load for first group

The relation between increasing of skins thickness and deflection is inversely. Figure 4.21 illustrates the relationship between the thickness of skins and deflection in midspan. This relation was taken by compering between value of deflection in less ultimate load in (PG3, PGU3) (7, 6.99 kN) respectively. The comparison between results is explain in Figures 4.22 and 4.23.

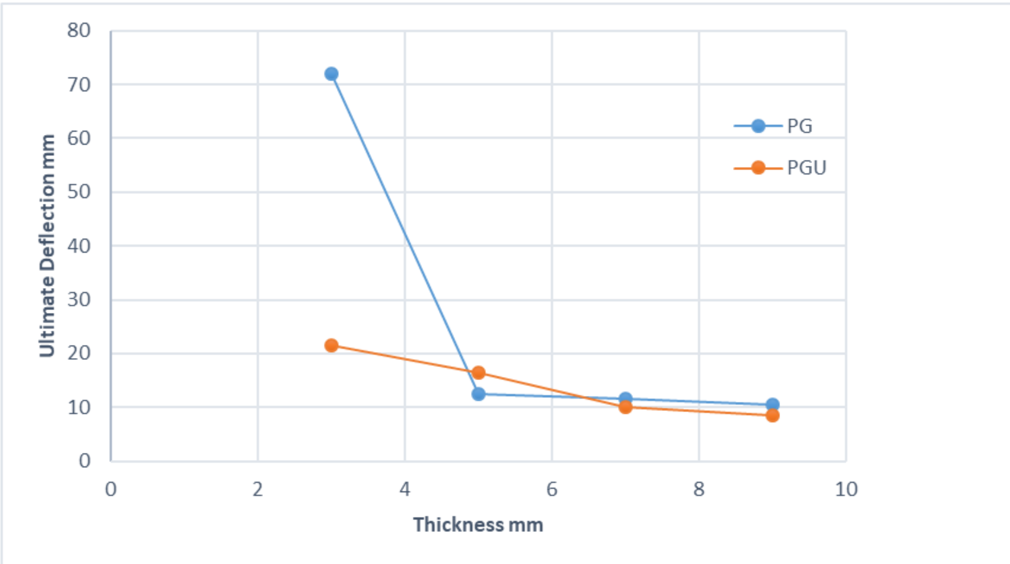
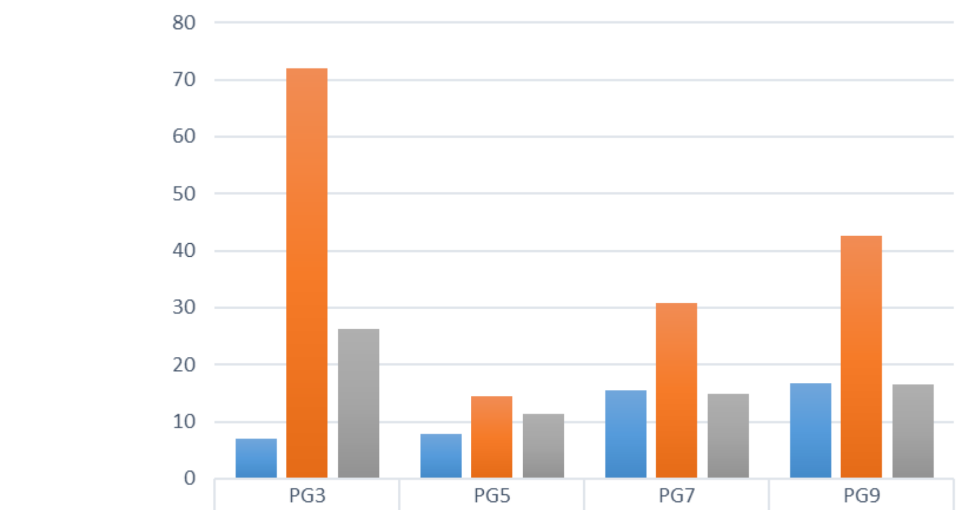
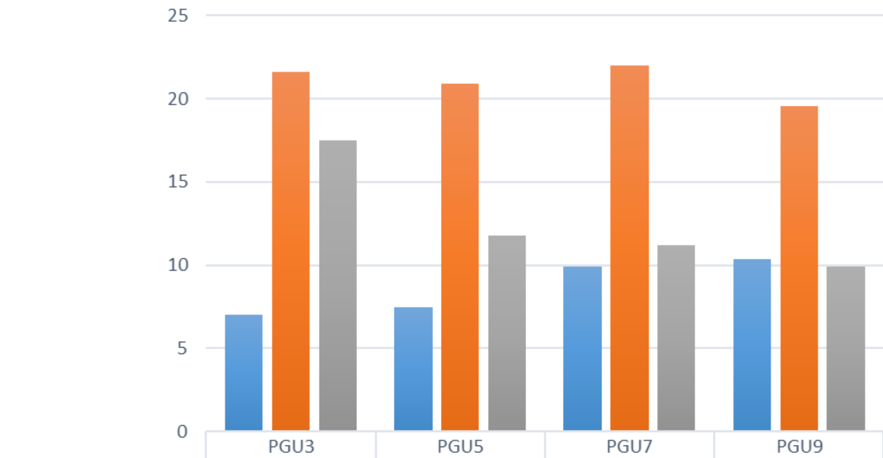


Figure 4.21 Relationship between the thickness of skins and deflection for first group



	PG3	PG5	PG7	PG9
Ultimate load kN	7.04	7.7938	15.54	16.77
deflection(mm)	72.0697	14.5376	30.797	42.51
Ultimate stress Mpa	26.269	11.36	14.77	16.57

Figure 4.22 Comparison between results of parametric study for small scale of sandwich panel with GFRP skins and PU foam core without U profile



	PGU3	PGU5	PGU7	PGU9
Ultimate load kN	6.99	7.473	9.879	10.38
deflection(mm)	21.59	20.93	22	19.529
Ultimate stress Mpa	17.5	11.8	11.19	9.88

Figure 4.23 Comparison between results of parametric study for small scale of sandwich panel with GFRP skins and PU foam core with U profile

In second group, the FE results for small scale of sandwich panel with CFRP skins and PU foam core (without U, and with U profile). In Table 4.3 was listed all results, from these result we can conclude, the relation between the ultimate load and thickness of skins is positive relationship. Where the thickness of skin was 3 mm the ultimatum load in two cases (with U, without U profile) (7.25, 7kN) respectively, but the ultimatum load in thickness of skins 9mm in two cases (with U, without U profile) was (9.52, 8.3 kN) respectively. In Figure 4.24 the relation between the thickness of skins and ultimate load is explaining.

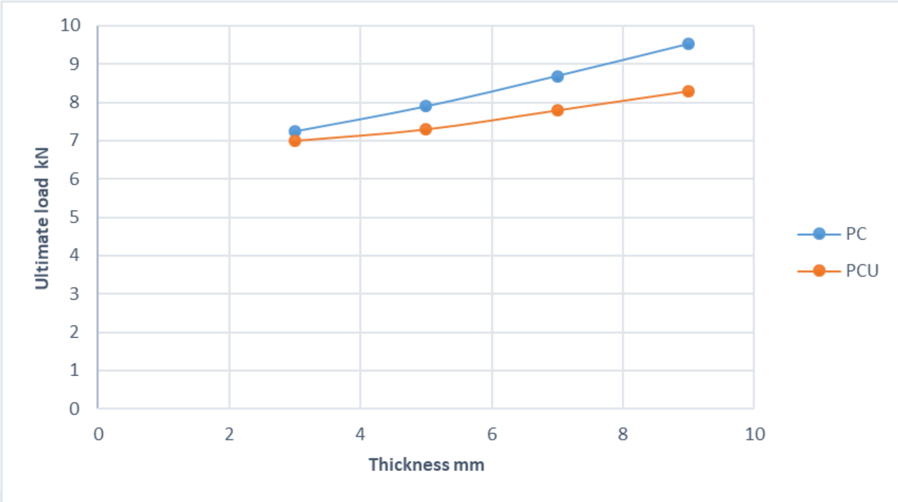


Figure 4.24 Relationship between the thickness of skins and ultimate load for second group

The relation between increasing of skins thickness and deflection is inversely. Figure 4.25 illustrating the relationship between the thickness of skins and deflection in midspan. This relation was taken by compering between value of deflection in less ultimate load in (PC3, PCU3) (7.25, 7kN) respectively. The comparison between results is explain in Figures 4.26 and 4.27.

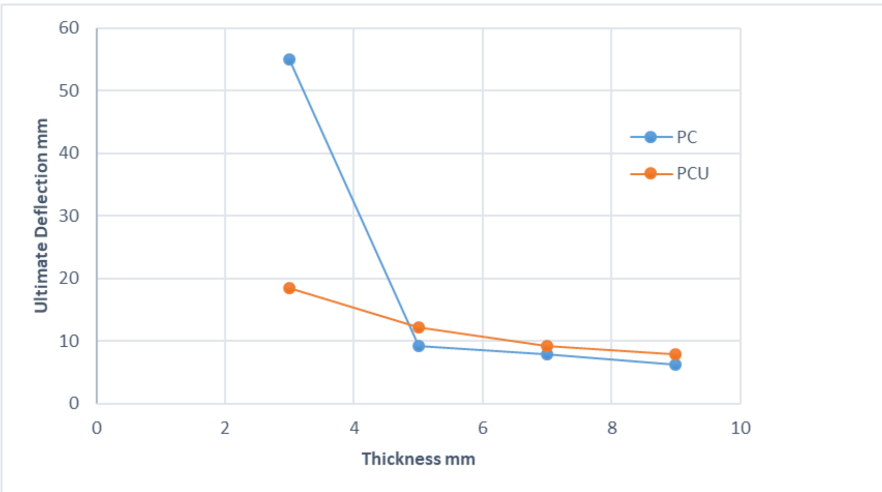


Figure 4.25 Relationship between the thickness of skins and deflection for second group

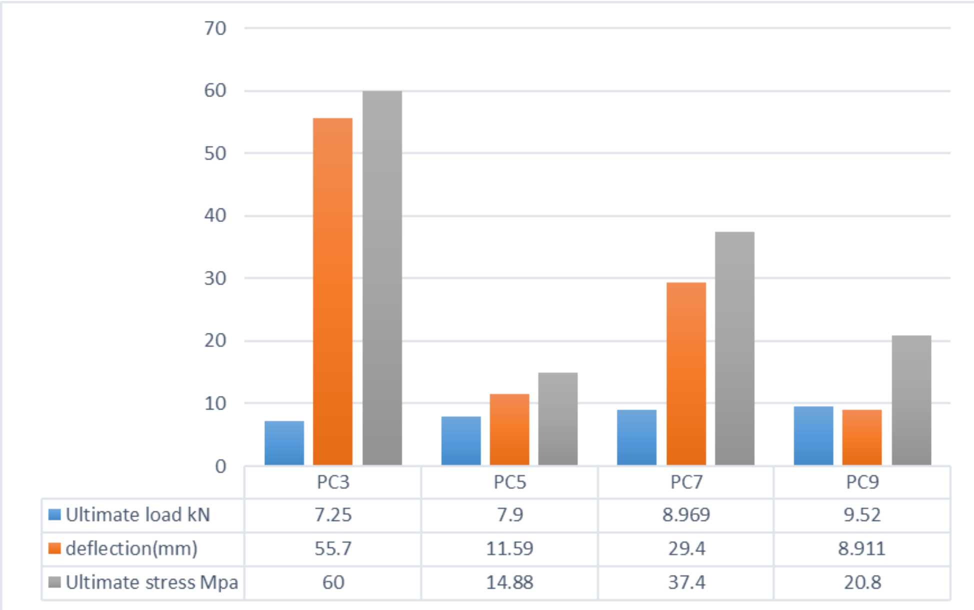


Figure 4.26 Comparison between results of parametric study for small scale of sandwich panel with CFRP skins and PU foam core without U profile

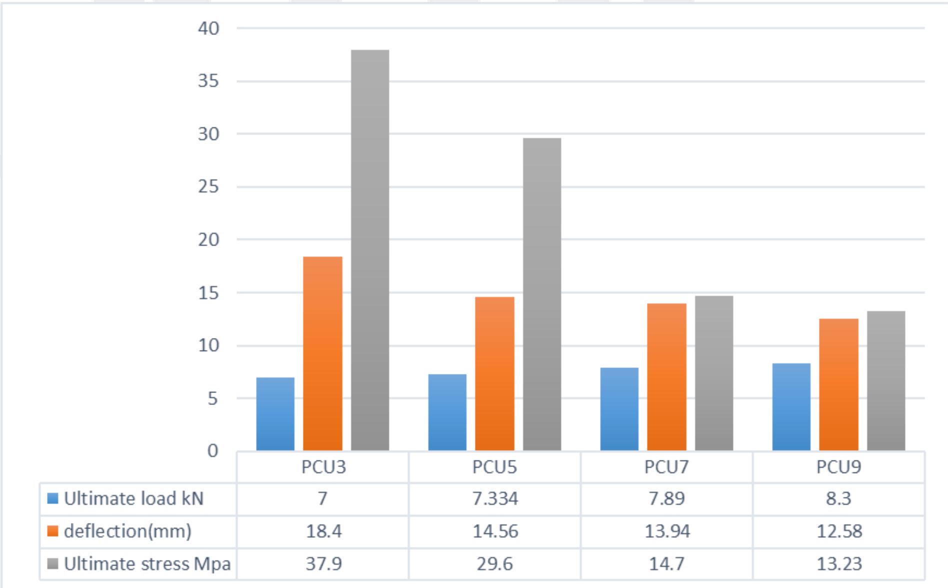


Figure 4.27 Comparison between results of parametric study for small scale of sandwich panel with GFRP skins and PU foam core with U profile

For the third group and fourth group the relation between ultimate load and thickness of skins is positive relationship, Figures 4.28,4.31 explaining the relation between the thickness of skins and ultimate load. And The relation between increasing of skins thickness and deflection is inverse, Figures 4.29,4.32 explaining the relationship between the thickness of skins and deflection in midspan. The comparison between results is explain in Figures 4.30,4.33.

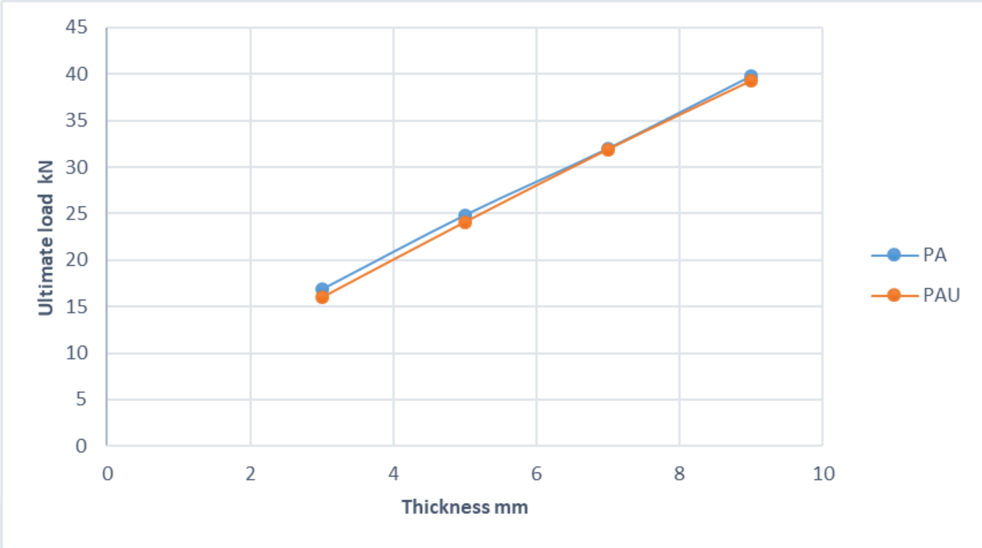


Figure 4.28 Relationship between the thickness of skins and ultimate load for third group

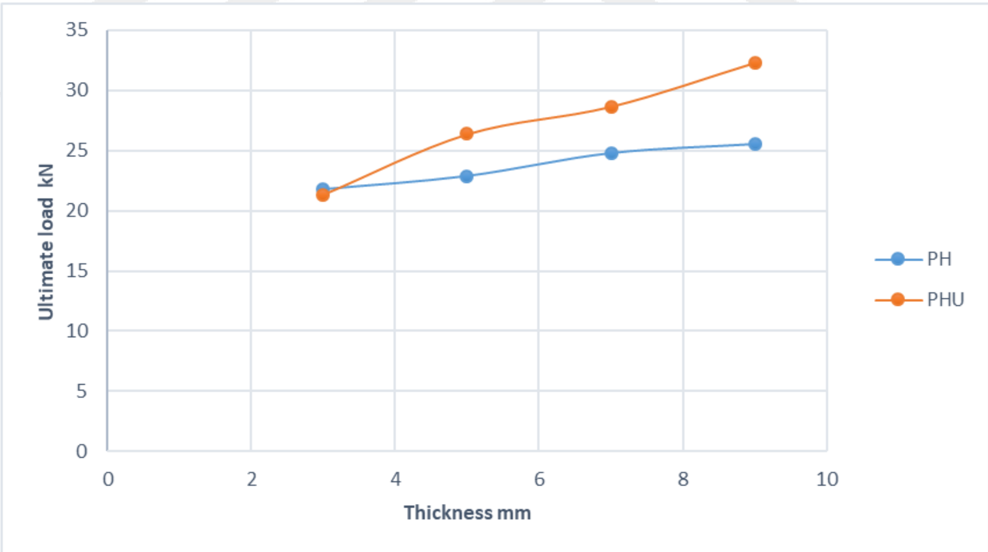


Figure 4.29 Relationship between the thickness of skins and ultimate load for fourth group

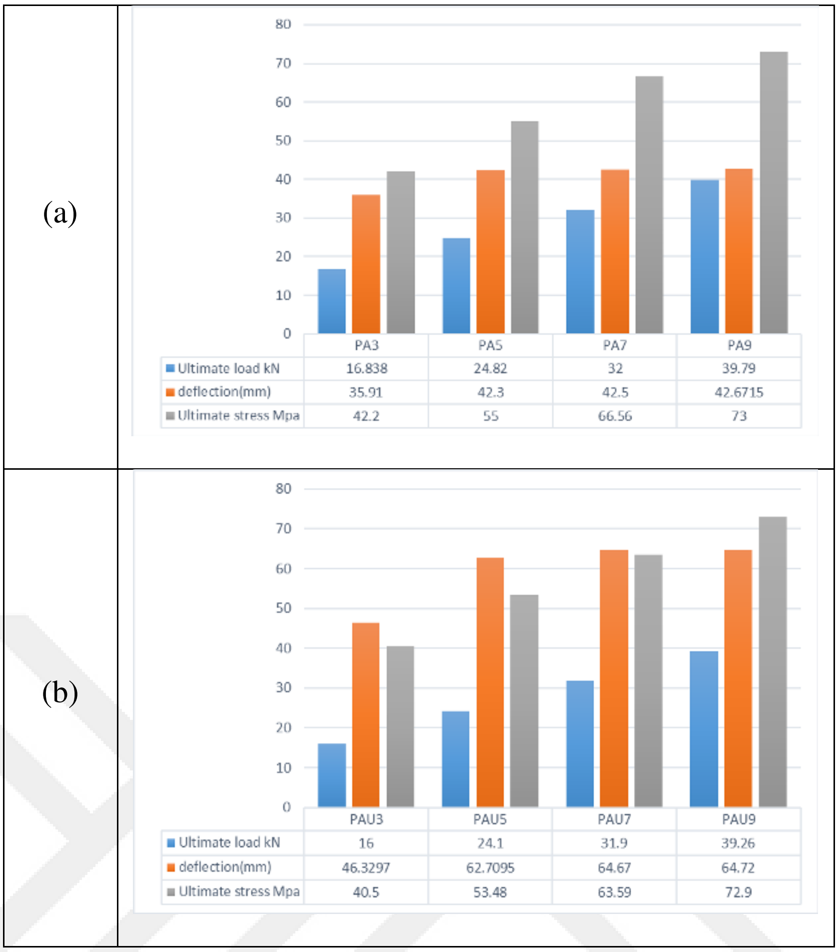


Figure 4.30 Comparison between results of parametric study for small scale of sandwich panel with aluminum skins and PU foam core: (a) with U profile (b) without U profile

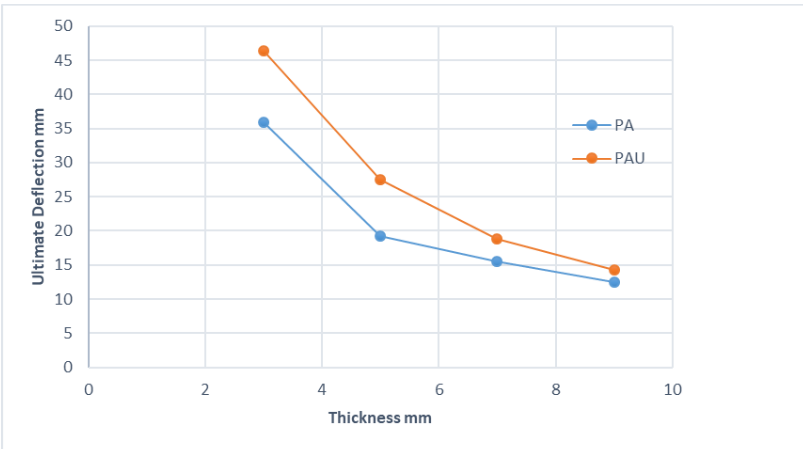


Figure 4.31 Relationship between the thickness of skins and deflection for third group

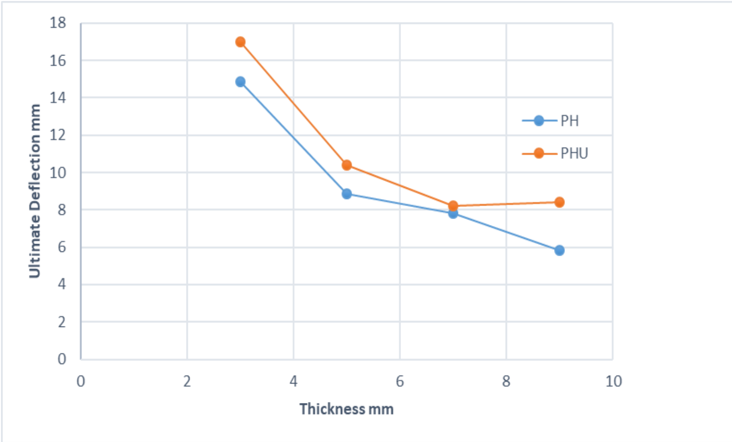


Figure 4.32 Relationship between the thickness of skins and deflection for fourth group

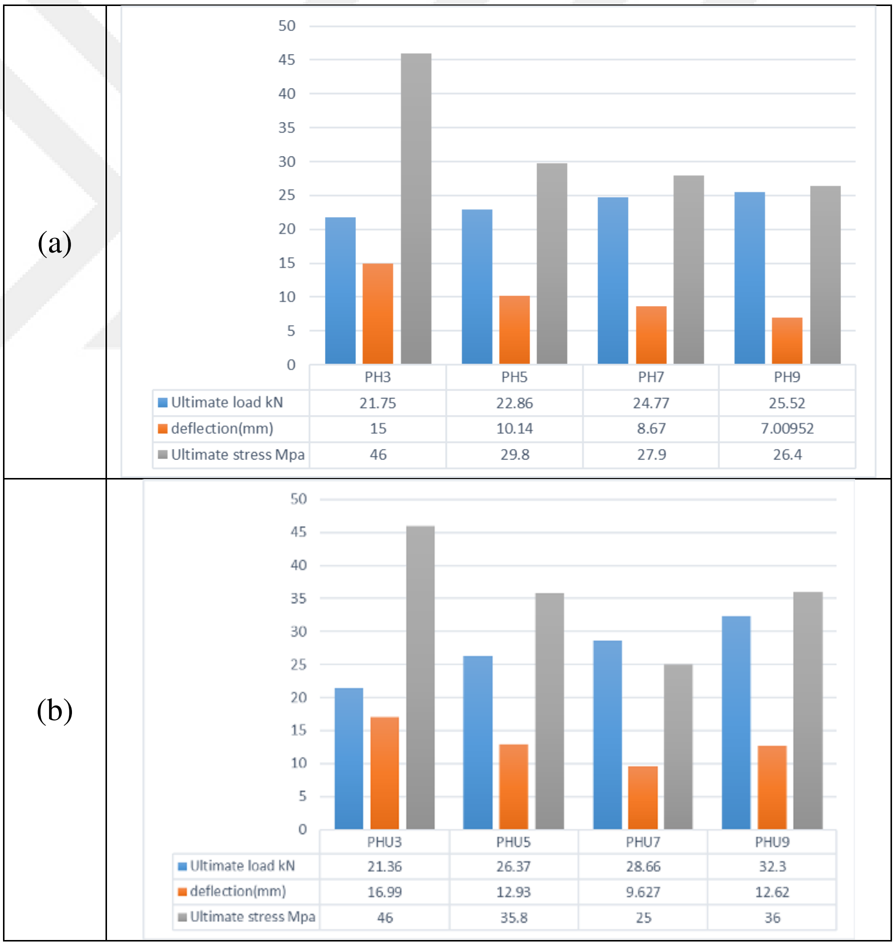


Figure 4.33 Comparison between results of parametric study for small scale of sandwich panel with GFRP skins and honeycomb core: (a) with U profile (b) without U profile

CHAPTER 5

CONCLUSIONS

5.1 General

Numerical tools to perform advanced numerical analyses of sandwich panels are now widely available and well-documented. However, one needs to choose wisely the modeling strategy and hypotheses to suit the problem studied. Unnecessary complexity of a model must be avoided because it increases the number of assumptions and could lead to additional model uncertainty. When complex models are required, they should always be validated with simpler numerical models, and if possible, with experimental tests.

The object of this thesis is numerical investigation of structural behavior of sandwich panel, and more specifically studying the structural behavior for small scale of sandwich panel with GFRP skin and filled with PU foam to core. The numerical results are compared with the experimental work [36].

In this thesis encompassed two phases, first one verification phase, it was simulated two model of small scale of sandwich panel is similar to the experimental work (PG, PGU) by using ANSYS APDL software. The results of these models is closer to the experimental results. The failure occurs in the PU foam because it has been a little compressibility as well as little resistance to shear. The skin sheets have a tensile strength and stress higher than PU foam. In the sandwich panel supported by U profile, the failure occurs the near part of the U profile because of shear and also in the contact area between skin and core of the sandwich panels.

Second a parametric study, this phase has four group, and it encompassed the modeling of thirty small scale of sandwich panel for studying the effect of skins thickness, skins material and core material. The thicknesses were 3, 5, 7, and 9mm. Two types of panel with/without U profile ends were studied. For the effect of skin material; GFRP, CFRP, and aluminum is investigated. In fourth group, the effect of core material which may be PU or honeycomb is studied.

5.2 Conclusion

The main conclusions drawn from this thesis may be listed as follow:

- The results of sandwich panel models developed using The ANSYS software are closer to the experimental results. There is excellent agreement between numerical results and experimental data.
- It was found that the relationship between the thickness of skins and deflection is an inverse matter. When the skin thickness increases the deflection decrease. This behavior is observed for all skin material type.
- The relationship between thickness of skins and ultimate load is proportional. That is, when the thickness of skin increases, the ultimate load increases as well.
- The best structural performance is observed in aluminum skin. Even the performance of the aluminum higher than CFRP and GFRP. The main reason, in all cases, failure occurred at the core. So the skin materials are not reach their ultimate stress value.
- The best performance occurs in the use of honeycomb core as expected. In the case of change of PU foam to honeycomb core, it was found that the ultimate load is increased.

5.3 Recommendation for future

Huge progress has been made in analysis and design of composite materials by many researcher and industry, but many important research and technical questions needs remain. Some of the research subjects need to be studied are:

- Nonlinear (geometric and material) analysis of sandwich panels subject to various load combinations.

- Investigation of the sandwich panel under fatigue load and creep.
- The optimization of the sandwich panels.
- Thermal properties of sandwich panels.
- Investigation of the use of the sandwich panels in other civil engineering structures, such as floor, bridge etc.
- Durability of sandwich panels.
- Investigation of the correlation between core thickness and mechanical behavior of sandwich panel.

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