REPUBLIC OF TURKEY
ERCIYES UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
DEPARTMENT OF MECHANICAL ENGINEERING

INVESTIGATION OF LOW-VELOCITY IMPACT BEHAVIORS OF ALUMINUM FOAM SANDWICH STRUCTURES REINFORCED WITH ALUMINUM PLATES

Prepared by
Noor JASIM

Supervisor
Prof. Dr. Recep GÜNEŞ

MSc Thesis

December 2021
KAYSERİ

REPUBLIC OF TURKEY
ERCIYES UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
DEPARTMENT OF MECHANICAL ENGINEERING

INVESTIGATION OF LOW-VELOCITY IMPACT BEHAVIORS OF ALUMINUM FOAM SANDWICH STRUCTURES REINFORCED WITH ALUMINUM PLATES

(M. Sc. Thesis)

Prepared By
Noor JASIM

Supervisor
Prof. Dr. Recep GÜNEŞ

This study was supported by the Scientific Research Projects Unit of Erciyes University (ERU/BAP) under the research Grant No. FYL-2021-10509

December 2021
KAYSERİ

SCIENTIFIC ETHICS SUITABILITY

I declare that all information in this work was obtained in accordance with academic and ethical rules. All results and materials that not been at the essence of this work are also transferred and expressed by giving reference as required by these rules and behavior.

Noor JASIM
Signature

SUITABILITY FOR GUIDE

The MSc thesis entitled **Investigation of Low-Velocity Impact Behaviors of Aluminum Foam Sandwich Structures Reinforced with Aluminum Plates** has been prepared in accordance with Erciyes University Graduate Education and Teaching Institute Thesis Preparation and Writing Guide.

Student	Supervisor
Noor JASIM	Prof. Dr. Recep GÜNEŞ

Chairman of the Department of Mechanical Engineering
Prof. Dr. Veysel ÖZCEYHAN

ACKNOWLEDGMENTS

I wish to express my sincere gratitude to the individuals listed below. This thesis would not have been possible without their assistance.

First and foremost, I am heartily thankful to my supervisor, Prof. Dr. Recep GÜNEŞ. His support and guidance throughout this thesis have made my study possible. His unstinting willingness to share knowledge is greatly appreciated. I am forever indebted to this great mentor, Prof. Recep I am grateful in every possible way for all your support and guidance.

Special thanks are also extended to the members of my thesis committee: Assoc. Prof. Dr. Recep EKİCİ and Doç.Dr. Kürşad Göv for their help with valuable suggestions.

I would like to express my sincere gratitude in particular to Asst. Mevlüt HAKAN and Asst. Muhsin ALÇI their involvement and throughout this thesis work has made my study possible.

I also would like to thank Ramiz AL-SAMARAAE for his valuable assistance, and always being there whenever I needed him.

My family have always understood and encouraged my academic endeavors. I am grateful to them all. My parents deserve special mention for their unstinting support and prayers. They are a constant source of inspiration to me.

NOOR SAAD JASIM
Kayseri, December 2021

ALÜMİNYUM PLAKALAR İLE TAKVİYELENDİRİLMİŞ ALÜMİNYUM KÖPÜK SANDVİÇ YAPILARIN DÜŞÜK HIZLI DARBE DAVRANIŞLARININ İNCELENMESİ

Noor JASIM

Erciyes Üniversitesi, Fen Bilimleri Enstitüsü
Yüksek Lisans Tezi, Aralık 2021
Danışman: Prof. Dr. Recep GÜNEŞ

ÖZET

Bu tez çalışmasında, alüminyum plakalar ile güçlendirilmiş alüminyum köpük çekirdekli sandviç yapıların düşük hızlı darbe davranışları incelendi. Çalışmada sandviç yapıların darbe cevapları üzerinde Al-köpük çekirdeğin yoğunluğu ve darbe enerjisinin etkileri araştırıldı.

Sandviç plakalar, Al-6061-T6 takviye plakalar arasına yerleştirilen 0.37, 0.52 ve 0.70 g/cm^3 olacak şekilde üç farklı yoğunlukta Al-köpüklerin epoksi yapıştırıcıyla birleştirilmesiyle üretildi. Her bir numuneye 15, 30, 45 ve 60J darbe enerjilerinde düşük hızlı darbe testleri uygulandı.

Hazırlanan numunelerin düşük hızlı darbe testleri, Erciyes Üniversitesi Mühendislik Fakültesi Makine Mühendisliği Bölümü Mekanik Laboratuvarında bulunan CEAST Fractovis marka darbe cihazında yapıldı.

Testler sonucu elde edilen temas kuvveti-zaman ve enerji-zaman grafikleri ile darbe sonrası numunelerde oluşan kalıcı deformasyonların ön ve kesit görüntüleri üzerinden alüminyum plaka takviyeli Al-köpük çekirdekli sandviç yapıların düşük hızlı darbe davranışları üzerinde köpük çekirdeğin yoğunluğu ve darbe enerjisinin etkileri detaylı olarak irdelendi.

Anahtar Kelimeler: Al-köpük, Sandviç plaka, Düşük hızlı darbe, Hasar.

INVESTIGATION OF LOW-VELOCITY IMPACT BEHAVIORS OF ALUMINUM FOAM SANDWICH STRUCTURES REINFORCED WITH ALUMINUM PLATES

Noor JASIM

Erciyes University, Graduate School of Natural and Applied Sciences

MSc. Thesis, December 2021
Thesis Supervisor: Prof. Dr. Recep GÜNEŞ

ABSTRACT

In this thesis, the low-velocity impact behavior of sandwich structures having aluminum foam core reinforced with aluminum plates was investigated. In this study, the effects of the Al-foam core density and the impact energy on the impact response of sandwich structures were investigated.

Sandwich plates were produced by combining of Al-foams with three different densities of 0.37, 0.52, and 0.70 g/cm^3, placed between Al-6061-T6 reinforcement plates with epoxy adhesive. Low velocity impact tests were carried out for each sample at 15, 30, 45 and 60J impact energies.

The low-velocity impact tests of the prepared samples were carried out with the CEAST Fractovis impact device in the Mechanic Laboratory of the Mechanical Engineering Department of Erciyes University.

The effects of the foam core density and the impact energy on the low-velocity impact behavior of the aluminum plate reinforced Al-foam core sandwich structures were examined in detail using contact force-time and energy-time graphics, and after impact permanent deformation photographs taken from the front and cross-section of the sandwich specimens.

Keywords: Al-foam, Sandwich plate, Low-velocity impact, damage.

TABLE OF CONTENTS

INVESTIGATION OF LOW-VELOCITY IMPACT BEHAVIORS OF ALUMINUM FOAM SANDWICH STRUCTURES REINFORCED WITH ALUMINUM PLATES

CHAPTER ONE

GENERAL INFORMATION AND LITERATURE REVIEW

CHAPTER TWO

MATERIALS AND METHODS

CHAPTER THREE

RESULTS

CHAPTER FOUR

CONCLUSIONS AND FUTURE WORKS

LIST OF FIGURES

INTRODUCTION

I.1. Importance of Study

Sandwich structure is one of the ancient known structures of composite materials. In the past, the use of metal plates in insulating structures was more common, were used as basic materials with the development of science. In 1993, a new door was opened for the development of new types of lightweight porous materials and closed-cell aluminum foam, Lee et al. [1]. Aluminum foam is known as lightweight materials with good properties for energy absorption. Because of these excellent properties of aluminum foam, it is likely to be used in different applications like automotive components to improve fuel economy and safety for drivers, passengers, and pedestrians [2,3]. The sandwich structure consists essentially of three components: the top and bottom layers, which are relatively thin; the middle base material, which is thick and relatively light; and the adhesive layers, which provide good contact between the layers. In this way, the sandwich structure is designed to have high mechanical strength and low weight. The base task of the core material is to maintain the spacing between the face layers and to provide higher bending stiffness and higher momentums in the area of the sandwich structure [4].

Sandwich structures can be exposed to low-velocity impacts such as falling tools, airborne tapes and unexpected impacts during their production, maintenance or operation. It is very important to know the damages that may arise from the effects of low speed in sandwich structures. In addition to their low weight, these structures are expected to absorb impact energy without deteriorating their structural strength when exposed to impact load. Despite all the studies that have been done to understand the behavior of the sandwich structures that are exposed to the effects of low velocity, there are great difficulties in predicting their damage due to the mechanical complexity of their behavior [5].

I.2. Aim of Study

Sandwich structures are especially used in structures that require high mechanical strength, where the energy generated under impact loads acting on the structure is absorbed. Thus, besides obtaining very light systems, a structure with high mechanical strength will be obtained.

The aim of this study is to investigate the low velocity impact behavior of Aluminum foam sandwich structures reinforced with Aluminum plates. Foam structure with different porosities will be used as core material in the sandwich specimens to be used for the tests. Impact tests will be carried out at different energy levels. The effects of impact energy and Al-foam core density on the impact behavior of the structure will be investigated. As a result of the experiments, maximum strength, fracture and deformation values and energy absorption properties of sandwich structures with Al foam core will be determined under compression and impact loads.

I.3. Scope of Study

Sandwich structures are widely used in both the aerospace and commercial industries because they are extremely lightweight structures that exhibit high stiffness and strength-to-weight ratios. The basic concept of a sandwich panel is that the surface plates carry bending loads (tensile and compressive) while the core structure carries shear loads similar to the I-beam comparison shown in Figure I.1 As shown in Figure I.2, honeycomb core construction in sandwich construction is highly structurally effective, especially in critical stiffness applications [6].

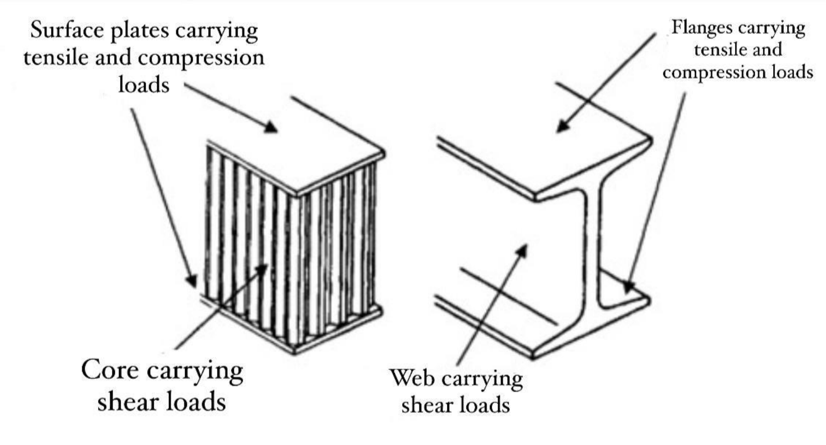
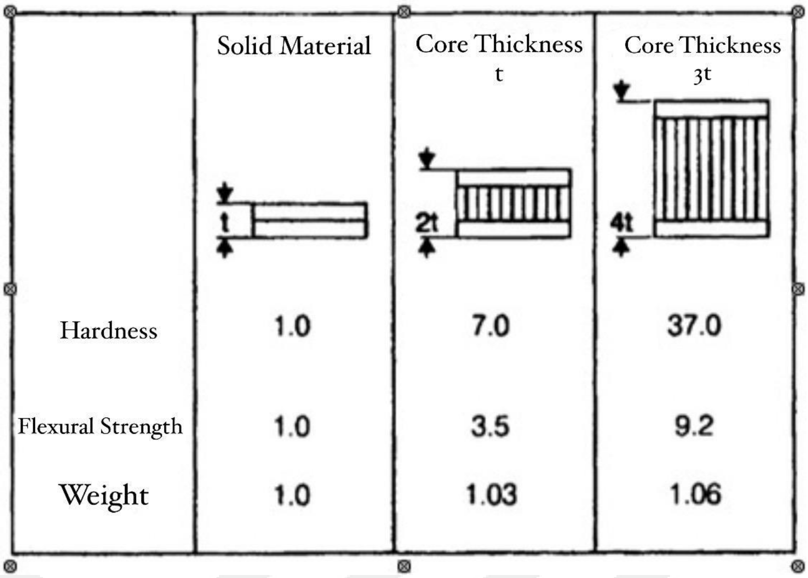


Figure I.1. sandwich structures [6].



	Solid Material	Core Thickness t	Core Thickness 3t
	t	2t	4t
Hardness	1.0	7.0	37.0
Flexural Strength	1.0	3.5	9.2
Weight	1.0	1.03	1.06

Figure I.2. The efficiency of the aluminum sandwich structure [6]

Making the thickness double increases the hardness 7 times, while the increase in weight in the structure is only 3%. Quadrupling the core thickness results in an increase in weight of only 6%, while the increase in hardness is 37 times (Figure I.2). Considering this data, it's no wonder that structural designers like to use sandwich construction whenever possible. Sandwich panels are typically used for their structural, electrical, insulating and/or energy absorbing properties. Normally used surface plate materials are aluminum, glass, carbon or aramid. A typical sandwich plate has a core structure with densities in the 1-30 pcf (pounds per cubic foot) range, and relatively thin (0.010-0.125 inch) surface plates.

Core materials include metallic and non-metallic honeycomb core, balsa wood, open and closed cell foams. The cost and performance comparison of these structures is given in Figure I.3 [6].

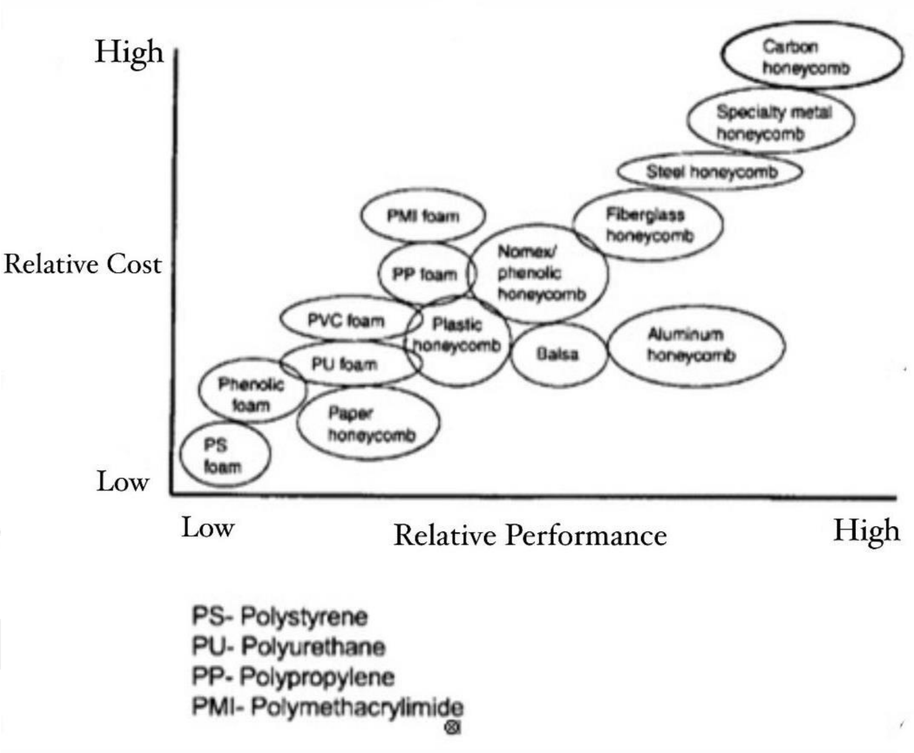


Figure I.3. Cost and performance for core materials [6].

In general, it is known that honeycomb structure as core material is costlier than foam structure, but offers superior performance. This explains why many commercial applications use foam cores, while higher performance but costlier honeycomb cores are used for aerospace applications. It should also be noted that normally it is easier to work with foam materials than with honeycomb materials. A relative strength and hardness comparison of different core materials is given in Figure I.4 [6].

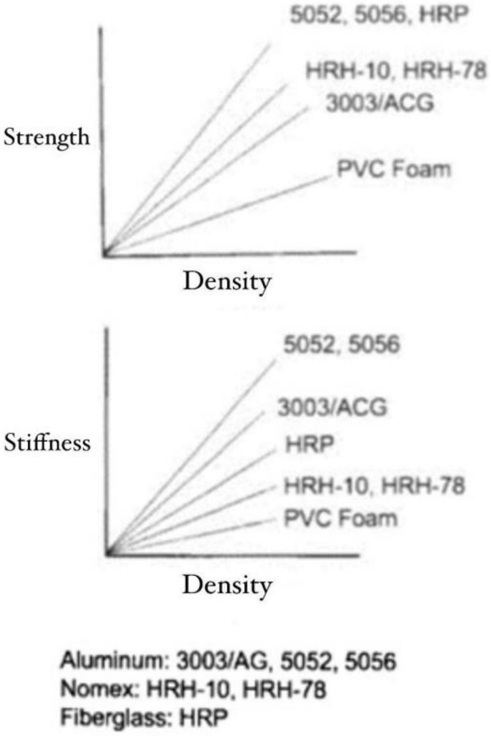


Figure I.4. Strength and stiffness of various core materials [6].

As can be seen from Figure I.4, aluminum foams have been preferred as the core material in this thesis study because they offer high performance at a low cost compared to other core materials and also have high strength and hardness at low density. Aluminum plates will be used as surface plates, and sandwich structures will be obtained by combining these two main components using an appropriate joining technique and will be made ready for impact tests.

CHAPTER ONE

GENERAL INFORMATION AND LITERATURE REVIEW

1.1. Introduction

Sandwich structures are formed by combining at least two different sheet materials in layers. A sandwich structure has three important elements. As shown in Figure 1.1, it consists of upper and lower surface plates at the outermost part, core material (foam) it will be in the middle, and the adhesive layers that provide connection in intermediate layers.

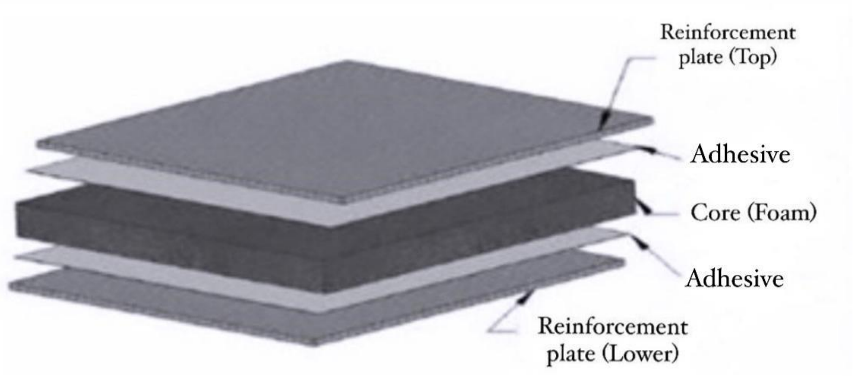


Figure 1.1. Basic elements of the sandwich structure

While the outer surfaces have a thin but durable structure, the strength value of the core material is lower than the surfaces, its damping feature is high and light. In this way, a high-strength element is formed and a low-weight structure is obtained in terms of structure. The core material gives high bending strength to the sandwich material because its main role is inside to maintain the distance between the outer surfaces at the moment of inertia.

Due to their low cost with a suitable combination of materials, lightweight, high flexural stiffness, thermal insulation properties, soundproofing properties, and high speeds resistance, the sandwich structures are widely used in industrial applications [7,8]. In recent years, sandwich materials have received a lot of attention lately because it plays an important role in the aviation and space industry, automotive industry, shipping industry, and military applications, especially where lightness and rigidity are important. Previously, the use of heavy stiffeners in traditional panel structures was common, and now the weight can be saved by getting rid of them and replacing them with these lightweight sandwiches [9,10]. Nowadays, there is a large and growing interest in aluminum sandwich structures with foam core [4,5]. With the increasing focus on environmental impact, the waste issue has become an important consideration for the marine and automotive industries. Sandwich structures made of aluminum alloys are a good alternative, so we can classify aluminum as a green material because of its unique properties that do not accept competition [11].

1.2. Literature Review

There are different studies in the literature on the impact behavior of sandwich structures. Common core configurations used in these studies include corrugated cores, honeycomb cores, foam cores, and lattice cores [12].

Foam core sandwich composites have emerged as an important class of lightweight building materials in a wide variety of engineering fields, including aerospace, automotive and marine structures. This is due to its attractive mechanical properties such as high specific bending stiffness and high bending strength. In the new integrated AFS (Aluminum Foam Sandwich) production process, a strong metallic bond is formed between the Al alloy surface sheets and cores. However, sandwich structures with non-metallic surface plates and polymer foam cores show less bond strength compared to their metallic counterparts [12]. Therefore, this study has been focused on the investigation of low velocity impact behavior of aluminum foam sandwich structures reinforced with aluminum plates.

Yu et al. [13] have experimentally studied the responses of sandwich beams with aluminum alloy surface plates and closed-cell Al-foam cores under quasi-static and low-speed impact bending and had compared the deformation and damage mechanisms with theoretical results.

Mocian et al. [5] numerically and experimentally investigated the mechanical behavior of sandwich panels consisting of aluminum surface plates exposed to low-velocity impact and poly-urethane or polystyrene foam cores. The mechanical responses of the structure are characterized by the absorbed energy, peak force, duration of the impact, and total deformation of the panel.

Liu et al. [14] investigated the low velocity impact responses of a newly developed sandwich panel with an aluminum foam core and fiber metal laminate (FML) surface plates composed of aluminum sheet and plain woven E-glass fibers. Weight drop impact tests were carried out and the effects of the thickness of the foam core and FML surface plates on the impact response of the panels were investigated experimentally. A finite element model was also developed and validated against experiments to analyze the response of sandwich panels under low velocity impact, to prove effectiveness and accuracy.

Jing et al. [15] investigated the low velocity impact response of sandwich beams with a layered-gradient foam core using a drop-weight impact device. Experiments were performed for three different core configurations, namely, the positive layered-gradient core, the negative layered-gradient core, and the gradient-free monolithic core. Based on the experimental results, the relevant finite element simulations were performed using LS-DYNA software. The effects of energy absorption mechanism and boundary conditions on the force-displacement response for sandwich beams with three different core configurations at different impact energy levels are compared. Finally, Multi-objective Design Optimization (MDO) has been performed for sandwich beams in their work.

Sun et al. [16] experimentally and numerically investigated the dynamic response of sandwich panels with homogeneous and graded aluminum foam cores subjected to impact loading. Low-velocity impact tests were carried out using a drop-weight impact device at four different speeds; their results were compared in terms of force-displacement response, energy absorption and damage status. They found that the density gradient of the stepped foam cores had a significant effect on the deformation and damage behavior of the faceplate reinforcement plates.

Mohan et al. [17] experimentally investigated the impact response of aluminum foams with various special surface plates represented by elastic, elastic-ideal plastic and elastic-plastic strain hardening. The experiments were carried out using a hemispherical impactor on aluminum foam blocks with and without a surface plate. Competing failure modes for fault initiation are discussed based on comparison of energy absorption capacity. The results show that the increase in foam thickness and the use of the face layer increase the impact energy absorption capacity. The energy absorption capacity of different damage modes is discussed by comparing the initiation of damage. The results showed that the increase in foam thickness and the use of surface plate increased the impact energy absorption capacity.

Hangai et al. [18] performed impact tests on uniform A1050 and A6061 Al foams together with A1050/A6061 functionally graded Al foams exhibiting ductile deformation produced with the pre-foaming process. The distribution of porosity in the resulting Al-foams was non-destructively observed by X-ray computed tomography (CT). In conclusion, they showed that by varying the base materials, it is possible to control the compression deformation behavior of functionally graded Al-foam with the desired plateau stress during impact tests, which is dependent on the strength of the base materials.

Crupi et al. [9] studied the comparison of static and low velocity impact response of two types of aluminum sandwiches (foam and honeycomb sandwiches). The parameters affecting the static and dynamic response of the examined aluminum sandwiches and their energy absorption capacities were analyzed.

Tang et al. [19] carried out experimental studies on the damage properties of CFRP/aluminum foam sandwich structure subjected to high velocity impact. In this study, the effects of the impact velocity and the density of the bullet on the damage properties of the CFRP/aluminum foam sandwich structure and the attenuation effect of the shock wave in the sandwich structure were investigated.

Güneş and Arslan [4] studied numerically and experimentally the behaviors of the aluminum honeycomb sandwich structure under low-velocity impact loads. They developed a numerical realistic finite element model. Predicted and experimental results have been compared, and results have exhibited good agreement.

Jilin Yu et al. [13] investigated a static and low-velocity impact behaviors of sandwich beams with closed-cell aluminum-foam core in three-point bending.

Lin and Fatt [20] have developed an advanced analytical model that has been based on a group of experimental results for perforating composite sandwich panels that have been subjected to the low-velocity and quasi-static impact load by the hemispherical projectiles/indenters. They have researched the effects of the geometry of the projectiles/indenters upon perforation and deformation, involving successive failures of the core, top face sheet, and bottom face sheet of sandwich panels.

Foo et al. [21] have studied failure responses of Al sandwich panels under the low-velocity impacts. Therefore, they have developed a 3-D geometrically correct finite element model of honeycomb sandwich plate to exhibit more understanding concerning parameters that affect the impact damage initiation and propagation. Foo et al. [22] have extended their previous study including a progressive damage model of composite materials in order to accurately predict the damage mechanisms and failure of composite sandwich structures. The model developed by them gave results that were in good agreement with the experimental results.

Lee et al. [23] carried out experimental and numerical studies for the impact and penetration damage of honeycomb sandwich panels under the low-velocity impact. When they compared the obtained results, they observed that the numerical and experimental results were compatible in terms of damage areas and depths.

Griškevičius et al. [24] studied on the impact performance of sandwich composites made of woven fiberglass and polyvinyl ester resin composite face sheets and a polypropylene honeycomb core. Depending on the geometric properties of the sandwich structure, they presented results on its use in safety-related structures.

Lee et al. [25] have conducted numerical and experimental studies on the impact behavior of aluminum honeycomb sandwich panels. Ultimately, they presented a numerical model based on continuum damage mechanics fully coupled with elasto-visco-plasticity.

Sharma et al. [26] investigated low-velocity impact behavior of aluminum honeycomb core sandwich panels by varying the core height with a flat impactor. They focused on the effect of core height on the energy absorption capacity of the honeycomb panel and found that varying the core height had no significant effect on the energy absorption capacity of the sandwich panel.

Butukuri et al. [27] the response of sandwich panels under low-velocity impact loads has investigated experimentally based on data from factorial experiments were performed by them.

Manes et al. [28] carried out numerical and experimental studies on sandwich panels subjected to low-velocity impact. They presented a detailed finite element model using data from compression tests of honeycomb cores, ductile failure of aluminum skins and calibration of the constitutive law.

Menna et al. [29] performed a set of experimental study to calibrate their numerical model, and satisfactory agreement was obtained between the numerical predictions and the experimental results for simulating the dynamic behavior between sandwich structures and Nomex core.

Yoshihiko Hangai et al. [30] investigated the drop-weight impact behaviors of functionally graded aluminum foam consisting of A1050 and A6061 aluminum alloys.

Kolopp et al. [31] performed a study to establish a relationship between the performance of metallic sandwich structures, and the material and geometry parameters.

Ivañez and Sanchez-Saez [32] developed a numerical model for the impact behavior of honeycomb-core sandwich beams at low velocities. In order to verify the numerical model, they performed experimental tests. With the help of this model, the knowledge was obtained about the contribution of each component to energy absorption capacities of the composite sandwich beams.

Crupi et al. [33] carried out a numerical study of aluminum honeycomb sandwiches subjected to low velocity impact, which they had previously studied experimentally [34].

CHAPTER TWO

MATERIALS AND METHODS

In this chapter, the materials used for the preparation of the aluminum foam sandwich structures reinforced with aluminum plates, the production process of the specimens, and the experimental methods used throughout this thesis study will be described.

2.1. Materials

In this thesis study, the low velocity impact behaviors of sandwich plates with Al foam core supported by Aluminum surface plates will be investigated experimentally. 1 mm thick Al-6061-T6 plate will be used as surface plates, and 30 mm thick aluminum foam to be selected in three different densities (0.37, 0.52 and 0.70 g/cm^3) will be used as core material. Surface plates and foam cores will be bonded to each other with Araldite 2015 epoxy (Figure 2.1).

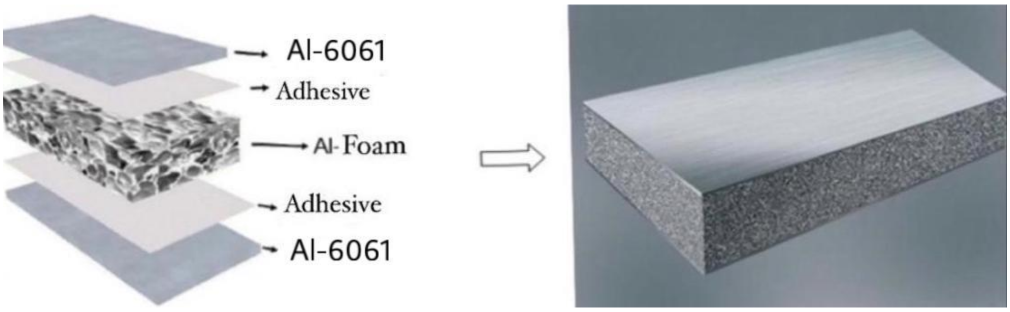


Figure 2.1. Components of the aluminum foam sandwich plate.

2.2. Production of Sandwich Specimens

The first step of the research is to prepare the samples that will be tested for low-velocity impact. Cutting processes for Aluminum face plates was in the laboratories of the College of Aviation using the guillotine machine (Figs 2.2 and 2.3).

Figure 2.2. Guillotine cutting machine.

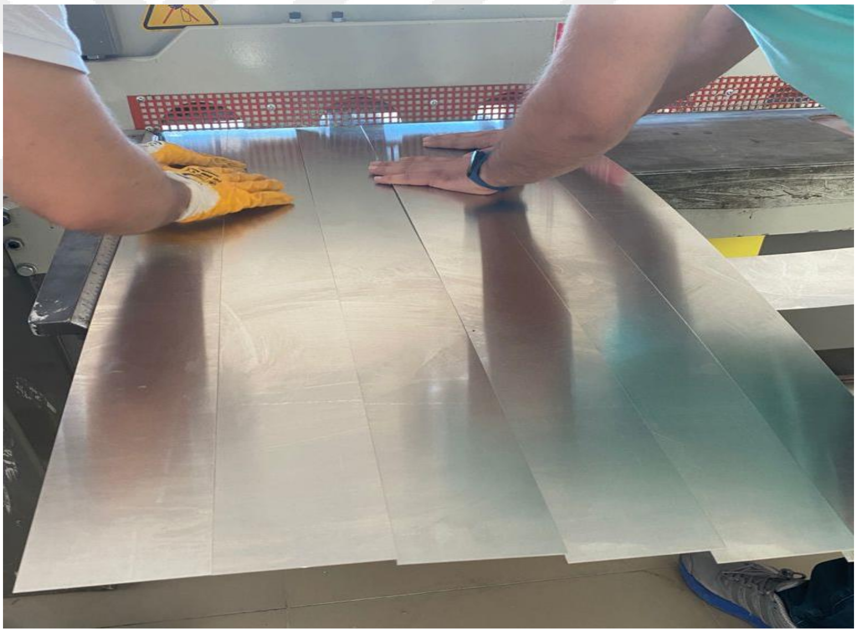


Figure 2.3. Cutting processes in the guillotine machine.

After cutting process, the surface plates have the same size and a final dimension of approximately 150×100 mm (Fig. 2.4).

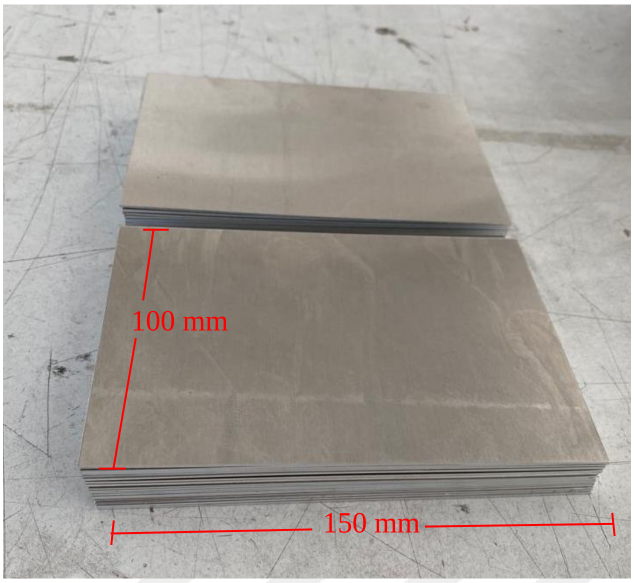


Figure 2.4. Al-6061 surface plates after cutting process.

Al-foam core structures with different densities were prepared to be combined with surface plates by cutting 150×100 mm dimensions by means of a special cutting machine (Fig. 2.5). Metacut machine is used to cut various metals in order to obtain a regular specimen. It is a kind of manual/automatic cutting machine and can be switched between manual and automatic modes. The cutting surface is cooled by spray nozzles which a closed-loop recirculating water jets hit both the cutting wheel and the specimen. This provides efficient cooling of the specimen and prevents the overheating of the structure.

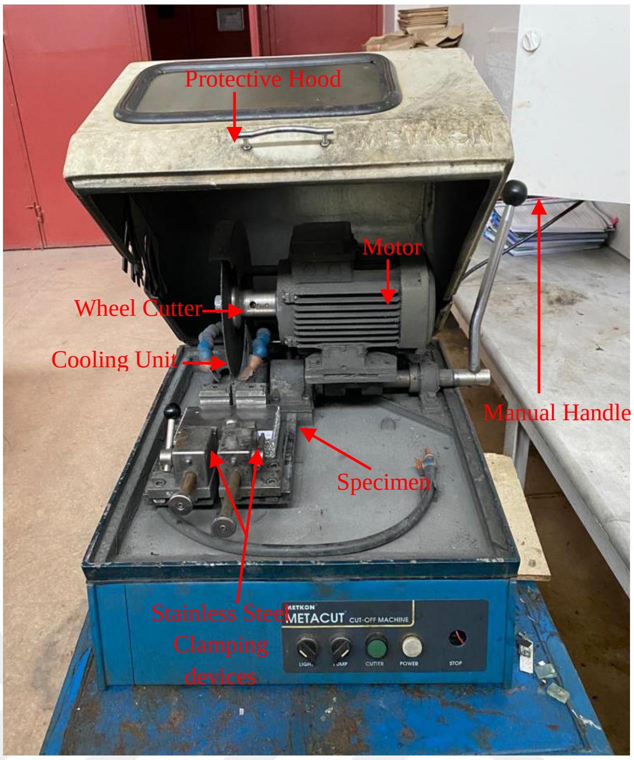


Figure. 2.5. Metacut Cutting Machine

After the cutting process is completed, the next step is to clean the aluminum surface plates and Al-foams from foreign materials and dust using Acetone and Paraffin (Fig.2.6).

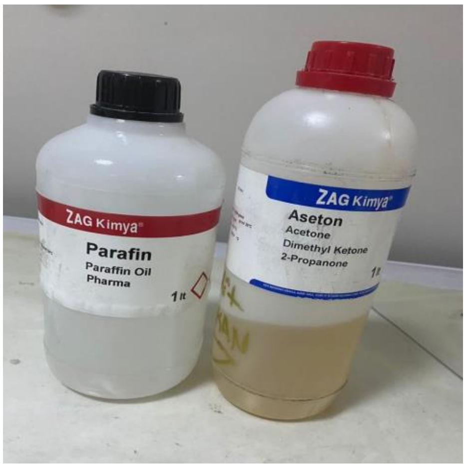


Figure 2.6. Acetone and Paraffin.

Then a relatively thin layer of Araldite epoxy adhesive (Fig.2.7) was applied to both surfaces in order to bond the two aluminum surface plates to the Al-foam core (Fig. 2.8).

Figure 2.7. Araldite 2015 epoxy adhesive.

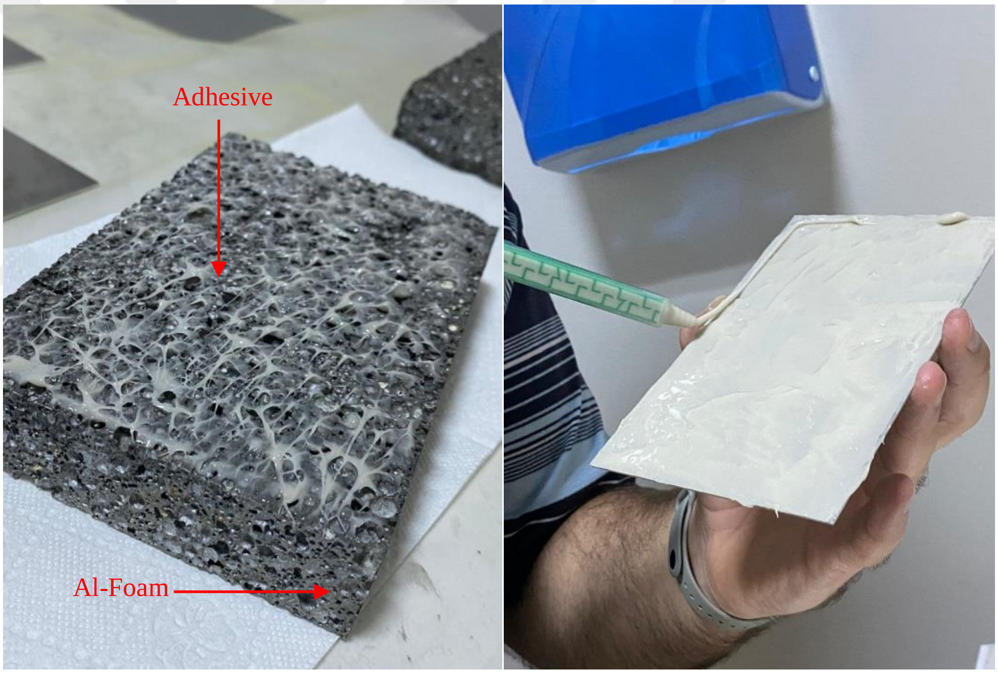


Figure 2.8. Application of Araldite epoxy adhesive to the surfaces to be adhered.

After bonding, suitable weights were placed on the sandwich plates to ensure a strong adhesion between the surface plates and Al-foam core. They were then left to dry at room temperature for 72 hours. At the end of this period, the sandwich specimens having approximately 32 mm total thickness were ready for impact tests (Fig. 2.9).

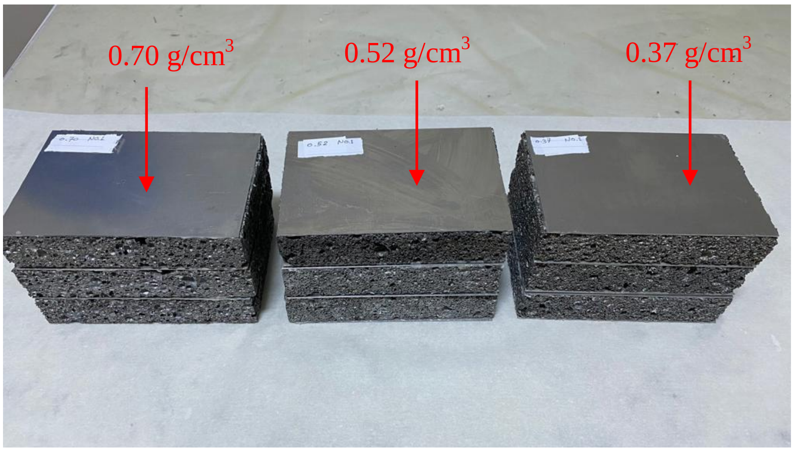


Figure 2.9. Sandwich plates prepared for impact tests.

2.3. Impact Test Machine and Test Parameters

The sandwich plates, which were cut into specimen sizes and produced to have three different core densities (porosity), were prepared to be subjected to low-speed impact tests at different energy levels.

For the impact tests, the CEAST brand impact test device will be used in the infrastructure of the Mechanics Laboratory (Figure 2.10). CEAST brand Fractious Plus impact device was developed to create an impact by using the "Guided Weight Reduction" technique. This instrument is capable of testing films, rigid samples, finished materials, pipes, and more. The modular infrastructure of the device offers the users the opportunity to determine the initial configuration in line with their changing needs. The device can perform potential energy experiments at room temperature ranging from 4.6-24 m/s velocities, in other words, between 755-1800J according to standards of ISO, ASTM, DIN, BS, etc. There are also sample fastening apparatus by the standards, an anti-rebound system device that prevents repetitive impact (Fig 2.10.b). Thanks to the high-speed data acquisition system DAS 16000, 20,000 samples can be taken in 10 ms (milliseconds). Experiments will be performed at four different energies levels for each sandwich plate configuration and the impact behavior at different energy levels will be determined. The test specimens were placed in a holding apparatus prepared according to the ASTM D7136 standard, and pneumatic clamping system of device fixed the specimen by subjecting it to an out-of-plane force. The holding apparatus is shown in Figure 2.11. The impactor used in the tests has a semi-spherical geometry having a diameter of 20 mm and connected to 45 kN capacity force transducer and its total mass is 5.295 kg. The potential energy of the drop-weight, as defined by the mass and drop height of the impactor, is specified before the test. Equipment and procedures are provided for optional measurement of contact force and velocity during the impact event. The damage resistance is quantified in terms of the resulting size of damage in the specimen.

The test begins with the dropping of the impactor. Once it reaches the aluminum sandwich structure, it is triggered by the signal from the timing sensor. At this point, the impact velocity is calculated based on the time it takes to pass the two triggers. If the heat and energy loss during impact is ignored, the energy generated by the impactor is transferred to the specimens directly. In each impact test, the impactor contacts the specimens at the center, which is named central impact (Fig. 2.10.c).

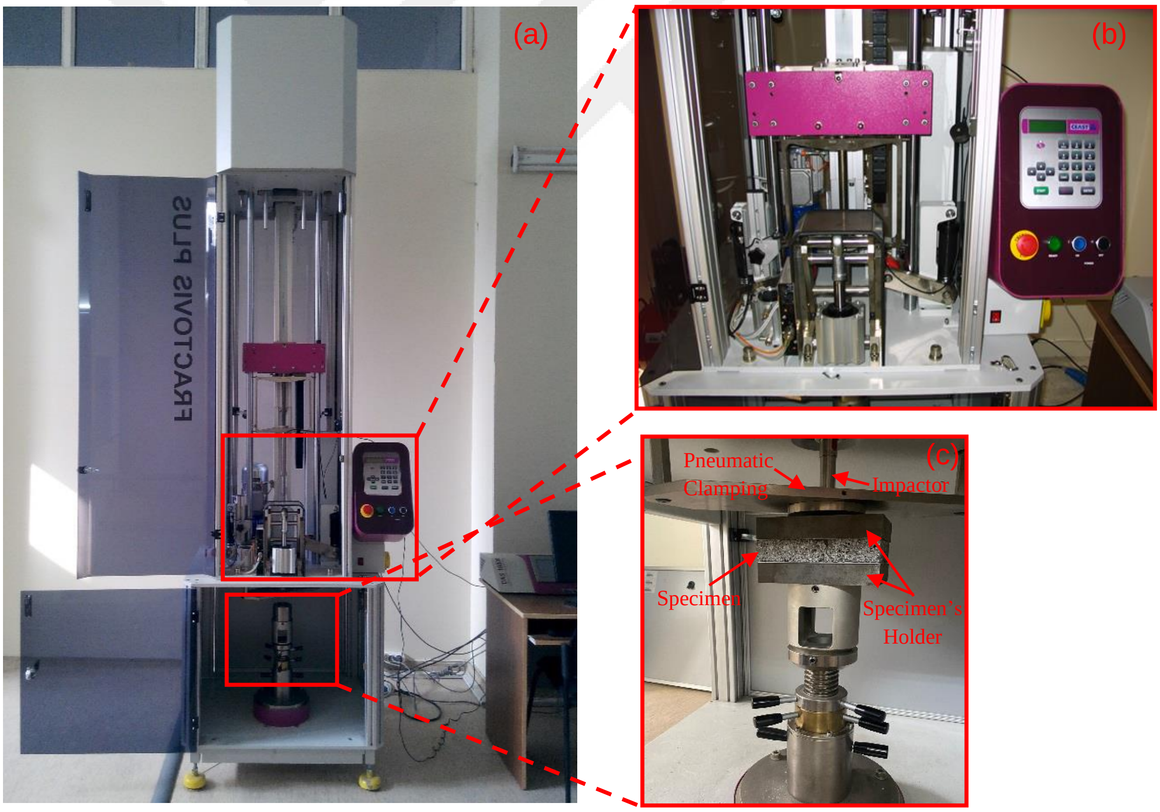


Figure 2.10. a) Drop-weight test system, b) Anti-rebounding system, and c) Specimen connection apparatus.

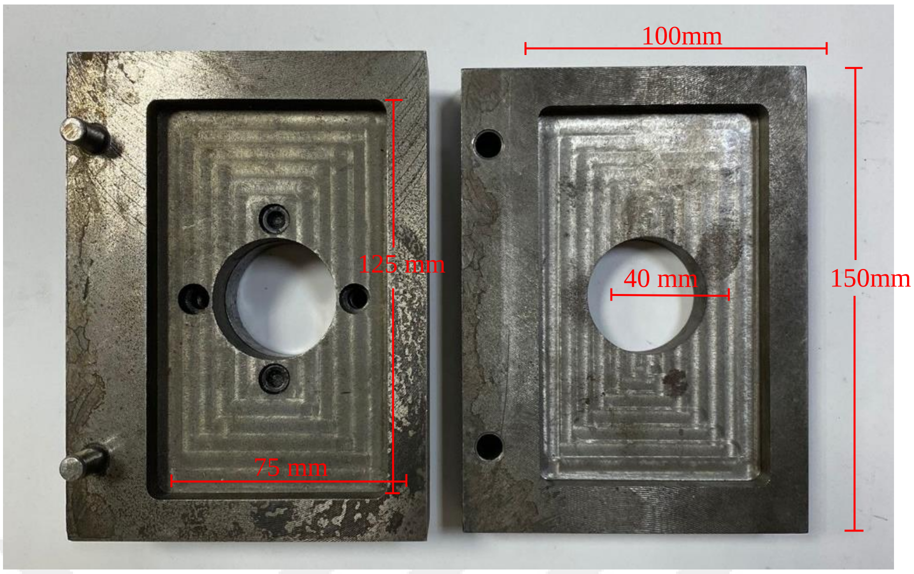


Figure 2.11. Specimen holder

The impacted specimens were subjected to a second cutting process from its impact center in order to take the cross-sectional images of the permanent deformations occurring in the sandwich samples after the impact tests. Figure 2.12 shows the images of the impacted samples before and after cutting from its impact center. Permanent deformations in the specimens after impact were determined by precise measurements made from their cross-sections.

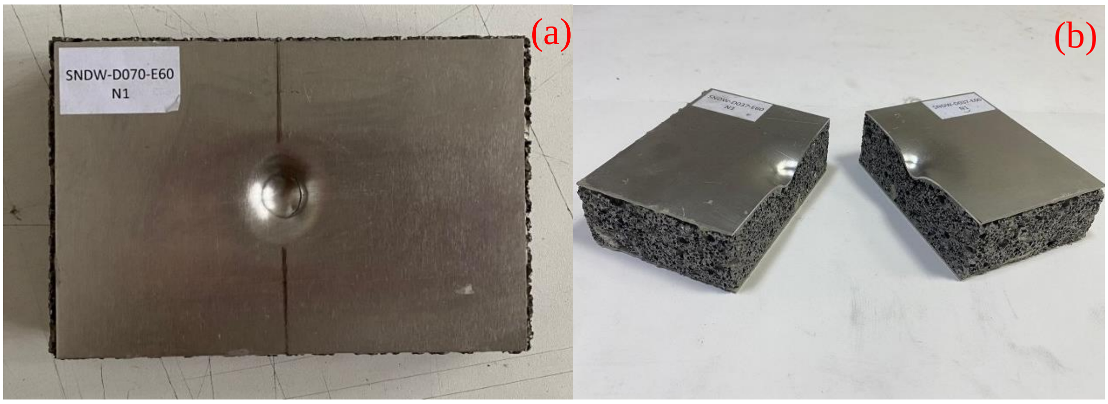


Figure 2.12. a) Determination of impact center, b) the specimen after cutting from its impact center.

2.4. Low Velocity-Impact Theory

The equations resulting from integrating Newton's second law, F = ma, were considered. This was conducted to the principle of momentum and linear impulse and this principle is very valuable when resolving problems in which we are interested in defining the global effect of a force performing on a particle over an interval of time.

2.4.1. Linear Momentum

Taking into consideration the curvilinear motion of a particle having mass of m under the effect of the force F, supposing that the mass does not changing, this was derived from Newton's second law,

$$F = m.a = m\,\frac{dv}{dt} = \frac{d}{dt}\,(mv)$$

In case where the mass of the particle changing with the time will be taking into consideration the linear momentum vector, G, is defined as

$$G = m.v$$

Therefore, another form of Newton's second law is

$$F = \dot{G} \qquad (2.1)$$

which makes the total force performing on a particle equal to the time changing rate of its linear momentum.

The force is considered to effect the particle between time t_1 and time t_2. Equation (2.1) be able then be integrated in time to achieve,

$$\int_{t1}^{t2} F\,dt = \int_{t1}^{t2} \dot{G}\,dt = G_2 - G_1 = \Delta G \qquad (2.2)$$

here, $G_1 = G(t_1)$ and $G_2 = G(t_2)$. The term

$$I = \int_{t1}^{t2} F\,dt = \Delta G = (mv)_2 - (mv)_1$$

is called the linear impulse. Therefore, the linear impulse on the particle is equivalent to the linear momentum changing ΔG. In many applications, the force is on an impulse model, for example a great force acting during a small time. However, this restriction is needless. All that required is to be able to perform the integral of $\int_{t1}^{t2} \mathrm{F\,dt}$. If the force is a constant F, then

ΔG = $\int_{t1}^{t2} \mathrm{F\,dt}$ = F (t_2 - t_1). If the force is set as a function of time, then ΔG =$\int_{t1}^{t2} \mathrm{F(t)\,dt}$

2.4.2. Conservation of Linear Momentum

It is shown from equation (2.1) that if the resultant force on a particle is zero during an interval of time, then its linear momentum G must stay constant. Meanwhile equation (2.1) is a vector quantity; we have conditions in which just a few components of the resultant forces are zero. For case in Cartesian coordinates, if the resultant force has just a non-zero component in the y direction, then the x and z components of the linear momentum will be preserved meanwhile the force components in x and z are zero. Two particles are then considered, m_1 and m_2, which interact through an interval of time. Assuming that interaction forces among them are the only unstable forces on the particles. Let **F** be the interface force that particle m_2 acts on particle m_1. Formerly, according to Newton's third law, the interaction force that particle m_1 exerts on particle m_2 will be **-F**. With expression (2.2), we have that $\Delta G_1 = - \Delta G_2$, or $\Delta G = \Delta G_1 + \Delta G_2 = 0$. That is, the changing of momentum of particles m_1 and m_2 are the same in magnitude and opposite in sign, and then the total momentum changing equal to zero. This is correct only if the only unbalanced forces on the particles are the interaction forces. It is shown that the above argument is also acceptable in a component wise sense. That is, when two particles interact and there is no external unbalanced forces towards the assumed directions, so the total momentum changing along that direction should be zero.

CHAPTER THREE
RESULTS

3.1. Introduction

In this thesis study, the effects of different foam densities and different impact energies on the low-velocity impact behavior of aluminum foam core sandwich plates were experimentally investigated. Sandwich plates with three different foam core densities (0.37, 0.52, and 0.70 g/cm^3) were subjected to four different impact energies (15, 30, 45, and 60J). In terms of the reliability of the obtained results, the impact tests were repeated three times for each specimen. The impact response of aluminum foam core sandwich plates has been inspected utilizing contact force-time curves, energy profiles, and damage photographs taken from the front and cross-section of the sandwich specimens.

3.2. Effect of Impact Energy Levels

To understand the effect of impact energy on the impact behavior of sandwich plates with aluminum foam cores, sandwich plates with different core densities were subjected to low-velocity impact under four different impact energies.

Firstly, sandwich plates with 0.37 g/cm^3 density Al-foam core were exposed to impact energies of 15, 30, 45, and 60J, respectively. The contact force-time and kinetic energy-time graphs obtained as a result of these tests and the front and cross-sectional images of the deformations after impact are shown in Fig. 3.1. The peak contact force became 5.865 kN while the contact time was 2.721 ms for the impact energy of 15J. The through-thickness experimental permanent displacement was measured as 3.8 mm for the impact energy of 15J and absorbed energy by the sandwich plate as 14.061J. For the impact energy of 30J, the peak contact force was obtained as 7.407 kN at the contact time was 3.064 ms. While the energy absorbed by the sandwich plate was 28.569J, the after permanent impact deformation of the sandwich plate was determined as 6.2 mm. As a result of the experiments with the impact energy of 45J, the peak contact force was determined as 9.843 kN when the contact time was 2.774 ms. The permanent deformation measured in the impact region was measured as 6.6 mm, and the absorbed energy by the sandwich plate was around 43.6J. Finally, for the 60J impact energy, the peak contact force reached 9.519 kN while the contact time was 2.697 ms. As a result of the impact, the permanent deformation of the sandwich plate was measured as 10.3 mm, and the absorbed energy by the plate was 59.147J. As a result of this experiment, when the contact force reached the peak level, a sudden decrease in the contact force was observed depending on the tearing damage in the upper reinforcement plate. This tear damage can also be seen from the front view of the sandwich plate. In addition, it was observed that separation occurred in the adhesive connection between the reinforcement plate and the foam core due to the damage. This is because the density of Al-foam used in the core of the sandwich plate is low, and the impact energy is high. From the impact tests for 45J and 60J energy levels, it is seen that the peak contact forces are almost at the same level (approximately 9.5 kN). In other words, it is understood that the energy level that the sandwich plate can meet at this core density (0.37 g/cm^3) is around 45J and that damage may occur in the structure at higher energy levels (Fig. 3.1).

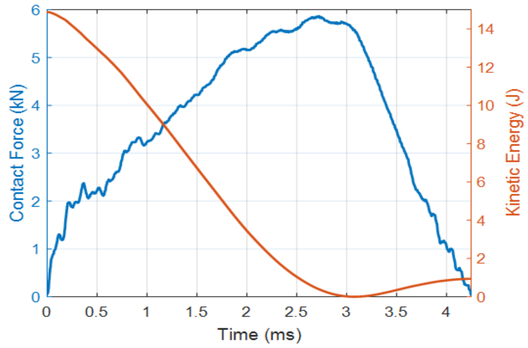
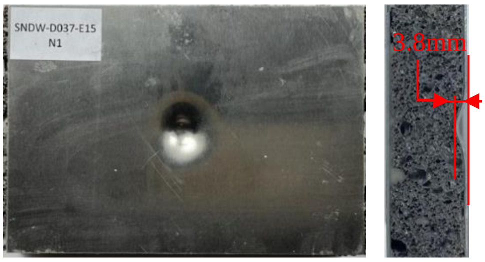
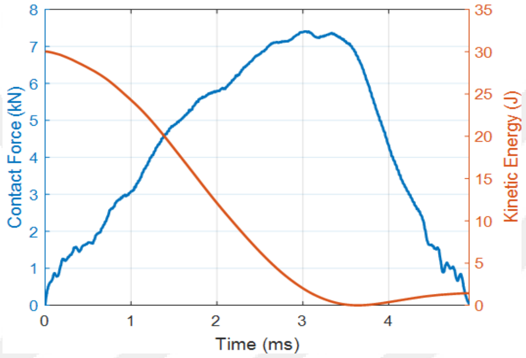
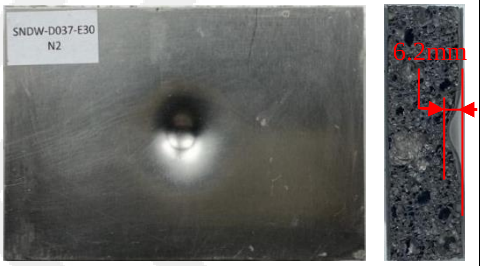
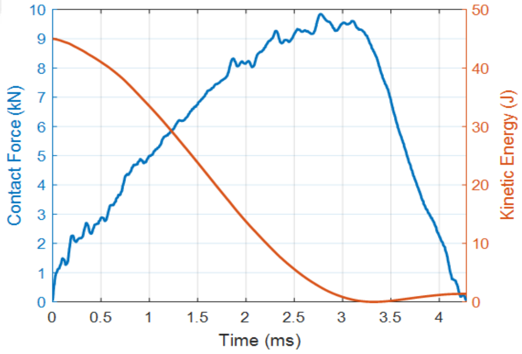
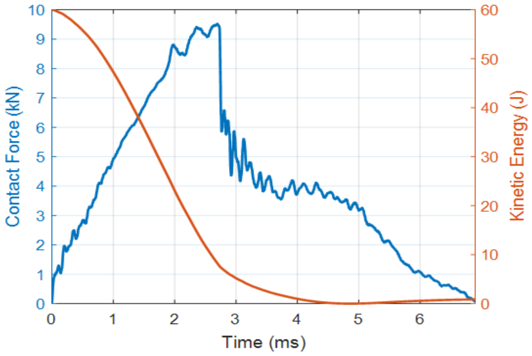
Impact Energy **J**	The density of Al-foam core: 0.37 g/cm^3	
15		
30		
45		
60		

Figure 3.1. The contact force-time and kinetic energy-time graphs, and the front and cross-sectional images of the permanent deformations after impact tests (core density of 0.37 g/cm^3).

Secondly, the low-velocity impact responses of sandwich plates having Al-foam core with a density of 0.52 g/cm^3 were investigated subjected to impact energies of 15, 30, 45, and 60J, respectively.

The contact force-time and kinetic energy-time graphs obtained as a result of these tests and the front and cross-sectional images of the deformations after impact are shown in Fig. 3.2. The peak contact force was measured as 5.688 kN, while the contact time was 2.746 ms for the impact energy of 15J. The through-thickness experimental permanent displacement has occurred as 3.6 mm for the impact energy of 15J, and absorbed energy by the sandwich plate is 14.22J. For the impact energy of 30J, the peak contact force was obtained as 9.041 kN at the contact time was 2.242 ms. While the energy absorbed by the sandwich plate was 29J, the after permanent impact deformation of the sandwich plate was determined as 5 mm. As a result of the experiments with the impact energy of 45J, the peak contact force was determined as 10.13 kN when the contact time was 2.651 ms. The permanent deformation measured in the impact region was measured as 6.1 mm, and the absorbed energy by the sandwich plate was around 43.483J. Finally, for the 60J impact energy, the peak contact force reached 14 kN while the contact time was 2.301 ms. As a result of the impact, the permanent deformation of the sandwich plate was measured as 6.8 mm, and the absorbed energy by the plate was 57.974J.

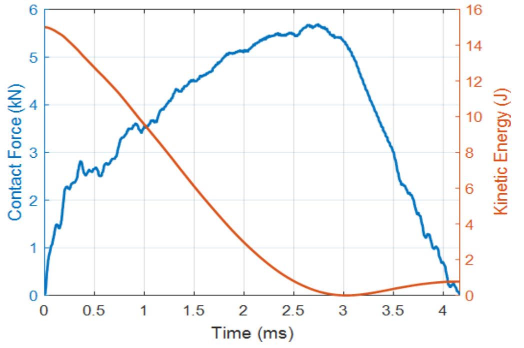
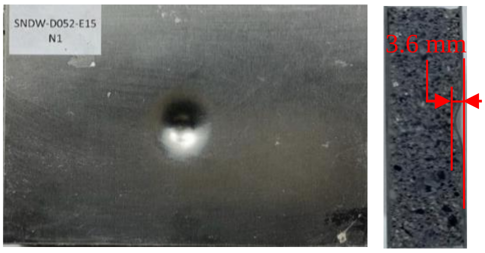
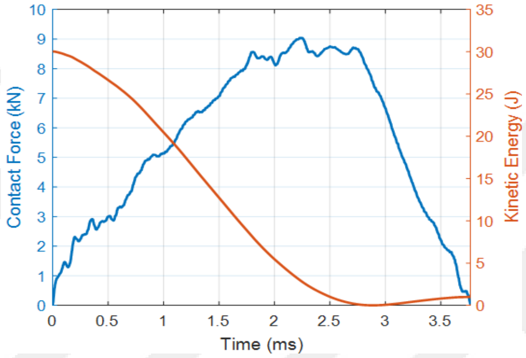
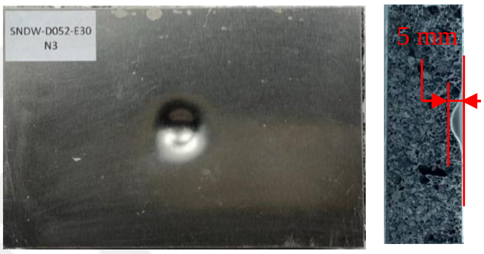
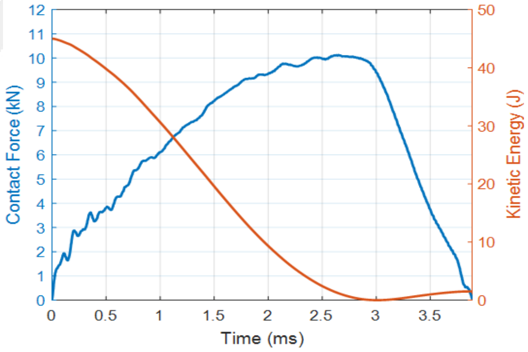
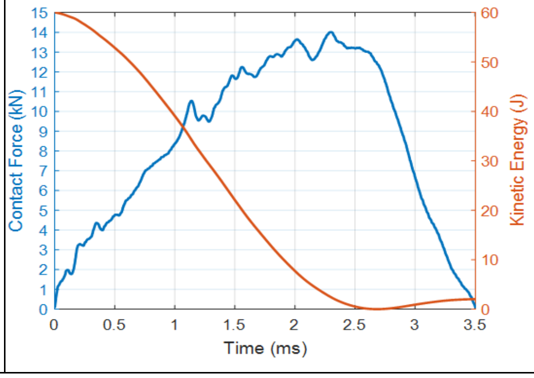
Impact Energy **J**	The density of Al-foam core: 0.52 g/cm^3	
15		
30		
45		
60		

Figure 3.2. The contact force-time and kinetic energy-time graphs, and the front and cross-sectional images of the permanent deformations after impact tests (core density of 0.52 g/cm^3).

Thirdly, the low-velocity impact responses of sandwich plates having Al-foam core with a density of 0.70 g/cm^3 were investigated subjected to impact energies of 15, 30, 45, and 60J, respectively.

The contact force-time and kinetic energy-time graphs obtained as a result of these tests and the front and cross-sectional images of the deformations after impact are shown in Fig. 3.3. The peak contact force became 6.744 kN, while the contact time was 2.126 ms for the impact energy of 15J. The through-thickness experimental permanent displacement was measured as 2.6 mm for the impact energy of 15J and absorbed energy by the sandwich plate as 14.307J. For the impact energy of 30J, the peak contact force was obtained as 9.265 kN at the contact time was 2.139 ms. While the energy absorbed by the sandwich plate was 29.132J, the after permanent impact deformation of the sandwich plate was determined as 4.2 mm. As a result of the experiments with the impact energy of 45J, the peak contact force was determined as 12.759 kN when the contact time was 2.374 ms. The permanent deformation measured in the impact region was measured as 5.5 mm, and the absorbed energy by the sandwich plate was around 43.771J. Finally, for the 60J impact energy, the peak contact force reached 14.17 kN while the contact time was 2.411 ms. As a result of the impact, the permanent deformation of the sandwich plate was measured as 6.3 mm, and the absorbed energy by the plate as 57.596J.

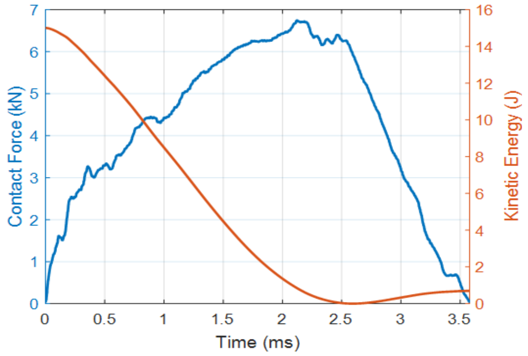
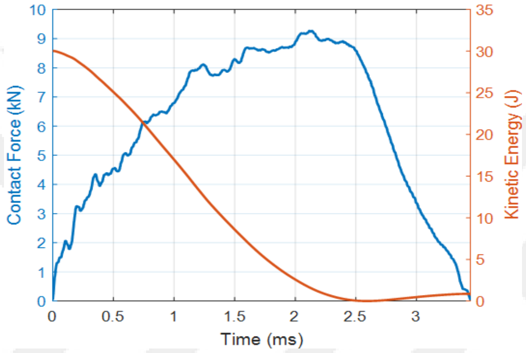
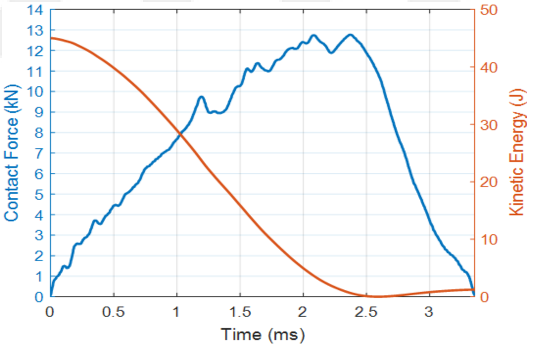
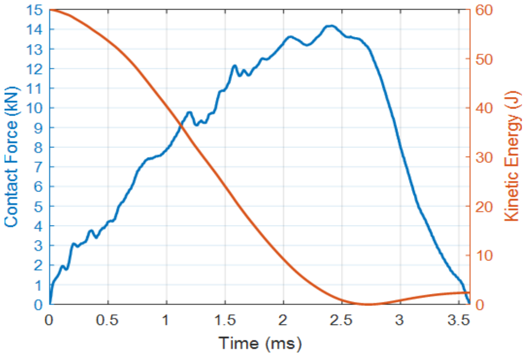
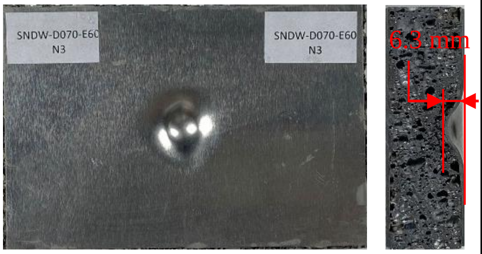
<table>
<tr><th>Impact Energy
J</th><th colspan="2">The density of Al-foam core: 0.70 g/cm^3</th></tr>
<tr><td>15</td><td>
</td><td>
</td></tr>
<tr><td>30</td><td>
</td><td>
</td></tr>
<tr><td>45</td><td>
</td><td>
</td></tr>
<tr><td>60</td><td>
</td><td>
</td></tr>
</table>

Figure 3.3. The contact force-time and kinetic energy-time graphs, and the front and cross-sectional images of the permanent deformations after impact tests (core density of 0.70 g/cm^3).

It was observed that the permanent deformations of sandwich plates with all three Al-core densities increased with increasing impact energy. As a result of the 60J impact tests performed on sandwich plates with all three core densities, damage occurred in the sandwich plate with a density of 0.37 g/cm^3, while no damage was observed in the sandwich plates with core densities of 0.52 and 0.70 g/cm^3 (Figs 3.1, 3.2 and 3.3).

Figure 3.4 shows the effect of different energy levels on the contact force-time variations of the sandwich plates having an Al-foam core density of 0.52 g/cm^3. It is seen that the peak contact forces increase and the contact durations decrease with increasing impact energy levels. As can be seen from the graphics, the impact energies were absorbed in the form of plastic deformation without any damage to the plates at all applied energy levels.

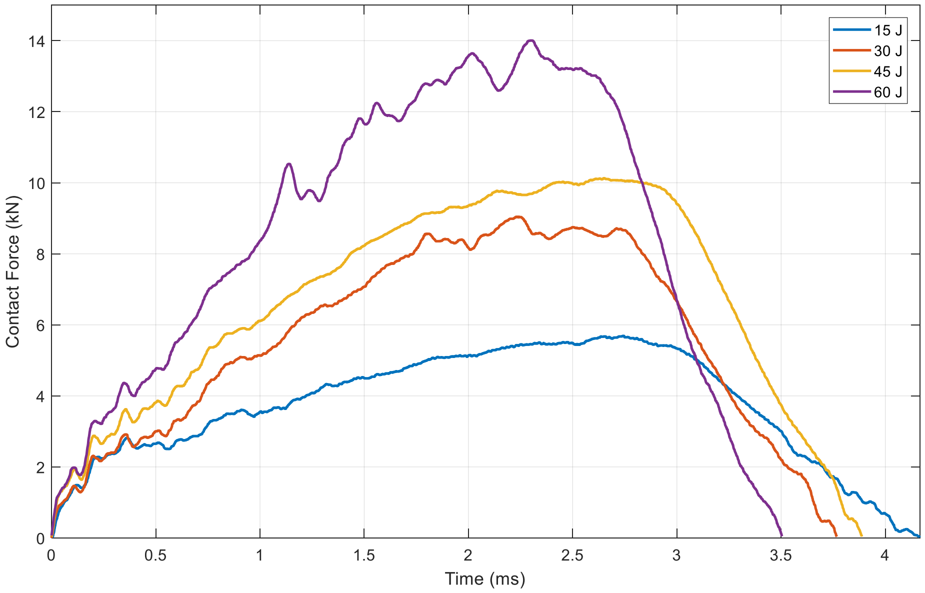


Figure 3.4. The effect of different energy levels on the contact force-time variations of the sandwich plates (Al-foam core density of 0.52 g/cm^3).

Figure 3.5 shows the Kinetic Energy-Time variations of the sandwich plates and absorbed energies by the sandwich plates with Al-foam core density of 0.52 g/cm^3 subjected to different impact energies. It is seen that almost all of the applied impact energies are absorbed by the sandwich plates in the form of plastic deformation. Namely, 14.2273J for 15J impact energy, 29.0085J for 30J impact energy, 43.483J for 45J impact energy, and 57.974J for 60J impact energy were absorbed by the sandwich plates. As a result, it is understood that the energy-absorbing capabilities of these Al-foam core sandwich plates supported by Aluminum plates are quite high and they can maintain this ability at different energy levels.

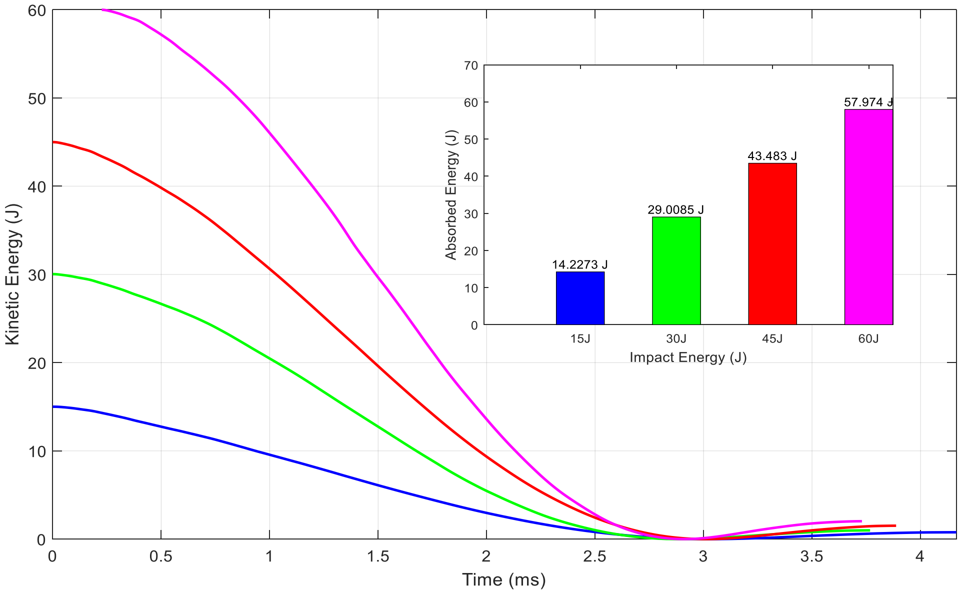


Figure 3.5. Kinetic energy-time variations and absorbed energies by the sandwich plates for different impact energies (Al-foam core density of 0.52 g/cm^3).

3.3. Effect of Al-Foam Core Density

In this section, the effect of different Al-foam core densities on the impact behaviors of sandwich plates with aluminium foam cores was investigated. Sandwich plates produced with foam materials with three different Al-core densities (0.37, 0.52, and 0.70 g/cm^3) were subjected to impact with 45J impact energy.

The contact force-time and kinetic energy-time graphs and the front and cross-sectional images of the permanent deformations after impact are shown in Fig. 3.6. The peak contact force became 9.843 kN, while the contact time was 2.774 ms for the sandwich plate with an Al-foam core density of 0.37 g/cm^3. In this plate configuration, the through-thickness experimental permanent displacement was measured as 6.6 mm and absorbed energy by the sandwich plate as 43.621J. For the sandwich plate having an Al-foam core density of 0.52 g/cm^3, the peak contact force was obtained as 10.130 kN at the contact time was 2.651 ms. While the energy absorbed by the sandwich plate was 43.483J, the after impact permanent deformation of the sandwich plate was determined as 6.1 mm. For the experiments with the sandwich plate having an Al-foam core density of 0.70 g/cm^3, the peak contact force was determined as 12.759 kN when the contact time was 2.374 ms. The permanent deformation measured in the impact region was measured as 5.5 mm, and the absorbed energy by the sandwich plate was 43.771J.

It was observed that the peak contact forces in the sandwich plates increased with the increase in the density of the Al-foam core, while the permanent deformations in the impact area decreased (Fig. 3.6).

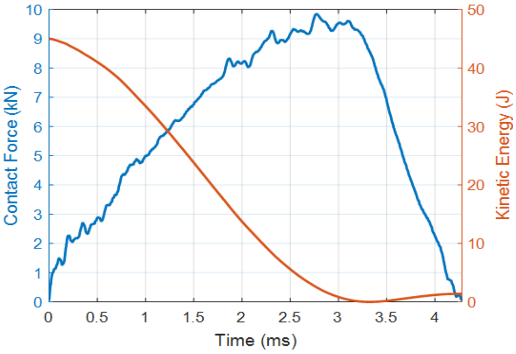
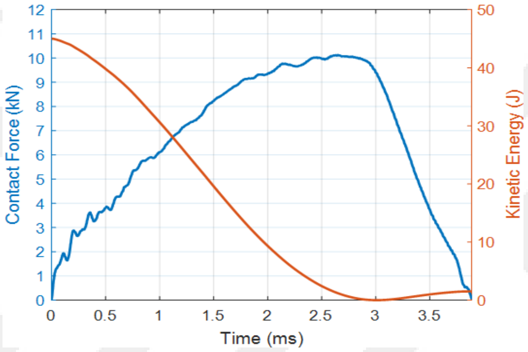
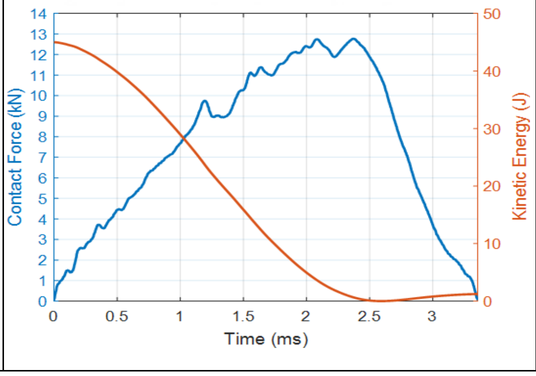
Al-foam density, g/cm^3	Impact Energy: 45J	
0.37		
0.52		
0.70		

Figure 3.6. The contact force-time and kinetic energy-time graphs, and the front and cross-sectional images of the permanent deformations after impact tests (impact energy of 45J).

Figure 3.7 shows the effect of different Al-foam core densities on the contact force-time variations of the sandwich plates. It is seen that the peak contact forces increase and the contact durations decrease with increasing density of the Al-foam core. As can be seen from the graphics, the impact energies were absorbed in the form of plastic deformation without any damage to the plates at an applied energy level of 45J.

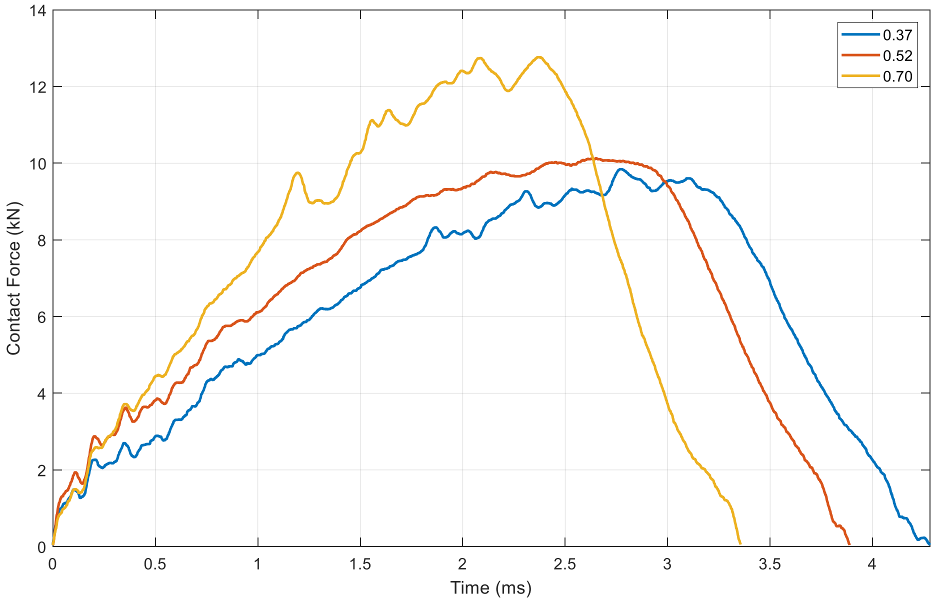


Figure 3.7. The effect of different Al-foam core densities on the contact force-time variations of the sandwich plates (Impact energy of 45J).

Figure 3.8 shows the Kinetic Energy-Time variations of the sandwich plates and absorbed energies by the sandwich plates with three different Al-foam core densities such as 0.37, 0.52, and 0.70 g/cm^3 subjected to impact energy of 45J. It was observed that the energies absorbed by the sandwich plates with different Al-core densities exposed to the same impact energy are at almost the same levels. It is clear that while the absorbed energies by the structures remain the same, they have different permanent deformations in their response to impact. That is, the permanent deformations in the impact region decreased with increasing Al-foam core density.

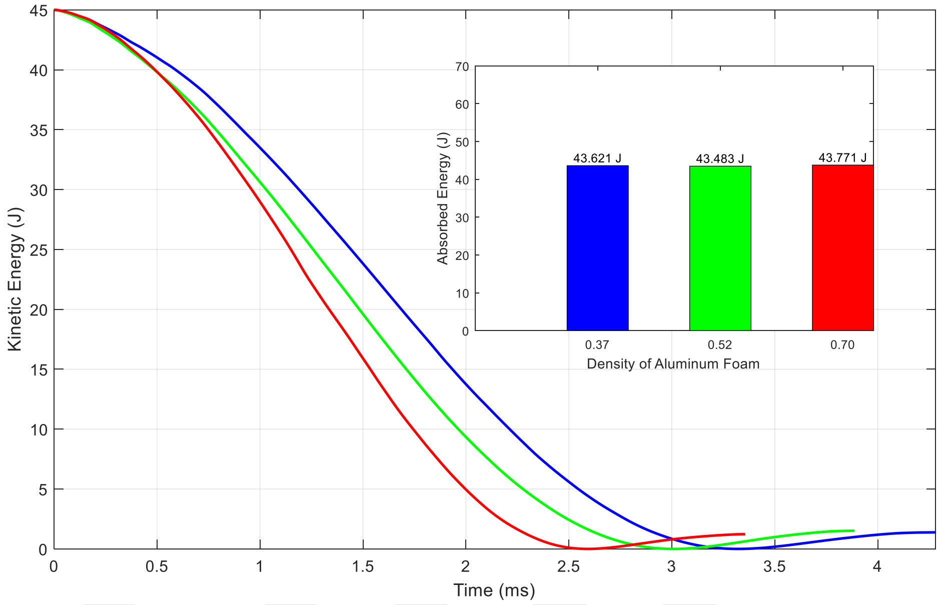


Figure 3.8. Kinetic energy-time variations and absorbed energies by the sandwich plates for different Al-foam core densities (Impact energy of 45J).

CHAPTER FOUR

CONCLUSIONS AND FUTURE WORKS

4.1. Conclusions

In this thesis study, the low-velocity impact behaviors of Aluminum sandwich plates with Al-foam core having three different densities such as 0.37, 0.52, and 0.70 g/cm^3 were experimentally investigated. Impact tests were carried out for each specimen at four different energy levels, such as 15, 30, 45, and 60J. Thus, the effects of Al-foam density and impact energy on the impact behavior of Aluminum sandwich plates with Al-foam core were examined in detail.

The conclusions drawn from the findings and suggestions that can be made in the light of these results are given below:

- Increasing impact energy levels cause the peak contact forces to increase and the contact durations to decrease.

- It was observed that the permanent deformations of sandwich plates with all three Al-core densities increased with increasing impact energy.

- For the 60J impact tests, the sandwich plate with a density of 0.37 g/cm^3 was damaged, while the sandwich plates with a core density of 0.52 and 0.70 g/cm^3 were not damaged.

- The applied impact energies were absorbed by the sandwich plates in the form of plastic deformation. The energy absorption capability of Al-foam core sandwich plates supported by aluminum face sheets is quite high and can maintain this capability at different energy levels.

- The peak contact forces increase and the contact durations decrease with increasing density of the Al-foam core.

- The permanent deformations in the impact region decreased with increasing Al-foam core density.

- The applied energies were absorbed in the form of plastic deformation without any damage to the sandwich plates up to the 45J energy level.

- The absorbed energies by the sandwich plates with different Al-core densities exposed to the same impact energy are at almost the same levels. It is clear that while the absorbed energies by the structures remain the same, they have different permanent deformations in their response to impact.

4.2. Future Works and Recommendations

In addition to the research carried out in this thesis, the following suggestions were made for future research:

- The effects of the thickness of the surface plates and Al-foam core on the impact behavior of sandwich plates can be investigated.

- Low-velocity impact behavior of sandwich structures with composite surface plates can be investigated.

- The effects of impactor tip geometry (flat, spherical, conical, etc.) on the impact behavior of sandwich plates can be investigated.

- Impact behavior of sandwich plates under different temperature conditions (hot or cold) can be investigated.

- The effect of the type of connection (bonding, brazing, etc.) between the surface plates and the foam core on the impact behavior of sandwich plates can be investigated.

- The ballistic impact behavior of such sandwich structures can be investigated.

REFERENCES

[1] S.-W. Lee and C. T. Sun, 1993. “Dynamic penetration of graphite/epoxy laminates impacted by a blunt-ended projectile,” **Compos. Sci. Technol., vol. 49**, no. 4, pp. 369–380.

[2] J. Banhart, 2001. “Manufacture, characterisation and application of cellular metals and metal foams,” **Progress in Materials Science, vol. 46**, no. 6. Pergamon, pp. 559–632, Jan. 01, 2001, doi: 10.1016/S0079-6425(00)00002-5.

[3] T. R. Neu, P. H. Kamm, N. von der Eltz, H. W. Seeliger, J. Banhart, and F. García-Moreno, 2021. “Correlation between foam structure and mechanical performance of aluminium foam sandwich panels,” **Mater. Sci. Eng. A, vol. 800,** p. 140260, Jan. doi: 10.1016/j.msea.2020.140260.

[4] R. Gunes and K. Arslan, 2016. “Development of numerical realistic model for predicting low-velocity impact response of aluminium honeycomb sandwich structures,” **J. Sandw. Struct. Mater., vol. 18**, no. 1, pp. 95–112, Jan. doi: 10.1177/1099636215603047.

[5] O. Mocian, D. M. Constantinescu, M. Sandu, and S. Sorohan, 2018. “Experimental and numerical analyses of the impact response of lightweight sandwich panels,” **Mater. Today Proc., vol. 5**, no. 13, pp. 26634–26641, 2018, doi: 10.1016/j.matpr. 08.128.

[6] F. C. Campbell, 2003. *Manufacturing Processes for Advanced Composites*. Elsevier Inc.,.

[7] K. B. Shin, J. Y. Lee, and S. H. Cho, “An experimental study of low-velocity impact responses of sandwich panels for Korean low floor bus,” **Compos. Struct., vol. 84**, no. 3, pp. 228–240, Jul., doi: 10.1016/j.compstruct.2007.08.002.

[8] S. Ferraris and L. M. Volpone, 2005. “Aluminum alloys in third millennium shipbuilding: materials, technologies, persepectives,” **5th Int. Forum Alum. Ships**, pp. 1–10.

[9] V. Crupi, G. Epasto, and E. Guglielmino, 2013. “Comparison of aluminium sandwiches for lightweight ship structures: Honeycomb vs. foam,” **Mar. Struct., vol. 30**, pp. 74–96, doi: 10.1016/j.marstruc.2012.11.002.

[10] J. Banhart, C. Schmoll, and U. Neumann, 1998. “Light-weight aluminium foam structures for ships,” in **Proceedings of the Conference on Materials in Oceanic**

Environment, , pp. 55–63.

[11] J. Baumeister, J. Banhart, and M. Weber, 1997. “Aluminium foams for transport industry,” **Mater. Des., vol. 18**, no. 4–6, pp. 217–220, , doi: 10.1016/s0261-3069(97)00050-2.

[12] J. Xiong, Y. Du, D. Mousanezhad, M. Eydani Asl, J. Norato, and A. Vaziri, 2019. “Sandwich Structures with Prismatic and Foam Cores: A Review,” **Adv. Eng. Mater., vol. 21**, no. 1, p. 1800036, doi: 10.1002/adem.

[13] J. L. Yu, E. Wang, J. Li, and Z. Zheng, 2008. “Static and low-velocity impact behavior of sandwich beams with closed-cell aluminum-foam core in three-point bending,” **Int. J. Impact Eng., vol. 35**, no. 8, pp. 885–894, doi: 10.1016/j.ijimpeng..

[14] C. Liu, Y. X. Zhang, and J. Li, 2017. “Impact responses of sandwich panels with fibre metal laminate skins and aluminium foam core,” **Compos. Struct., vol. 182**, pp. 183–190, Dec. 2017, doi: 10.1016/j.compstruct09.015.

[15] L. Jing, X. Su, De Chen, F. Yang, and L. Zhao, 2018. “Experimental and numerical study of sandwich beams with layered-gradient foam cores under low-velocity impact,” **Thin-Walled Struct., vol. 135**, pp. 227–244, Feb. 2019, doi: 10.1016/j.tws..

[16] G. Sun, E. Wang, H. Wang, Z. Xiao, and Q. Li, 2018. “Low-velocity impact behaviour of sandwich panels with homogeneous and stepwise graded foam cores,” **Mater. Des., vol. 160**, pp. 1117–1136, Dec. 2018, doi: 10.1016/j.matdes.

[17] K. Mohan, T. H. Yip, S. Idapalapati, and Z. Chen, 2011. “Impact response of aluminum foam core sandwich structures,” **Mater. Sci. Eng. A, vol. 529**, no. 1, pp. 94–101, Nov. 2011, doi: 10.1016/j.msea..

[18] Y. Hangai, N. Kubota, T. Utsunomiya, and H. Kawashima, 2015. “Materials Science & Engineering A Drop weight impact behavior of functionally graded aluminum foam consisting of A1050 and A6061 aluminum alloys,” **Mater. Sci. Eng. A, vol. 639**, pp. 597–603, 2015, doi: 10.1016/j.msea.

[19] E. Tang, X. Zhang, and Y. Han, 2019. “Experimental research on damage characteristics of CFRP/aluminum foam sandwich structure subjected to high velocity impact,” **J. Mater. Res. Technol., vol. 8**, no. 5, pp. 4620–4630, Sep. 2019, doi: 10.1016/j.jmrt..

[20] C. Lin and M. S. H. Fatt, 2005. “Perforation of Sandwich Panels with Honeycomb Cores

by Hemispherical Nose Projectiles," **J. Sandw. Struct. Mater., vol. 7**, no. 2, pp. 133–172, Mar. doi: 10.1177/1099636205048369.

[21] C. C. Foo, L. K. Seah, and G. B. Chai, 2007. "Low-velocity impact failure of aluminium honeycomb sandwich panels," **Compos. Struct., vol. 85**, no. 1, pp. 20–28, Sep. 2008, doi: 10.1016/j.compstruct..

[22] C. C. Foo, G. B. Chai, and L. K. Seah, 2007. "A model to predict low-velocity impact response and damage in sandwich composites," **Compos. Sci. Technol., vol. 68**, no. 6, pp. 1348–1356, May 2008, doi: 10.1016/j.compscitech.

[23] J. Y. Lee, K. B. Shin, and J. C. Jeong, 2009. "Experimental and numerical simulation studies of low-velocity impact responses on sandwich panels for a BIMODAL tram," **Adv. Compos. Mater., vol. 18**, no. 1, pp. 1–20, Feb., doi: 10.1163/156855108X385311.

[24] P. Griškevičius, D. Zeleniakienė, V. Leišis, and M. Ostrowski, 2010. "Experimental and Numerical Study of Impact Energy Absorption of Safety Important Honeycomb Core Sandwich Structures",.

[25] I. T. Lee, Y. Shi, A. M. Afsar, Y. Ochi, S. I. Bae, and J. I. Song, 2010. "Low velocity impact behavior of aluminum honeycomb structures," **Adv. Compos. Mater., vol. 19**, no. 1, pp. 19–39, doi: 10.1163/156855109X434810.

[26] R. S. Sharma, V. P. Raghupathy and G. M. Priyamvada, 2011. Investigation of low velocity impact response of aluminium honeycomb sandwich panels, APRN **J. Eng. Appl. Sci., 6,** 7-14.

[27] R. Butukuri, V. Bheemreddy, K. Chandrashekhara, and V. Samaranayake, 2012. "Evaluation of low-velocity impact response of honeycomb sandwich structures using factorial-based design of experiments," **J. Sandw. Struct. Mater., vol. 14**, no. 3, pp. 339–361, doi: 10.1177/1099636212442667.

[28] A. Manes, A. Gilioli, C. Sbarufatti, and M. Giglio, 2012. "Experimental and numerical investigations of low velocity impact on sandwich panels," **Compos. Struct., vol. 99**, pp. 8–18, May 2013, doi: 10.1016/j.compstruct.

[29] C. Menna, A. Zinno, D. Asprone, and A. Prota, 2013. "Numerical assessment of the impact behavior of honeycomb sandwich structures," **Compos. Struct., 106**, pp. 326–339, Dec. 2013, doi: 10.1016/j.compstruct.

[30] Y. Hangai, N. Kubota, T. Utsunomiya, H. Kawashima, O. Kuwazuru, and N. Yoshikawa, 2015. “Drop weight impact behavior of functionally graded aluminum foam consisting of A1050 and A6061 aluminum alloys,” **Mater. Sci. Eng. A, vol. 639**, pp. 597–603, doi: 10.1016/j.msea.2015.05.007.

[31] A. Kolopp, R. A. Alvarado, S. Rivallant, and C. Bouvet, “Modeling impact on aluminium sandwich including velocity effects in honeycomb core,” **J. Sandw. Struct. Mater., vol. 15**, no. 6, pp. 733–757, doi: 10.1177/1099636213501102.

[32] I. Ivañez and S. Sanchez-Saez, 2013. “Numerical modelling of the low-velocity impact response of composite sandwich beams with honeycomb core,” **Compos. Struct., vol. 106**, pp. 716–723, doi: 10.1016/j.compstruct.2013.07.025.

[33] V. Crupi, G. Epasto, E. Guglielmino, H. Mozafari, and S. Najafian, 2014. “Computed tomography-based reconstruction and finite element modelling of honeycomb sandwiches under low-velocity impacts,” **J. Sandw. Struct. Mater., vol. 16**, no. 4, pp. 377–397, doi: 10.1177/1099636214531515.

[34] V. Crupi, G. Epasto, and E. Guglielmino, 2011. “Collapse modes in aluminium honeycomb sandwich panels under bending and impact loading,” **Int. J. Impact Eng., vol. 43**, pp. 6–15, May 2012, doi: 10.1016/j.ijimpeng.

CURRICULUM VITAE

PERSONAL DATA

Name and Surename : Noor Saad JASIM
Nationality : Iraqi (IQ)

Degree graduation	**Institute**	**Date of**
MSc	Erciyes University, Graduate School of Natural and Applied Sciences	2022
Bachelor's	North Technical University - Technical College of Kirkuk	2016
High School	Al-Shaahba High school	2010

LANGUAGES

Arabic, English, Turkish