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Investigation of the Compressive Strength, Energy Absorption Properties and Deformation Modes of the Reinforced Core Cell Produced by the FDM Method

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ABSTRACT

Keywords: Additive manufacturing, core structure, honeycomb core, mechanical performance, compression testing.

Sandwich panels are used in many sectors that require structural weight savings such as defence, aviation and automotive industry. The most important factor over the mechanical strength of sandwich panels is the core design. The core design of sandwich panels with periodic cells is formed by repetitive production of the unit cell geometry. In this study; the compressive strength of the developed reinforced core cell was experimentally investigated under quasi-static compression load, and the test results were compared with the conventional honeycomb core. Experimental test samples were carried out by Fused Deposition Modeling (FDM) using PLA filament material. When the experimental test results for two different core designs were compared, it was determined that the reinforced core cell produced at 20% filling rate increased the maximum crushing resistance of the core by 28.54% and the energy absorbing capacity by 23.4%. According to the observed deformation behaviours, it was determined that the reinforced core cell kept the deformation load on the core axis during the compression test and delayed the core wall buckling. In addition, it was determined that the filling rate determined during production was effective on the deformation of the core and compression strength.

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FDM Yöntemi ile Üretilen Güçlendirilmiş Çekirdek Hücrelerin Basınç Dayanımı, Enerji Sönümleme Özellikleri ve Deformasyon Modlarının İncelenmesi

ÖZET

Sandviç paneller savunma sanayisi, havacılık ve otomotiv gibi yapısal ağırlık tasarrufu gerektiren birçok alanda kullanılmaktadır. Sandviç panellerin mekanik performansı büyük oranda çekirdek tasarımından etkilenmektedir. Periyodik hücrelere sahip sandviç panellerin çekirdek tasarımı ise birim hücre geometrisinin tekrarlı olarak üretilmesi ile oluşturulmaktadır. Bu çalışmada; geliştirilen güçlendirilmiş çekirdek hücrenin basma mukavemeti yarı statik basma yükü altında deneysel olarak incelenmiş, test sonuçları geleneksel bal peteği çekirdek ile karşılaştırılmıştır. Deneysel test numuneleri Eklemeli İmalat Yöntemi ile PLA Filament kullanılarak gerçekleştirilmiştir. İki farklı çekirdek tasarımı için deneysel test sonuçları kıyaslandığında, %20 doluluk oranında üretilen güçlendirilmiş çekirdek hücrenin, çekirdeğin maksimum ezilme direncini %28.54 oranında, enerji sönümleme kapasitesini ise %23.4 oranında arttırdığı tespit edilmiştir. Çekirdeklerin deformasyon davranışları incelendiğinde, güçlendirilmiş çekirdek hücrenin basma testi sırasında deformasyon yükünü çekirdek ekseninde tutuğu, duvar ayrılmasını geciktirdiği tespit edilmiştir. Ayrıca üretim esnasında belirlenen doluluk oranının çekirdeğin deformasyonu ve sıkışma direnci üzerinde etkili olduğu belirlenmiştir.

Anahtar Kelimeler: Eklemeli imalat, çekirdek yapısı, balpeteği çekirdek, mekanik performans, sıkıştırma testi

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1. Introduction

The design and functionality of engineering materials have been one of the important issues that researchers have focused on for centuries. With the developing production technologies, the usage areas of engineering materials with different properties have increased even more. New structural components with advanced features are used in the design and production of transportation vehicles such as airplanes, high-speed trains and automotive, and even satellites [1]. In the design of these components, low density and weight as well as high mechanical strength factors are taken into account. Moreover, the contribution of easy manufacturability and sustainable materials to the design is important.

With the development of three-dimensional printers, it has become possible to produce parts with complex geometries. The additive manufacturing method, which is a much faster and cheaper production technique compared to traditional production methods, is being used in more and more areas [2, 3, 4]. The fact that the production parameters can be easily changed also brings many advantages in terms of optimization studies. Depending on the usage areas of the products to be developed, researchers can use filaments produced from different materials and optimize the weight or mechanical strength of the product in accordance with the preferences [4, 5]. In addition, it can be said that the additive manufacturing technique, which does not create waste during production, minimizes the negative environmental effects. This flexible production technique has become an increasingly popular subject in academic studies due to the advantages it provides.

Optimization of engineering designs aims to reveal the most efficient design by optimizing parameters such as mechanical strength, weight, production time and cost. Structural weight was the most important factor affecting the energy consumption of light transportation systems and thus carbon dioxide emissions [6, 7]. For this reason, while increasing the structural mechanical strength, other parameters should be optimized at certain rates.

When the studies in the related literature are examined, it is seen that instead of increasing the material thickness in order to save weight while increasing the strength of the structural components, the use of sandwich panels as body components in the structural design is recommended [8-10]. Sandwich structures consist of two thin surface plates separated by a core structure. Although sandwich panels have low weight, they have high crush resistance and bending strength [11]. Surface plates are usually produced using aluminium and its alloys, steels, titanium and composite materials [12]. The core design of the sandwich structure is one of the most important factors affecting the mechanical performance under different loads [13, 14]. For this reason, studies on the mechanical performance of sandwich panels generally focus on core design [19]. It is stated that the mechanical properties of sandwich structures are mainly affected by three factors: density of the core, material properties and core geometry [15]. Many types of periodic core structures, often defined as cellular structures, have been proposed and developed to further improve the mechanical properties of sandwich structures [16, 17].

Although different core geometries are used in sandwich structures, one of the most used core structures is honeycomb cells with hexagonal geometry [8]. Sandwich structures with honeycomb core are preferred due to their high energy absorption capacity, lightness, high shear and compression stiffness, sound insulation and high corrosion resistance [18-20]. The honeycomb core structure consists of periodic core unit cells similar to the corrugated core, but unlike the corrugated core structure, about 90-99 percent of the cores consist of open spaces [21]. It is observed in the studies in the literature that the hexagonal honeycomb core dimensions determine the density of the sandwich structure and in this direction, the cell density is increased in order to obtain more durable structures [22]. In order to benefit from the mechanical advantages of hexagonal honeycomb core structures in different areas, it is important to understand the mechanical properties of these structures. Compression, bending, impact and tensile tests are the most commonly used methods for determining the mechanical properties of core structures.

Crupid et al., in their study, examined the mechanical properties of the panels by applying bending and impact tests to aluminum honeycomb sandwich panels. They observed that the energy absorption capacity of the sandwich panel was strongly influenced by the size of the honeycomb cells [23]. Aktay et al. applied experimental tests to composite sandwich panels and stated that core deformation is the determining factor for the energy absorption capacity of sandwich panels [24]. Wu and Jiang focused on investigating the compression behavior of hexagonal honeycomb structures under static and dynamic loading conditions. For higher energy dissipation under quasi-static loading conditions, they recommended the use of honeycomb structures made of high-strength material with small cell size and low core height [25]. Yamashita and Gotoh investigated the effect of cell shape and honeycomb cell wall thickness on crushing behavior by examining the quasi-static compression response of aluminium honeycomb structures. Experimental test results showed that the damage occurred in all cases, the crushing strength was higher for smaller cell angle, and also the effect of honeycomb thickness on crushing strength [26]. In order to determine the damage types and mechanical properties, bending tests were performed on sandwich structures with hexagonal honeycomb cores and it was determined that the damage occurred when the surface plate exceeded the mechanical strengths [27]. In another study, the researchers examined the behavior of sandwich panels under quasi-static compression load and stated that the cores have high energy absorption ability and crushing force [28]. When the literature studies were evaluated, it was determined that the mechanical properties of cores with honeycomb geometry depend on their relative density, cell geometry and elastic modulus. In addition, more experimental studies are needed to determine the deformation failure modes of hexagonal honeycomb core sandwich panel cores.

In this study, a new core cell design was developed to examine and improve the effect of core design on the mechanical strength of the sandwich panel. For this purpose, an experimental study was conducted to examine the mechanical properties and damage modes of hexagonal honeycomb core structures produced using additive manufacturing technology under compression force. In experimental studies, the effect of core design on mechanical strength was compared by using samples with traditional honeycomb core design and reinforced core design.

In this study, an experimental study was carried out to examine and improve the effect of core design on the mechanical strength of the sandwich panel. For this purpose, an experimental study was conducted to examine the mechanical properties and deformation modes of hexagonal honeycomb core structures produced using additive manufacturing technology under compression force. In experimental studies, the effect of core design on mechanical strength was compared by using samples with traditional honeycomb core design and reinforced core design.

2. Material and Method

In order to increase the mechanical strength of the hexagonal honeycomb core structure under axial compression load, reinforced core cell was used. The reinforced core cell has conical support bars to increase the mechanical strength of the cell walls and maintain cell integrity during deformation.

The reinforced core unit cell design and the full cross-sectional view of the cell components are given in Figure 1. Conical support bars aim to provide load transfer under crushing load by connecting to the cell walls. The transfer filler will connect the surface and core cells both when connecting the tapered support bars and when using surface plates for sandwich panels.

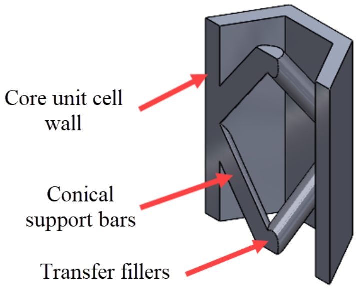
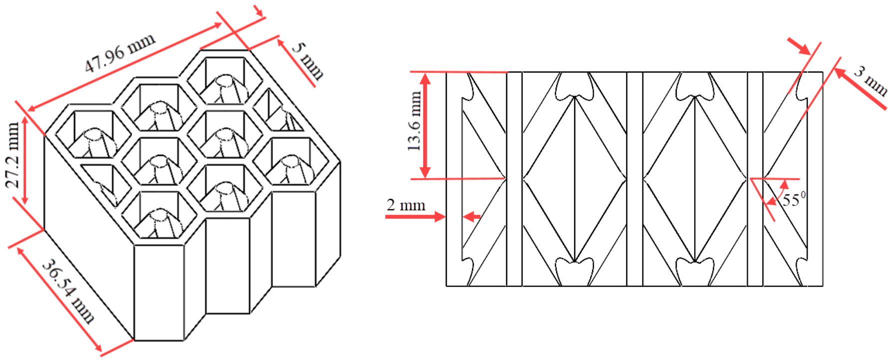


Figure 1. Reinforced core unit cell design

In order to experimentally determine the mechanical performance of the core cell design, three-dimensional solid models of honeycomb (HC) and reinforced core cell (RC) samples consisting of 3x3 unit cells were created using solid modelling software. The core dimensions are 27.2 x 46.54 x 47.96 mm, the cell wall thickness is 2 mm, and the outer circumference diameter of the hexagonal unit cell is

20 mm. The diameter of the conical support bars of the HC and RC samples is 3 mm (Figure 2). The conical support bars in the cores of the HC and RC samples are designed to make an angle of 55° from the base plane. The isometric and top views of the core cell models are given in Figure 3.



(a) (b)

Figure 2. Dimensions of the sandwich panel core: a) isometric view, b) full section view

Hexagonal honeycomb cores, whose solid models were prepared, were sliced and converted into STL format. The production of the cores was carried out on the Creality Ender 3 branded 3D printer using the Fused Deposition Modeling (FDM) method (Figure 4). PLA (Polylactic acid) filament was used in the production of the samples, and three of each sample were produced. The properties of the PLA filament material supplied by the supplier were given in Table 1.

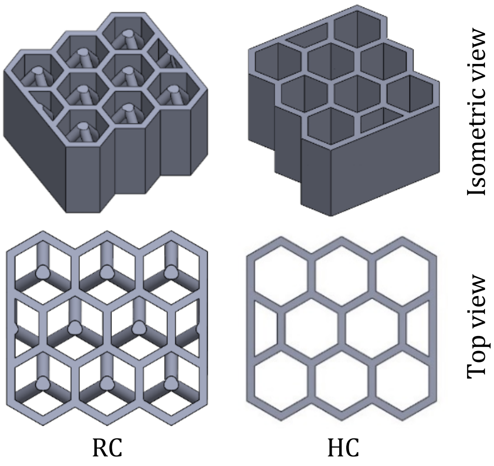


Figure 3. Images of core solid models

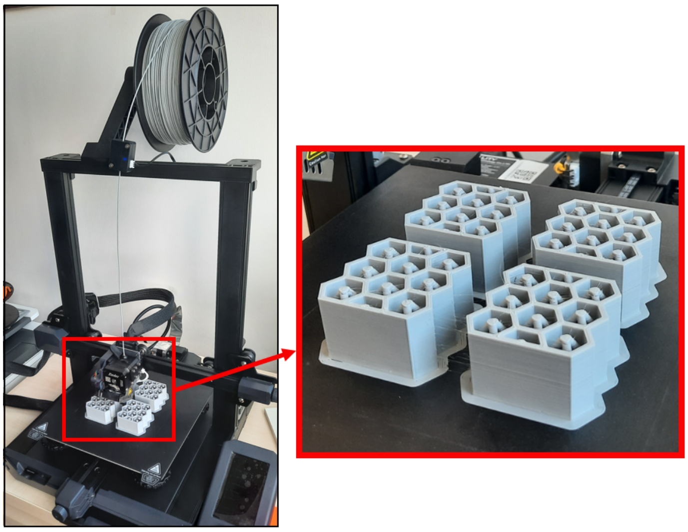


Figure 4. Production of samples with a 3D printer

Table 1. Technical properties of PLA filament

Material	Colour	Diameter	Density (kg/m3)	Elasticity modulus (MPa)	Tensile strength (MPa)	Elongation at break (%)
PLA	Grey	1.75	1240	1500	50	7

In determining the printing temperatures for the production of the samples, the brochure information of the PLA material manufacturer was taken as reference, the nozzle temperature was determined as 220 °C and the table temperature 70 °C. Productions were carried out at room temperature. A single filament material from the same package was used for the production of all samples. The samples consist of 227 layers. The printing parameters used in the production of the experimental samples are given in Table 2.

Table 2. Printing parameters used in the production of samples

Parameter	Value
Nozzle diameter (mm)	0.40
Nozzle temperature (°C)	220
Bad temperature (°C)	70
Layer height (mm)	0.12
Print speed (mm/min)	50
Fill rate (%)	20
Filament diameter (mm)	1.75
Fill geometry	Lines
3d printer brand	Creality Ender 3 S1
Production method	FDM

The weights of the experimental test samples, three of which were produced for each core design, were weighed with a Precision brand precision balance, and the results are given in Table 3.

Table 3. Weight values of samples

Sample type	Average weight (gr)	Average weight difference (%)
HC	19.40	20.77
RC	23.43	

In this study, it is aimed to compare the mechanical properties of the weakest cell wall and core designs by producing with the lowest compression density. While low fill rate saves weight, it can cause negative effects on mechanical strength. Therefore, the effect of fill rate on mechanical strength should be examined. Figure 5 shows the gaps in the core cell walls produced with 20% fill rate.

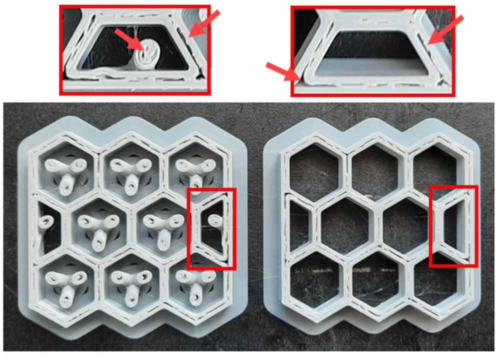
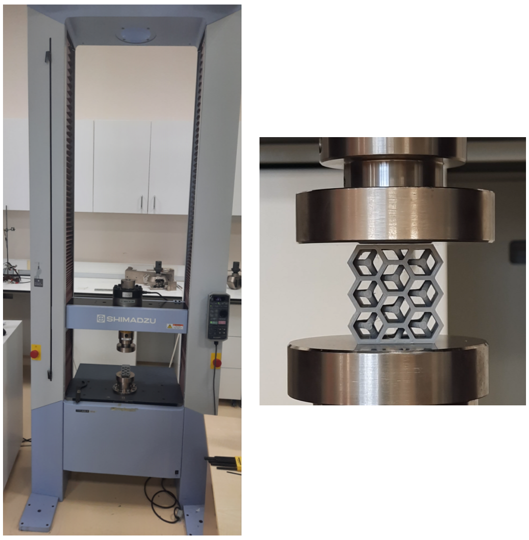


Figure 5. The gaps in the internal structure of the samples produced with 20% fill rate

In order to determine the compression strength of cores with different geometries and to observe the deformation under compression load, quasi-static compression tests were applied to the samples. The tests were carried out in the Shimadzu Autograph AGS-X 100 KN capacity compression device in Kastamonu University Central Research Laboratory at a compression speed of 1 mm/s and in accordance with ASTM C365/365M standards.

Honeycomb core geometry show high strength to vertical loads because their cell walls are difficult to fold, but they are weaker to lateral loads. For this reason, in the experiments carried out, the samples were placed in the test device in a horizontal position (Figure 6b). Thus, it is aimed to evaluate the contribution of conical support bars to lateral deformation. Experiments were repeated three times for each type of sample to ensure experimental accuracy. The compression test was continued until fracture occurred in the samples. As a result of the experiments, force-displacement graphs of the samples were obtained. The images of the samples placed on the test setup and compression test device are given in Figure 6a.



a) b)

Figure 6. a) Compression test setup, b) placement of samples

3. Experimental Findings

3.1. Investigation of the effect of core design on compression strength

During the compression tests, the deformation changes of the core samples were recorded with a camera, while the force-displacement curves of the samples were measured by the load and displacement sensors connected to the compression test device. The deformation modes in the samples are given in Figure 7.

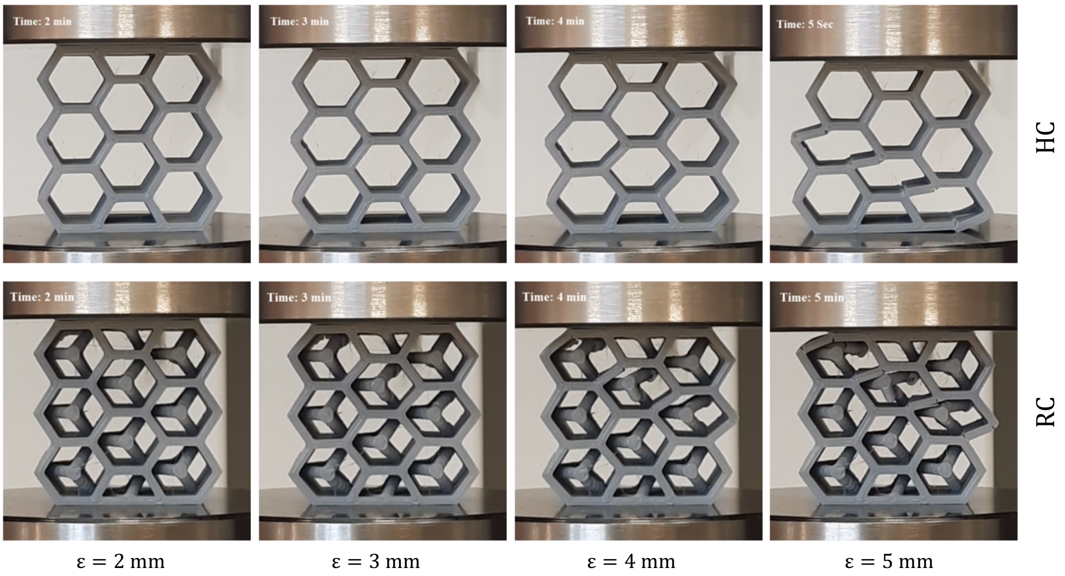


Figure 7. Deformation modes in the samples

As a result of the experimental study, force-displacement curves of hexagonal honeycomb cores with different core designs were obtained. Mechanical performance of hexagonal honeycomb cores; the maximum crushing force (F_{maks}) and the total energy absorbed (SE) were evaluated over the performance criteria. Maximum crush strength is the maximum strength of the core against compression load.

Absorbed energy is the amount of energy that the core absorbs by undergoing plastic deformation against the impact load. Maximum crushing force and total absorbed energy values are widely used parameters in the academic literature to evaluate the mechanical performance of structures [29]. The force-displacements curves obtained as a result of the compression test of HC and RC samples are given in Figure 8.

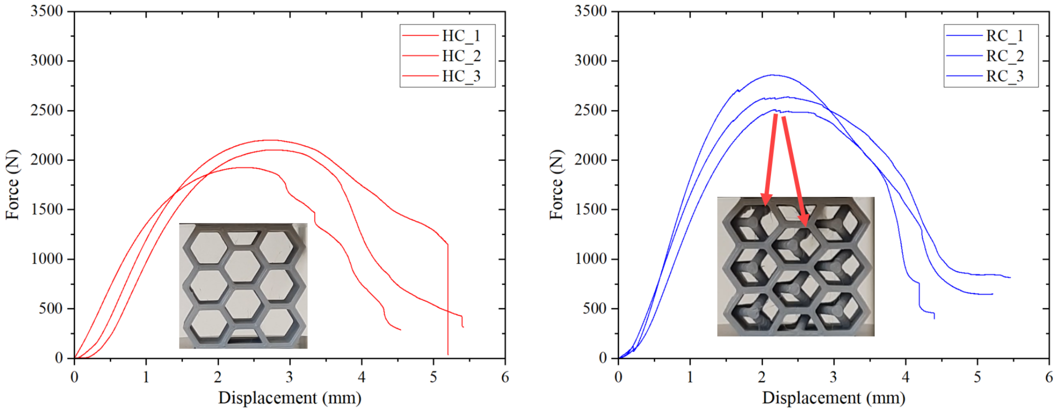


Figure 8. Force - displacements curves of core samples

When the force - displacements curves and maximum crush force values of HC and RC samples with hexagonal honeycomb core structure are examined, it is revealed that the conical support bars added to the cell walls increase the crushing strength of the cell. Average F_{maks} values of cores are given in Table 4.

Table 4. Average maximum crushing force values of the samples

Core Type	**Average F_{maks} (N)**	**Difference ratio (%)**
HC	2076.87	28.54
RC	2669.79	

While the hexagonal honeycomb HC sample had a maximum strength of 2076.87 N, the crushing resistance of the reinforced core unit cell increased up to 2669.79 N. This increase indicates that the compressive load strength has increased by approximately 28%. Conical support bars increased the axial deformation resistance by allowing the cell walls to move as a whole.

According to the force-displacement curves of the RC samples, it is seen that the force value fluctuates just before the maximum crushing strength is reached. This fluctuation was caused by the formation of high mechanical strength -induced cracks in the conical support bars during deformation (Figure 8). Studies in the academic literature have shown that printing parameters under loading conditions, as well as load range and frequency, can affect crack formation in samples [30].

The integral of the area under the force-strain curve gives the total energy absorbed through a specific crushing distance (d) by the samples. Equation 1 is used to calculate the amount of energy absorbed by the samples. Calculated absorbed energy values are given in Table 5. Compared to the conventional HC sample, the RC sample absorbs approximately 23.4% more compression force.

$$SE = \int_{0}^{d_{maks}} F(\delta) d\delta \qquad (1)$$

where d is crushing distance and $F(\delta)$ is the instantaneous force at displacement δ.

Table 5. Absorbed energy values

Core Type	Average Absorbed Energy (J)	Difference ratio (%)
HC	6881.27	23.4
RC	8491.12	

3.2. Investigation of the effect of core design on deformation modes

Although hexagonal honeycomb cores show high resistance to vertical loads applied along the cell walls, they are more sensitive to horizontal loads. Horizontal loads force the cell walls to fold. In this study, conical support bars added to the cell walls increased the crushing strength of the cores. The deformation formations of the core were observed and the deformation modes in the core were determined. In Figure 9, deformation formations occurring in HC samples produced from PLA material were given.

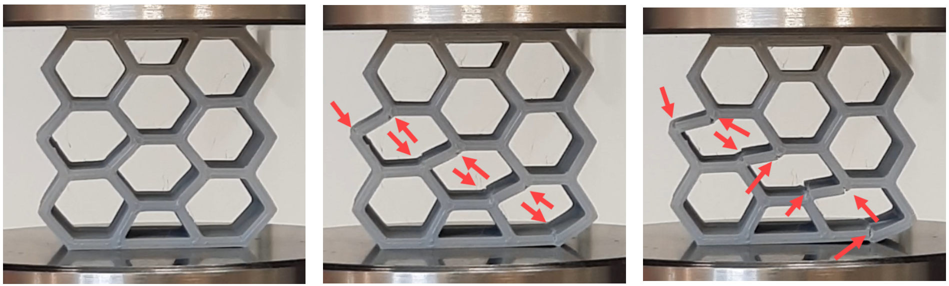

$\varepsilon = 3mm$ $\varepsilon = 4mm$ $\varepsilon = 5mm$

Figure 9. Deformation modes of the HC sample

When the effects of the compression load on the core are examined; It was determined that with the increase of the compression load, the core showed elastic behavior in the first stage and as a result, the unit cell structure began to deteriorate (Figure 9a). Studies in the literature confirm that the components produced with PLA material show elastic deformation behavior at low load values and subsequently have plastic deformation behavior after a peak load [31, 32]. As the crushing continued, cracks occurred in the layers forming the cell walls, and fractures occurred along a plane (Figure 9b). As the crushing increased, the cracked cell walls were broken and separated from the body. As the compression force reached the maximum point, a sudden break occurred as can be seen from the force-displacement curve of the HC sample (Figure 9c). Researchers revealed that the 3D-printed samples had a lower peak stress than that of the filaments and showed even lower ductility. It is thought that the sudden fractures in the core as a result of high stress are caused by the low ductility of the imprinted PLA filament [33, 34]. Thus, the deformation resistance of the cells decreased.

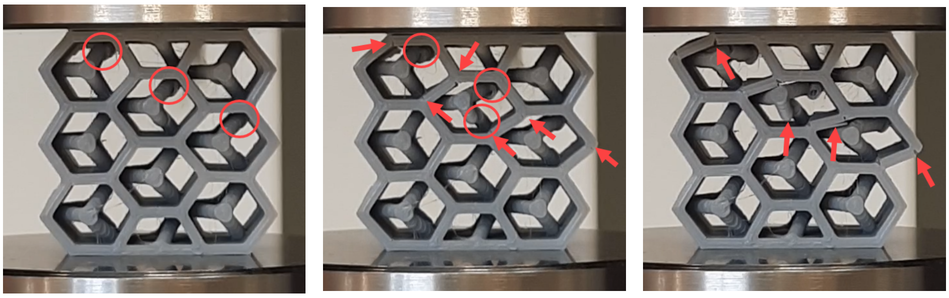

$\varepsilon = 3mm$ $\varepsilon = 4mm$ $\varepsilon = 5mm$

Figure 10. Deformation modes of the RC sample

When the deformation modes of the RC sample are examined, it is seen that the deformation first starts from the conical support bars. In the first stage of the deformation, the cell walls showed plastic deformation behaviour and with the continuation of the crushing, the conical support bars started to separate from the layer adhesion point. This behaviour caused fluctuations at the maximum point of the force-displacement curve. Also, the fractures in the conical support bars started to occur in the same direction (Figure 10a). As the deformation continued, cracks occurred in the weakened cell walls in this plane (Figure 10b). With the breakage of the conical support bars, the cell walls weakened and fractures occurred (Figure 10c).

4. Discussion and Conclusion

In this study, the mechanical performance and deformation formation of HC and RC samples produced using PLA-based hexagonal honeycomb core structure with two different core designs under compression load were investigated. As a result of the evaluated mechanical performance and deformation formations:

It has been determined that the changes made in the core design have a significant effect on the weight and mechanical behavior of the core. Conical support bars added to the core walls of the traditionally used HC design increased the core weight by an average of 20.77%.

The highest maximum compression force load was measured as 2669.79 N in the PLA-based hexagonal honeycomb RC sample, and the lowest compression force load was 2076.87 N in the HC sample. The improved RC design increased the maximum crushing strength of the cores under compression load by an average of 28.54% compared to the HC samples.
Deformations in the conical support bars caused fluctuations in the force-displacement curves of the cores.

The RC sample formed by adding conical support bars to the cell walls absorbs an average of 6881.27 J of compression energy, while the HC sample absorbs an average of 8491.12 J. The improved RC design increased the total absorbed energy value of the cores under compression load by 23.4% compared to the HC samples.

When the deformation behavior of the hexagonal honeycomb RC and HC samples under compression load was examined, it was observed that the core first underwent elastic deformation and the core cell walls expanded with the increase in compression load.

With the progression of the deformation, cracking firstly occurred in the core cell walls of the HC sample, while the onset of deformation was observed in the conical support bars of the RC sample. Fractures occurred along an axis in the cell wall. With the increase in the compression load, the cell walls broke and the core completely lost its resistance.

When the experimental test results and deformation formations are examined together, the production gaps in the cores produced with 20% filling ratio directed the deformation. Although the gaps in the middle of the conical support bars caused weakening and earlier fracture, it still increased the crushing resistance of the nucleus and delayed cell wall ruptures. Conical support bars also preserved the integrity of the core walls. The results show that the core design has an effect on the deformation behavior of the sandwich panels.

Conflict of Interest Statement

The authors declare that there is no conflict of interest.

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