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MECHANICAL PROPERTIES OF 3D PRINTED CONTINUOUS CARBON FIBER/ POLYPROPYLENE LATTICE CORE COMPOSITE SANDWICH STRUCTURE

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Abstract: The production of functional parts with 3D manufacturing techniques has started to disclose fascinating studies. Although only thermoplastic filaments were initially used, fiber-reinforced composite parts can be produced using developing techniques. This study investigated the quasi-static and dynamic mechanical performance of 3D printed continuous Carbon Fiber Reinforced (CFR) composite sandwich panels. Sandwich panels were designed with a prismatic lattice core between CFR composite facesheets. Continuous CFR Thermoplastic (Polypropylene (PP)) Monofilament Composites (CCTMC) were used to produce sandwich structures. CCTMC sandwiches were produced with a laboratory-scale production system, including thermoplastic extruder and mold designed specifically. Facesheets of sandwiches were manufactured in a hot compression mold as [0°/90°/0°] stacking sequence as three-layers using the same CCTMCs. The sandwich panels were fully recyclable and ultra-lightweight, and pyramidal-shaped truss-type lattice cores were placed as the core of the structure. Test results showed test specimens had stand ~270 kN peak force in the compression test and ~240 kN peak force in 3-point bending, and the deformation in the structure occurred when the mono composite element reached the buckling limit. In the dynamic 3-point bending, the peak force value increased approximately 2 times and reached 450 kN due to the strain-rate dependence of the material.

Keywords: Additive manufacturing, Composite materials, Lattice core structures, Mechanical properties, Sandwich structures.

3D Baskılı Sürekli Karbon Fiber / Polipropilen Kafes Çekirdekli Kompozit Sandviç Yapının Mekanik Özellikleri

Öz: 3Boyutlu üretim teknikleriyle fonksiyonel parçaların üretimi üzerine ilgi çekici çalışmalar ortaya konmaya başlamıştır. Başlangıçta sadece termoplastik filamentler kullanılmasına rağmen gelişen teknolojiler sayesinde elyaf takviyeli kompozit parçalar da üretilebilmektedir. Bu çalışmada, 3Boyutlu baskılama ile üretilmiş sürekli karbon elyaf takviyeli (CFR) kompozit sandviç panellerin yarı-statik ve dinamik yüklemeler altındaki mekanik performansı deneysel olarak incelenmiştir. Sandviç paneller, CFR kompozit yüzey levhaları arasında prizmatik kafes çekirdek olacak şekilde tasarlanmıştır. Sandviç yapıları üretmek için sürekli CFR termoplastik (polipropilen (PP)) monofilament kompozitler (CCTMC) kullanılmıştır. CCTMC sandviç yapıları, özel olarak tasarlanmış bir kalıp içeren laboratuvar ölçekli bir termoplastik ekstrüder sistemi ile üretilmiştir. Sandviçlerin yüzey levhaları, aynı CCTMC'ler kullanılarak üç katman halinde [0°/90°/0°] istifleme sırasına göre sıcak sıkıştırma kalıbında üretilmiştir. Geliştirilen

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sandviç paneller tamamen geri dönüştürülebilir ve ultra hafiftir ve piramit şeklindeki kafes tipi kafes çekirdekleri sandviç yapının çekirdeği olarak yerleştirilmiştir. Test sonuçları; test numunelerinin basınç testinde 270 kN maksimum kuvvetine ve 3 nokta eğilme testinde de 240 kN maksimum kuvvetine dayanabildiğini göstermiş ve yapıdaki deformasyonun mono kompozit elemanın burkulma sınırına ulaşmasıyla meydana geldiğini ortaya koymuştur. Dinamik 3 nokta eğilme testinde, malzemenin deformasyon hızına bağımlılığı nedeniyle tepe kuvvet değeri yaklaşık 2 kat artarak 450 kN değerine ulaşmıştır.

Anahtar Kelimeler: Eklemeli üretim, Kompozit malzeme, Kafes çekirdek yapı, Mekanik özellikler, Sandviç yapılar

1. INTRODUCTION

Fiber Reinforced Composites (FRC) have gained an important place in many fields due to their excellent mechanical, physical, and chemical properties (Stephon et al., 2021; Yang et al., 2019; Li et al., 2023). If the matrix material used in the structure of the composite consists of a thermoplastic polymer, recyclability is added to these unique properties (Balıkoğlu et al., 2022). Due to these features, they are frequently encountered in the automotive (Wan and Takahashi, 2021; Güçlü et al., 2020), marine (Rubino et al., 2020), and extreme sports (Zakaria et al., 2019) industries, especially in aerospace and aviation (Sharma and Srinavas, 2020; Parveez et al., 2022). Many production methods have been developed over the years for the production of FRC parts. Among these, the most widely known and used systems are basically mold-based systems such as vacuum forming, filament winding, pultrusion, vacuum infusion, compression molding, etc. With the recently developed 3D production systems, could produce composite parts using continuous fiber-reinforced filaments, the limitations of molding-based production methods, high mold costs, and difficulty of production of complex parts have been eliminated (Quan et al., 2020; Wang et al., 2019; Ueda et al., 2020; Yang et al., 2021). Particularly in the manufacturing of sandwich structures, which have high specific stiffness, high specific strength, and high impact energy absorption capacity (Sarvestani et al., 2018). Sandwich structures, with their different core configurations, are a group of materials that play a leading role in both lightweighting and strength-increasing studies in a wide variety of areas. Although the most used core structures forms are foam materials (Vinyagar et al., 2020) and honeycomb geometries (Wang et al., 2021); lattice truss core structures have attracted attention as both their stiffness and strength properties are superior to other materials and they allow sandwich structures to be used more multifunctionally (Finnegan et al., 2007; Zhang et al., 2012). Lattice structures are formed by the combination of periodic porous units. The mechanical properties of these structures depend largely on the geometry of the unit cells. Truss lattice structures consist of interconnected solid struts arranged in a particular spatial layout. Since the versatile spaces they leave in the sandwich structure can be used for many different purposes, they bring the mentioned multifunctionality to the structure. Besides the existing advantages, difficulties in the production of such structures with traditional manufacturing methods can be a disadvantage.

With the growing out of Additive Manufacturing (AM) methods, it has become possible to manufacture digitally designed parts in the desired geometry at once and without the need for additional processing. AM methods, make it possible to produce complex and costly parts that are difficult to produce with traditional methods (Kousiatza et al., 2019). Fused Deposition Modeling (FDM) technique is the most widely used among additive manufacturing methods (Heidari-Rarani et al., 2019). With this technique, the desired geometry is achieved by stacking the melted raw material in layers and solidifying it. Although production with this technique is generally required by using raw materials with no additives, particle additives, or short fiber additives (Wickramasinhe et al., 2020; Çantı and Aydın, 2018; Elazeim et al., 2023; Tian et al., 2022). In recent years, new and advanced devices using continuous fiber-reinforced thermoplastic polymers have started to emerge. In this way, 3D fiber-reinforced composite parts can be manufactured in desired geometries (Zhao et al., 2019; Zhang et al., 2021; Caminero et al., 2019; Li et al., 2021). Unlike the production of laminated composite plates, the production of sandwich structures, especially with lattice truss core geometry, includes different stages. Lattice truss core production, which is made with many cut-and-join steps with conventional methods, can be carried out quickly in one go with AM technology. In addition, in the traditional cut-to-join process, there is a certain loss of strength as a discontinuity is created in the fiber in the cut piece. When this loss of strength is added to the lack of sufficient bonding at the junction points, the expected performance from the structure may not be achieved at the desired level.

Although research using continuous fiber-reinforced filaments in additive manufacturing methods is still limited, current studies have revealed important results. In their study, Yang et al. (2017) produced composite materials with 3D printing technology. They used Acrylonitrile Butadiene Styrene (ABS) as the polymer in the study they carried out with the logic of impregnating the polymer to the fiber by passing the carbon fibers through the melted thermoplastic polymer. They have developed and applied a new extrusion apparatus to the existing 3D printing equipment to produce the composite structure. They performed mechanical tests of the composite structures they obtained and examined the interface performance with scanning electron microscopy images. Experiments have shown that the flexural and tensile strengths of the composite materials they produce are much higher than those of ABS and very close to the values of ABS/CF composites produced by injection molding. However, they added that the shear strength and interface performance between the layers were lower. Hou et al. (2018), in their research, aimed to produce continuous fiber-reinforced composite structures with varying complexity. Using continuous aramid fibers impregnated with thermoplastic Polylactic Acid (PLA) polymer, complex sandwich composite samples were produced with 3D printer technology. In this study, the main purpose of which is to examine the production (process, structure, density, fiber amount, etc.) parameters, also aimed to be optimized, the strength and fracture properties of the produced composite structures were also examined. According to their results, they experimentally demonstrated that this new and improved manufacturing process has great potential for producing complex shaped, high mechanical properties and multifunctional continuous fiber-reinforced composite parts. In their study published, Sugiyama et al. (2018) used 3D printers to produce continuous fiber-reinforced sandwich structures with different core geometries as one piece. They used 3D printer technology with commercially produced Carbon Fiber Filaments in their production. The functional properties and shape evaluations of the sandwich structures they produced were measured by bending tests. By experimentally comparing the different core structures they produced, the researchers concluded that 3D printers with continuous carbon fiber reinforcement are suitable for use to provide the desired durability, strength, and rigidity from the structures, as well as to increase the flexibility of production. Mohammadizadeh et al. (2019), in their study, researched the damage behavior of continuous fiber reinforced additive manufactured composite structures. They investigated the correlation between microstructure and damage behavior by examining the SEM (Scanning Electron Microscopy) images of the structures they damaged with structural tests. In their studies investigating the effects of different fiber types, orientations, and infill densities on the tensile, fatigue, and creep behavior of composite structures, they used Nylon as matrix material and Glass, Carbon, and Aramid fibers as reinforcement material. As a result of their study, they observed that the main damage mechanisms of continuous fiber-reinforced additive manufactured composites are fiber pull-out, fiber breakage, and delamination. They also revealed that there is a correlation between the stacking density of the fibers and the mechanical properties. Dong et al. (2020) preferred PLA as the matrix material and Kevlar, which is the best compatible with PLA as the fiber, in their work on the manufacturing of composite materials by additive manufacturing method by impregnating the melted thermoplastic resin with continuous fiber. They investigated the effects of printing and structure parameters in their studies aiming to optimize the printing path and scheme in the manufacturing of sandwich composite structures with cellular cores. They revealed that the structural parameters are directly affected by the printing parameters such as fiber orientations and layer thicknesses. They also observed that the increase in fiber content caused an effective increase in the tensile strength of the structures. Zeng et al. (2021) practiced a study in which they produced continuous fiber-reinforced composite sandwich structures with shape memory using Fused Filament Fabrication (FFF) technology. In-plane and out-of-plane compression and energy dissipation behaviors of the sandwich structures they produced were experimentally investigated. Afterward, they showed that the analysis model they developed and the results of the analysis they made were in good agreement with the experimental data. Kabir et al. (2021) published their work, where they produced Glass Fiber/Nylon composites with maximum fiber content in different fiber orientations with 3D printing technology. They experimentally investigated the microstructural and performance properties such as tensile and impact resistance of the composite structures they produced. According to their results, it has been revealed that composite structures with the maximum possible fiber content have a magnificent effect on increasing their performance, although they contain internal voids that cause early damage to the structures. In most of the studies available in the literature, it is seen that the thermoplastic resin is impregnated with the filament before printing and the printing process is carried out. It is also known that very few of them are produced by using commercially produced low fiber ratio ready-to-use filaments.

In this study, ready-to-use 3D printer filament with a high-fiber ratio was obtained by using PP thermoplastic resin and carbon fibers. A preliminary process was carried out to obtain the filaments. A suitable apparatus was designed for a standard extruder and the fibers were coated with resin. In this way, a ready-to-use composite filament in the 3D printer was obtained. With these produced composite filaments, lattice truss core structures were manufactured with a 3D printer. Sandwich structures were obtained by combining these produced cores with composite plates consisting of the same mixture (PP/CF). The mechanical properties of the sandwich structures obtained were investigated under quasi-static compression, quasi-static bending, and dynamic bending loads.

2. MATERIALS and METHOD

2.1. Manufacturing of Composite Filaments

In this study, unlike many in the literature, PP-coated carbon fiber filaments are produced in a preliminary production process. For the production of this composite filament, an existing extrusion machine has been modified to make it suitable for producing continuous carbon fiber-reinforced thermoplastic composite filaments. The extruder used is a conventional device with a single screw system and an L/d ratio of 20. This device was developed and produced as a consequence of Applied Mechanics and Advanced Materials Research Group (AMAMRG) Laboratory studies. The device basically follows a standard extrusion procedure. However, there is a mechanism that allows carbon fiber to be inserted into the molten polymer at the die head part at the end of the device. While the PP polymer melted at 180 degrees in the extrusion machine progresses along the screw under homogeneous melting conditions, carbon fiber is included in the system thanks to an apparatus added to the device at the tip of the screw and this carbon fiber is impregnated and coated with the melted PP polymer then removed from the mold tip for cooling. The process was carried out in room conditions and laboratory environments. An image of the production system is given in Figure 1 below.

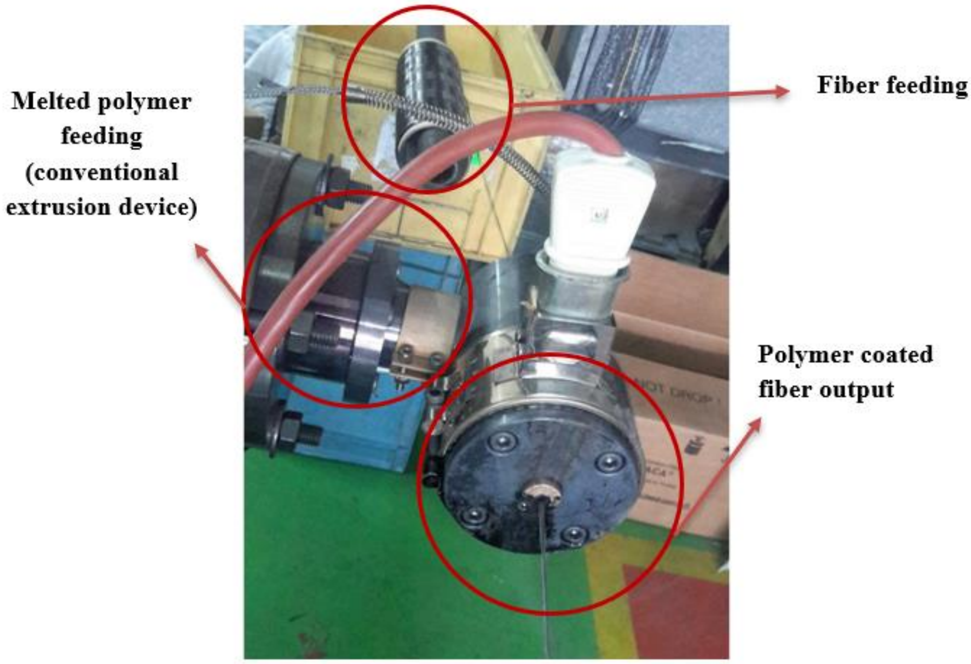

Figure 1:
Continuous carbon fiber reinforced thermoplastic filament manufacturing by modified die head extrusion device

The thermoplastic raw material utilized as the matrix in creating composite filaments is a commercial Polypropylene (PP) product that can be acquired from PETKIM-Izmir/Türkiye and has the code MH 418. Its flow index is 4-6 gr/10min. This PP material has a density of 0.905 gr/cm^3 at room temperature, a yield strength of 34 MPa, and a bending stiffness of 1450 MPa. The reinforcement material, known as continuous carbon fiber (CF), is made of 1k microfiber and is based on polyacrylonitrile (PAN), manufactured by Toho-Tenax in Germany. CF has a density of 1.78 gr/cm^3, a tensile strength of 3930 MPa, and a tensile modulus of 234 GPa. The improved method yielded composite filaments with a cross-sectional area of 0.784 mm^2 and an elliptical cross-section geometry, as illustrated in Figure 2 below.

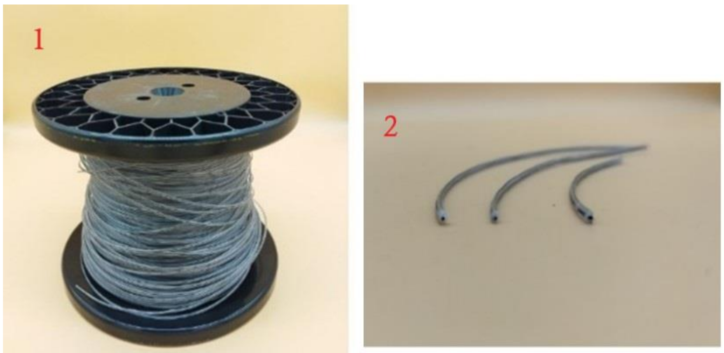

Figure 2:
Composite filaments manufactured by modified extruder with pp and carbon fiber 1)Wrapped on reel 2) Cross-section views of fiber-reinforced composite filament

2.2. 3D Manufacturing Process

The 3D printer used in this study is a standard device of the FLSUN brand, which is commercially produced and sold. An extruder head has been developed to print on the existing device with CFR composite filament. The image of the extruder part of the device used in 3D production is given in Figure 3 below.

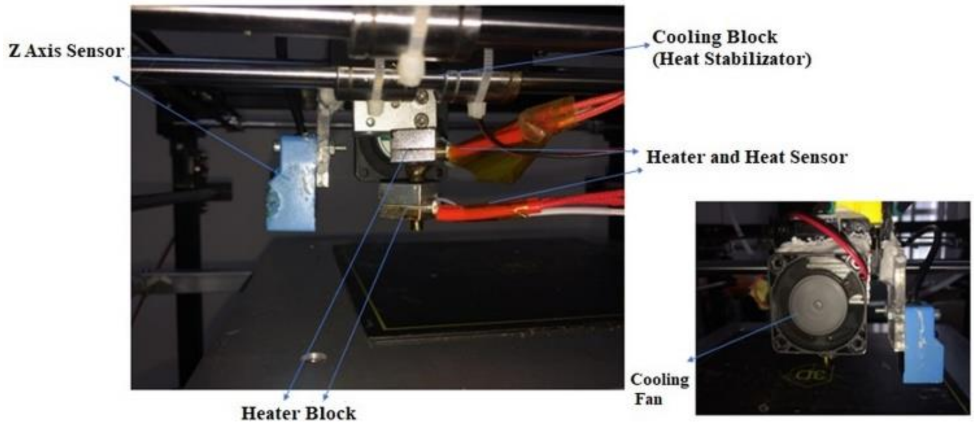

Figure 3:
Improved 3D extruder head for continuous carbon fiber reinforced composite filament

The extruder head developed here comprised a nozzle suitable for composite filaments, double heater, double thermocouple, fan, and Z-axis distance sensor. Nozzles produced as standard are generally made of brass material. Since the filament used here contains carbon fiber, which is highly abrasive, the nozzle is made of steel material, which is more durable than brass. In addition, the diameter of the nozzle is also produced in 3 mm width appropriately for the filaments. Due to the characteristics of the matrix material used, a double heater system is used, so that the material enters the flow regime before printing and remains stable. A fan system is also used to prevent the filament from melting and forming a blockage in the area where the filament should not melt due to the heating effect in the system. In the adjustment of the printing layer thickness, the Z-axis distance sensor comes into play.

Another critical point is that minor changes have been made in the program used to produce the lattice core structure. Due to the heat losses that may occur between the thermal bridges and the extruder during production, certain changes have been made in the program for the temperatures of the 3D printer and the printing table. As a result, a temperature setting of 235 °C for the extruder and 100 °C for the printing table was made, depending on the properties of the PP matrix used.

2.3. Improvement of 3D Manufacturing Process

Problems and some unwanted situations that needed to be corrected occurred in the 3D production process. These problems were identified and the necessary improvements were determined to ensure that the production yielded more accurate results. The distance between the nozzle and the heated printing plate is essential in the examination made in the 3D printer. If the distance between these is not suitable, the material will not adhere to the table ideally. This problem is also encountered with non-reinforced thermoplastic filaments. Another challenge confronted is that the distortion of the matrix material used prevents the material from sticking to the plate.

The produced carbon fiber reinforced filaments have an elliptical cross-section resulting from production systems. However, in the current 3D printing system, the filament motion path has a circular cross-section, which creates a mismatch in the matrix-reinforcement ratio. This causes the filament supply to be uneven. In order to minimize this situation, the printing and movement speed settings were changed, and the necessary adjustments (such as wall printing speed, shell printing speed, infill flow rate, and retraction parameters) were made to reach the ideal printing.

Since the part of the composite material in contact with the printing plate is the PP matrix material, it is aimed to provide a good adhesion by adjusting the speed values to a lower speed compared to the commonly used PLA and ABS materials. Printing speeds are set as 5 mm/sec. The tension of the fibers in the matrix is important in terms of strength. The extrusion coefficient was determined as 1.15 to have the ideal stretch.

In Figure 4, it is seen that there are twists in the fiber during production. The error seen here is due to the rotations that occur during the extrusion production while the resin is coated before the filament enters the mold. The matrix-coated fiber that comes out by melting at the nozzle tip tries to return to its original state during printing. Therefore such distortions occur. Speed settings minimize this situation.

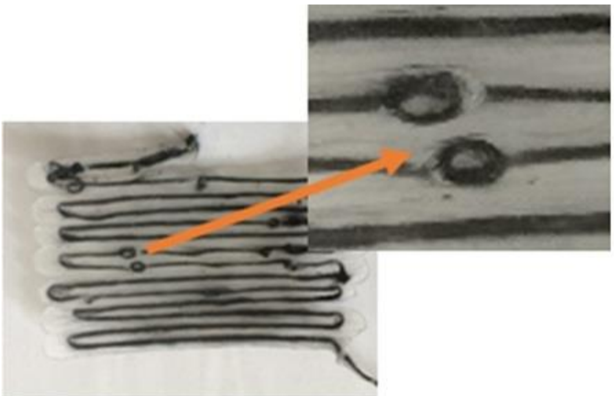

Figure 4:
Twisting of carbon fibers in matrix

Another handicap is that the matrix material used in the study is a material with a high deterioration rate. This deterioration prevents the matrix from sticking to the table during production. In order to prevent this situation, the distance between the nozzle and the hot plate was minimized and the ambient temperature where the production was carried out was increased above the room temperature.

2.4. Production of Sandwich Panels

Sandwich surface plates were obtained by placing continuous CFR composite filaments obtained from the extruder in a hot mold with a [0°/90°/0°] array and pressing under pressure. The mold dimensions in which the surface plates are produced are designed to obtain composite plates with the dimensions of 1000 mm x 1200 mm x 1.5 mm at the end of the process. The surface plates were cut with a water jet to create compression and 3-point bending test specimens from the produced composite plates in the dimensions specified in the standards. The visuals of the sandwich surface plates with a thickness of 1.5 mm are given in Figure 5.

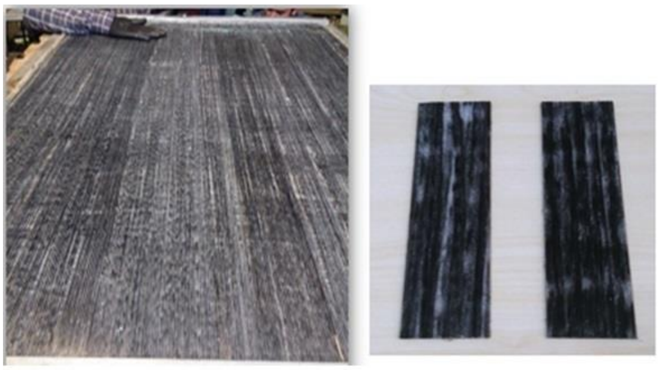

Figure 5:
Laminated carbon fiber reinforced composite plate and [0°/90°/0°] stacked sandwich face plates

The lattice core structure is printed in a 3D printer. Figure 6 shows the printing process of the lattice cores. While the lattice core structures are joined together, they are placed inverted and straight pyramidal. Subsequently, faceplates and lattice core structures were combined using hot silicone adhesive. Figure 7 shows the combined form of sandwich panels with lattice core.

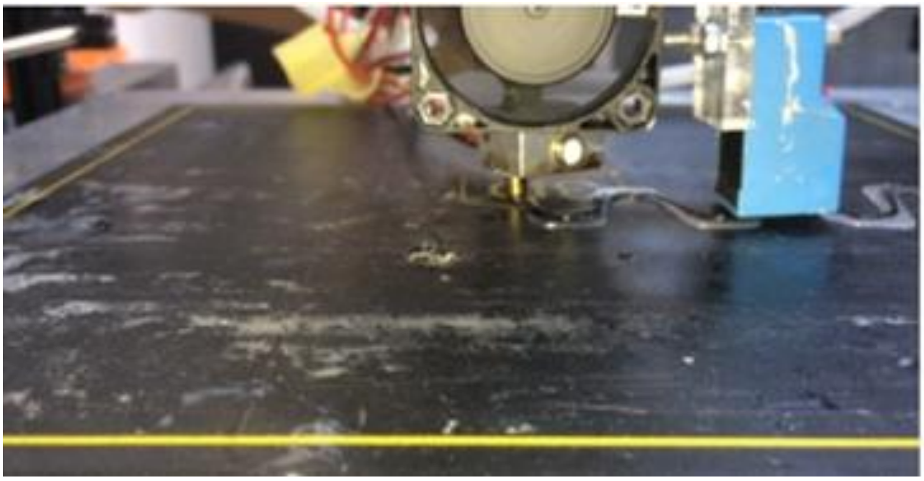

Figure 6:
3D printing of lattice core structures

Figure 7:
Produced composite sandwich panel

3. RESULTS and DISCUSSIONS

3.1. Tensile Strength of Continuous Carbon Fiber Reinforced PP Filaments

Determining the mechanical strength of continuous fiber-reinforced composite filament structures is an important step before the tests of sandwich structures are produced. In the filament structure, a tensile test was carried out to determine whether there is sufficient bonding between fiber and matrix material and to determine whether the produced filaments are at appropriate strength values. Tensile tests were carried out using the Zwick Proline Z010 testing machine at 10 mm/min crosshead speed. Figure 8 shows the test device, and Figure 9 shows a graphic of the test result. The tensile strength has been obtained around 267.5 ± 4.2 MPa.

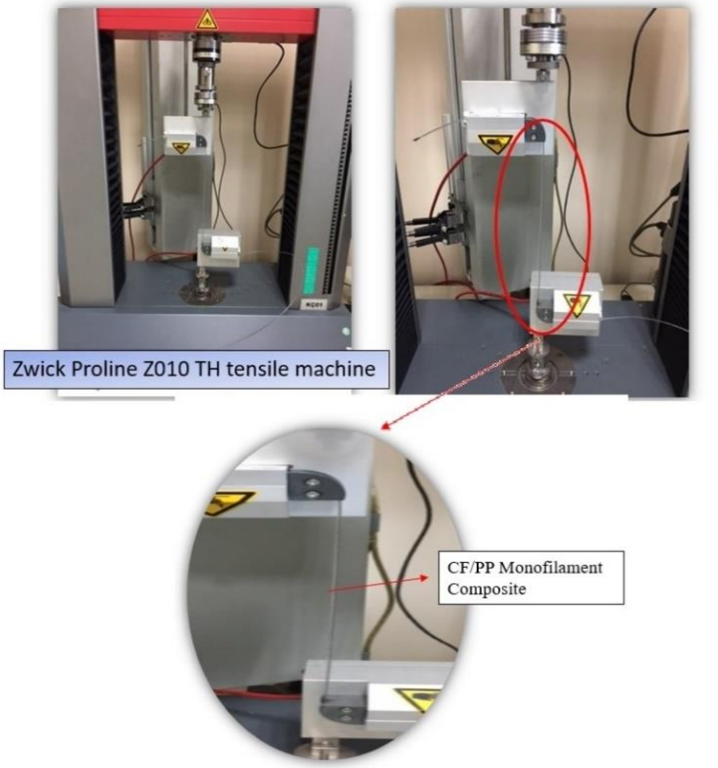

Figure 8:
Tensile test device and tensile test of CF/PP mono filament

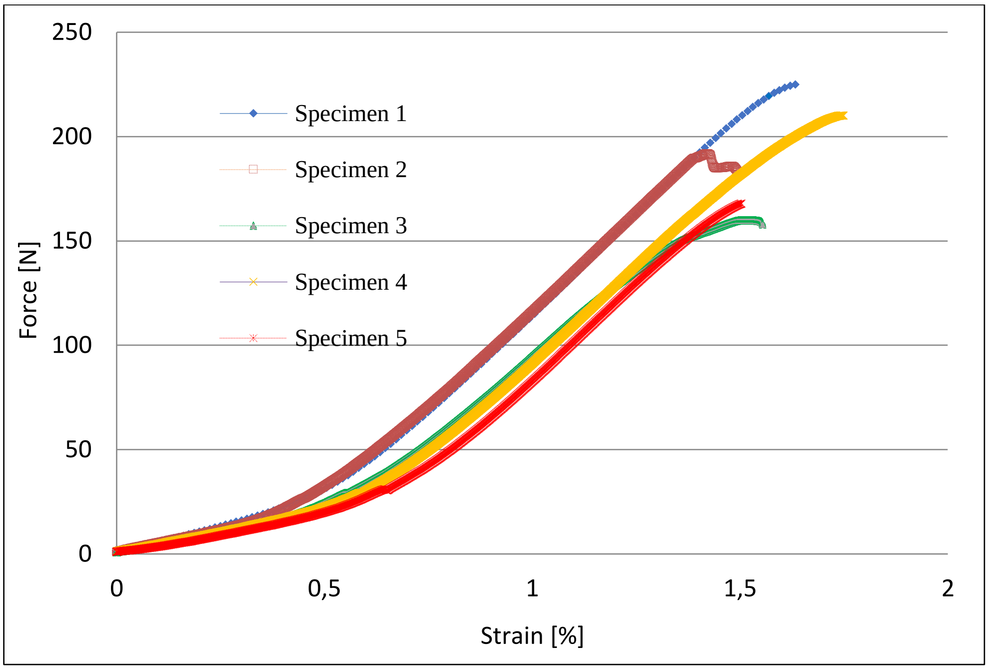

Figure 9:
Tensile test result of CF/PP mono filament composite

3.2. Flatwise Compression Tests of Sandwich Structures

A flatwise compression test was performed to determine the strength of sandwich structures under compression load and to find the amount of energy they absorb under compression load. In this test, the part that carries the load and performs the energy absorption mechanism depending on this load is the lattice truss core structure. The compression test was carried out using the Zwick Proline Z010 test machine at a speed of 10 mm/min. Figure 10 shows the compression test sample, and the samples are composed of four pyramidal structures in 50 mm x 50 mm x 25 mm sandwich core and composite face sheets.

Figure 10:
Sandwich specimen for flatwise compression test

In quasi-static compression experiments, three specimens were performed. The calculated average curve is presented in Figure 11. The maximum peak load was obtained as 269 ± 8.7 N. The test results show that the lattice core maximum load was achieved when arriving at the mono composite elements buckling limits. Therefore, the load-carrying capacity of the core immediately dropped after the maximum load, as expected from theory. While each member of the lattice core passes to the bending mode from the buckling stage, the carried load starts to increase as classical sandwich behavior, which is like the densification behavior.

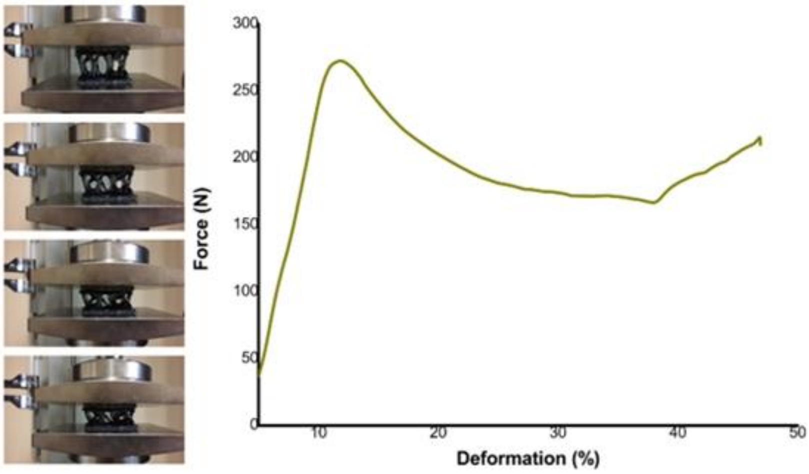

Figure 11:
Deformation behaviors of sandwich structures during quasi-static flatwise compression test and average force-deflection curve of sandwich structures

3.3. Quasi-Static and Dynamic 3-Point Bending Tests of Sandwich Structures

Both quasi-static and dynamic bending tests were executed to experimentally determine the bending stiffness and energy-absorbing capacity under bending loads of sandwich structures. Below, the visual of the test sample is given in Figure 12. The sample dimensions were determined to be 50 mm x 200 mm x 25 mm conviniently with the standards. The core of the sandwiches consists of fourteen pyramidal lattice truss structures with 2 mm x 7 mm base dimensions.

Figure 12:
3-point bending specimen of sandwich structure

An image of the quasi-static 3-point bending test is given in Figure 13 below. Here, the progress of the deformation in the lattice truss core structure is seen during the test.

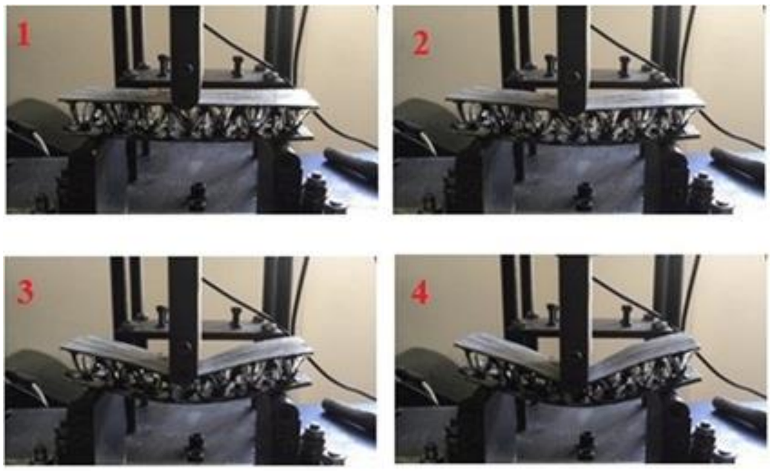

Figure 13:
Failure behavior of lattice truss core structures under quasi-static 3-point bending test

The average force-displacement graph obtained from the tests with sandwich structures is given in Figure 14 below. The maximum average peak load was obtained as 240 ± 1.73 N.

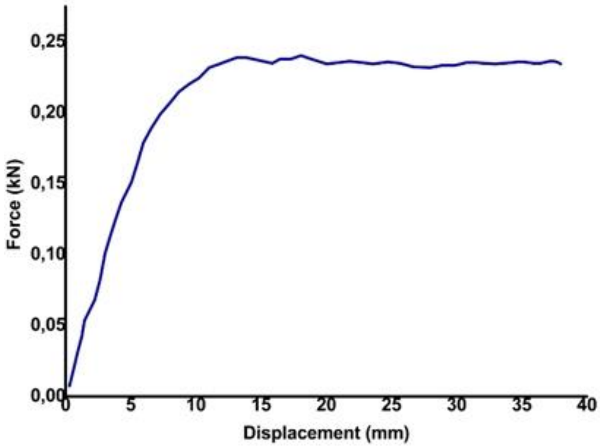

Figure 14:
Average load-displacement graphic of quasi-static 3-point bending test of sandwich structures

In order to perform dynamic 3-point bending tests, the Split Hopkinson Pressure Bar (SHPB) test system in AMAMRG laboratories has been modified to make it capable of performing dynamic bending tests. The gas gun and barrel system of the SHPB test system was preserved, and a part consisting of an impact bar with a bending head at the end and two fixed supports was placed on it. The visual and schematic of the test system are given in Figure 15.

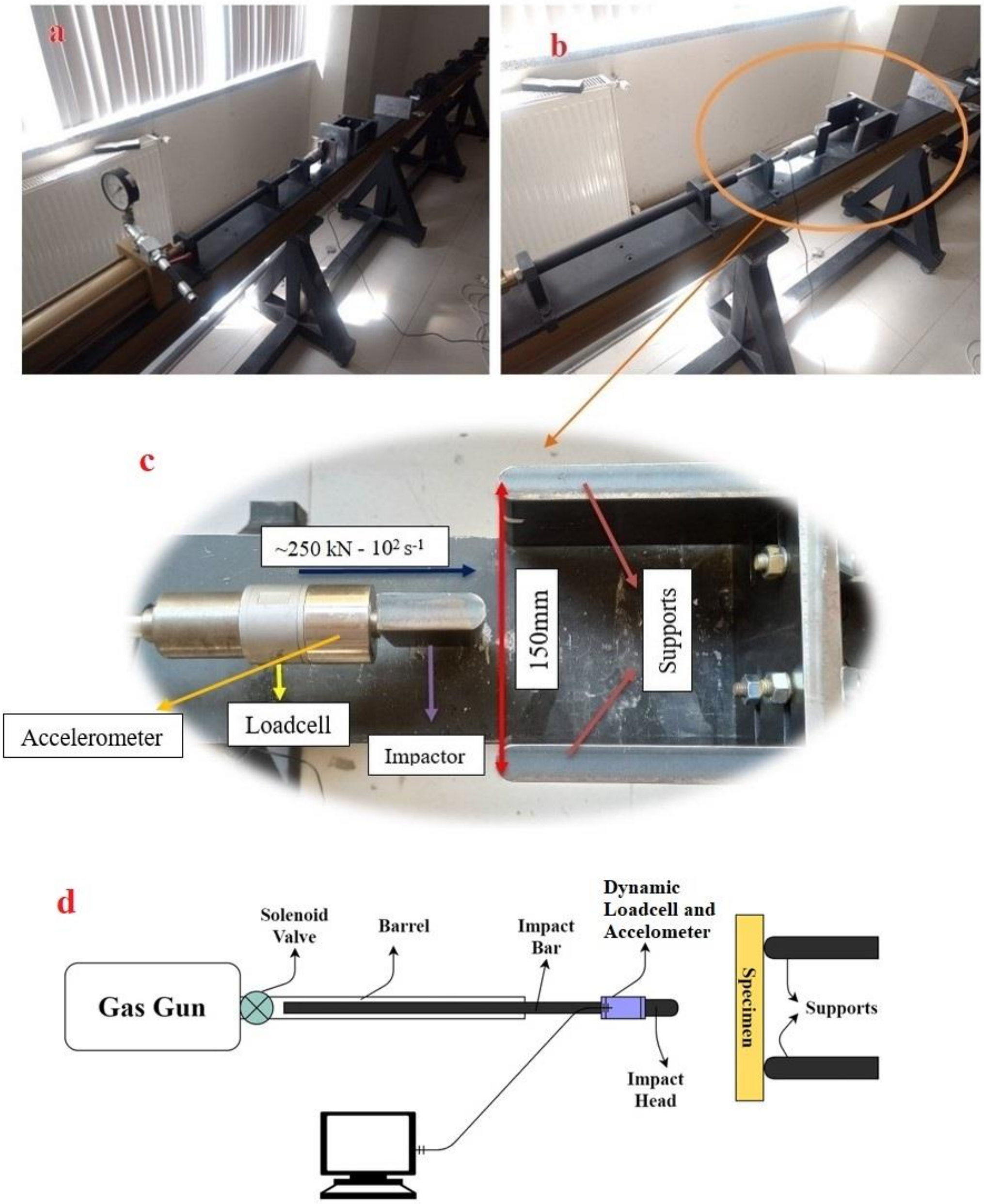

Figure 15:

Dynamic 3-point bending test system a) Whole modified dynamic 3-point bending test system b) Impact head and fixed support to place specimen c) Impact head and fixed support dimensions and components d) Schematic of the test system

The total weight of the impact head with all its equipment was measured as 3.24 kg. The pressure required to operate the system was provided with argon gas, and the speed of the impact head was measured as 3.5 m/s at the time of contact, thanks to a gas gun total pressure of 5 bar.

The test results of the dynamic 3-point bending tests are given in Figure 16 as the average Force-Time curve. The maximum peak load was calculated as 450 ± 4.4 N. This curve shows that the load is increased with a high slope and then released. The deformation shapes are different from the quasi-static 3-point bending curves. Under dynamic loading, the maximum load capacity is also approximately two times higher than the quasi-static loading case.

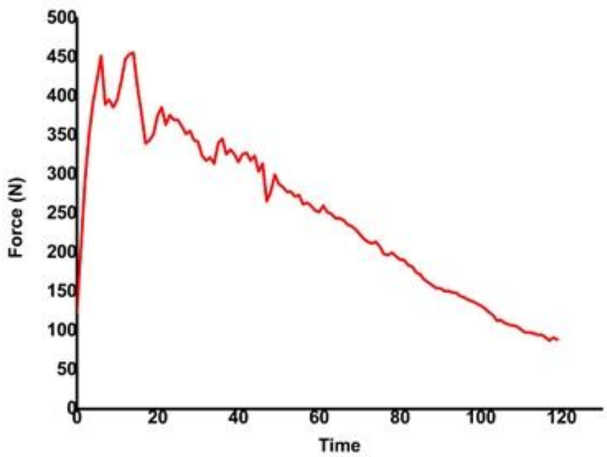

Figure 16:
Force-time graphic of sandwich structures under dynamic 3- point load

4. CONCLUSION

A laboratory-scale FDM printer for printing continuous CFR/PP matrix composite filament was improved and performed to manufacture composite lattice truss core structures. The composite filaments were produced in the AMAMRG Lab, by a specially designed and modified extruder system. Sandwich structures composed with 3D printed Lattice Truss cores and hot-pressed face plates with the same materials and [0°/90°/0°] arrangement were produced by combining these components. Produced all-thermoplastic composite lattice core sandwich panels were tested under quasi-static compression and 3-point bending and dynamic 3-point bending loads. The 3D printing processes were also observed and evaluated concerning production parameters such as temperature and hot plate-nozzle distance, and printing part quality. The findings regarding the mechanical properties of sandwich structures subjected to tests under the specified loading conditions are given below.

- The continuous carbon fiber reinforced thermoplastic composite filament printing process has many complex process parameters. Nozzle temperatures, the difference between the nozzle and hot plate, feeding mechanisms, fiber bending, and twisting during printing are the main difficulties.

- Developed lattice core sandwiches were shown elastic-plastic deformation behavior.

- The impact loading capacity of the sandwiches was two times higher than the quasi-static loading. It can be explained by the bending and buckling behavior of lattice truss cores.

- There is not any sudden load decrease or catastrophic damage was not observed in all experiments.

- The quasi-static compression results show that the lattice truss core composite sandwiches show similar force-deformation behavior with the conventional honeycomb or crushable foam core sandwiches except for the plateau region.

- In quasi-static 3-point bending tests, force-deflection curves present elastic-perfectly plastic deformation behavior during tests although there are no load-carrying elements; both composite lattice core and face sheets were deformed perfectly-plastic. According to experimental observations, the elastic buckling of the lattice core elements directed this behavior.

- Dynamically loaded 3-point bending test specimens showed more bending rigidity than the quasi-static loading case.

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CONFLICT of INTEREST

The authors confirm that they have no known conflict of interest or shared interest with any institution/organization or individual.

AUTHORS CONTRIBUTION

Tolgahan Bayram worked as a responsible person in the design of the 3D production system and the construction of the device. İ.Kürşad Türkoğlu worked as a responsible person in the production of the experimental samples, the execution of the tests, and the writing of the study. Murat Yazıcı contributed to the study as a responsible person in the execution of the tests of the test samples and the data analysis part.

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