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Tel Eritmeli İlkörnekleme (FDM) ile Üretilen Sandviç Yapıların Mekanik Davranışı Üzerinde Dolgu Parametrelerinin Etkisinin İncelenmesi

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ÖZ

Bu çalışma, Tel Eritmeli İlkörnekleme (FDM) tekniği kullanılarak üretilen sandviç yapıların mekanik davranışı üzerinde dolgu desenlerinin etkisini incelemektedir. Polilaktik asit (PLA), tercih edilen birincil malzeme olarak seçilmiştir ve mekanik özellikleri ile biyolojik olarak çözünebilir olmasıyla bilinmektedir. Kübik, çizgisel, üçgensel, üçlü altıgen, sekizli ve dönel olmak üzere altı farklı dolgu deseni, farklı dolgu yoğunlukları (%20, %30 ve %40) ile birlikte kullanılarak sandviç yapılar üretilmiştir. Numuneler, kenar yönde basınç dayanım testlerine tabi tutulmuş ve kuvvet-deplasman eğrileri yapıların performansını değerlendirmek için analiz edilmiştir. Sonuçlar, kübik dolgu deseninin tüm dolgu yoğunluklarında üstün mukavemet sergilediğini, diğer desenlerin performansta farklılıklar gösterdiğini ortaya koymuştur. Ayrıca, hasar tiplerinin analizi, dolgu deseni ve yoğunluğuna bağlı olarak çekirdek kayması ve yüzey plakasının burkulması gibi farklı hata modlarını göstermiştir. Bu bulgular, FDM ile üretilen sandviç yapıların mekanik özelliklerini artırmada dolgu desenlerinin rolünü anlamamıza katkı sağlamaktadır.

Investigation of the Effect of Infill Parameters on the Mechanical Behavior of Sandwich Structures Fabricated via Fused Deposition Modeling (FDM)

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ABSTRACT

This study focuses on the investigation of infill patterns and their influence on the mechanical behavior of sandwich structures fabricated using the fused deposition modeling (FDM) technique. Polylactic acid (PLA) was chosen as the primary material, known for its favorable mechanical properties and biodegradability. Six different infill patterns, including cubic, line, triangular, trihexagonal, octet, and gyroid, were employed to fabricate sandwich structures with varying infill densities (20%, 30%, and 40%). The samples were subjected to edgewise compressive strength tests, and the force-displacement curves were analyzed to evaluate the performance of the structures. The results revealed that the cubic infill pattern exhibited superior strength in all infill densities, while other patterns showed variations in performance. Moreover, the analysis of damage types indicated different failure modes, such as core shear and facesheet buckling, depending on the infill pattern and density. These findings contribute to understanding the role of infill patterns in enhancing the mechanical properties of sandwich structures fabricated via FDM.

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1. Introduction

Additive manufacturing, also referred to as 3D printing, is a technique for fabricating three-dimensional entities by sequentially depositing material layer by layer (Ren et al., 2022). This procedure entails employing a digital model, which is divided into thin layers, followed by the gradual addition of material by the printer until the final object is formed. Additive manufacturing boasts numerous benefits over conventional manufacturing methods, encompassing the capability to generate intricate geometries and economically produce small batches of components (Gu et al., 2021). The application of additive manufacturing extends to diverse sectors, including aerospace, automotive, and healthcare, enabling the production of an extensive array of objects ranging from miniature parts to colossal structures. This process is compatible with various materials such as plastics, metals, and ceramics (Ren et al., 2022).

Additive manufacturing encompasses several techniques, each with its own distinctive characteristics. These include bioprinting, laser-based additive manufacturing, functionally graded materials (FGMs), and nanolamellar high-entropy alloys, and FDM. It is important to note that the field of additive manufacturing is continually evolving, with ongoing advancements in both techniques and materials. This constant innovation is driven by the need to cater to the market requirements of various industries (Gu et al., 2021; Ren et al., 2022; Singh et al., 2022; Zhang et al., 2022).

FDM is an additive manufacturing technique that entails melting a thermoplastic material and sequentially depositing it layer by layer to fabricate a three-dimensional object. FDM is known for its affordability and finds extensive utilization in diverse domains, including medical sciences, the aerospace industry, biological research, engineering applications, and more. The mechanical characteristics of FDM components can be influenced by the printing temperature and filling percentage. Elevating the filling percentage or printing temperature has the potential to enhance properties such as the tensile Young's modulus, ultimate tensile strength, elongation, and shore hardness of the material (Dong et al., 2021; Hsueh et al., 2021).

FDM offers several advantages as an additive manufacturing method. FDM is generally more affordable compared to other additive manufacturing techniques, making it accessible to a wider range of users. It minimizes raw material waste since it selectively deposits material only where needed. Additionally, it has a lower technical threshold, meaning it is easier to learn and operate compared to some other additive manufacturing methods. It also allows for the creation of products with intricate and complex geometric shapes. By using different combinations of polymer matrices and reinforcing fillers, FDM can produce parts with varying properties and functionalities. It enables the fabrication of entire 3D assemblies in a single setup, without requiring tooling or human intervention. This consolidation simplifies the manufacturing process and can lead to cost and time savings (Rudrapati et al., 2018; Hsueh et al., 2021; Solovei and Oleksyshen V., 2021).

FDM holds significant value as a printing technique for the production of thermoplastic components. Through the application of FDM, sandwich structures can be manufactured, thereby enhancing the flexural properties of the material (Subramaniyan et al., 2022). Various core configurations can be devised and manufactured employing FDM technology to augment the mechanical characteristics of sandwich structures (Araújo et al., 2019; Eryildiz, 2023). Several factors, including curing pressure (Chen, 1994), material combinations (Baca Lopez and Ahmad, 2020), and cellular core geometry (Araújo et al., 2019), can influence the mechanical properties of sandwich structures fabricated using FDM technology. These factors can impact the strength and performance of the final product.

Improving the quality of parts produced using the widely employed FDM method holds great importance. Here are some approaches that can be followed to enhance production quality (Venkata et al., 2015; Rudrapati et al., 2018; Zagidullin et al., 2021). There are several ways to enhance the quality of FDM parts. Utilize techniques like response surface methodology (RSM) and Genetic Algorithm to optimize process parameters such as layer thickness, part orientation, raster angle, raster width, and air gap. This optimization aims to minimize variations in dimensions (i.e., length, width, and diameter) and surface roughness, leading to improved part quality. Conduct a thorough investigation into the impact of critical process parameters on FDM part quality. By understanding how layer thickness, part orientation, raster angle, raster width, and air gap affect the final product, it becomes possible to adjust these parameters to achieve desired quality outcomes. Employing parametric changes within the 3D printing software to eliminate or minimize defects in FDM parts. This can involve adjusting settings such as infill density, print speed, temperature, and support structures to optimize part quality. It ensures that process parameters are well controlled and consistent throughout the production of FDM parts. Maintaining a stable environment, such as temperature and humidity, and adhering to precise parameter settings can help minimize variations and improve overall part quality. By implementing these approaches, it is possible to enhance the quality of FDM parts, resulting in more accurate dimensions, better surface finish, and improved overall performance.

Indeed, the filament material used in FDM plays a critical role in determining the quality of the resulting parts (Venkata et al., 2015; Dong et al., 2021; Hsueh et al., 2021; Solovei and Oleksyshen, 2021). Various process parameters, including the filament material, have a significant impact on the physical and mechanical properties of FDM-made parts. The choice of filament material directly affects the outcomes of tests conducted to evaluate mechanical properties. While increasing the printing temperature and filling percentage can improve the mechanical properties of the material, it is important to consider the specific characteristics and behavior of the chosen filament material.

In order to assess the mechanical properties of parts produced through Fused Deposition Modeling (FDM), several tests are commonly conducted. These tests aim to evaluate the performance and behavior of FDM polymers and composites. Tensile tests are performed to understand how the inner structure of FDM polymers affects their mechanical properties, such as tensile strength, elongation, and elasticity modulus. These tests can help determine the material's response to applied forces and its ability to withstand stretching (Özen et al., 2021). Three-point bending tests are conducted to characterize the impact of various parameters, including build orientation, layer thickness, printing temperature, and printing speed, on the mechanical properties of FDM samples (Chalgham et al., 2021). This test helps evaluate the material's resistance to bending and its flexibility under different conditions. Impact strength tests are carried out to investigate the effects of FDM process parameters on the ability of the printed parts to withstand sudden forces or impacts. This test helps to assess the toughness and resistance to fracture of the material (Kam et al., 2023). Flexural tests are used to evaluate the bending behavior and stiffness of printed composite samples. These tests involve applying a force to the sample in a bending manner to assess its structural integrity and resistance to deformation (Muthu Natarajan et al., 2022).

The edgewise compressive strength test is important in sandwich structures for several reasons. It measures the ability of the sandwich structure to resist compressive loads applied perpendicular to the facesheets, which is a critical loading condition for many applications. The edgewise compressive strength of sandwich constructions can be influenced by various factors. The edgewise compressive strength of sandwich constructions can undergo significant changes with increasing curing pressure. Higher curing pressures can enhance the strength of the sandwich structure (Chen, 1994). Different sandwich structures, such as honeycomb fiberboard and AAB flute corrugated fiberboard, can exhibit variations in edgewise compressive strength. For example, honeycomb fiberboard tends to have approximately 50% higher compressive strength than AAB flute corrugated fiberboard (Hua et al., 2015). The yield strength of honeycomb paperboards can decrease as the aspect ratio (the ratio of the longer dimension to the shorter dimension) increases. More slender bodies with higher aspect ratios may experience reduced strength (Samad et al., 2018). The strength of sandwich specimens subjected to edgewise compressive loads can be affected by circular facesheet-core disbonds. Failures in the bond between the facing and core, along with wrinkling-type failures in the facing, may occur during the failure of honeycomb core sandwich specimens (Norris, 1956). The maximum stress in the facings of sandwich specimens can vary based on the type of core material used. For instance, honeycomb core sandwich specimens may exhibit lower stresses at failure compared to specimens with wood cores (Bergan, 2017).

The field of additive manufacturing, particularly FDM, has seen rapid advancements with a diverse range of infill patterns and densities being explored. However, there exists a knowledge gap regarding how specific infill configurations impact the mechanical behavior of sandwich structures. By identifying the optimal infill patterns and densities, we can enhance the overall mechanical performance of additively manufactured sandwich components, making them more suitable for a wider range of applications. In this study, sandwich structures with different filling densities and various filling geometries were produced using the FDM method with PLA filament. The edgewise compressive strength of the fabricated sandwich structures was experimentally measured. The edgewise compressive strength of compact sandwich structure samples was studied to evaluate their load-bearing capability, considering the effects of infill density and infill pattern on the strength of the sandwich parts.

2. Material and Method

In this study, polylactic acid (PLA) was selected as the primary material for fabricating the sandwich structures using the FDM technique. PLA is a biodegradable thermoplastic polymer derived from renewable resources such as corn starch or sugarcane. It is widely used in various industries due to its favorable mechanical properties, low cost, and ease of processing. The specific PLA filament utilized in this research had a density of 1.24 g/cm^3, a tensile strength of 62.6 MPa, and a Young's modulus of 2504 MPa (Algarni, 2021).

The fabrication process was carried out using an Ender 3-S1 3D printer (Figure 1). This printer is equipped with a heated build plate and a single extruder nozzle. The printer settings were carefully adjusted to ensure optimal printing conditions throughout the experiments. The nozzle temperature was set to 208 °C, while the build plate temperature was maintained at 60 °C. The printing speed was kept constant at 50 mm/s, and the layer height was set to 0.2 mm.

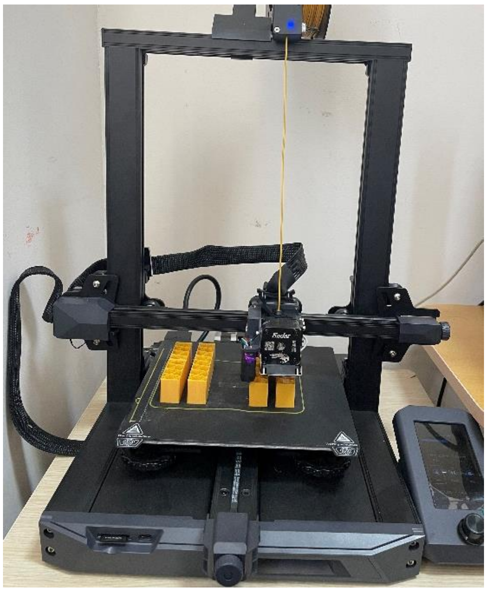

Figure 1. Fused deposition modeling (FDM) process

The sandwich structures were fabricated using the FDM technique, which involves the layer-by-layer deposition of the PLA filament. The design of the sandwich structures included a top and bottom layer, known as the "facing," and a cellular core. The infill pattern of the cellular core was varied to investigate its influence on the mechanical properties of the sandwich structures. Six different infill patterns were utilized: Cubic, line, triangular, trihexagonal, octet, and gyroid. The samples produced with different infill patterns are shown in Figure 2. Additionally, three different infill densities were tested, namely 20%, 30%, and 40%. All sandwich structure samples produced had standardized dimensions of (80 x 50 x 12) mm. The mass of each sample varied depending on the infill density, ranging from 19.5 grams to 30 grams. The mass measurements were conducted using a precision digital scale. The utilized parameters and masses of the produced samples are provided in Table 1.

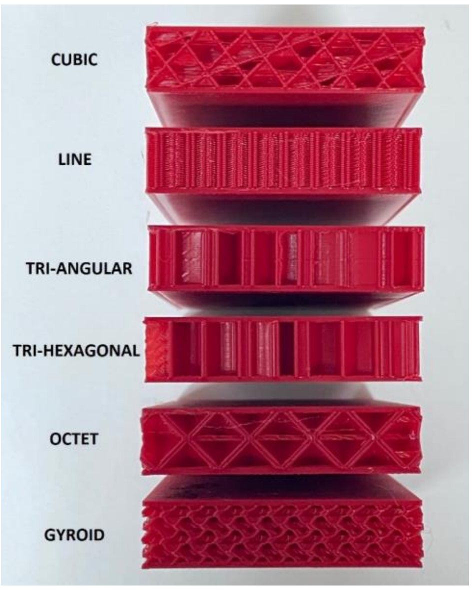

Figure 2. Section views of the specimens produced with different infill patterns

Table 1. The masses (g.) of the produced samples.

	Infill Densities		
Infill Patterns	**20%**	**30%**	**40%**
Cubic	19.558	24.986	29.376
Line	19.793	24.808	29.614
Triangular	19.694	24.572	29.323
Tri-Hexagonal	19.648	24.588	29.516
Octet	19.989	24.809	29.140
Gyroid	20.061	25.300	29.480

To evaluate the mechanical properties of the sandwich structures, edgewise compressive strength tests were performed according to the ASTM C64 standard. The ASTM C64 test method is specifically designed to assess the load-carrying capacity of sandwich constructions by measuring the facing stress developed during the test. The tests were conducted using a universal testing machine, where force and displacement data were collected. The collected data was then utilized to generate force-displacement graphs, enabling the analysis of the mechanical behavior of the sandwich structures. The obtained force-displacement graphs, along with visual observations of the samples, were analyzed to assess the performance and mechanical properties of the fabricated sandwich structures. The influence of the infill pattern and infill density on the edgewise compressive strength of the structures was thoroughly investigated. Furthermore, the presence of any structural damage or failure modes in the samples was carefully examined and discussed.

3. Results

The previous sections detailed the materials, methods, and experimental setup employed in this study to fabricate sandwich structures using PLA and the FDM technique. Now, we shift our focus to presenting and analyzing the obtained results, as well as engage in a comprehensive discussion regarding the implications and significance of these findings. The primary objective of this research was to investigate the influence of infill patterns and infill densities on the mechanical properties of the sandwich structures. To achieve this, six different infill patterns, namely cubic (Cu), line (Li), tri-angular (Ta), tri-hexagonal (Th), octet (Oc), and gyroid (Gyr), were implemented. Additionally, infill densities of 20%, 30%, and 40% were utilized in the fabrication process. The acceptable and unacceptable damage types are evaluated based on whether the damages occur at the points of contact with the test fixture in the tested specimens. Local damages observed at the points of contact with the test fixture are not taken into consideration. Production was also conducted at a 10% infill density; however, due to damages occurring near the clamps during the tests, they were excluded from the analysis. The acceptable and unacceptable types of damages are shown in Figure 3. During the fabrication process, particular attention was paid to maintain consistent printing parameters, including nozzle temperature, build plate temperature, printing speed, and layer height. This ensured the production of reliable and reproducible samples for subsequent testing and analysis.

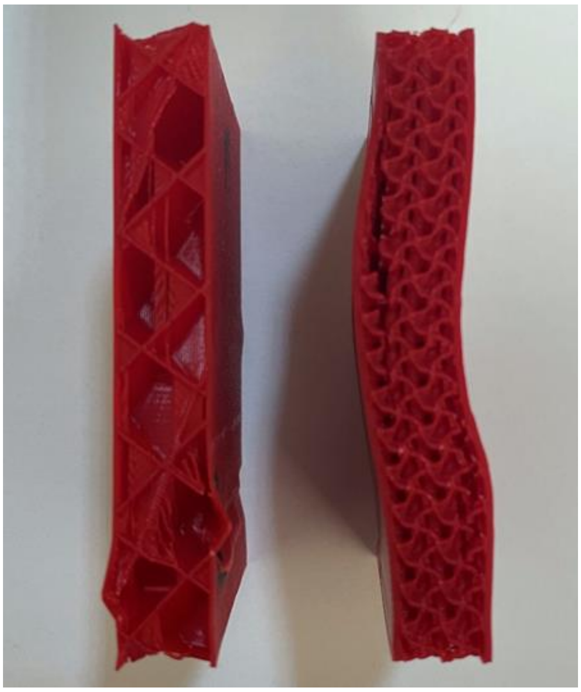

Figure 3. Unacceptable and acceptable types of damages

The edgewise compressive strength tests, conducted in accordance with the ASTM C64 standard, provided valuable insights into the load-carrying capacity of the sandwich structures. These tests enabled us to measure the facing stress developed during the experiments, allowing for a comprehensive evaluation of the mechanical performance of the structures. The collected data from the force-displacement graphs, coupled with visual observations of the samples, provide a comprehensive understanding of the structural behavior and failure modes exhibited by the sandwich structures. By analyzing these results, we aim to identify the optimal infill pattern and density combinations that yield enhanced mechanical properties, such as improved flexural strength and load-bearing capacity.

Moreover, by carefully examining any structural damage or failure modes observed in the samples, we can gain insights into the failure mechanisms and potential limitations of the fabricated sandwich structures. This analysis is crucial for understanding the structural integrity and durability of the produced components, and ensuring their suitability for practical applications in various industries. The damage modes observed in the specimens after the tests are provided in Table 2.

Table 2. The modes of damages observed in the specimens after the tests

	Infill Densities		
Infill Patterns	**20%**	**30%**	**40%**
Cubic	Facesheet Compression Failure	Core Shear Failure	Core Shear Failure
Line	Core Compression Failure	Core Compression Failure	Facesheet Buckling Failure
Triangular & Tri-Hexagonal	Facesheet Compression Failure	Facesheet Compression Failure	Facesheet Compression Failure
Octet	Core Shear Failure	Core Shear Failure	Facesheet Buckling Failure
Gyroid	Core Compression Failure	Core Compression Failure	Core Compression Failure

In the subsequent sections, we will present and discuss the results obtained from the comprehensive testing and analysis performed on the fabricated sandwich structures. Through an in-depth examination of these results, we aim to draw meaningful conclusions regarding the influence of infill patterns and densities on the mechanical properties of the structures. Additionally, we will explore the implications of these findings and discuss potential avenues for future research and development in the field of sandwich structure fabrication. By elucidating the relationship between infill patterns, infill densities, and mechanical properties, this study contributes to advance our understanding of optimizing the performance and functionality of sandwich structures fabricated using the FDM technique.

The force-displacement graphs of the samples with 20%, 30%, and 40% infill densities are presented in Figures 4, 5, and 6, respectively. Upon examining the graphs, it can be observed that the samples with a cubic infill pattern exhibit higher strength at all density levels. (Ma et al., 2020) stated in his study that the cubic infill type exhibited high performance in compression tests, and similarly, the samples with cubic infill pattern demonstrated high performance in edgewise compression tests as well. Evaluating the samples with a cubic pattern based on the damage types provided in Table 1, it is determined that compression damage occurs in the facesheet at 20% infill density, while core shear damage occurs at 30% and 40% densities. An increase in infill density leads to an increase in the material's Young's modulus (Farid et al., 2022). A decrease in the hollow structure ratio, thus increasing the bonding surface, has a significant effect on achieving this result. As the infill density increases, the bonding surface between the facesheet and core also increases. Consequently, at lower densities, the separation between the core and facesheet occurs at lower force values, resulting in compression damage to the facesheet. At higher infill densities, the increased bonding surface leads to a more evenly distributed load, resulting in core shear damage.

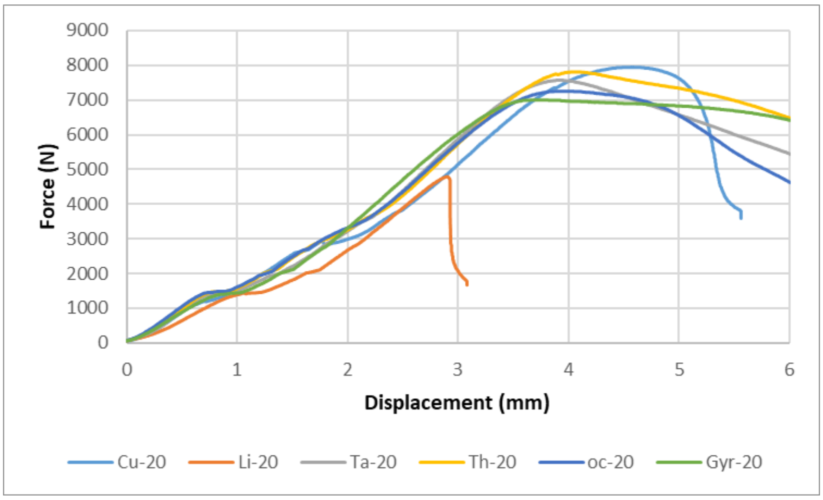

Figure 4. Force-displacement curves obtained from the samples with a 20% infill density

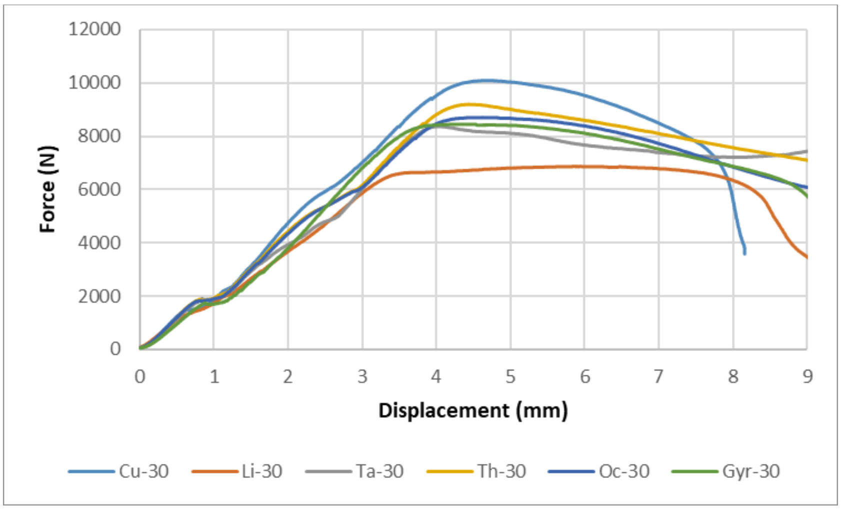

Figure 5. Force-displacement curves obtained from the samples with a 30% infill density

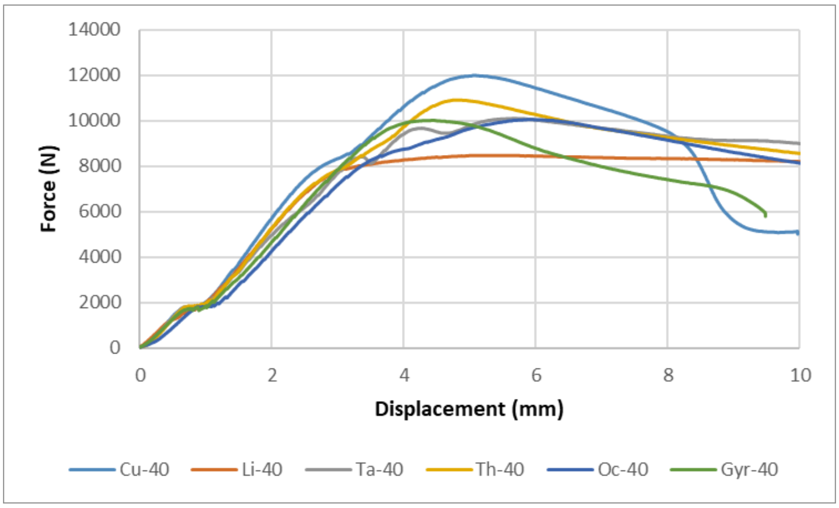

Figure 6. Force-displacement curves obtained from the samples with a 40% infill density

When examining the other infill patterns in terms of maximum load, it can be stated that the samples with Ta, Th, Oc, and Gyr patterns yield similar results. The sample with the Li infill pattern exhibits the lowest performance and has experienced a negative deviation. Analyzing the damage modes as indicated in Table 2, the sample with the Li pattern exhibits core compression damage at 20% and 30% densities, while facesheet buckling damage occurs at 40% density. These findings indicate that although the bonding between the core and facesheet is better, the Li pattern is weaker in terms of vertical loads. For the samples with tri-angular and tri-hexagonal patterns, facesheet compression damage occurs at all density levels, suggesting that these patterns have weaker bonding capabilities between the facesheet and core. In the case of samples with an octet pattern, core shear damage occurs at 20% and 30% infill densities, while facesheet buckling damage is observed at 40% density. These results demonstrate excellent bonding properties, to the extent that an increase in density leads to buckling damage. The sample with a gyroid pattern exhibits core compression damage at all density levels, indicating a strong bond between the core and facesheet. However, due to its pattern structure, the core section appears to be weak against vertical loads.

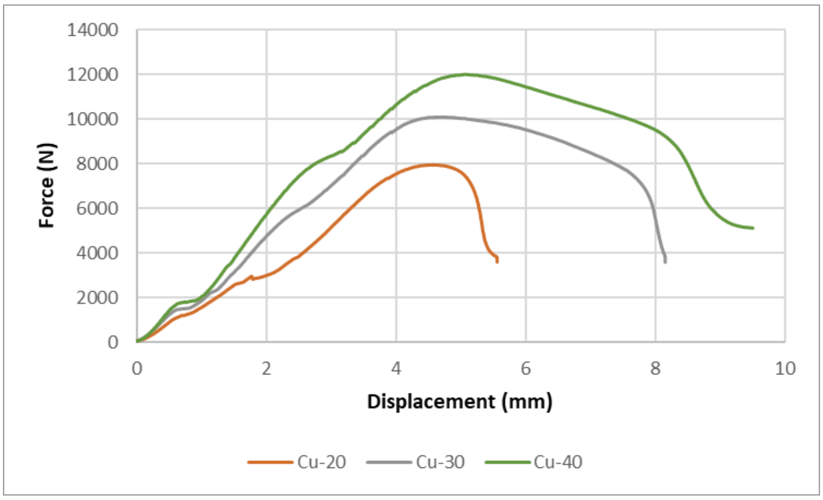

Figure 7. Force-displacement curves of the samples with a cubic infill pattern

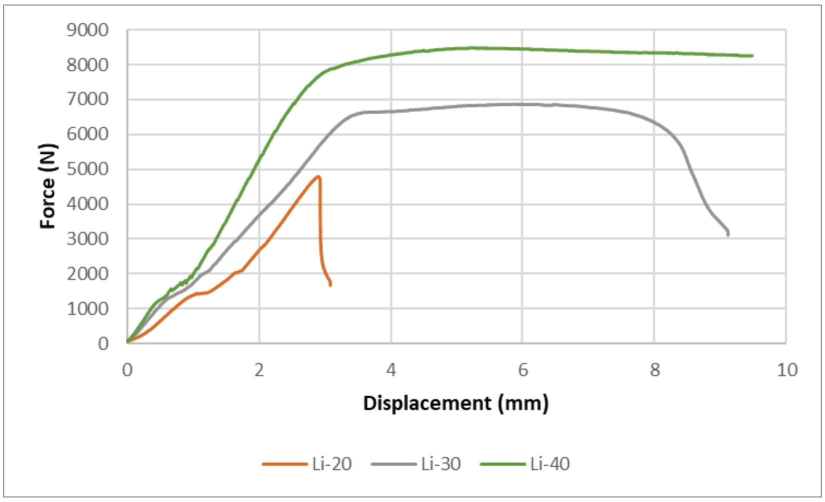

Figure 8. Force-displacement curves of the samples with a line infill pattern

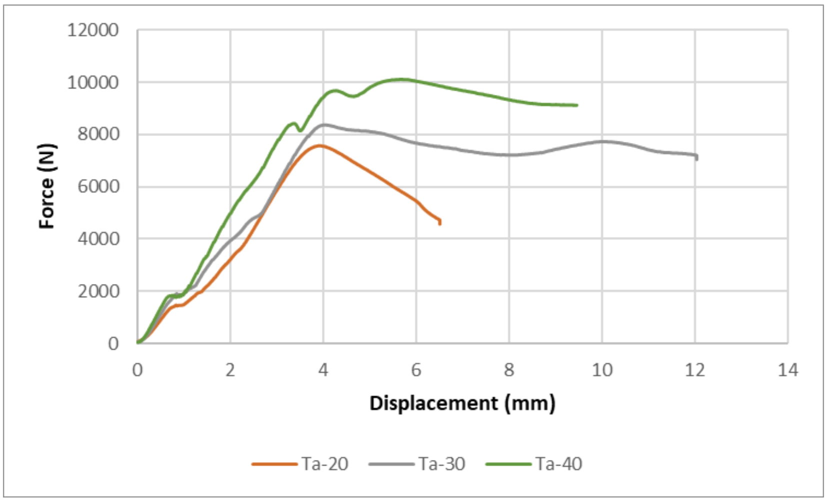

Figure 9. Force-displacement curves of the samples with a tri-angular infill pattern

Figures 7-12 illustrate the force-displacement graphs for all infill patterns at different densities. By examining these graphs, it is evident that the strength of the samples increases as the infill density increases. This conclusion can be inferred without the need for conducting tests. However, delving into numerical data, when considering the percentage increase in strength based on the maximum loads achieved as the range that corresponds to infill densities between (20% to 30%) and (30% to 40%), the sample with the Cu pattern shows an increase of 25% and 20% in strength, respectively, while the sample with the Li pattern exhibits an increase of 31% and 20%, respectively. According to these findings, the two sample types with the highest percentage increase in strength due to infill density are Cu and Li patterns. When considering the high strength exhibited by concentric and grid-type fillers (Mohammadreza et al., 2021), it would not be wrong to expect these types of specimens to show more positive differentials than density increase. The reason for the significant impact of density increase on these two samples lies at the low bonding areas in low infill densities. On the other hand, while the sample with a cubic pattern demonstrates the best performance, the sample with a line pattern exhibits the lowest performance. This result indicates that the infill pattern is the most crucial parameter for determining the strength of the component under this type of loading condition.

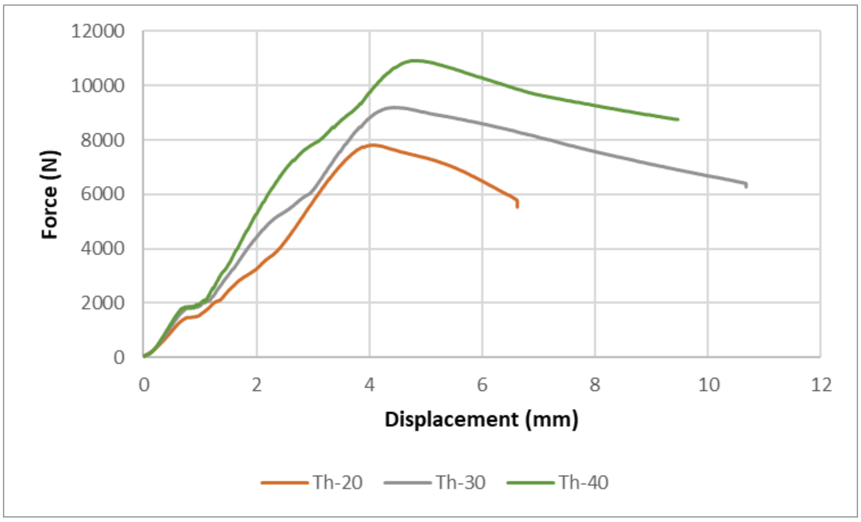

Figure 10. Force-displacement curves of the samples with a tri-hexagonal infill pattern

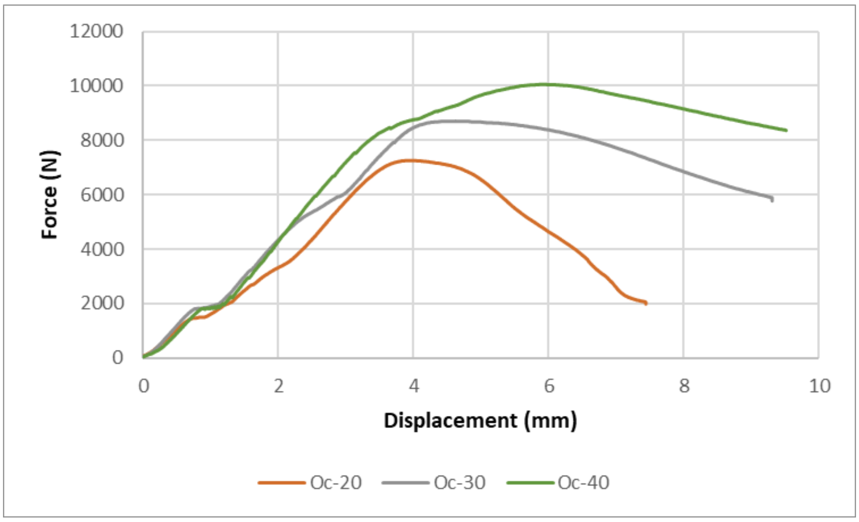

Figure 11. Force-displacement curves of the samples with an octet infill pattern

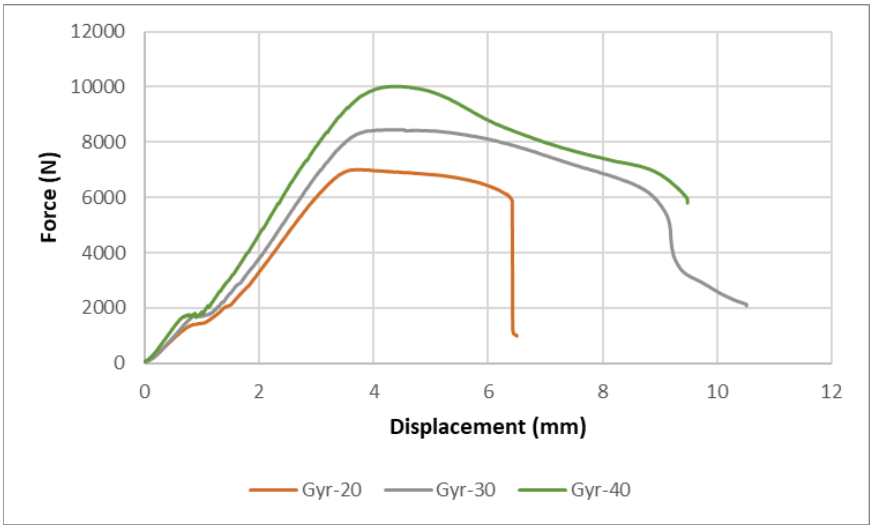

Figure 12. Force-displacement curves of the samples with a gyroid infill pattern

4. Conclusion

In this study, the mechanical properties and damage behavior of sandwich structures fabricated using the FDM technique with different infill patterns and densities were investigated. The results obtained provide valuable insights and important conclusions regarding the performance of the structures. Based on the force-displacement graphs and analysis of damage modes, several significant findings can be summarized. The samples with a cubic infill pattern consistently exhibited higher strength compared to other patterns at all infill densities. This indicates the crucial role of the infill pattern in determining the strength of the components. Furthermore, as the infill density increased, the bonding between the facesheet and core improved, resulting in higher load-carrying capacity and a more balanced force distribution.

The Li infill pattern showed the lowest performance, indicating its weakness in terms of vertical loads. On the other hand, the samples with Ta, Th, Oc, and Gyr patterns yielded similar results, suggesting comparable performance in terms of maximum load capacity. The tri-angular and tri-hexagonal patterns exhibited facesheet compression damage at all densities, highlighting their weaker bonding capabilities between the facesheet and core. The octet pattern demonstrated excellent bonding properties, with core shear damage observed at lower densities and facesheet buckling damage occurring at higher densities. The gyroid pattern exhibited strong bonding between the core and facesheet, although the core section appeared to be weaker against vertical loads due to its pattern structure.

The analysis of force-displacement graphs for all infill patterns at different densities revealed a clear trend: Increasing the infill density led to higher strength in the samples. Notably, the Cu and Li patterns exhibited the highest percentage increase in strength as the infill density increased. This finding emphasizes the importance of infill pattern in achieving improved mechanical properties.

In conclusion, this study highlights the significant influence of infill pattern and density on the mechanical behavior and damage characteristics of sandwich structures fabricated through FDM. The results provide valuable insights for optimizing the design and manufacturing process of such structures, particularly in terms of achieving enhanced strength and understanding the failure modes. Further research can focus on exploring additional infill patterns and optimizing the infill density to further improve the performance of FDM-printed sandwich structures.

Conflict of Interests

None declared

Researcher Contribution Statement

The author declares that he has contributed 100% to the article.

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