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EFFECTS OF 3D PRINTED PLA FILLER ON THE LATERAL CRUSHING BEHAVIOR OF NATURAL FIBER JUTE REINFORCED COMPOSITE TUBES

3B BASKIYLA ÜRETİLEN PLA DOLGU MALZEMESİNİN DOĞAL JÜT ELYAF TAKVİYELİ KOMPOZİT BORULARIN YANAL EZİLME DAVRANIŞI ÜZERİNDEKİ ETKİLERİ

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ABSTRACT

Composite materials continue to be an indispensable part of engineering applications. Their use is increasing due to their strength, lightness, and good performance in energy absorbing components. In this study, composite tubes were produced by infusing jute fiber, a natural fiber, with epoxy resin. Unlike traditional production methods for cylindrical composites, the vacuum infusion method was used. Three different types of filler materials, produced using a 3D printer, were placed inside the tubes, and their peak force, energy absorption, and specific energy absorption values were compared. The filler geometries used were linear, hilbert, and hexagonal honeycomb structures. Comparisons were made between jute fiber reinforced epoxy resin matrix composite (JFRP) without filler and the composite itself. The highest peak strength value was determined to be 1.94 kN in the JFRPHH sample with hexagonal honeycomb filler. The highest energy absorption and specific energy absorption were also obtained with the hexagonal honeycomb filled composite sample. The obtained values were 12.85 joules and 0.331 J/g, respectively. The lowest energy absorption value was obtained with the sample without filler; the obtained value was 6.70 joules. It was observed that the addition of filler material affected the peak strength and energy absorption values of the composite samples.

Keywords: Energy absorption, hexagonal honeycomb, natural fiber

ÖZET

Kompozit malzemeler, mühendislik uygulamalarının vazgeçilmez bir parçası olmaya devam etmektedir. Mukavemetleri, hafiflikleri ve enerji emici bileşenlerdeki iyi performansları nedeniyle kullanımları artmaktadır. Bu çalışmada, doğal bir lif olan jüt lifi, epoksi reçine ile infüzyon yöntemi kullanılarak kompozit tüpler üretilmiştir. Silindirik kompozitler için geleneksel üretim yöntemlerinden farklı olarak, vakum infüzyon yöntemi kullanılmıştır. 3B yazıcı kullanılarak üretilen üç farklı dolgu malzemesi tüplerin içine yerleştirilmiş ve tepe kuvveti, enerji emilimi ve özgül enerji emilimi değerleri karşılaştırılmıştır. Kullanılan dolgu geometrileri doğrusal, hilbert ve altıgen petek yapılardır. Dolgusuz jüt lifi takviyeli epoksi reçine matris kompoziti (JFRP) ile kompozitin kendisi arasında karşılaştırmalar yapılmıştır. En yüksek pik kuvveti değeri, altıgen petek dolgulu JFRPHH numunesinde 1,94 kN olarak belirlendi. En yüksek enerji emilimi ve özgül enerji emilimi de altıgen petek dolgulu kompozit numunede elde edildi. Elde edilen değerler sırasıyla 12,85 joule ve 0,331 J/g idi. En düşük enerji emilimi değeri ise dolgusuz numunede elde edildi; elde edilen değer 6,70 joule idi. Dolgu malzemesinin eklenmesinin kompozit numunelerin tepe dayanımı ve enerji emilim değerlerini etkilediği gözlemlendi.

Anahtar Kelimeler: Enerji absorpsiyonu, altıgen petek, doğal fiber

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INTRODUCTION

As the application areas of composite materials increase, the number of studies conducted is also increasing in parallel. Researchers focus on improving mechanical properties in their studies. These include peak strength values and energy absorption values (Kosedag et al., 2025; Kosedag, 2023). Lightness is one of the main reasons for choosing composite materials (Turan & Erkek, 2019). In some studies, it is desired to improve the mechanical properties of composite tubes, especially those produced in the form of cylindrical pipes, by adding filler material to them (Awd Allah et al., 2025; Altin et al., 2017). While doing this, researchers generally try to avoid causing a significant increase in the weight of the composite material by using lightweight filler material.

Wang et al. investigated the crash resistance of aluminum foam-filled crash boxes. They stated that the foam design with partial filling at the four corners increased the specific energy absorption value by 12.5% compared to the classic full-fill design. They also found that material savings were achieved by reducing the proportion of foam material used. Özen et al. (2023) conducted research on hollow and solid composite crash boxes. They examined square, hexagonal, and cylindrical carbon fiber reinforced composite crash boxes. They used fillings they produced as square, hexagonal, and cell-filled. They stated that cell-filled composite crash boxes showed good performance in terms of energy absorption. Awd Allah et al. (2023) investigated five different filling pattern structures in their study. They examined the energy absorption properties of circular, square, triangular, zigzag, and cross structures. They stated that the square filling pattern performed better than the other patterns. In another study, Awd Allah et al. (2024) investigated the collision resistance of 3D cellular structures. They examined gyroid, honeycomb, Schwarz P, and Schwarz D patterns. They stated that the honeycomb pattern structure yielded good results. Djumaladdin (2024) investigated the effect of foam filling in foam-filled crash boxes. Instead of completely filling the crash box with foam filling, he tried to determine the optimum energy absorption and peak force values by placing the foam filling in different ways inside. Hou et al. (2023) conducted a study on lattice-structured crash boxes produced with a 3D printer. In their study, they produced collision boxes of hexagonal, kagome, triangular, and re-entrant types. They stated that the use of the kagome structure in collision boxes would be suitable in terms of performance. Xie et al. (2022) investigated vinyl ester resin composite fibers in their study. They examined their effects on Nomex honeycombs. They determined that carbon fiber reinforced vinyl ester resin matrix composites greatly reduced the specific energy absorption of Nomex honeycombs. Liu et al. (2023) investigated lattice-filled multicellular tubes in their study. They examined carbon fiber reinforced polyamides with the help of a 3D printer. They found that the energy absorption of lattice-filled tubes increased by 55.6% compared to empty cell tubes. Huo et al. (2023) investigated the properties of auxetic circular and square tubes filled with aluminum foam in their study. They stated that the foam-filled square tube showed the best value in terms of specific energy absorption. They concluded that the energy absorption of the tube filled with foam was higher than the sum of the energy absorption of the foam and the tube separately.

Although the studies focus on filler materials, sometimes the fillers are added to epoxy resin instead of inside the composite tube to affect its mechanical properties, which has attracted the attention of researchers. The added nanoparticles are sometimes pumice, as well as materials such as carbon nanotubes or graphene produced under laboratory conditions, and have been the subject of study for many researchers (Erkek et al., 2025; Ahmad et al., 2024; Ekici & Kosedag, 2017). Of course, some researchers have tried to affect the mechanical properties by changing the type of filler, i.e., by making changes to the filler geometry. Zhang et al. (2022) conducted a study on the energy absorption of composite tubes with hexagonal and indented honeycomb fillers. In their study, they 3D printed the honeycomb filler of the composite tube. They compared the hexagonal-filled honeycomb and the indented honeycomb filled tubes. They stated that the indented-filled structure had better ductility and that the experimental and numerical results were consistent with each other. Saeed et al. (2025) investigated the compressive strength and energy absorption properties of triangular, hexagonal, triangular grid, honeycomb, gyroscope, cubic, and concentric fillers produced by 3D printing. They stated that the triangular, hexagonal, and triangular grid models showed the best performance in terms of compressive strength and energy absorption values. Alagumalai et al. investigated the filler density in nylon fiber-reinforced composites produced by printing. They determined the filler patterns as 2D (line, grid, cross, and triangular-hexagonal) and 3D (cubic, gyroid, octagonal, and cross 3D). They determined the parameters by increasing the density by 20% in increments of 40% until it reached 100%. They stated that the 2D patterns showed better results.

Numerous studies exist in the literature regarding composite tubes. The commonly used fiber types are readily available glass and carbon fibers. Various methods have been employed for the filling process. Mechanical properties

have sometimes been investigated using metallic materials as fillers. In our study, jute fiber, a sustainable natural fiber widely available on the market, was used. Furthermore, instead of the commonly used filament winding or hand lay-up methods for the production of composite tubes, the vacuum infusion method was employed. The filler used in the composite tubes was polylactic acid (PLA), a biodegradable filament produced using a 3D printer. Three filler types were selected: linear, hexagonal-honeycomb, and Hilbert. These three fillers were placed inside epoxy resin matrix composite tubes and compared with empty cylindrical tubes and with each other. The comparison parameters were peak force, energy absorption, and specific energy absorption values used to compare the different materials.

MATERIALS and METHODS

Cylindrical composite tubes were produced using jute fiber, which has a natural fiber structure. Jute fiber was chosen because of its widespread availability in the market and its natural properties. The epoxy resin and hardener were sourced from Dost Kimya Limited, a company operating in Turkey. The epoxy used is LR 160, and the hardener is LH 160. The jute fiber was wound onto a cylindrical spool in nine layers. The production length was set at 30 mm. The inner diameter of the sample was 33 mm, depending on the spool it was wound onto. The fillers placed inside the produced empty samples were manufactured using a 3D printer. Three different filler types were determined. The filament type used in the 3D printer is PLA, which is polylactic acid. It was chosen because of its low melting point and superior chemical compatibility, making it suitable for many printers. It was also preferred because its lightweight structure does not significantly affect the weight of the composite. First, empty cylindrical tubes (JFRP) were produced, and then the fillers were placed inside. When naming the samples, letters according to the filler material placed inside were added to the end of the JFRP jute fiber reinforced composite material. The distinguishing characteristics of the samples are given in Table 1.

Table 1. Characteristics of the Samples

Sample Name	Form of filler material
JFRP	None
JFRPLI	Linear
JFRPHI	Hilbert
JFRPHH	Hexagonal honeycomb

Before production began, the fibers were cut to appropriate sizes. Then, to ensure a seal in the vacuum infusion method, cardboard spools were wrapped around the fibers using tape, making them ready for winding. After the fibers were wound, a separator fabric and grid were wrapped around them, and then they were placed in a nylon bag for sealing. Epoxy resin and hardener were mixed at a 25% ratio and stirred for 10 minutes to ensure a homogeneous distribution. Epoxy resin was applied to one side, and vacuuming was performed. The samples were left at room temperature for 1 day to cure the epoxy. Then, the nylon, grid, and separator fabric were removed, and the samples separated from the cardboard inside were cut. The production process is shown in Figure 1. The cutting process was carried out using the Metcon Metacut device located in the laboratory of Van Yüzüncü Yıl University. Then, PLA filler materials suitable for the sample dimensions were produced using a 3D printer and placed inside the samples (Figure 2). The flowchart of the study is given in Figure 2. Three different filler materials were selected: linear, Hilbert, and hexagonal honeycomb filler materials.

The tests were conducted at Van Yüzüncü Yıl University. A Raagen brand device was used in the laboratory. Quasi-static compression tests were applied to the samples at room temperature. The test speed was selected as 2 mm/min (Li et al., 2025). Stress-displacement curves were obtained during the test. This curve was converted into a force-displacement curve, and the area under it was calculated. Thanks to this area, the energy absorption values of the composite tubes could be calculated. MATLAB program was used to perform this calculation. The calculation was done using the trapz command in this program. Peak force, another property, is also one of the experimental outputs. The last property is the specific energy absorption value, which is used to compare different materials. This value is calculated by dividing the energy absorption value by the weight. Related formulas;

$$SEA = \frac{EA}{m} \quad (1)$$

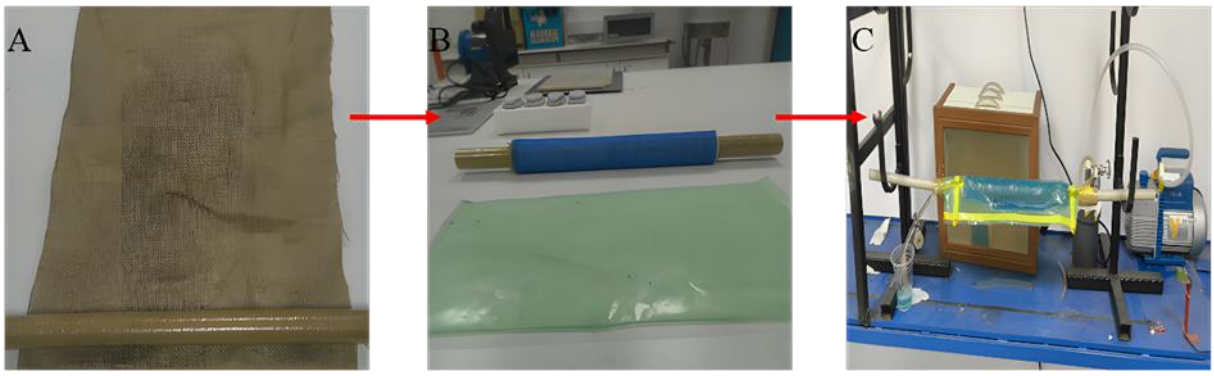

Figure 1. Production Stage

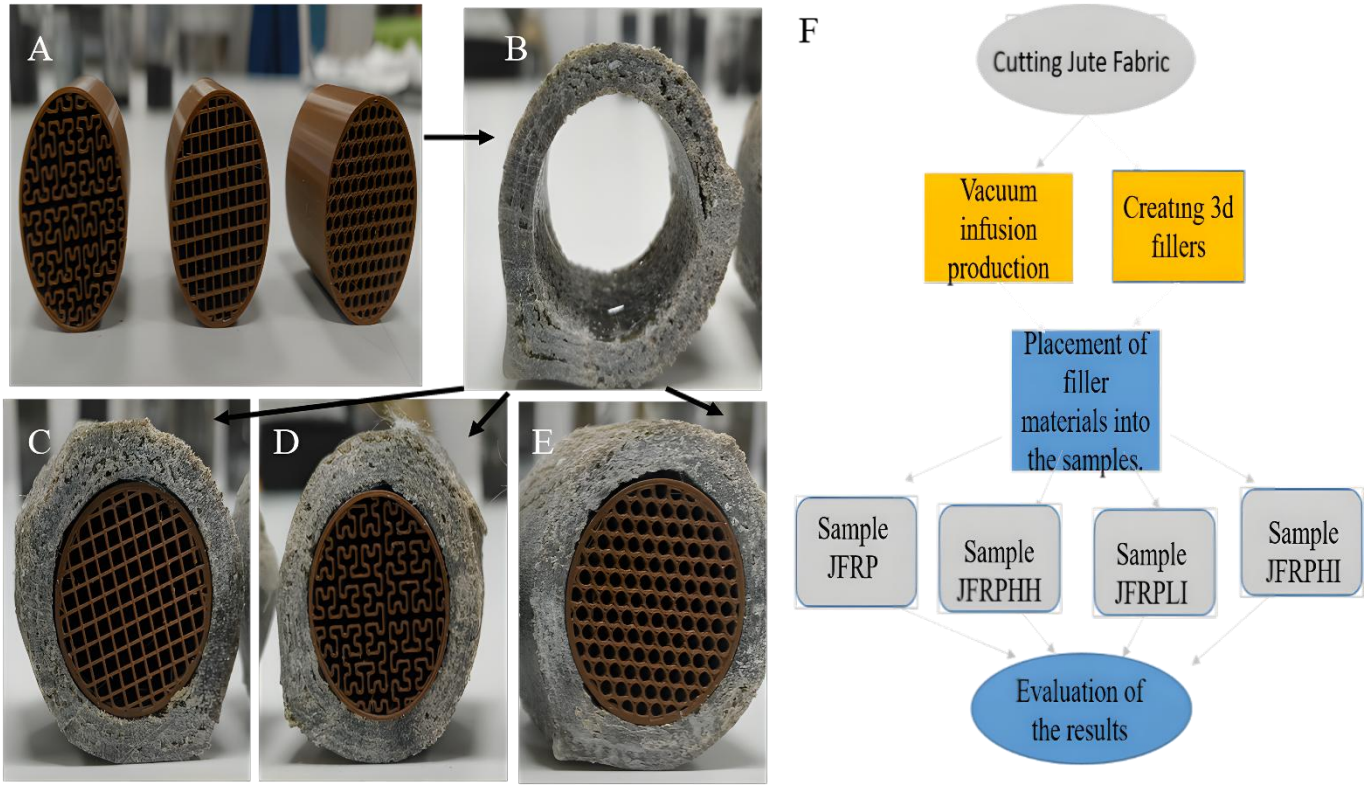

Figure 2. Placement of the Produced Filler Materials into the Composites A) Shapes of the Filler Materials, B) Hollow Composite Tube (JFRP), C) Linear-Filled Specimen (JFRPLI), D) Hilbert-Filled Specimen (JFRPHI), E) Hexagonal Honeycomb-Filled Specimen (JFPRHH), F) Flowchart

RESULTS and DISCUSSION

In this section, the force-displacement curves of JFRP – JRPHH samples were examined, and the peak force values, energy absorption values, and specific energy absorption values of these samples were investigated. The force-displacement curves of JFRP, JFRPLI, JFRPHI, and JRPHH samples are given in Figure 3.

As shown in Figure 3, the first sample, a jute fiber reinforced epoxy resin matrix composite tube (JFRP) without any filler material, reached a peak strength of 0.85 kN. Calculating the under-curve, the resulting value was 6.70 joules. This value represents the energy absorption value of that sample. Energy absorption is an important property in composite tubes as it reflects the amount of energy a sample will absorb under impact. Another property is the specific energy absorption value, which depends on the weight of the sample. The calculated value for the JFRP sample was

0.294 J/g. During the experiment, the sample fractured at the lower compression jaw and attempted to bend inwards (Figure 4). Delaminations were also observed on its sides. Diameter-to-thickness ratios affect the damage mechanisms. Due to the elliptical structure formed during compression, matrix and fiber fractures were also observed during the experiment. The structural changes during and after the experiment for this sample are shown in Figure 4.

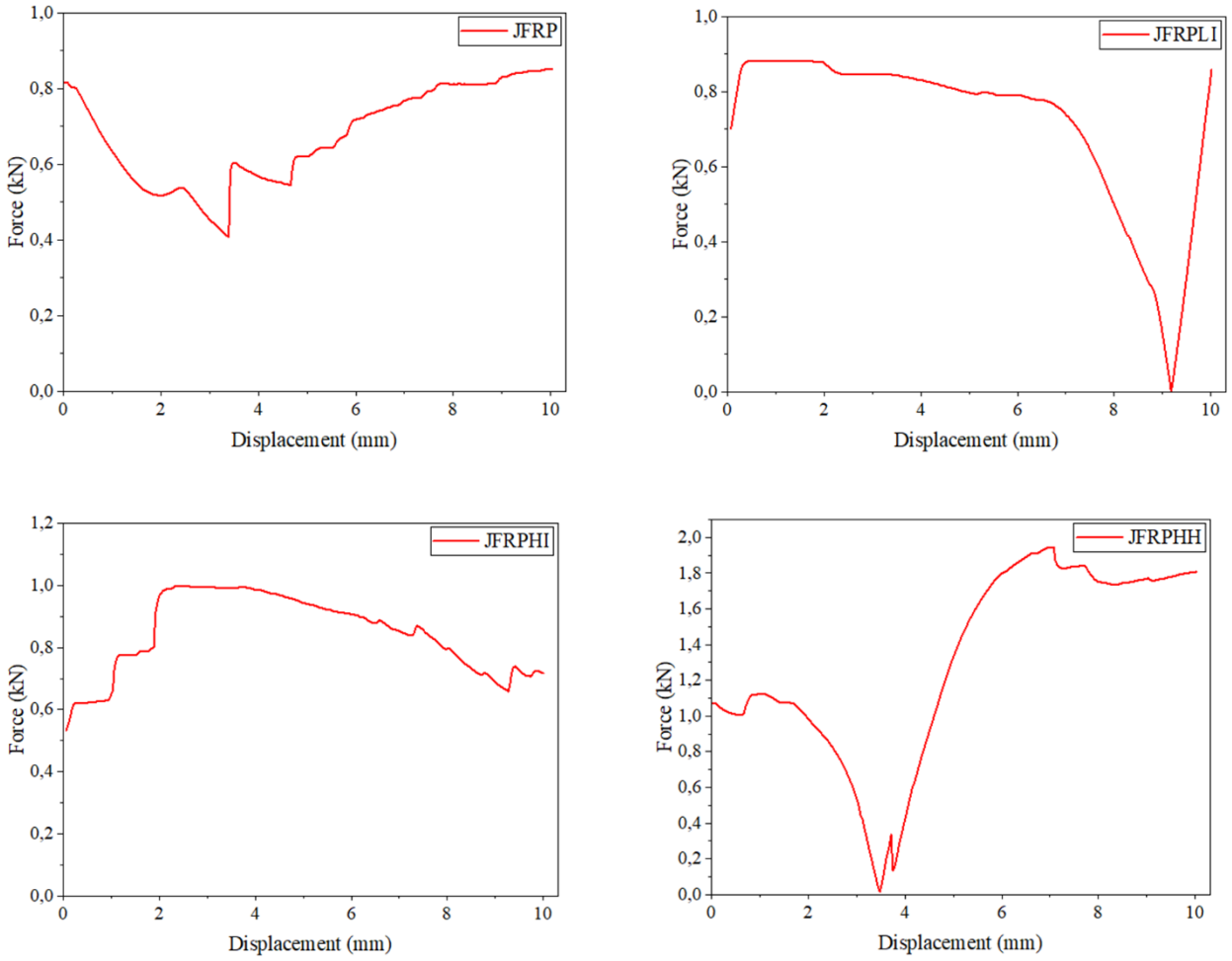

Figure 3. Force-Displacement Curves for JFRP - JFRPHH Samples

The other sample, a JFRP sample containing a linear, geometrically packed material produced with PLA using a 3D printer, showed slight variations in values. The peak force obtained was 0.88 kN. This value is 3.52% higher than the JFRP sample without the packed material. The energy absorption value was calculated as 7 joules. The PLA packed material provided a very slight increase, with a 4.47% increase in energy absorption. Although these two values appear to have increased, the situation in specific energy absorption is the opposite. The addition of the packed material added extra weight to the sample. The specific energy absorption value calculated for this sample was 0.197. This value is approximately 32.99% lower than that of the JFRP sample without the packed material. During the experiment, fiber and matrix fractures were observed due to circumferential stresses at the contact point of the compression jaws and on the sides of the side tube. The packed material inside was also crushed due to this force. The force transfer caused the sample to transform into the shape shown in Figure 5, depending on its strength. The structural changes in the sample during the experiment and the images obtained after the experiment are given in Figure 5.

To understand the effects of different filler materials, another sample was filled with a filler material called Hilbert. This was also produced using a 3D printer and placed inside the JFRP composite. The peak force value obtained with this sample, called JFRPHI, was 0.99 kN. This value is higher than both the JFRP sample without filler and the JFRPLI sample with linear filler, by 16.47% and 12.50%, respectively. Another output value was the energy absorption value, calculated as 8.36 joules in this sample. This value is also higher than the other two samples.

Changing the filler type had a positive effect on the peak force and specific energy absorption values. The energy absorption value obtained was 24.77% higher than the JFRP sample and 19.42% higher than the JFRPLI sample. Similar to the linearly filled sample, the increases observed in this sample were not reflected in the peak force and energy absorption in specific energy absorption. The weight of the added filling material is a negative characteristic for specific energy absorption. The specific energy absorption value obtained in this sample was calculated as 0.237 J/g. This value is 20.30% higher than the specific energy absorption value of the JFRPLI, i.e., linearly filled material.

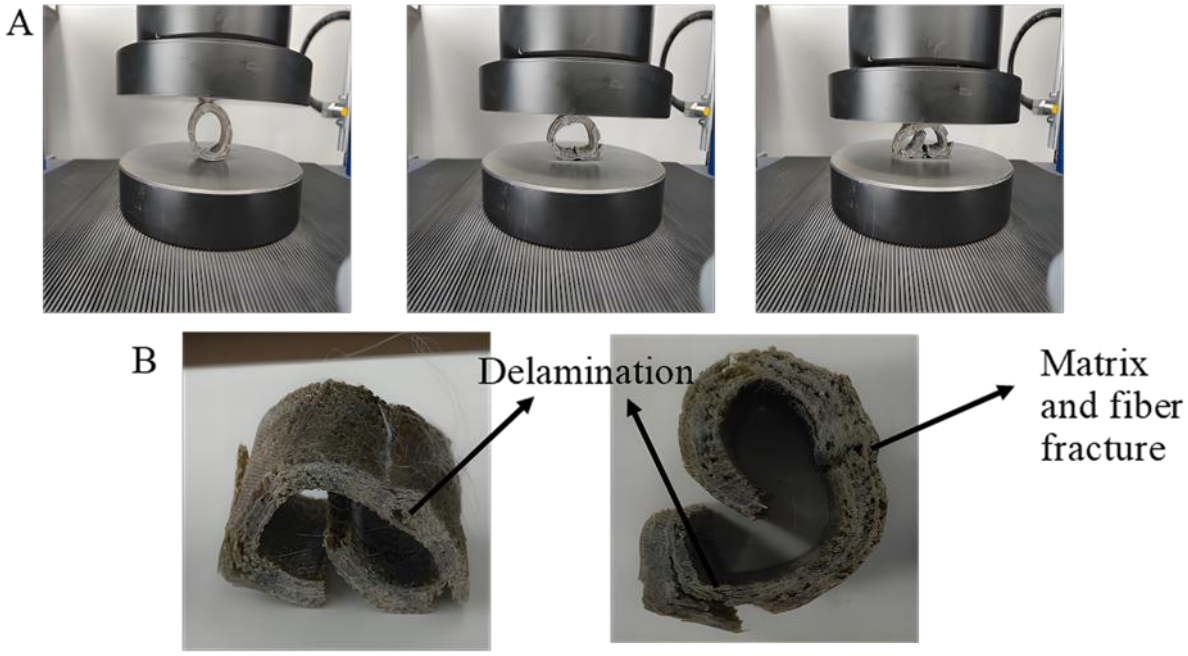

Figure 4. Structural Changes in the JFRP Sample During the Experiment and Subsequent Images.

Figure 5. Structural Changes in the JFRPLI Sample During the Experiment and Subsequent Images

However, it is 19.38% lower than the specific energy absorption value of the JFRP sample without any filling material. Similar observations were made during the experiment as in the other samples. Stresses in the side panels of the tube compressed between the upper and lower jaws caused ruptures in the matrix-fiber interface connections, and subsequently, fiber-matrix fractures and delaminations became inevitable. In the Hilbert filling, a cross-shaped

gap image was formed depending on the applied force (Figure 6). The images of the JFRPHI sample during and after the experiment with structural changes are given in Figure 6.

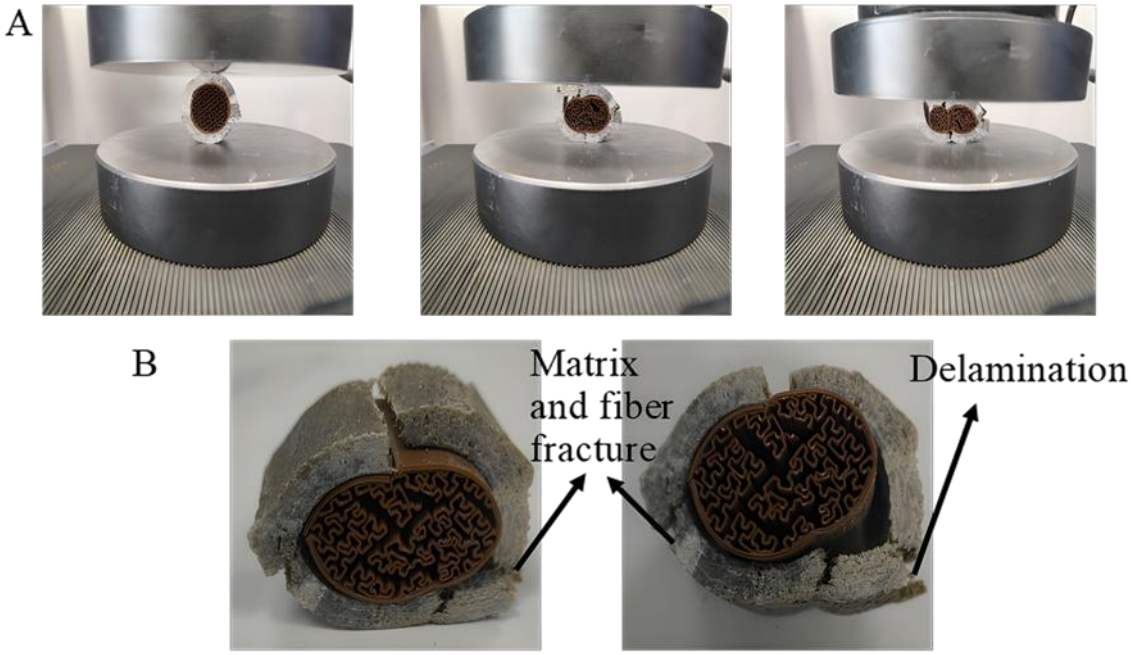

Figure 6. Structural Changes in the JFRPHI Sample During the Experiment and Subsequent Images

Our latest filled sample, the JFRPHH sample, filled with a hexagonal honeycomb structure inspired by nature and used in many fields, achieved a peak force value of 1.94 kN. This value is higher than the values obtained with all other samples. It is 128.23% higher than the unfilled JFRP sample. It is also 120.45% and 95.95% higher than our other two samples, namely the linearly filled JFPRLI and the Hilbert-filled JFRPHI samples, respectively. Energy absorption values also showed significant increases, similar to peak force. The energy absorption value obtained with this sample was 12.85 joules. This value is 90.37% higher than the unfilled JFRP sample. Compared to the other JFRPLI and JFRPHI samples, it is 83.57% and 53.70% higher, respectively. Another difference of this sample is that the increases in peak force and energy absorption values are also reflected in the specific energy absorption. The calculated specific energy absorption value was 0.331 J/g. Although not as high as the increase in peak force or energy absorption values, the value increased by 12.58% compared to the JFRP sample. Compared to JFRPLI and JFRPHI samples, these increases were calculated as 68.02% and 39.66%, respectively. The positive contributions of the hexagonal honeycomb filling on the mechanical properties of the material were clearly observed. During the experiment, delaminations and fiber fractures, followed by matrix fractures, similar to those in other samples, were observed (Figure 7). These fractures and delaminations were observed at the contact point of the compression jaws and on the sides. Images of this sample during and after the experiment are given in Figure 7.

Peak force values, energy absorption values, and specific energy absorption values for JFRP and JFRPHH samples are given in Table 2. Comparative graphs of these values are also given in Figure 8.

Peak force is defined as the maximum compressive force recorded during the lateral crushing test and represents the initial resistance of the composite tube to deformation. While a higher peak force indicates greater structural stiffness, excessively high peak force values are not always desirable in energy-absorbing applications, as they can transmit large impulsive loads to surrounding structures during the initial moment of impact. Energy absorption (EA) is calculated as the area under the force-displacement curve and quantifies the total mechanical energy dissipated by the specimen during crushing. This parameter directly reflects the capacity of the composite tube to absorb kinetic energy under impact loading conditions, making it a primary design criterion for crashworthiness applications such as automotive crash boxes and protective structural components.

Specific energy absorption (SEA), calculated by dividing the energy absorption value by the mass of the specimen, is a weight-normalized metric that allows meaningful comparison between specimens of different masses and material configurations. SEA is considered the most critical parameter in crashworthiness assessment because it reflects the energy absorption efficiency per unit mass, which is particularly important in lightweight structural

design. In this study, the sample weights were measured as follows: JFRP 22.79 g, JFRPLI 35.53 g, JFRPHI 35.28 g, and JFRPHH 38.82 g. The considerably higher mass of the filled samples relative to the unfilled JFRP explains why the linear and Hilbert-filled samples exhibited lower SEA values despite their higher absolute energy absorption. Only the hexagonal honeycomb filler achieved sufficient energy absorption to offset its additional mass contribution, resulting in a SEA value of 0.331 J/g, which exceeded that of the unfilled JFRP sample (0.294 J/g) by 12.59%.

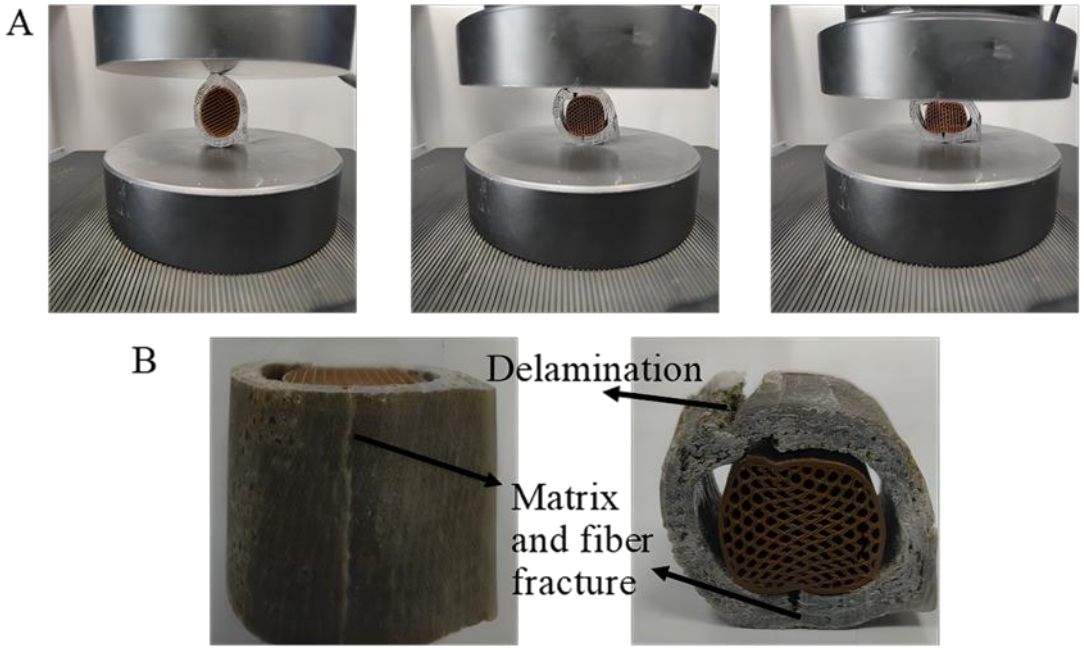

Figure 7. Structural Changes in the JFRPHH Sample During the Experiment and Subsequent Images

Table 2. Peak Force Values, Energy Absorption Values and Specific Energy Absorption Values for JFRP - JFRPHH

Samples	Peak force (kN)	Energy absorbtion (J)	Spesific energy absorbtion (J/g)
JFRP	0.85	6.70	0.294
JFRPLI	0.88	7.00	0.197
JFRPHI	0.99	8.36	0.237
JFRPHH	1.94	12.85	0.331

Naturally, the shape of the filler material also affects the energy absorption values depending on its force transfer and absorption. Linear filler type exhibits low energy absorption, while Hilbert-filled material gives slightly better results. Honeycomb-structured filler material gives the highest result. In the specific energy absorption, a method of comparing different types of materials, different results were obtained from the other two comparison values. Although the honeycomb structured filler stood out in this value obtained by dividing the energy absorption by the weight, the high result was immediately followed by the unfilled JFRP sample as seen in Figure 8. In the other two filler types, namely Hilbert and linear filler types, low values were observed because the weight they added to the cylindrical tube was greater than the increase they affected in energy absorption. The mechanical properties of honeycomb structure composites have been reported by researchers (Bader et al., 2025). It is a predictable result that the mechanical properties are affected by the filling materials. The type of filling material used, i.e., its components and geometric shape, also has an effect on the mechanical properties. The hexagonal honeycomb filled structure showed better results because it provides geometric stability and efficiently distributes the load(Awd Allah, Abd El-Halim, et al., 2025; Özen et al., 2023). The results obtained in this study demonstrate that the geometry of the filler material plays a decisive role in determining the mechanical performance of jute fiber reinforced composite tubes under lateral compression.

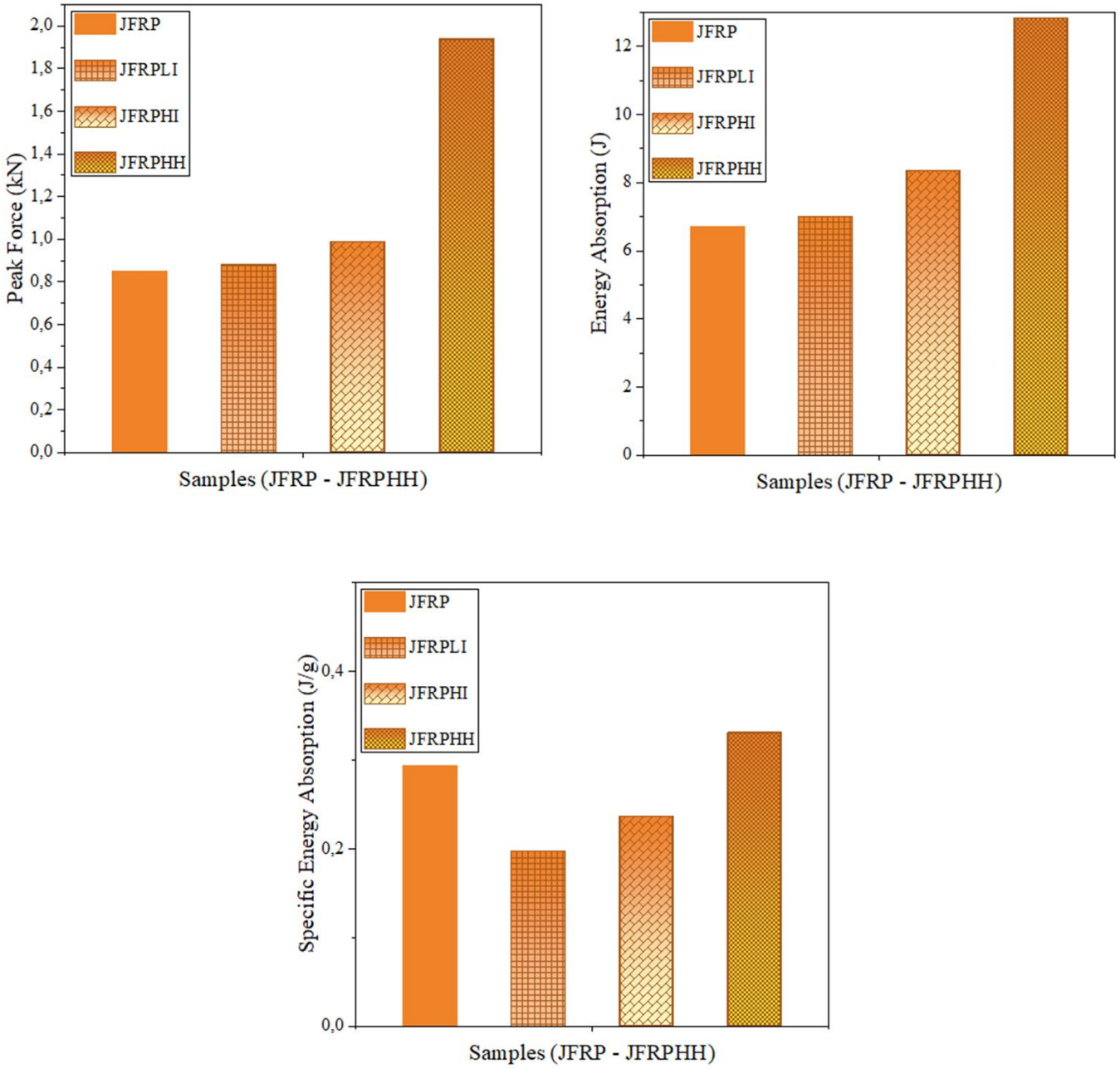

Figure 8. Comparative Graphs of Peak Force Values, Energy Absorption Values and Specific Energy Absorption Values for JFRP and JFRPHH Samples

As seen in Figure 8, peak force and energy absorption values show a progressive increase from the unfilled JFRP sample toward the hexagonal honeycomb filled JFRPHH sample, indicating that filler geometry is a more influential factor than the mere presence of filler material. The linear filler provided only marginal improvements in peak force (3.52%) and energy absorption (4.47%) compared to the unfilled sample. This limited contribution can be attributed to the simple geometric arrangement of the linear structure, which does not effectively distribute compressive loads across the cross-section of the tube. As a result, the additional weight introduced by the linear filler outweighed its mechanical contribution, leading to a significant reduction in specific energy absorption (32.99% lower than JFRP). The Hilbert filler, with its more complex space-filling geometry, offered intermediate performance. The 16.47% increase in peak force and 24.77% increase in energy absorption compared to the unfilled sample suggest that the greater surface contact and more intricate load transfer pathways of the Hilbert structure contribute positively to the mechanical response. However, the weight penalty associated with this filler still resulted in a lower specific energy absorption value (0.237 J/g) compared to the unfilled tube (0.294 J/g), indicating that the geometry alone is insufficient to offset the mass increase. The hexagonal honeycomb filled JFRPHH sample exhibited by far the most favorable mechanical performance across all measured parameters. The 128.23% increase in peak force and 90.37%

increase in energy absorption relative to the unfilled JFRP sample clearly demonstrate the structural efficiency of the honeycomb architecture. Unlike the linear and Hilbert fillers, the hexagonal honeycomb geometry also yielded a higher specific energy absorption value (0.331 J/g) than the unfilled sample, confirming that this filler type achieves an effective balance between weight and mechanical contribution. The hexagonal cell arrangement enables uniform load distribution and promotes progressive, stable crushing behavior, which is reflected in the smoother force-displacement curve observed for this sample. The delaminations and fiber fractures observed during testing are consistent with the typical failure modes of natural fiber reinforced composites under lateral compression, and the presence of the honeycomb filler appeared to delay the onset of catastrophic failure by providing internal support to the tube walls. Overall, the findings indicate that not all filler geometries are beneficial in terms of specific energy absorption. The selection of filler geometry must be carefully considered, as fillers that add significant weight without a proportional increase in energy absorption may reduce the weight efficiency of the composite structure. Among the configurations tested, the hexagonal honeycomb filler stands out as the most effective choice for improving both absolute and weight-normalized mechanical performance of jute fiber reinforced composite tubes.

CONCLUSION

This study investigated the effects of 3D-printed filler materials with different geometries inside jute fiber-reinforced composite tubes. PLA filament was used as the filler material, and three different filler geometries linear, Hilbert, and honeycomb hexagonal were employed. Cylindrical tubes were produced using the vacuum infusion method, and peak force, energy absorption, and specific energy absorption values were compared after being subjected to a semi-static compression test with and without filler material. The highest peak force value was obtained with the JFRPHH sample, which had a hexagonal honeycomb filler. Similarly, the highest energy absorption and specific energy absorption values were also obtained with the JFRPHH sample. The lowest results were obtained with the hollow cylindrical tube JFRP, which lacked filler material, in terms of peak force and energy absorption values. The lowest specific energy absorption value was observed in the JFRPLI sample, which had a linear geometry filler. It was determined that the addition of filler material played an enhancing role in peak force and energy absorption in composite tubes. Regarding specific energy absorption, differences have been observed among filler types, and it has been determined that not every filler has an enhancing effect. If fillers are to be used in composite tubes, it is recommended that hexagonal honeycomb fillers are suitable for composite tubes.

Artificial Intelligence Contribution Statement

This manuscript was entirely written, edited, analyzed, and prepared without the assistance of any artificial intelligence tools. Language and grammatical adjustments were made with the help of AI. All content, including text, data analysis, and figures, was solely generated by the authors.

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