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Design and Development of 3D Printed High Performance Textile Structures for Composites

Kompozitler için 3D Yazıcı İle Yüksek Performanslı Tekstil Yapılarının Tasarlanması ve Geliştirilmesi

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DESIGN AND DEVELOPMENT OF 3D PRINTED HIGH PERFORMANCE TEXTILE STRUCTURES FOR COMPOSITES

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ABSTRACT: Three dimensional **(**3D) printers offer a variety of design and geometry options, which are substantially demanded in textile industry. In this study, the aim is to produce neat nylon and glass fiber reinforced 3D printed honeycombs and introduce them into the structural composites to enhance the overall flexural and compressive properties. A significant increase in the mechanical response is observed, both in flexural and compression modes, when compared to sandwich composites with commercial aluminum honeycombs. In particular, the increase in compressive properties of 3D printed glass fiber reinforced nylon structures is attributed to the combined effect of the two factors as the inherent strength of glass fibers and well-designed filler geometry.

Keywords: 3D printer, aerospace, honeycomb, glass fiber, composite.

KOMPOZİTLER İÇİN 3D YAZICI İLE YÜKSEK PERFORMANSLI TEKSTİL YAPILARININ TASARLANMASI VE GELİŞTİRİLMESİ

ÖZET: Üç boyutlu 3D yazıcılar tekstil endüstrisi için çok çeşitli tasarım ve geometri seçenekleri sunmaktadır. Bu çalışmada, 3D yazıcı ile naylon ve cam elyaf takviyeli naylon bal peteği yapılar üretmek ve onları yapısal kompozitlere eğme ve basma özelliklerini geliştirmek üzere entegre etmek hedeflenmektedir. Üç noktadan eğme ve basma mekanik test sonuçları, ticari alüminyum bal peteği dolgulu sandviç kompozitlere kıyasla geliştirilen kompozitlerin oldukça önemli bir iyileştirme sağladığını göstermiştir. Özellikle, 3D yazdırılmış cam elyaf takviyeli naylon yapı dolgulu kompozitlerde basma özelliğinde elde edilen gelişme, cam elyafın kendi mukavemeti ve iyi tasarlanmış dolgu geometrisi olmak üzere iki esas faktörden kaynaklanmaktadır.

Anahtar Kelimeler: 3D yazıcı, havacılık, bal peteği, cam lifi, kompozit

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1. INTRODUCTION

Since the invention of three dimensional (3D) printers, they have attracted a lot of attention in materials and applied research due to proposing unique and fascinating designs and structures [1-2]. One specific application is to use 3D printers in textiles to increase the design range and productivity, particularly in fashion industry [3-8]. Eujin expressed that polymer materials, which are directly printed onto the fabric, produce novel functional products such as orthopedic braces for medical applications and accessories [5]. Traditional knitted textile structures can be also produced by 3D printers [8]. However, the use of these printers is comparably new and limited in areas such as aerospace and composite applications [10]. Nevertheless, these advanced applications are open to novel materials and designs. In aerospace industry, light-weight honeycomb fillers including aluminum and Nomex® are widely preferred [7]. To the best of authors' knowledge, 3D printed honeycomb structures have not been yet explored for their reinforcing ability in composites. Thus, we believed that it can be advantageous to use high performance materials such as Kevlar®, carbon and glass filaments for 3D printed honeycomb structures, as an alternative to commercial aluminum and Nomex® fillers.

In this paper, the objective is to produce neat nylon and glass fiber reinforced 3D printed honeycombs and introduce them into the structural composites to enhance flexural and compressive properties. The mechanical properties of structural composites with 3D printed honeycomb structures are compared to the ones with commercial aluminum honeycombs. The hypothesis here in is that it can be advantageous to reinforce honeycomb fillers with glass fibers to substantially improve the strength and modulus of sandwich composites due to both the inherent strength of fibers and well-designed filler geometry. Our present experimental procedure began with designing honeycomb structures, which can be produced by 3D printers. Then, 3D printed honeycombs were used as fillers in sandwich laminated carbon composites. Next, the mechanical response under flexural and compressive loadings was investigated for the 3D printed honeycomb and aluminum honeycomb reinforced sandwich composites.

2. MATERIALS AND METHOD

2.1. Materials

The commercial aluminum honeycombs (Figure 1a) were supplied by *Methyx Co*, whereas T2/2 patterned carbon prepregs were purchased from *SPM Composite Co*. The other two sets, which are glass fiber, reinforced honeycombs (Figure 1b) and neat nylon honeycombs (Figure 1c) were designed and printed by 3D printer. For nylon filler, nylon filaments were used as raw material and purchased from *Mark-Forged Co*. Nylon filaments were preferred due to their good heat resistance compared to metals [9], as lightweight and strong reinforcement, glass fiber was chosen [11]. Out-of-the freezer time and conditions of the prepregs plies were kept consistent throughout the study.

2.2. Methods

For the production of these novel materials in this work, a variety of techniques and equipment were used. First, honeycomb designs were developed in SolidWorks® (Figure 2a and Figure 2b for compression and flexural test specimens, respectively), and converted into *.stl* file extension to upload to 3D printer software.

Mark-Forged printer (Figure 3a) uses Fused Deposition Modelling (FDM) method [2]. In this approach, printer has two nozzles at the head while one is operating with nylon and the other one is used for fiber replacement as seen in Figure 3b. Nylon filament was heated up to the melting temperature at around 265°C by printer head and guided through printer nozzle. Protruded nylon was immediately solidified by cooling fans and a layer of polymer was formed onto print bed. As FDM principle, printing was accomplished layer by layer. After layering, filling took place as tool path generation.

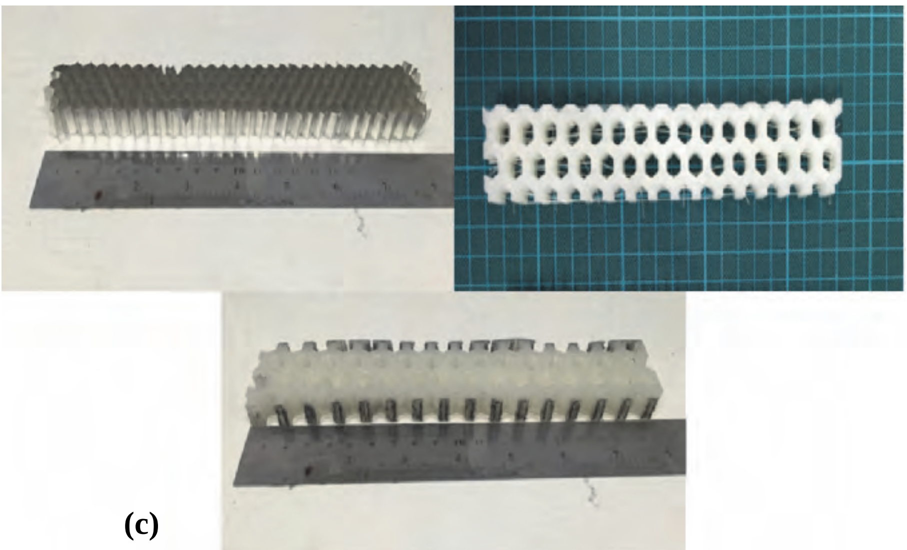


Figure 1. Camera image of a) commercial aluminum honeycomb, b) glass fiber reinforced 3D printed honeycomb structure c) neat 3D printed nylon honeycomb structure

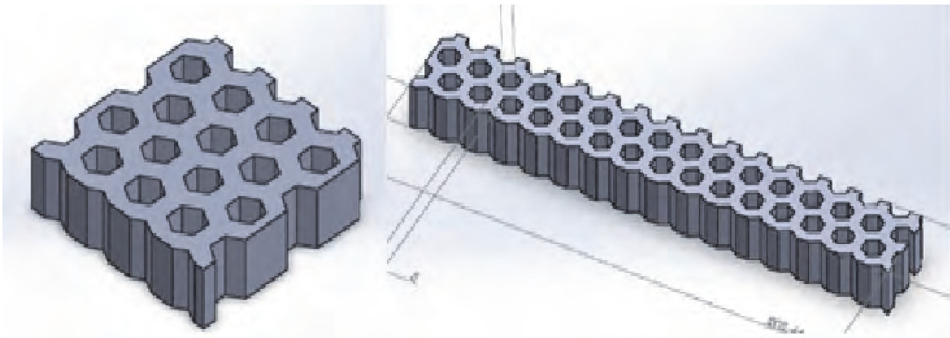
(a)  (b)

Figure 2. SolidWorks drawings of a) compression test specimens, b) flexural test specimens

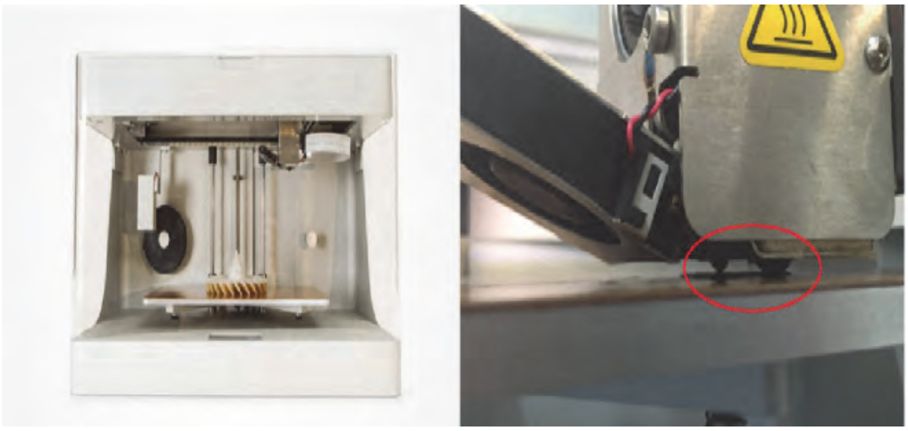
(a)  (b)

Figure 3. a) MarkForged Mark One Printer b) Printer head with two nozzles shown at operation

For the preparation of sandwich composites, each plies and honeycombs were cut into given standard dimensions. Top and bottom surfaces of the honeycombs were encompassed with four plies of carbon prepregs as shown in Figure 4. It is important to note that to fulfill uniformity, twill direction of each plies must be the aligned along the faces. After stacking the plies for intended laminates, each stack was put on a metallic tooling plate along with a release film and peel ply. Another sheet of peel ply was then laid on the pile of plies followed by a nonwoven breather layer, as seen in Figure 4.

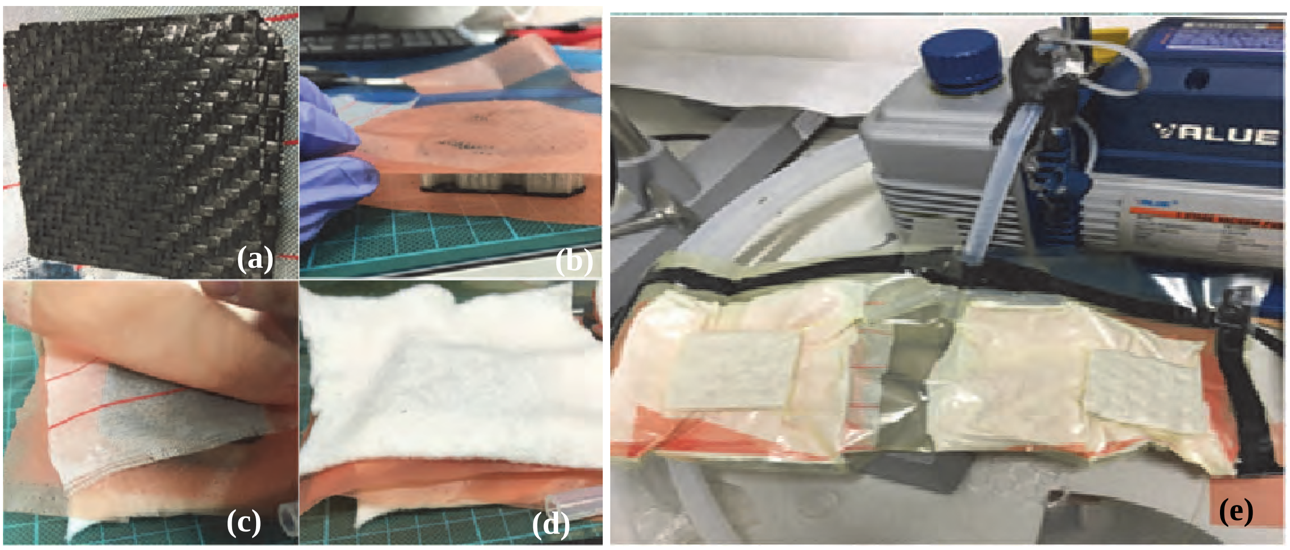


Figure 4. a) Carbon prepreg layers onto the honeycomb structure, b) Release film at the top of carbon prepreg layers, c) Peel ply laid between two layers of release film, d) Breathable fabric placed at the top, e) Vacuum bagging of prepared composites

After ply collation was completed, the tool was sealed into a vacuum bag, and kept under vacuum during the cure cycle. Prepregs stacks were heated up 120˚C at a rate of 3 ˚C/min, and hold time was 2 h. Additionally, in aluminum honeycomb sandwich composites, adhesive tape was placed to obtain effective bonding between aluminum honeycomb and carbon prepregs. The flexural properties of sandwich composites were tested according to ASTM D7250/ D7250M standards by using Universal Test Machine (UTM) -Shimadzu AG-X Plus 100kN whereas ASTM C365/C365M standard was used to investigate the mechanical properties of sandwich composites at compressive loading. The dimensions were set to 30mm x 200mm x 14mm (head speed was 1mm/min) and 50mm x 50mm x 14mm (head speed was 0.5 mm/min), for three-point bending and compression tests, respectively. Each test was repeated at least three times for data analysis.

3. RESULTS&DISCUSSION

Sandwich composites with commercial aluminum, neat nylon and glass fiber reinforced nylon honeycombs were subjected to two different loadings such as 3-point bending (Figure 5a) and compression (Figure 5b). The effect of fiber reinforcement on honeycomb structures was investigated both in compressive and flexural modes, while the applicability of 3D printers was explored for the first time in literature. In each test, ultimate strength and elongation (%) were recorded, and stress/strain curves were provided to monitor the initiation and propagation of different failure mechanisms. Three-point bending results as given in Figure 6, demonstrated that sandwich composites with aluminum honeycombs exhibited the lowest flexural strength, whereas sandwich composites with glass fiber reinforced 3D printed honeycombs revealed three-fold increase in flexural strength (See Table 1). Compared to composites with neat nylon 3D printed honeycombs, glass fiber reinforcement increased flexural properties remarkably, even though only five layers of fiber were replaced on the middle of 100 nylon printed layers. Besides, specimens with 3D printed honeycombs exhibited retarded failure under flexural loadings.

Figure 6 also demonstrates that the 3D printed honeycomb structures provide more durable lightweight solutions to commercial aluminum honeycombs with their easily tunable geometry. Table 1 summarizes mean ultimate strength, mean maximum force and strain at break (%) of each composite. It is pointed out that sandwich composites with 3D printed glass fiber reinforced honeycomb structures increased toughness by increasing both strain (%) and stress values. In addition, fiber replacement increased both yield strength and yield strain (%) compared to other specimens.

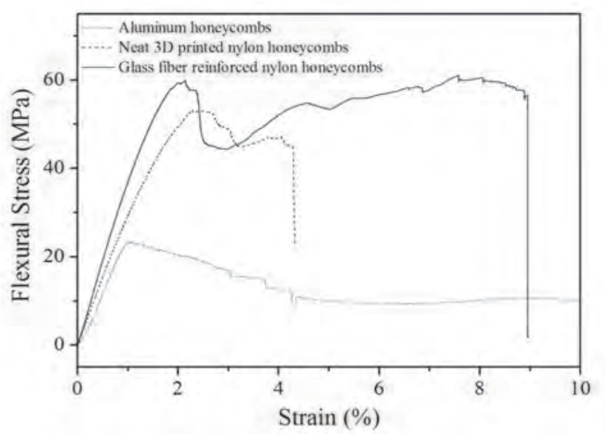


Figure 6. Stress-strain curves of sandwich composites with commercial aluminum, neat nylon and glass fiber reinforced nylon honeycombs under flexural loadings.

Sandwich panels are often subjected to compression. Thus, to investigate out-of-plane compressive strength, as seen in Figure 5b, we also performed compression testing, where Table 2 reveals the compressive behavior of these three different type of honeycomb cores. Figure 7 shows the typical compressive stress-strain curve of materials. The increase in compressive strength due to 3D printed cores is much clearer. Ultimate compressive strength increased around 3.5 and 5.5 fold compared to composites with aluminum cores for composites with, 3D printed neat nylon and glass fiber reinforced nylon honeycombs, respectively. Moreover, 3D printed cores also enhanced the ductility of composites due to their better adhesive properties. Thus, 3D printing of core structure promised much better compressive properties than flexural properties. It is important to note that sandwich composites with glass fiber reinforced nylon honeycombs sustained to higher strains and that leads to retarded deformation.

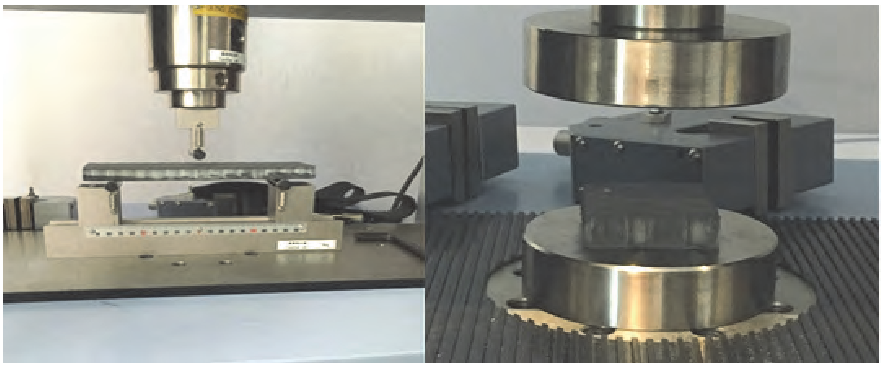
(a)  (b)

Figure 5. a) Three-point bending testing b) Compression testing of sandwich composites

Table 1. Flexural properties of sandwich composites

Sandwich composites with	Maximum Force (KN)	Ultimate Stress (MPa)	Ultimate Strain (%)
Aluminum honeycombs	1.5 (±0.1)	28.7 (±1.4)	1.4 (±0.4)
Neat 3D printed nylon honeycombs	1.4 (±0.4)	53.2 (±5.0)	2.3 (±0.5)
Glass fiber reinforced nylon honeycomb	1.7	61.0	7.6

Table 2. Compressive properties of sandwich panels

Sandwich composites with	Maximum Force (kN)	Ultimate Compressive Stress (MPa)	Ultimate Strain (%)
Aluminum honeycombs	11.3 (±0.4)	-4.5 (0.1)	5.5 (±0.3)
Neat 3D printed nylon honeycombs	46.1 (±1.2)	-17.3 (±0.6)	21.7 (±0.2)
Glass fiber reinforced nylon honeycombs	67.4 (±1.6)	-25.8 (±0.6)	50.0 (±1.6)

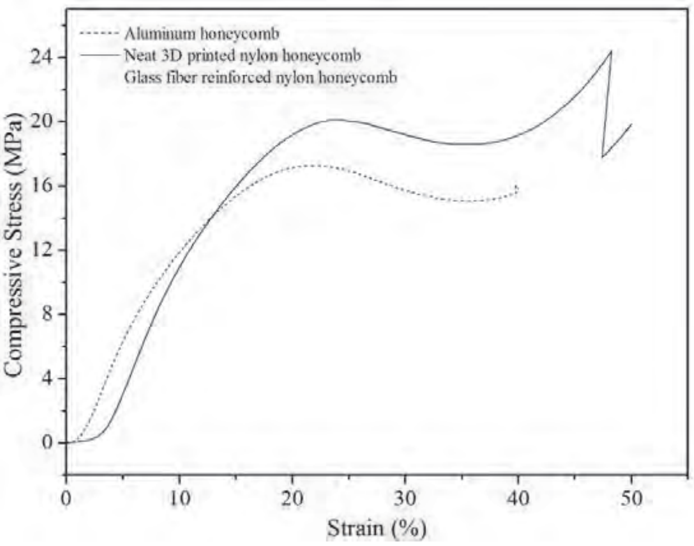


Figure 7. Compressive stress-strain curves of sandwich composites with commercial aluminum, neat nylon and glass fiber reinforced nylon honeycombs under compression loadings.

4. CONCLUSION

This study explored the potential of 3D printers in structural composites by proposing novel honeycomb structures. Test results demonstrated that glass fiber reinforced 3D printed honeycomb sandwich composites have higher mechanical performance than commercial aluminum and 3D printed neat nylon honeycomb structures. These fibers reinforced 3D printed parts might lead to better solutions in aerospace applications due to their lightweight and promising flexural and compressive properties. The significant increase was observed in the mechanical response up to 5.5 fold in compressive strength compared to sandwich composites with commercial aluminum cores. The increase is attributed to the combined effect of the two factors: the strength of glass fiber reinforcement in the structure and tunable filler geometry. In fact, an increase in the flexural strength by nearly 200%, due to glass fiber reinforcement was also noted.

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