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FULL RESEARCH ARTICLE

Failure mechanics of fused filament fabricated nylon/carbon-reinforced composites

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Abstract

This work focuses on understanding the failure mechanisms of nylon-reinforced chopped carbon fiber (Onyx) composite and its reinforcement with carbon fiber printed using different infill patterns, i.e., solid fill, honeycomb, and triangular via fused filament fabrication (FFF) to enhance the sustainable manufacturing processes. The solid fill with carbon fiber reinforcement showcased a maximum tensile strength and flexural strength of ~ 300 MPa and ~ 22 MPa which were more than twice that of non-reinforced composites with fiber pull-out and layer debonding as predominant failure mechanisms. On the other hand, non-reinforced samples indicated matrix debonding as predominant failure behavior. The solid fill samples illustrated a lower failure mechanism owing to their higher bonding between each layer with limited voids whereas honeycomb and triangular samples failed faster due to the high number of voids limiting their bonding behavior. Furthermore, the load transfer capacity of honeycomb and triangular infill composites was limited due to reduced adhesion between the layers. Although the mechanical properties of onyx-based composites do not make them suitable for structural applications, the fused filament fabrication approach makes onyx a potential material for internal non-loading structures with complex geometries.

Keywords Onyx · Fused filament fabrication · Carbon fiber composites · Mechanical properties · Failure mechanics

1 Introduction

Additive manufacturing (AM) is a technology that uses data from computer-aided design (CAD) software to build 3D objects by adding layer-upon-layer or particle by particle to form complex shapes and geometry [1]. AM has revolutionised the design and manufacture of end-use products and has seen its uptake in various sectors such as aerospace, automotive, and biomedical [1, 2]. The usage of AM in industrial applications makes it a preferred choice over traditional manufacturing processes owing to its capabilities of manufacturing critical and intricate products with comparatively lesser manufacturing cost [3, 4]. AM has several techniques based on materials, i.e., solid, powder and liquid to prepare complex-shaped components [5, 6]. However, fused filament fabrication (FFF) is considered one of the common techniques owing to its speed and associated low cost, making it ideal for a variety of commercial applications [7, 8]. FFF has continuously developed and utilized to print various materials including metals, polymers, and ceramics which has gained interest in aerospace applications [9, 10].

Fiber-reinforced polymer composites (FRPC) have superior mechanical properties and have been used in the aerospace and automotive industries for interior structures [11–13]. Carbon, glass, and aramid fibers are typically utilized in various aerospace and automotive components owing to their mechanical properties and ability to form complex geometries through various traditional manufacturing routes [14]. However, these traditional composites manufacturing processes are considered to be not sustainable, i.e., these production methods affect the environment,

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economy, and health of the people while not showcasing any sort of recycling or reducing strategies [15–17]. Recently, FFF has been a fast-growing AM technology for printing FRPC owing to its reduced material wastage and cost [18]. Further, use of FFF could also support in minimizing the environmental impacts while moving toward sustainable goals [19]. However, FFF-produced components are utilized as conceptual prototypes rather than functional components as they lack superior mechanical properties compared to other AM processes like SLS or SLA [5]. This has encouraged researchers to develop FFF parts with increased performance. This performance of FFF components is affected by several factors which make the mechanical strength analysis difficult and the complex failure nature of the FFF printed materials must be investigated in detail to enhance the applications of these products [20]. For instance, Ali et al. studied the mechanical properties with respect to infill density and determined that nylon carbon composites with 50% density and triangular pattern showcased a tensile strength of 153 MPa which was more than rectangular and honeycomb patterns owing to lower voids in struts [21]. Likewise, Ahmadifar et al. examined the impact of monotonic and fatigue loadings on polymer-based composites (specifically onyx) that were reinforced with continuous glass fiber prepared using fused filament fabrication which revealed that during fatigue loading, the temperature rises because of self-heating, which led to a decrease in the fatigue life of composites [22]. These studies were undertaken with carbon- or carbon-based reinforcements as predominant material owing to its rapid utilization in the field of automobile, aerospace industries. There are several more studies on carbon-based 3D printing which indicated that carbon reinforcement could improve the properties [23–26]. However, there has been always a dispute on the performance of carbon composites prepared via AM approaches as most of its failure mechanisms have not been detailed [27, 28]. To close the gap and to enhance the performance and reliability of such composite materials, it is imperative to delve into the intricate dynamics of their failure mechanisms. The manipulation of material distribution through the utilization of diverse infill patterns plays a pivotal role in shaping the mechanical properties of additively manufactured (AM) composites.

This research is dedicated to investigating how distinct infill patterns impact the failure mechanics, with a specific focus on comprehending the tensile and flexural attributes of composites composed of nylon–carbon (onyx) and onyx reinforced with carbon fibers using fused filament fabrication (FFF) technology. The primary objective of this study is to provide insights into which infill patterns yield superior tensile and flexural characteristics. This knowledge will empower engineers and designers to make informed decisions when dealing with applications that demand specific mechanical features. In addition, the application of infill patterns can significantly assist manufacturers in optimising their production processes, thereby contributing to sustainability efforts by minimizing material wastage. By gaining a profound understanding of the intricacies of failure mechanics, the components produced can be rigorously tested and validated to meet the performance standards of a wide array of industries, ranging from aerospace to automotive and beyond. Manufacturers can then fine-tune their composite materials to align with the unique requirements of various applications, making well-informed decisions based on their comprehension of the intricate interplay between mechanical characteristics and infill patterns.

2 Materials and methods

2.1 Materials and design

Onyx, the material utilized for this study was commercially available and attained from Markforged, US. It was a blend of nylon-based material reinforced with chopped short carbon fibers which comprises 80% nylon and 20% carbon [29]. Further, for additional carbon reinforcements, continuous carbon fibers filaments were procured from Markforged, US. The properties of onyx and carbon fiber reinforcements are provided in Table 1. The test samples were designed in accordance with ASTM D3039 standard with dimensions of $127 \times 12.7 \times 3.4$ mm as illustrated in Fig. 1 [30]. These designed samples were exported in STL format, and the model was prepared for printing by employing slicing software—Eiger. The printing configurations including infill type, fill density, and layer height were set as per the specifications outlined in Table 2.

Three different types of infill patterns, i.e., solid, honeycomb, and triangular infill patterns as illustrated in Fig. 2 were printed onto the respective samples. For reinforced carbon samples, an orientation of [0°/45°/90°/− 45°] was

Table 1 Properties of onyx and continuous carbon fibers attained from the manufacturer

Material	Tensile modulus (GPa)	Tensile stress (MPa)	Flexural modulus (GPa)	Heat deflection temperature (°C)	Density (g/cm^3)	Izod impact notched (J/m)
Onyx	2.4	40	71	145	1.2	330
Continuous carbon fiber	60	800	51	105	1.4	960

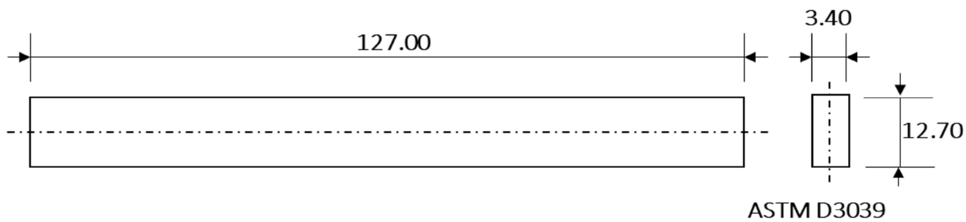


Fig. 1 Schematics of FFF printed specimens as per ASTM D3039

Table 2 Parameters and nomenclature utilized for printing nylon-reinforced carbon fiber composites

Fill pattern	Fill density (%)	Material	Reinforcement material	Layer height	Nomenclature
Solid fill	100	Onyx	None	0.100 mm	SF
	100	Onyx	Carbon fiber		SFC
Honeycomb fill	50	Onyx	None		HF
	50	Onyx	Carbon fiber		HFC
Triangular fill	50	Onyx	None		TF
	50	Onyx	Carbon fiber		TFC

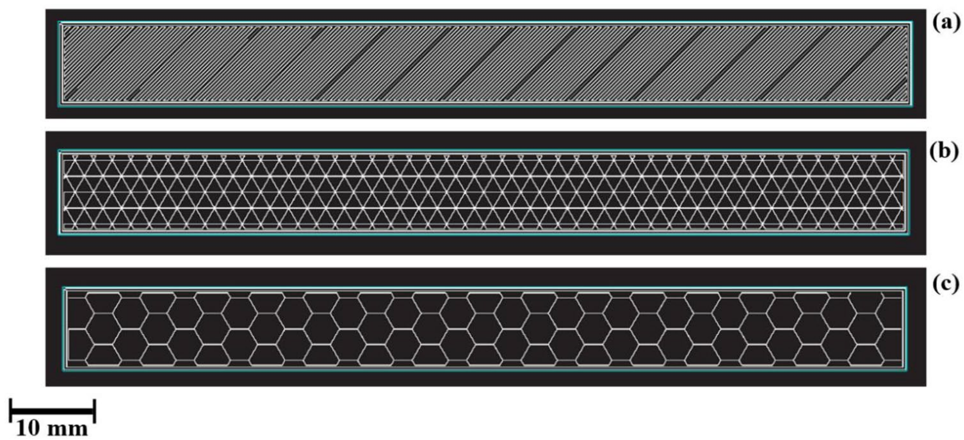


Fig. 2 2D view of various infill patterns (**a**) solid fill, (**b**) 50% triangular and (**c**) 50% honeycomb

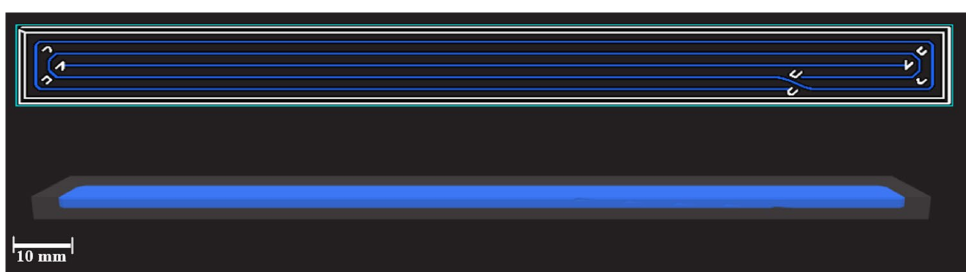


Fig. 3 2D and 3D view on carbon fiber layers inside Onyx composites

Table 3 FFF printing parameters for carbon fiber composites

Nozzle diameter (mm)	Nozzle temperature (°C)	Carbon fiber nozzle temperature (°C)	Bed temperature (°C)	Layer height (mm)	Roof wall layer height (mm)	Floor wall layer height (mm)
0.4	200	220	45	0.1	0.4	0.2

utilized for carbon fiber reinforcement along with infill pattern as reported in Fig. 3 with each composite comprising 80% onyx and 20% continuous carbon fiber reinforcement. Layer height was maintained at 0.1 mm for all the samples. Some other parameters towards FFF printing are reported in Table 3, like roof and floor layers and wall layers were kept at 0.4 mm and 0. 2 mm, respectively. Markforged printers Mark Two was utilized for both the printing processes. The onyx and carbon-reinforced onyx composites were printed through layer deposition and for composite printing, dual deposition was utilized.

2.2 Methods

Tensile and flexural testing was carried out in accordance with the ASTM D3039. Both tests were carried out using a universal testing machine (ZwickRoell 10 kN, Coventry University, UK). Both experimental studies were carried out five times to enhance the statistical accuracy and an average of five studies has been plotted in results. Tensile study was carried out at a displacement of 1 mm/min using a static extensometer to measure the strain rate. Flexural studies were conducted using a three-point bending technique with a crosshead displacement of 2 mm/min and a span of 40 mm in accordance with ASTM D7264 [31]. The fractured samples from the experimental tests were analyzed for their failure mechanisms using a scanning electron microscope (Zeiss Sigma 500VP, Coventry University, UK) and optical microscopy (Nikon Eclipse LV150NL, Coventry University, UK).

3 Results and discussion

3.1 Tensile behavior

The onyx and carbon-reinforced onyx were subjected to uniaxial tensile tests to understand the mechanical properties of the composites with respect to infill pattern and carbon fiber reinforcements. The stress–strain plot is reported in Fig. 4a. The solid fill (SF) showcased an ultimate tensile strength (UTS) of 102 MPa which was higher than TF and HF by ~ 61% and 51%, respectively. These UTS results correlate with the influence of infill density as a determining factor in the strength of FFF parts, especially with an infill pattern comprising rectilinear or solid pattern design [32]. This increase in tensile strength could be due to the higher bonding area between the layers offered by 100% infill density which reduces porosity between the bonding layers and enhances its resistance toward deformation [32]. Onyx with 50% dense patterns of honeycomb (HF) and triangular (TF) infill had a UTS of 50 MPa and 40 MPa, respectively. This reduction in the UTS could have been due to continuous empty gaps/spaces in these infills.

Figure 4b indicates the stress–strain plot for carbon-reinforced onyx composites which indicated higher UTS compared to non-reinforced onyx composites for all three infill patterns. Carbon-reinforced onyx composites indicated UTS ~ 3 times more than the non-reinforced composites

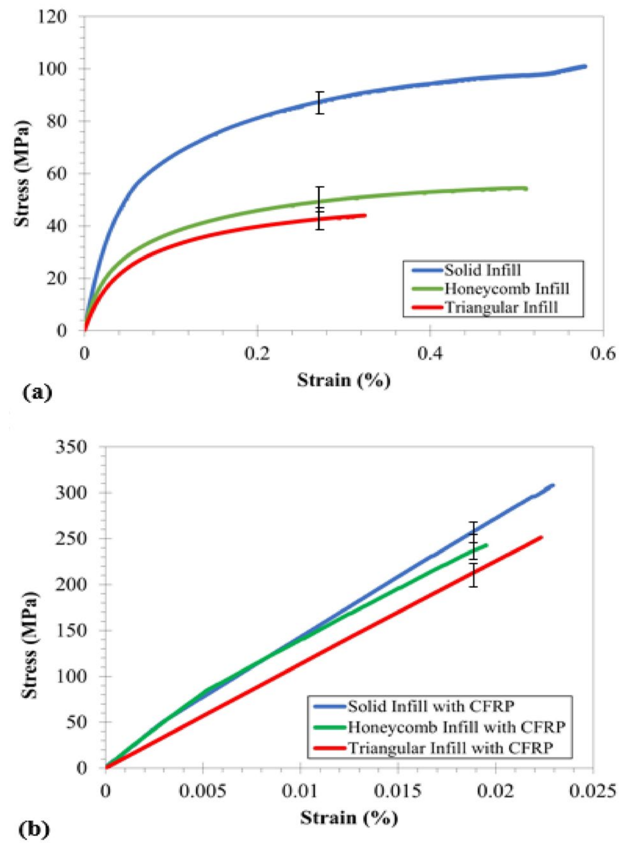


Fig. 4 Stress–strain plot of (**a**) onyx and (**b**) onyx-reinforced carbon fiber polymer composites

with significant variation in graph including minimum elongation attributing linear behavior. SFC indicated a UTS of ~ 300 MPa before its fracture failure. Likewise, TFC and HFC indicated a closer UTS of ~ 250 MPa and ~ 240 MPa, respectively, which were 17% and 25% lower than SFC composites. The linear behavior and higher UTS on all the carbon-reinforced composites could be because of the presence of carbon reinforcements which led to brittle fracture behavior due to the stiffness of carbon fibers onto the onyx matrix [33]. On the other hand, TFC infill had relatively higher tensile strength than HFC due to its more contact points per unit area, this is attributed to the fact that the number of contact points also influenced the mechanical performance of the infill pattern [32]. By observing the area of failure for both the reinforced and non-reinforced composites, it was noted that the fracture occurred predominantly on the neck region as illustrated in Fig. 5 and similar to previously reported work on failure in ABS prepared via FFF. [34]. The area of fractures was observed by scanning electron microscopy to understand the failure mechanism of each failure.

The SEM microstructure reported in Fig. 6 indicates the cross-section of SF of onyx which evidences a matrix-based failure due to tensile load. The matrix of the onyx

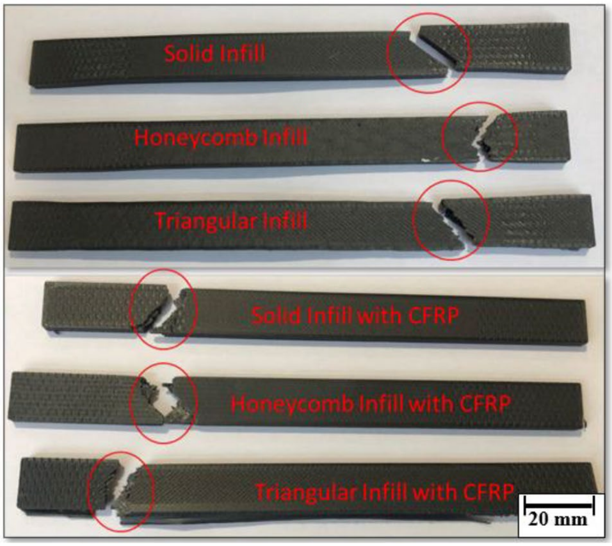
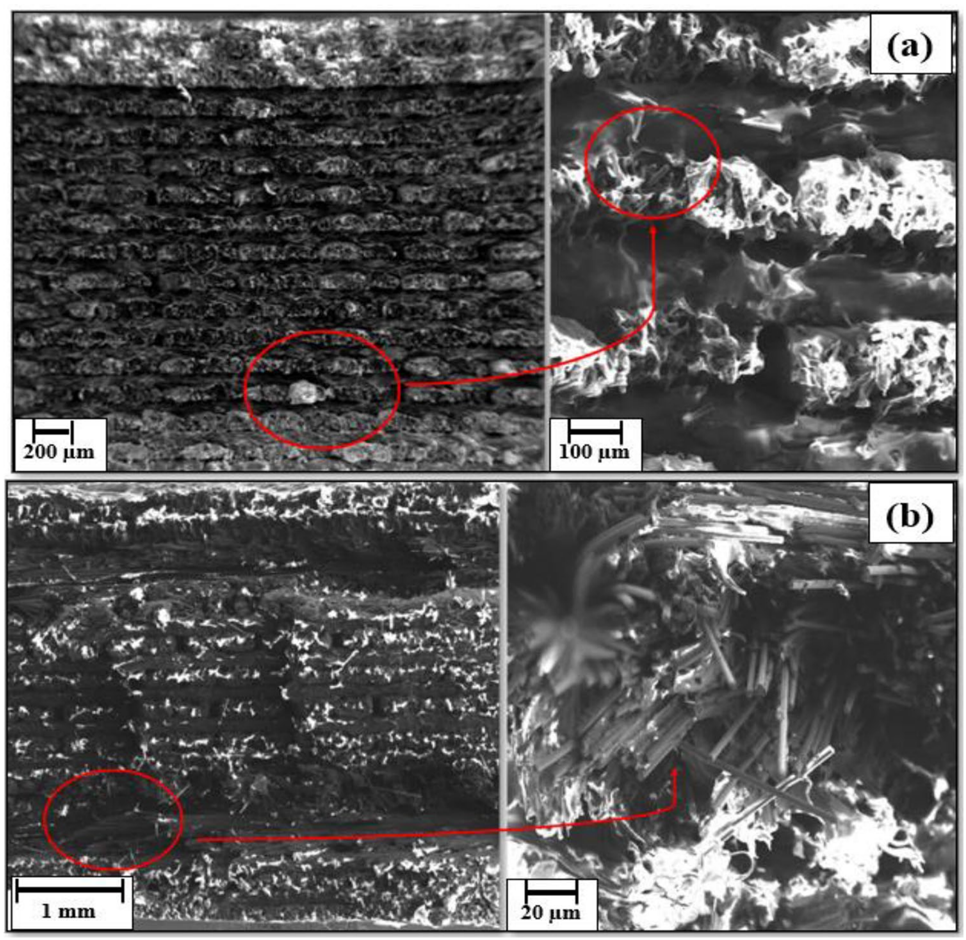


Fig. 5 Area of fractured regions in non-reinforced and reinforced onyx composites

SF composites showcased a large amount of matrix cracking and debonding with very limited to no traces of fibers-based failures throughout the SF composites. These matrix cracks could have been attributed to small void pockets which form with matrix debonding due to the dense nature of the sample and the layer orientation when no reinforcement is utilized [35]. This was the case for other composites with triangular and honeycomb infills as well. However, SFC composites evidenced traces of fiber pull-out as illustrated in Fig. 6b along with matrix debonding. Along with fiber pull-out and matrix debonding, a small scale of delamination was also observed between carbon fiber and matrix material due to poor adhesion in different layers [29].

The fracture microstructure of the HFC and TFC composites illustrated in Fig. 7 indicates a significant amount of fiber debonding along with fiber pull-out. This may be attributed toward the higher amount of porosity on the surfaces which reduced the bonding between the carbon fiber and onyx. Furthermore, due to the large number of voids and cavities on the surfaces, there was a drop in adhesion between carbon and onyx layers leading to extensive fiber pull-out which reduced the mechanical strength [36]. From Fig. 7a, b, there is evidence of fiber pull-out critical mechanism which led to failure of the onyx and onyx composites.

Fig. 6 Cross-sectional SEM of (**a**) SF and (**b**) SFC composites indicating area and type of failure



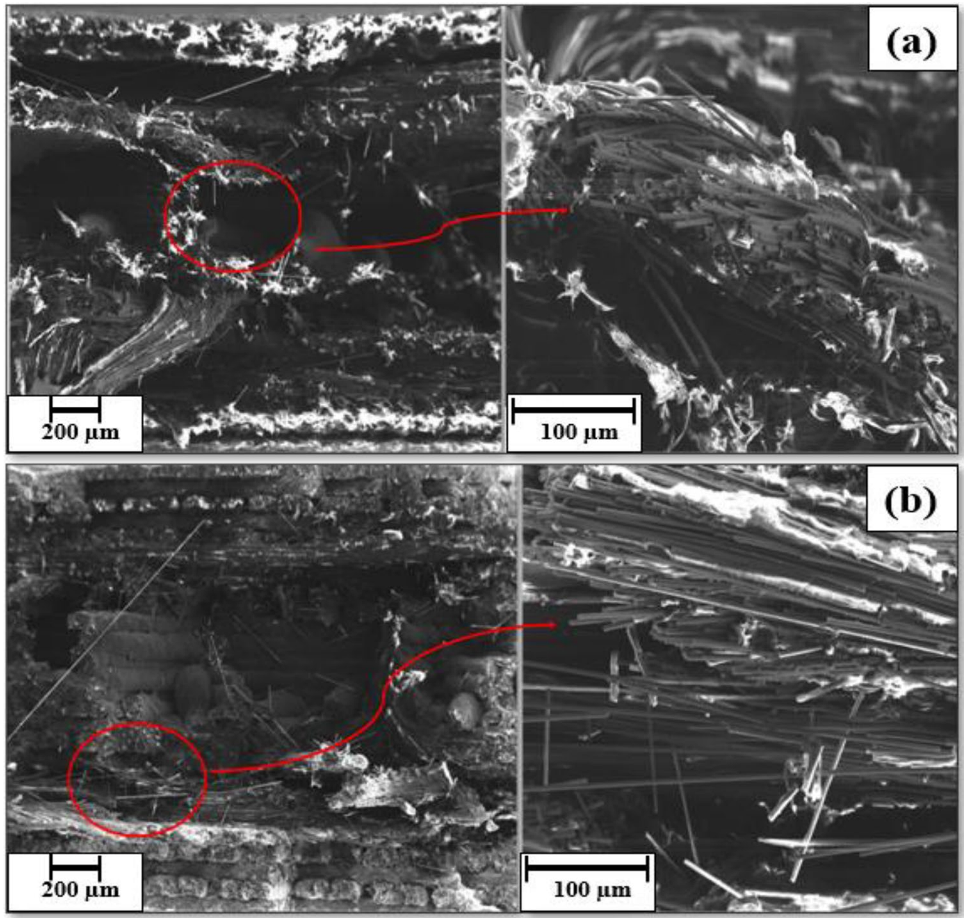


Fig. 7 Fiber pull-out and matrix debonding on (**a**) TFC and (**b**) HFC

3.2 Flexural behavior

A flexural study was carried out with displacement load of 2 mm/min using a three-point bending on onyx and onyx/carbon composites, and stress–strain graphs are plotted and reported in Fig. 8. Like the tensile behavior, solid infill pattern showcased the maximum flexural strength with a load-bearing capacity of 10 MPa at a strain of 0.55% which could have been due to the closely packed structure which allows superior load transfer capabilities [29]. However, TF and HF patterns indicated a flexural strength of 5.2 MPa and 4.6 MPa, respectively, which was about half of SF composite. Although the flexibility of TF and HF composites was higher, its flexural strength dropped due to the presence of voids on the surfaces. All the three non-reinforced composites showcased a matrix debonding behavior as main failure mechanism with extensive uniform load transmission, resulting in good deformation resistance and increased stiffness [37].

Onyx with carbon reinforcement composites indicated higher flexural strength as illustrated in Fig. 8b. The SFC composites showcased a strength of 22 MPa, while HFC and TFC composites had 16 MPa and 13 MPa, respectively. The flexural strength of the composites was about twice that of non-reinforced onyx which may have been related to the fiber direction which aids in distributing the stress throughout the geometry from the center where the load is applied [29, 34]. The strain at break was much quicker but the interesting phenomenon is that there was visible deformation in the specimen, i.e., which was not a failure of stability, but a failure of strength. When unloading, the specimens partially returned to their original state with no fracture on the structure which was reported in a previous study [38]. Figure 9 indicates the post-view on the samples after flexural study where TFC samples showcased a layer delamination on the surface. However, SFC and HFC samples showcased reduced fractures which partially returned to their original state.

The layer delamination on TFC could have been due to print defects on the surface where when force was exerted, the stress between the two triangular bases results in failure which leads to lowering of bonding behavior between matrix and carbon fiber reinforcements [39]. Layer delamination might also be attributed to the low interfacial bonding in the samples as a result of the temperature gradient experienced during FFF printing. As the material is extruded out

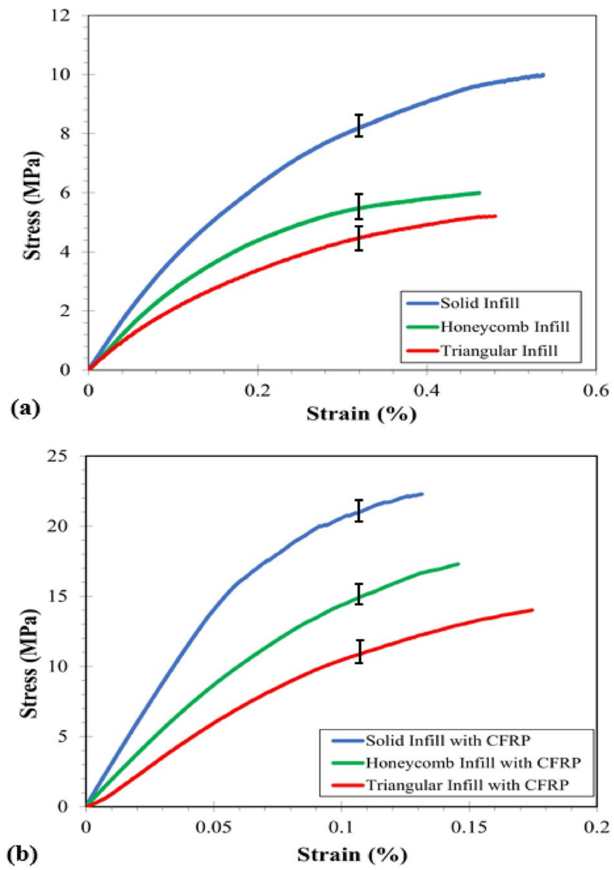


Fig. 8 Flexural strength of (**a**) onyx and (**b**) onyx/carbon-fiber-reinforced composites

of the nozzle and onto the previous layer, it is rapidly cooled and often does not weld to adjacent roads or layers because of the lower temperature not allowing for enough polymer chain mobility to create a strong bond. This temperature gradient is also magnified with the use of honeycomb and triangular infills because the heat can dissipate more quickly due to the higher surface area that is exposed to the ambient air and temperature.

4 Conclusion

Tensile and flexural testing of FFF-prepared nylon/carbon (Onyx) and nylon/carbon (Onyx with carbon fiber) composites were evaluated for its mechanical properties and its failure mechanisms. At [0/45/90/− 45], solid fill, honeycomb, and triangle infill were printed with and without carbon reinforcement. Onyx reinforced with carbon fiber has higher UTS and flexural strength than unreinforced composites. SFC, HFC, and TFC have greater UTS values than SF, HF, and TF (102, 50, and 40 MPa, respectively). The flexural strength of reinforced composites SFC (22 MPa), HFC (16 MPa), and TFC (13 MPa) was approximately double that of unreinforced composites SF (10 MPa), HF (5.2 MPa), and TF (4.6 MPa). Due to their 100% dense infill and higher adhesive bonding between layers with fewer voids, SF and SFC composites have greater tensile and flexural strength than other infill patterns. The primary failure mechanism of onyx-reinforced carbon composites was fiber pull-out and debonding, whereas onyx composites exhibited matrix debonding and fracture. During flexural testing, the majority of composites reverted to a portion of their original shape, demonstrating their flexibility and rigidity. Although onyx's mechanical properties prevent it from being used for structural applications, it can be used for interior aerospace structures where mechanical properties are not crucial, and FFF enables intricate composite structures with minimal material waste. The printing of composites via FFF could lead to a

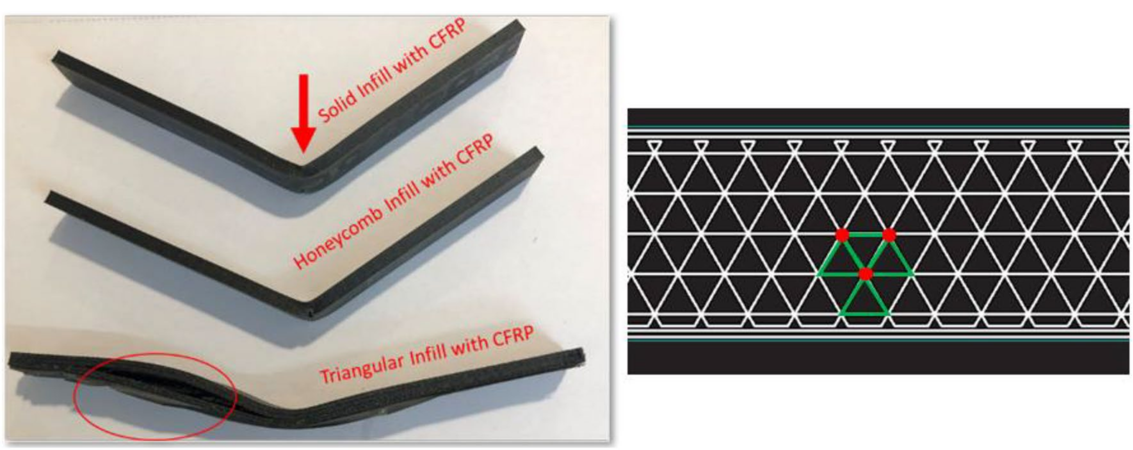


Fig. 9 Post-view on three-point bend tested onyx/carbon composites and 2D view on area which might be affected while loading on triangular infill

new and improved sustainable way of manufacturing carbon-based composites.

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Author contribution KR—research idea creation and implementation, original and review draft writing, and project management. PR—experimental testing and original draft writing. NBS—original draft writing. MNA—revision draft and review written draft, MO and CLG—review written draft.

Data and code availability The raw/processed data required to reproduce these findings cannot be shared at this time as the data also form part of an ongoing study. There is no code availability toward this study.

Declarations

Conflict of interests Authors declare no completing interest toward this publication.

Ethical approval Not applicable.

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