

Directional dependency and loading rate sensitivity of 3D-printed continuous fiber-reinforced composite gyroid structures

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Abstract

Purpose – This study aims to investigate how fiber type, loading direction, and loading velocity affect the structural and energy-absorption performance of three-dimensional (3D)-printed gyroid structures manufactured from continuous fiber-reinforced composites (CFRCs), thereby assessing their suitability for advanced energy-absorbing applications.

Design/methodology/approach – Gyroid structures were fabricated via fused filament fabrication using Onyx and Onyx reinforced with glass, Kevlar, and carbon fiber filaments. X-ray computed tomography (CT) imaging was employed to characterize the morphology and locations of internal voids. Mechanical performance was evaluated through quasi-static compression of Onyx and GFF/Onyx gyroids in three orthogonal directions, followed by quasi-static and dynamic compression tests on Onyx, GFF/Onyx, KFF/Onyx, and CFF/Onyx gyroids.

Findings – CT analysis revealed voids in Onyx concentrated in the infill region due to bead placement, while GFF/Onyx showed voids at fiber-wall interfaces in high-curvature regions. Under quasi-static loading, GFF/Onyx exhibited higher stiffness but lower specific energy absorption (SEA) in the X and Y directions due to interlaminar failure, whereas the Z direction showed stable progressive folding with enhanced SEA linked to bead alignment. Under dynamic loading, Onyx gyroids fragmented, whereas fiber-reinforced variants retained structural integrity through fiber bridging. GFF/Onyx achieved the highest plateau stress in both loading regimes, while KFF/Onyx displayed the greatest strain-rate sensitivity, with plateau stress and SEA increases of 67.43% and 84%, respectively.

Originality/value – The work provides a comprehensive, directional, and rate-dependent assessment of CFRC gyroid lattices, linking void morphology and fiber architecture to mechanical response. These insights inform the tailored design of 3D-printed CFRC gyroid structures as lightweight, high-performance energy absorbers for advanced engineering applications.

Keywords Additive manufacturing, Continuous fiber-reinforced composite, Sheet-based gyroid, Strain sensitivity, Anisotropic properties

Paper type Research paper

1. Introduction

High-performance fiber-reinforced composites have a high strength-to-weight ratio and specific modulus, making them widely used in diverse industrial applications (Rana and

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Funding: This research was conducted within the Aerostructures Innovation Research (AIR) Hub, supported by the Victorian government under the Victorian Higher Education State Investment Fund (VHESIF).

Received 26 September 2025

Revised 10 January 2026

Accepted 10 February 2026

The current issue and full text archive of this journal is available on Emerald Insight at: <https://www.emerald.com/insight/1355-2546.htm>



Rapid Prototyping Journal
32/8 (2026) 2027–2041
Emerald Publishing Limited [ISSN 1355-2546]
[DOI 10.1108/RPJ-09-2025-0468]

Fangueiro, 2016). However, conventional methods for manufacturing these composites are labor-intensive, making it difficult to design functional components with intricate geometries and high precision. Additive manufacturing (AM) offers a promising solution by enabling rapid and cost-effective production of functional components without molding, making it particularly advantageous for small-scale manufacturing. The inherent capability of AM to fabricate complex structures and customized shapes has expanded new possibilities for creating functional components that were previously unachievable with conventional methods. Furthermore, using AM, the tailoring of mechanical properties, component weight, and performance can be easily achieved (Bakr et al., 2021).

Fused filament fabrication (FFF) has attracted significant attention as an efficient and straightforward approach to producing customized, complex, continuous-fiber composite structures (Ferreira et al., 2019). FFF utilizes thermoplastic filaments combined with continuous fiber bundles to enhance the mechanical properties of three-dimensional (3D)-printed parts. The layer-by-layer printing process enables the creation of intricate geometries with minimal or no material waste and reasonable production speeds. Recent advancements in FFF, combined with the availability of open-source commercial 3D printers, have driven breakthroughs in the development of continuous fiber-reinforced composites (CFRCs), enabling the economical production of 3D-printed CFRC parts with accuracy and repeatability (Cheng et al., 2023). Markforged® has pioneered a dual-nozzle extrusion technique in which continuous fibers are encased in a nylon (polyamide 6, or PA6) coating that serves as a binding material. The matrix comprises a proprietary composite known as Onyx, a blend of PA6 and short carbon fibers, used in conjunction with pure PA6. Nylon (PA6), a semi-crystalline thermoplastic polymer, is widely used in the automotive industry and other engineering sectors due to its excellent properties, including thermal stability, mechanical strength, and chemical resistance. Unlike thermoset epoxy resins, commonly used as the matrix material in conventional composites, which form irreversible chemical bonds, the PA6 thermoplastic matrix can be melted and reformed, allowing for reprocessing, repair, and recycling. The lack of chemical cross-linking in thermoplastic composites also increases ductility and toughness (Cao and Elverum, 2025).

Extensive research has explored the manufacturing of various geometric structures using 3D-printed CFRC and the analysis of their mechanical properties. These studies have highlighted the considerable influence of geometry and fiber arrangement on mechanical performance. Sugiyama et al. (2018) investigated the flexural strength of 3D-printed CFRC sandwich panels with varying core geometries, including rectangles, honeycombs, rhombi, and circles, demonstrating that the core shape can significantly impact the mechanical properties of composite sandwich panels. Dong et al. (2020) investigated the overlapping and interlacing fiber paths printing approach of CFRC structures with diamond cores by varying angles. They identified that the tensile strength increased with interlacing and larger obtuse angles. Zeng et al. (2021a, 2021b) investigated honeycomb structures with varying unit cell lengths and strut angles. Their results indicate that the failure modes of the 3D-printed CFRCs under out-of-plane loading are primarily lateral shearing and progressive folding failure. Zeng et al. (2021a, 2021b) also

conducted a bending test on corrugated sandwich structures with shape memory capability, highlighting the failure mechanisms of CFRCs and providing a practical guide for designing lightweight sandwich structures. Dou et al. (2022) compared honeycomb structures made from materials such as aluminum alloy, continuous carbon fiber filament, and polylactic acid (PLA) in the in-plane compression, finding that the continuous fiber honeycomb exhibited specific energy absorption (SEA) values 186.58% and 596.84% higher than those of PLA and aluminum alloy, respectively, in the longitudinal direction. Morales et al. (2021) developed thin-wall structures for automotive applications. They compared the crashworthiness of carbon and glass fiber reinforcements under both quasi-static and impact loadings in the radial directions of the fiber placement. It was found that under radial quasi-static conditions, the carbon fiber reinforcement exhibited a significantly higher SEA value than the glass fiber reinforcement. Nevertheless, the glass fiber reinforcement exhibited greater radial impact performance, demonstrating strain-rate dependency. Xiang et al. (2025) investigated continuous Kevlar fiber-reinforced multicell thin-walled structures fabricated using novel undulating 3D printing paths. Their study revealed that the printing path significantly influenced both the collapse mode and the energy-absorption behavior. Cheng et al. (2024) explored the impact of novel cellular crossing printing paths on the mechanical performance of continuous ramie fiber-reinforced bio-composite honeycomb structures. Their results demonstrated that different paths significantly influenced compressive, bending, and tensile properties, with the single crossing offering the best overall performance, achieving a comprehensive score 1.5 times that of the least effective path. Quan et al. (2020) successfully fabricated continuous fiber placements in reentrant honeycomb structures to assess the damage propagation and mechanical performance, comparing them with PLA as the reference specimen. Zhang et al. (2023a, 2023b) investigated 3D-printed continuous carbon fiber-reinforced (CCFR) auxetic structures with varying Poisson's ratios to assess their compressive behavior. The study showed that structural configuration significantly influenced energy absorption and deformation, with the structure having a Poisson's ratio of -0.531 achieving the highest SEA. Bend-induced fiber failure was identified as the dominant damage mode, providing valuable insights for designing high-performance CCFR auxetic structures. Chen et al. (2021) and Chen and Ye (2021) developed techniques that integrate homogenization-based topology optimization with fiber placement methods, examining the effect of carbon fiber reinforcement on negative Poisson's ratio and effective elastic modulus. Li et al. (2020) employed path-based topology optimizations to design complex load-bearing members tailored to specific loading conditions. Yang et al. (2022) developed an optimal structure based on traditional density-based solid orthotropic materials using a penalization topology optimization method that incorporates a printing path planning strategy for CFRCs. Zhang et al. (2023a, 2023b) studied sequentially coupled optimization by obtaining a geometry structure under a specific load, with continuous fibers placed along the principal stress trajectories. This optimized fiber layout technique achieved 305% and 256% higher strength and stiffness than the pessimistic structure. Yap et al. (2024) integrated finite element analysis (FEA) and experimentation to investigate strength-based

optimization; these two methods concurrently were used to identify topology and fiber paths. Huang *et al.* (2025) introduced a novel crossing-lap printing strategy for fabricating topology-optimized Messerschmitt–Bölkow–Blohm beams using 3D-printed CFRCs. By alternating crossing-lap and normal layers with varying layer ratios (α), they demonstrated improved mechanical performance in three-point bending tests as α increased. Digital image correlation, micro-CT, and FEA revealed changes in failure modes and accurately predicted stiffness, offering insights for optimizing structural performance in complex CFRC prints. The developments mentioned above include geometries such as honeycomb, diamond, horseshoe, rhombus, square, and reentrant honeycomb, as well as topologically optimized designs that form regular and irregular tessellations repeated layer-by-layer.

Complex geometries, such as triply periodic minimum surfaces (TPMS), have been developed and optimized for their high strength-to-weight ratio and energy-absorption capacity. TPMS designs are characterized by minimizing surface area subject to a zero-mean curvature boundary, 3D periodicity, and smooth topology (Araya-Calvo *et al.*, 2024). Notably, some of the TPMS include the Schwarz crossed layers of parallels, Schoen I-graph wrapped package-graph, Schwarz Primitive, Fischer-Koch S, and Schoen Gyroid. While these structures share a common family, they exhibit distinct characteristics (Claybrook *et al.*, 2024). The Schoen Gyroid has been extensively studied for its lightweight features, mechanical robustness, and structural integrity (Abueidda *et al.*, 2019). Gyroid structures are classified as strut-based and sheet-based: strut-based gyroids consist of an interconnected network of struts forming a 3D lattice, whereas sheet-based gyroids comprise interconnected sheets or layers that create a complex network (Martignoni *et al.*, 2024). Li *et al.* (2019) found that sheet-based gyroids exhibited more uniform layer collapse, higher elastic modulus, and improved energy absorption compared to strut-based gyroids. Graded gyroid structures, a specialized subset, exhibit various configurations and enable variable mechanical properties by adjusting the unit cell thickness, size, and configurations of cells of varying sizes across the lattice (Zhang *et al.*, 2020). Their mechanical properties under different strain rates have been extensively studied (Li *et al.*, 2021; Ramos *et al.*, 2022) and commonly investigated using materials including stainless steel, aluminum alloys, titanium, and polymers. Recent research by Peng *et al.* (2022) examined gyroid structures fabricated via FFF with Onyx, focusing on the reinforcing effects of short carbon fiber reinforcement, unit cell size, cell number, and loading direction.

Despite significant advancements in 3D printing of CFRCs, fabricating complex cellular structures with continuous fiber flow remains challenging. To the best of the authors' knowledge, no research has yet investigated the effects of loading direction and rate on the mechanical properties of gyroid structures in CFRCs. The present study aims to bridge and address this gap by providing essential insights into the performance of 3D-printed gyroid structures under different directions and high velocity loading, specifically within the context of CFRCs. Mechanical properties such as compressive plateau stress and *SEA* are evaluated, with comparative analyses conducted between different fiber reinforcements under quasi-static and dynamic loadings. This research is expected to contribute to the advancement of AM by detailing

how building orientation and loading velocity influence the mechanical behavior of a CFRC cellular structure, thereby laying a foundation for more efficient and resilient designs and enhancing the potential use of CFRCs in high-performance engineering applications.

2. Experimental

2.1 Materials

Thermoplastic filaments reinforced with short carbon fibers, known as Onyx, along with reinforced filaments composed of fiber bundles coated with thermoplastic PA6, were used in this study. The Onyx filaments, with a diameter of 1.75 mm, consist of thermoplastic nylon blended with approximately 9%–20% by volume of short carbon fibers (Nikiema *et al.*, 2023; Vedrtam *et al.*, 2023). According to Hetrick *et al.* (2021), these fibers range in length from 7.03–44.58 μm . Glass, Kevlar, and carbon filaments were sourced from EMONA Instruments, the local supplier of Markforged® (Massachusetts, USA) and used as the feedstock materials for 3D printing. These reinforced filaments have an average diameter of 350 μm , with fiber counts of approximately 380 for glass fibers, 260 for Kevlar fibers, and 1,000 for carbon fibers (Maier *et al.*, 2022). The mechanical properties of the filaments in the study are listed in Table 1.

2.2 Design of gyroid structures

The gyroid structure, a member of the TPMS family, is defined by mathematically continuous surfaces that extend infinitely into 3D space without any intersections or gaps. The sheet-based gyroid structure used in this work is described by the following equation (1):

$$F(x, y, z) = \left[\sin\left(2\pi\frac{x}{L}\right) \times \cos\left(2\pi\frac{y}{L}\right) + \sin\left(2\pi\frac{y}{L}\right) \times \cos\left(2\pi\frac{z}{L}\right) + \sin\left(2\pi\frac{z}{L}\right) \times \cos\left(2\pi\frac{x}{L}\right) \right]^2 - t^2 \quad (1)$$

where F is the implicit function, x , y , and z are the three mutually perpendicular Cartesian coordinates, L is the edge length of the unit cells, and t is the level parameter variable.

The gyroid model was created using SolidWorks (Dassault Systèmes SolidWorks Corporation, Waltham, MA, USA), based on equation (1). This model was subsequently converted

Table 1 Mechanical properties of Markforged® feedstock filaments (*data are from the Markforged website, accessed on 19 September 2025*)

Properties	Onyx	Glass fiber	Kevlar fiber	Carbon fiber
Tensile modulus (GPa)	2.4	21	27	60
Tensile strength (MPa)	40	590	610	800
Compressive modulus (GPa)	–	24	25	62
Compressive strength (MPa)	–	180	130	420
Source(s): Authors' own work				

into a stereolithography (STL) file. A 20 mm unit cell size was selected and arranged in a two-by-two configuration, yielding gyroid structures with dimensions of 40 mm × 40 mm × 40 mm.

2.3 Fabrication of gyroid structures

A commercial Markforged[®] Mark Two FFF 3D printer, operated via cloud-based Eiger[®] software, was used to fabricate the specimens. The STL files created in SolidWorks were imported into Eiger[®] for slicing, where the filament layers were configured. Onyx was used as the matrix material, while glass fiber filament (GFF), Kevlar fiber filament (KFF), and carbon fiber filament (CFF) served as reinforcement materials to fabricate GFF/Onyx, KFF/Onyx, and CFF/Onyx composite gyroid structures, respectively. The Mark Two printer featured a dual-nozzle extrusion technique, with a 320 mm × 132 mm × 154 mm build volume and a 100–200 µm print resolution. The default layer thickness was 0.1 mm for Onyx reinforced with glass or Kevlar fibers and 0.125 mm for carbon fibers. Nozzle temperatures were set to a default 275°C for Onyx and 255°C for the fiber filaments, with a default print speed of 0.05 m/s. The structures were fabricated by stacking layers of matrix and fiber, allowing precise control over fiber placement; each layer accommodates both matrix and fiber materials at adjustable fiber volume fractions. The fiber volume fraction was calculated using the Eiger[®] software, which reported the volumes of consumed fiber and matrix. Based on these values, the fiber volume fractions were 34.41% for the GFF/Onyx and KFF/Onyx gyroid structures, and 30.18% for the CFF/Onyx gyroid structures. A schematic diagram of the Markforged[®] Mark Two printer is shown in Figure 1.

Figure 2 provides an overview of the workflow for designing and fabricating gyroid structures using the Markforged[®] Mark Two printer. A single-unit cell is shown in Figure 2(a). The gyroid STL file was imported into Eiger[®] slicing software, where the matrix and fiber layout were configured according to the desired specifications, as shown in Figure 2(b) and (c). Two specimens were fabricated for each test. Figure 3(a)–(d) presents three principal views of the printed specimens. Each layer was fabricated with a single wall, a default thickness of 0.4 mm and a solid infill density of 100%. A brim was used to ensure proper adhesion of the first layer to the print bed,

minimizing the likelihood of warping. Table 2 summarizes the measured dimensions and masses of all the printed specimens used in different tests.

2.4 Mechanical testing

2.4.1 Quasi-static compressive tests

Quasi-static compressive tests were conducted according to ASTM D695 using a 250 kN MTS universal testing machine (Model 819). The machine was equipped with a position-controlled crosshead, set to a 2 mm/min loading speed to ensure consistent and uniform loading. The strain was measured using a laser extensometer (model LX500). A Nikon D5300 digital camera was employed to capture the deformation histories of specimens. Specimens were compressed between two steel platens until either a nominal strain of 70% was reached or a maximum force of 250 kN was achieved. Two specimens were tested for each configuration, and the average values were reported. Figure 4(a) presents the quasi-static compressive test setup.

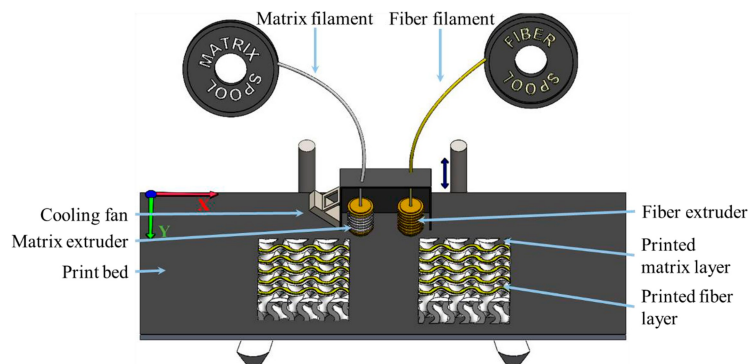
2.4.2 Dynamic compressive tests

Dynamic compressive tests were conducted on an Instron Very High Speed (VHS) testing machine (Model 8800) with a 100 kN load capability (Figure 4b). A loading velocity of 4 m/s was applied, corresponding to a nominal strain rate of 100/s, obtained by dividing the applied velocity by the initial specimen height. The VHS machine is equipped with a high-speed data acquisition system. Due to oscillations in the force signals during the initial stages of the tests, which were caused by the spring and noise, the adjacent averaging method in Origin was employed to smooth these oscillations. Deformation was captured using a Phantom v2511 high-speed camera, recording at 40,000 frames per second. Video footage was subsequently processed using Tracker software to analyze specimen displacement during dynamic compressive tests.

2.4.3 Key performance indicators

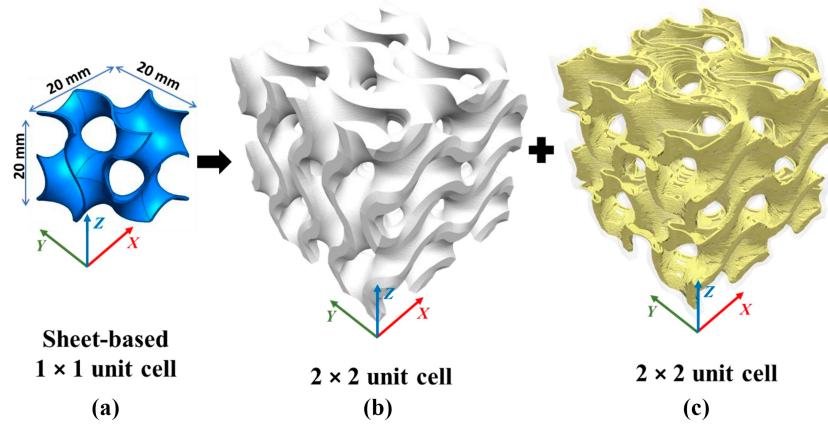
The nominal stress was calculated using the force data measured and recorded by the testing machines. The nominal strain was computed from displacements measured by a laser extensometer in quasi-static tests and by a high-speed camera and Tracker software in dynamic tests, divided by the original

Figure 1 A schematic diagram of the Markforged[®] Mark Two FFF printer



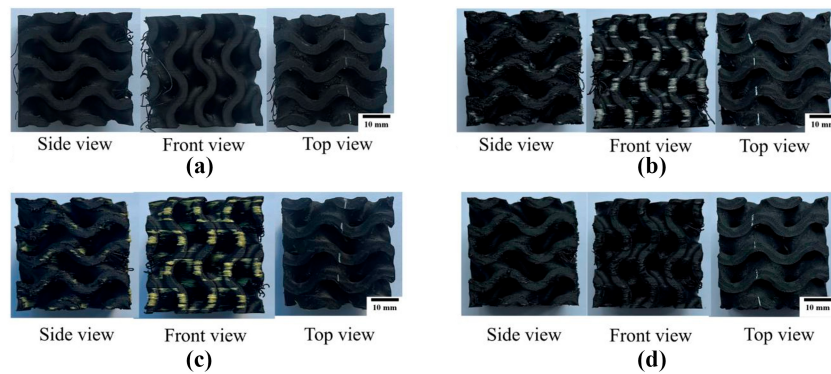
Source: Authors' own work

Figure 2 General design flow of a gyroid structure fabrication using Markforged® Mark Two printer: (a) a sheet-based gyroid unit-cell; (b) matrix of the gyroid; and (c) fiber-reinforcement inside the matrix of the gyroid



Source: Authors' own work

Figure 3 Photographs of printed specimens: (a) Onyx gyroid; (b) GFF/Onyx gyroid; (c) KFF/Onyx gyroid; and (d) CFF/Onyx gyroid at different principal views (side view: ZX plane; front view: ZY plane; and top view: XY plane)



Source: Authors' own work

height of the specimens. Nominal Young's modulus was determined from the slope of the initial linear region of the stress–strain curve. Plateau stress was calculated as the mean stress over the plateau range from 10% to 35% strain. Energy absorption per unit volume (W) was determined as the area under the stress–strain curve up to the densification strain, using numeric integration as follows:

$$W = \int_0^{\varepsilon_d} \sigma(\varepsilon) d\varepsilon \quad (2)$$

where σ and ε are instantaneous stress and strain; ε_d is the onset of densification at which energy absorption efficiency (η) reaches a maximum:

$$\left. \frac{d\eta(\varepsilon)}{d\varepsilon} \right|_{\varepsilon=\varepsilon_d} = 0 \quad (3)$$

where the energy absorption efficiency of the structure, η , was calculated using:

$$\eta(\varepsilon) = \frac{1}{\sigma(\varepsilon)} \int_0^{\varepsilon} \sigma(\varepsilon) d\varepsilon \quad (4)$$

The *SEA* is defined as the energy absorbed by the structure per unit mass and was calculated as:

$$SEA = \frac{W}{\rho} \quad (5)$$

where ρ is the density of the structure.

2.5 X-ray computed micro-tomography

X-ray computed tomography (CT) scans were performed to visualize voids and other internal imperfections across layers in specimens using a μ -CT scanner (Model: GE Phoenix v/tome/xS). The scans were conducted at 100 kV and 300 μ A, yielding voxel sizes of 35–40 μ m. Over 1000 images were captured during the scan with an average exposure time of 1,000 ms per image. The images were subsequently reconstructed using VG Studio Max Volume analysis software, with the 3D images rendered in iso-surface mode (which creates a surface at areas

Table 2 The measured dimensions and masses of specimens printed

Materials	Type of test	Specimen number	Measured dimensions ($X \times Y \times Z$ mm)	Measured mass (g)
Onyx	Quasi-static	X-Q-1	40.34 × 40.35 × 39.66	36.70
		X-Q-2	40.35 × 40.45 × 39.74	36.80
		Y-Q-1	40.38 × 40.38 × 39.75	37.21
		Y-Q-2	40.40 × 40.37 × 39.72	36.75
		Z-Q-1	40.38 × 40.47 × 39.68	36.81
		Z-Q-2	40.41 × 40.34 × 39.67	36.78
	Dynamic	Z-D-1	40.34 × 40.36 × 39.67	37.10
		Z-D-2	40.44 × 40.34 × 39.63	36.68
GFF/Onyx	Quasi-static	X-Q-1	40.66 × 40.97 × 39.80	41.20
		X-Q-2	40.64 × 40.88 × 39.78	41.38
		Y-Q-1	40.69 × 41.21 × 39.76	39.81
		Y-Q-2	40.67 × 41.23 × 39.67	39.92
		Z-Q-1	40.78 × 40.93 × 39.89	40.75
		Z-Q-2	40.72 × 40.93 × 39.79	40.62
	Dynamic	Z-D-1	40.66 × 40.97 × 39.80	41.22
		Z-D-2	40.67 × 41.23 × 39.67	39.91
KFF/Onyx	Quasi-static	Z-Q-1	40.35 × 40.73 × 39.73	36.82
		Z-Q-2	40.45 × 40.68 × 39.67	37.12
	Dynamic	Z-D-1	40.36 × 40.75 × 39.68	36.71
		Z-D-2	40.46 × 40.72 × 39.58	36.50
CFF/Onyx	Quasi-static	Z-Q-1	40.78 × 40.23 × 39.63	37.81
		Z-Q-2	40.73 × 40.21 × 39.65	36.94
	Dynamic	Z-D-1	40.84 × 40.33 × 39.75	36.62
		Z-D-2	40.34 × 40.63 × 39.85	36.80

Source(s): Authors' own work

of equal density, enhancing the visibility of internal structures). The histogram was segmented into intervals with specific colors to distinguish different materials.

3. Results and discussions

3.1 Computed tomography-scanned images of specimens

Figure 5(a) shows an X-ray CT image of the Onyx gyroid structure. Further analysis, including slicing and viewing different sections in the built direction, as shown in Figure 5(b), reveals that voids result from bead placement during printing. These voids tend to follow in the direction of bead placement and are primarily concentrated in the middle sections of the structure, particularly in the infill areas. The default infill pattern at $\pm 45^\circ$ on successive layers creates gaps between beads, contributing to the formation of voids. The outer wall layers, serving as the structure's shells, exhibit strong interlaminar bonding with the infill. Figure 5(c) provides a sliced sectional view perpendicular to the building direction, showing void patterns across three sections of the Onyx gyroid structure. The perpendicular void flow indicates that the voids are directly related to the bead placement (Gómez-Ortega *et al.*, 2024). The overall void content in the Onyx gyroid structure is higher in the middle section due to gaps formed by the bead placement of the infill, which is constrained by the gyroid geometry and resolution limits of the printer.

Figure 6(a) presents an X-ray CT image of the GFF/Onyx gyroid structure, where the orange color indicates fiber placement within the structure. Figure 6(b) shows a sliced

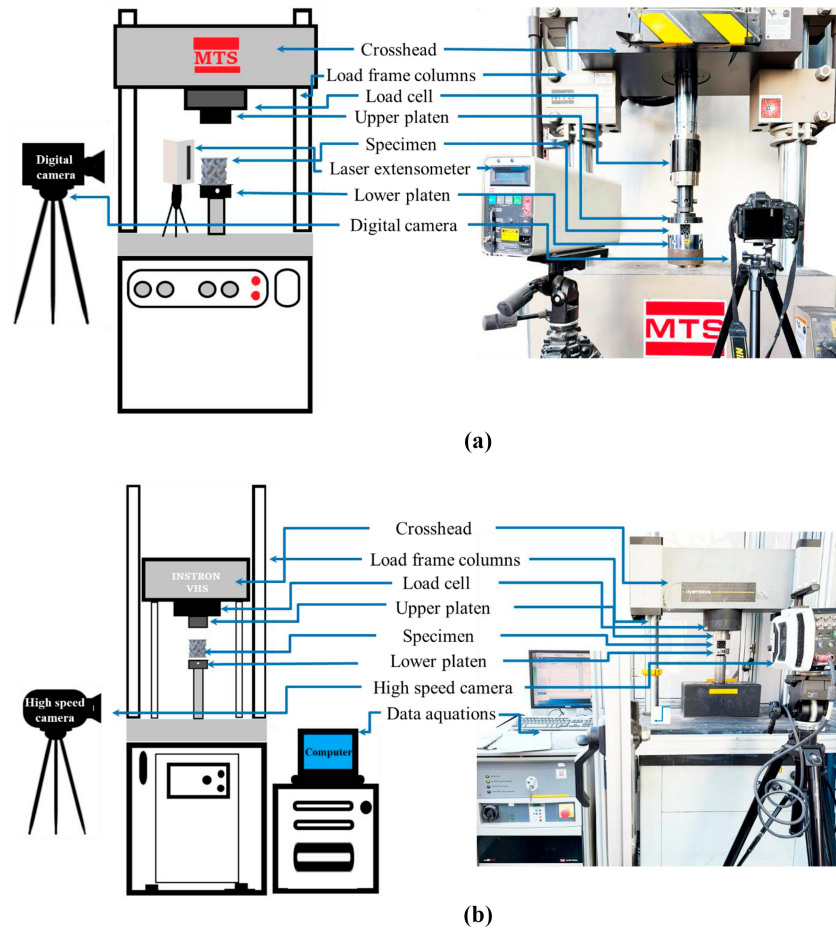
sectional view in the build direction, revealing that voids are not concentrated in the middle sections, as observed in the Onyx gyroid. Instead, voids are primarily located between the fiber and wall layers. The curved path of the gyroid geometry presents challenges for aligning the flattened fiber filaments, leading to larger voids between the wall and fiber layers, particularly in areas with higher curvature, such as turning points. Figure 6(c) provides a sliced sectional view perpendicular to the build direction, illustrating voids along the wall with larger curvature. These voids are continuous over successive layers, forming substantial gaps when viewed from the side. The overall void concentration is observed at the interface between the fiber and wall layers, which can be attributed to the gyroid structure's geometry, highlighting a significant challenge in fabricating fiber-reinforced cellular structures.

3.2 Deformation patterns and failure mechanisms

3.2.1 Effect of loading direction

Onyx and GFF/Onyx gyroid structures were tested under quasi-static compression to evaluate the directional dependence of loading. Onyx and GFF/Onyx gyroid specimens exhibited similar deformation patterns. Therefore, the deformations of Onyx specimens compressed in the X , Y , and Z directions at various strain levels are presented in Figure 7. In the X and Y directions, Figures 7(a) and (b), both Onyx and GFF/Onyx specimens exhibited interlaminar failure due to weak bonding between layers, exacerbated by voids generated from the FFF process (Zhang *et al.*, 2024). This failure was initiated at approximately 20% strain, with central cracks propagating parallel to the loading direction, ultimately leading

Figure 4 Schematic and experimental compressive test setups: (a) quasi-static test and (b) dynamic test. The images on the left are sketches, while the images on the right are photographs



Source: Authors' own work

to layer separation and specimen disintegration as densification approached. In the Z direction (Figure 7c), deformation was marked by lateral shearing and progressive folding failure, a characteristic response of gyroid structures. The intricate network of interconnected channels in the gyroid made it susceptible to localized buckling, particularly in regions aligned with the loading direction. Cracks initiated at or beyond a strain of 30%, and as the load increased toward densification, temporary facets appeared, deviating from the structure's smooth surface until densification was reached.

3.2.2 Effect of loading velocity and fiber type

To investigate the strain sensitivity across different fiber reinforcements, gyroid structures fabricated from Onyx, GFF/Onyx, KFF/Onyx, and CFF/Onyx were tested under both quasi-static and dynamic compressive loads in the Z direction, along which the gyroids are strongest compared with the X and Y directions. Due to the limitations of the dynamic testing machine, gyroid structures could only be compressed up to 35% strain. Therefore, comparisons were restricted to strains of up to 35%. Figure 8 compares the deformation of the Onyx gyroid structure and various fiber-reinforced samples up to 35% strain under both quasi-static and dynamic compression.

For Onyx gyroid specimens under quasi-static compression, layers collapsed uniformly, leading to densification with localized buckling in specific regions. However, during dynamic compression, the specimens exhibited similar resistance to the load up to a strain of 15%; beyond this, they rapidly buckled, leading to layer separation and fragmentation.

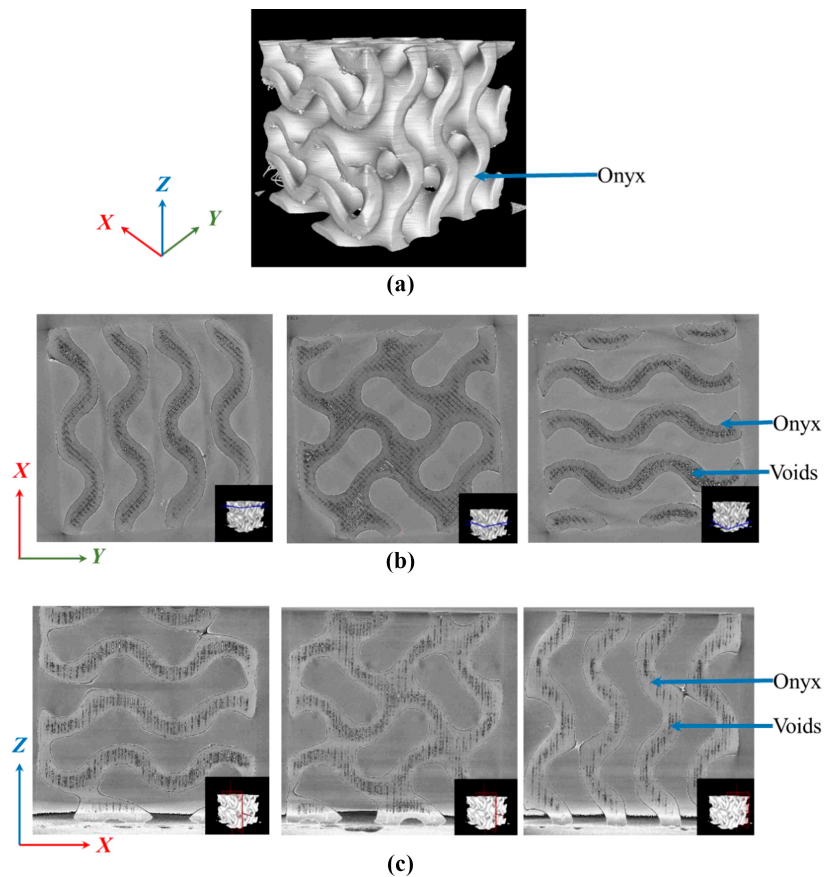
For fiber-reinforced gyroid specimens, deformation was consistent, with uniform layer collapse up to 35% strain under quasi-static and dynamic loadings. While localized buckling and lateral shearing caused cracks to develop by 30%, no explosive failure or layer disintegration occurred during dynamic testing due to reinforcement provided by fibers. Fiber reinforcement effectively prevented such failures, with fibers aligned perpendicular to the loading direction experiencing transverse push-out under increasing load. As strain continued to rise, the fiber reinforcement maintained structural cohesion, compressing the layers into a solid block.

3.3 Stress-strain curves

3.3.1 Effect of loading direction

The stress-strain curves for Onyx and GFF/Onyx gyroid structures compressed in the X , Y , and Z directions are shown in Figures 9 (a) and (b), respectively. Consistent stress-strain

Figure 5 The X-ray CT images of Onyx gyroid structures: (a) a 3D image; (b) a build direction section view; and (c) a side section view



Source: Authors' own work

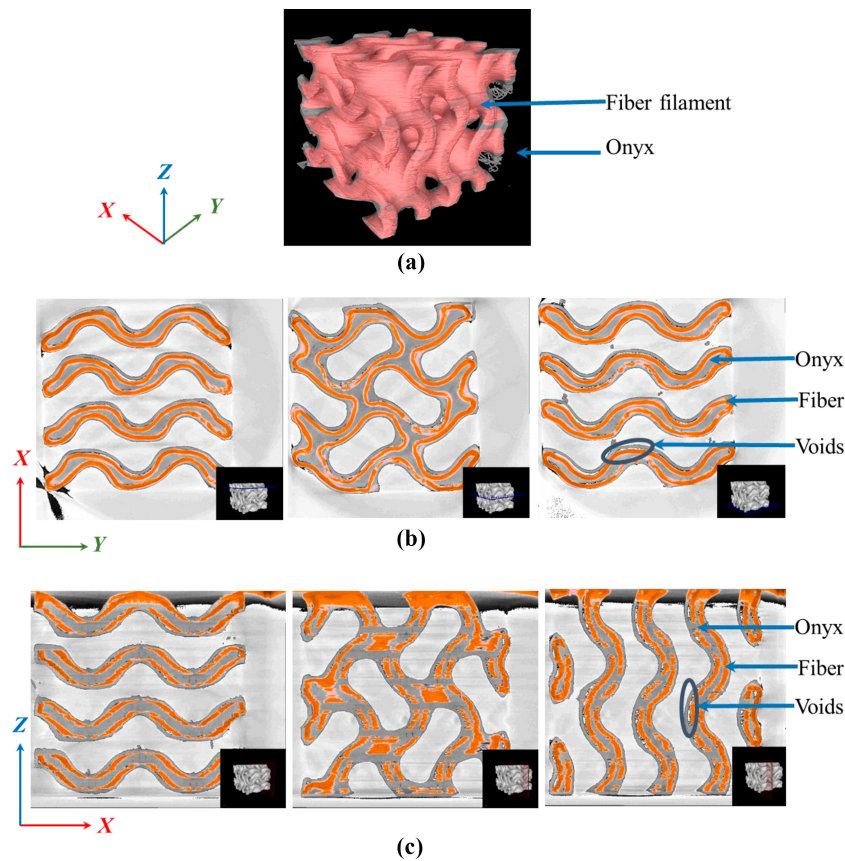
curves were obtained from two repeated tests for each material and loading direction. Moreover, all the curves demonstrate a typical compressive response of a cellular structure, consisting of three distinct regions: an elastic region, where stress increases linearly with strain; a plateau region, where stress increases nonlinearly with strain hardening or the softening effect; and a densification region, where stress rises sharply with strain.

The slope of the linear elastic region was slightly higher in the *X* and *Y* loading directions than in the *Z* direction for both Onyx and GFF/Onyx gyroids, due to the parallel alignment of the printed bead to the loading directions and voids. This effect was also observed in the study conducted by Peng *et al.* (2022). The curve has a smooth transition to the plateau region. Under compression in the *X* and *Y* directions, the specimens exhibited very similar stress–strain curves, with slight strain-softening: the stress gradually decreased with strain due to delamination observed in the specimens and then increased steeply after reaching the densification strain. In contrast, under compression in the *Z* direction, specimens exhibited strain hardening, with stress increasing gradually with strain, then rising sharply at the densification strain. In addition, the plateau region of the gyroid structure loaded in the *Z* direction is higher than that of the gyroid structure made of the same material loaded in the *X* and *Y* directions.

Figure 10 compares the mechanical properties of the Onyx and GFF/Onyx gyroid structures in the *X*, *Y*, and *Z* loading directions. The gyroid structures exhibited higher nominal Young's moduli in the *X* and *Y* directions compared with those in the *Z* direction for both Onyx and GFF/Onyx gyroids, as depicted in Figure 10(a). This behavior is attributed to the alignment of the printed layers parallel to the loading directions. In all the loading directions, Young's modulus of GFF/Onyx exceeded that of Onyx, with increases of 3.65% in the *X* direction, 31.89% in the *Y* direction and 22.69% in the *Z* direction.

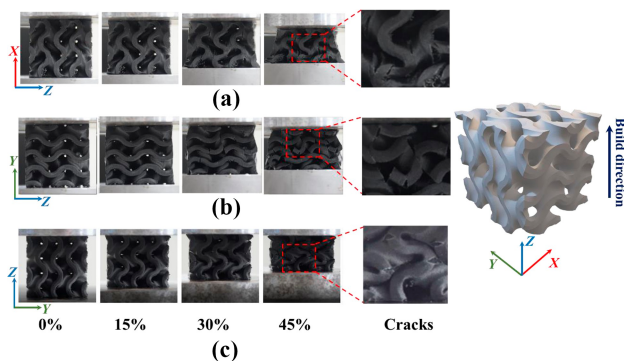
The densification strain, shown in Figure 10(b), was slightly higher in the *X* and *Z* loading directions than in the *Y* direction for both materials. The GFF/Onyx gyroid displayed even higher densification strains, with increases of 10.26%, 11.38% and 12.26% compared with the counterparts of the Onyx gyroid in the *X*, *Y* and *Z* directions, respectively. Plateau stress trends, illustrated in Figure 10(c), were similar for both the Onyx and GFF/Onyx gyroids, with the *Z* direction showing higher values than the *X* and *Y* directions. For GFF/Onyx, plateau stress decreased by 15.49% in the *X* direction and 15.89% in the *Y* direction, but increased by 34.91% in the *Z* direction, as compared with Onyx gyroids loaded in the same direction (Figure 10c). *SEA*, a crucial parameter for crashworthiness, presented in Figure 10(d), mirrored those of

Figure 6 The X-ray CT images of the GFF/Onyx gyroid structure: (a) isometric view; (b) a build direction section view; and (c) a side section view



Source: Authors' own work

Figure 7 The deformation of Onyx gyroid structures at various strain levels: (a) X direction; (b) Y direction; and (c) Z direction



Source: Authors' own work

the plateau stress. *SEA* values for GFF/Onyx decreased slightly by 6.23% and 4.96% in the *X* and *Y* direction, respectively, compared to Onyx, but increased significantly by 46.93% in the *Z* direction. The decrease in the plateau stress and *SEA* in the *X* and *Y* directions, along with the increase in the *Z* direction for GFF/Onyx, is attributed to weaker interlaminar bonding between the fiber-reinforced layers compared to Onyx (Iragi *et al.*, 2019).

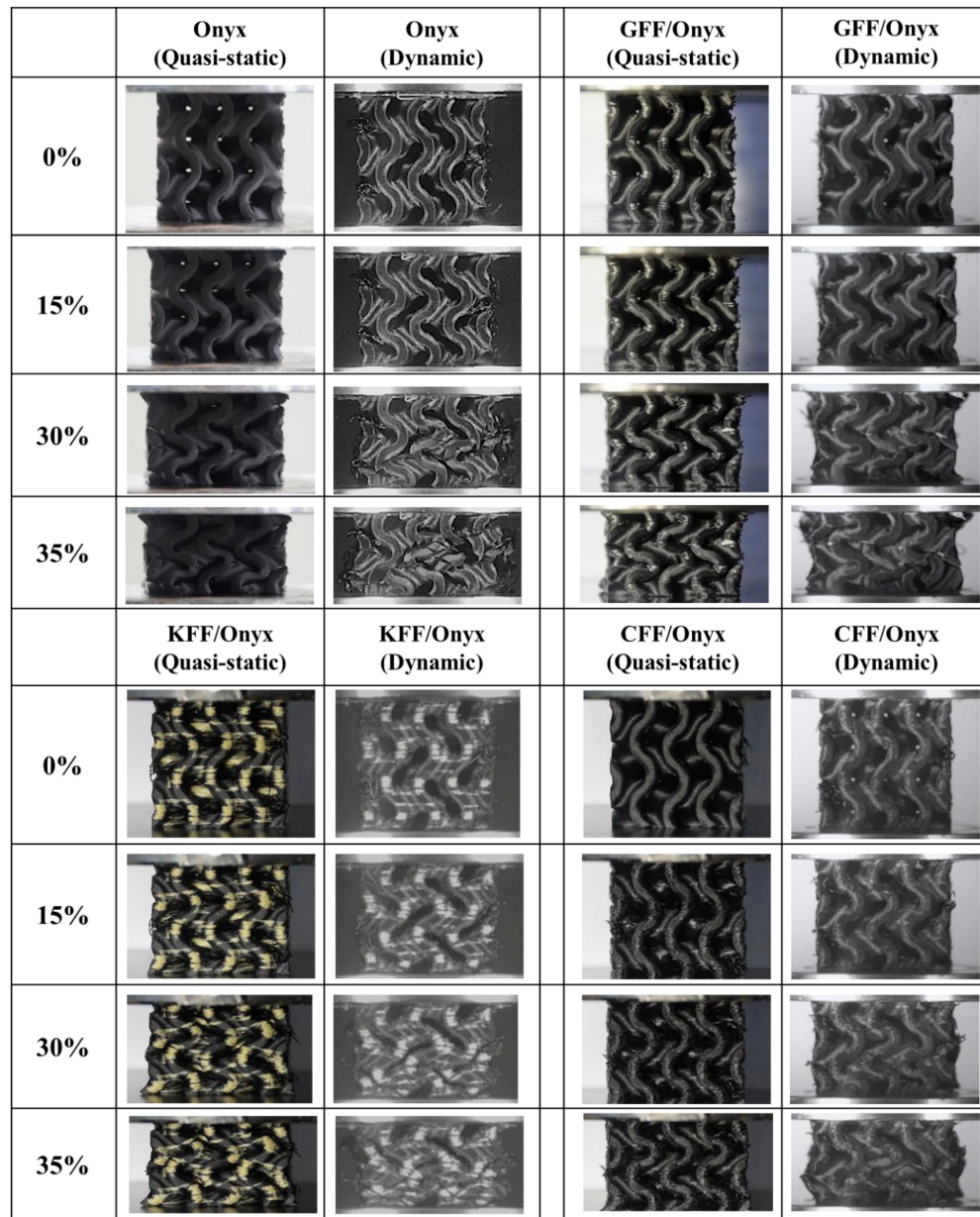
3.3.2 Effect of loading velocity and fiber type

Due to the reduced mechanical properties of GFF/Onyx compressed in the *X* and *Y* directions, attributed to weak interlaminar bonding, further tests were carried out in the *Z* direction, which aligns with the build direction. This subsection compares the stress–strain curves and mechanical properties of Onyx and Onyx reinforced with different fiber filaments under quasi-static and dynamic loadings.

Specimens were compressed to only 35% strain due to limitations of the testing machine. Figure 11(a)–(d) compares the nominal stress–strain curves under quasi-static and dynamic loadings. Figure 11(a) illustrates that the quasi-static test of Onyx gyroid demonstrated promising repeatability, while the two dynamic curves are slightly different. The compressive stress–strain curves of Onyx gyroids exhibited a linear elastic region but showed only a very short plateau under dynamic compression, which decreased with increasing strain. With increased strain, crack formation undermines the structural integrity, leading to disintegration and a steep drop in stress.

Figure 11(b)–(d) displays the quasi-static and dynamic loading curves for GFF/Onyx, KFF/Onyx and CFF/Onyx gyroids, respectively, showing good repeatability. Under quasi-static loading, the specimens with Onyx, GFF/Onyx, and CFF/Onyx gyroids indicated that the layer collapsed with a dip in the stress–strain curve, beyond which the densification was

Figure 8 Comparison of the various deformation stages of the gyroid structure made of Onyx, GFF/Onyx, KFF/Onyx, and CFF/Onyx up to 35% strain under quasi-static and dynamic compression



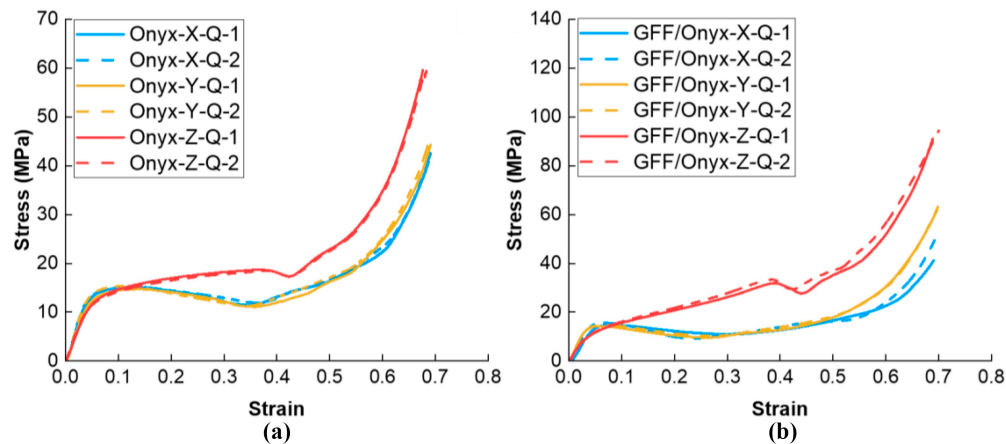
Source: Authors' own work

initiated. In contrast, KFF/Onyx gyroids demonstrated no layer collapse, transiting smoothly from the linear elastic region to the plateau and densification regions, similar to a typical solid compressive block. On the other hand, under dynamic loading, the specimens exhibited higher peak stress in the linear region, transiting to the plateau region and faster layer collapse, with a dip in the stress–strain curve. Densification was not observed due to the limitation in the testing equipment.

Figure 12 compares the mechanical properties of Onyx, GFF/Onyx, KFF/Onyx, and CFF/Onyx gyroid structures

under quasi-static and dynamic loading conditions, revealing significant strain rate sensitivity.

Figure 12(a) compares the plateau stress of the gyroid structures with Onyx and fiber reinforcements under both quasi-static and dynamic loadings. Under quasi-static loading, GFF/Onyx had the highest average plateau stress at 22.80 MPa, followed by Onyx at 16.90 MPa, CFF/Onyx at 16.70 MPa, and KFF/Onyx at 15.46 MPa. Under dynamic loading, GFF/Onyx again showed the highest plateau stress at 29.04 MPa, followed by CFF/Onyx at 25.88 MPa, KFF/Onyx at 23.25 MPa, and Onyx at 19.12 MPa. The dynamic increase

Figure 9 The stress–strain curves of gyroid specimens were printed out using: (a) Onyx and (b) GFF/Onyx

Source: Authors' own work

factor (DIF) for plateau stress was 13.13% for Onyx, 27.36% for GFF/Onyx, 67.43% for KFF/Onyx, and 39.19% for CFF/Onyx.

Although carbon fibers have higher intrinsic mechanical properties, the compression tests show that the GFF/Onyx gyroid exhibits a higher plateau stress than the CFF/Onyx counterpart under both quasi-static and dynamic loadings. The possible reasons are as follows. The GFF/Onyx specimens were fabricated with a default layer thickness (0.1 mm) compared with the CFF/Onyx specimens (0.125 mm). This reduced layer thickness leads to a higher fiber volume fraction in GFF/Onyx gyroid (34.41%) than in CFF/Onyx gyroid (30.18%), contributing to enhanced compressive performance of GFF/Onyx gyroid. Moreover, a thinner layer thickness improved interlayer bonding and load transfer within the sheet-based gyroid structure.

In this section, plateau stress is evaluated up to 35% strain to enable a direct and fair comparison with the dynamic tests, as machine limitations restricted the maximum compressive strain to 35% under dynamic loading. Under dynamic loading, the GFF/Onyx gyroid exhibits a nearly constant mean plateau stress over the strain range of 10%–35%. In contrast, the CFF/Onyx gyroid shows a reduction in mean plateau stress when averaged over the same strain interval, due to structural failure occurring beyond 23% strain. These results indicate that deformation stability has a more pronounced influence on the compressive plateau behavior of gyroid structures than the intrinsic stiffness hierarchy of the reinforcing fibers. Accordingly, the GFF/Onyx gyroid, with its higher fiber volume fraction and more stable deformation response, demonstrates superior plateau stress performance compared with CFF/Onyx under both quasi-static and dynamic loading conditions.

SEA is compared in Figure 12(b). Under quasi-static loading, GFF/Onyx had the highest *SEA* of 10.81 J/g, followed by Onyx at 9.22 J/g, CFF/Onyx at 8.51 J/g, and KFF/Onyx at 8.00 J/g. Under dynamic loading, KFF/Onyx exhibited the highest *SEA* at 14.72 J/g, followed by GFF/Onyx at 14.31 J/g, CFF/Onyx at 12.44 J/g, and Onyx at 9.74 J/g. The DIF, defined as the dynamic to quasi-static performance indicator, for *SEA*

was 5.63% for Onyx, 32.37% for GFF/Onyx, 84.00% for KFF/Onyx, and 46.18% for CFF/Onyx at a loading velocity of 4 m/s (i.e., nominal strain rate of 100/s). This analysis indicates that KFF/Onyx is the most strain rate-sensitive material, with a higher DIF, while Onyx is the least sensitive, with a lower DIF in both plateau stress and *SEA*, due to the disintegration of the specimens.

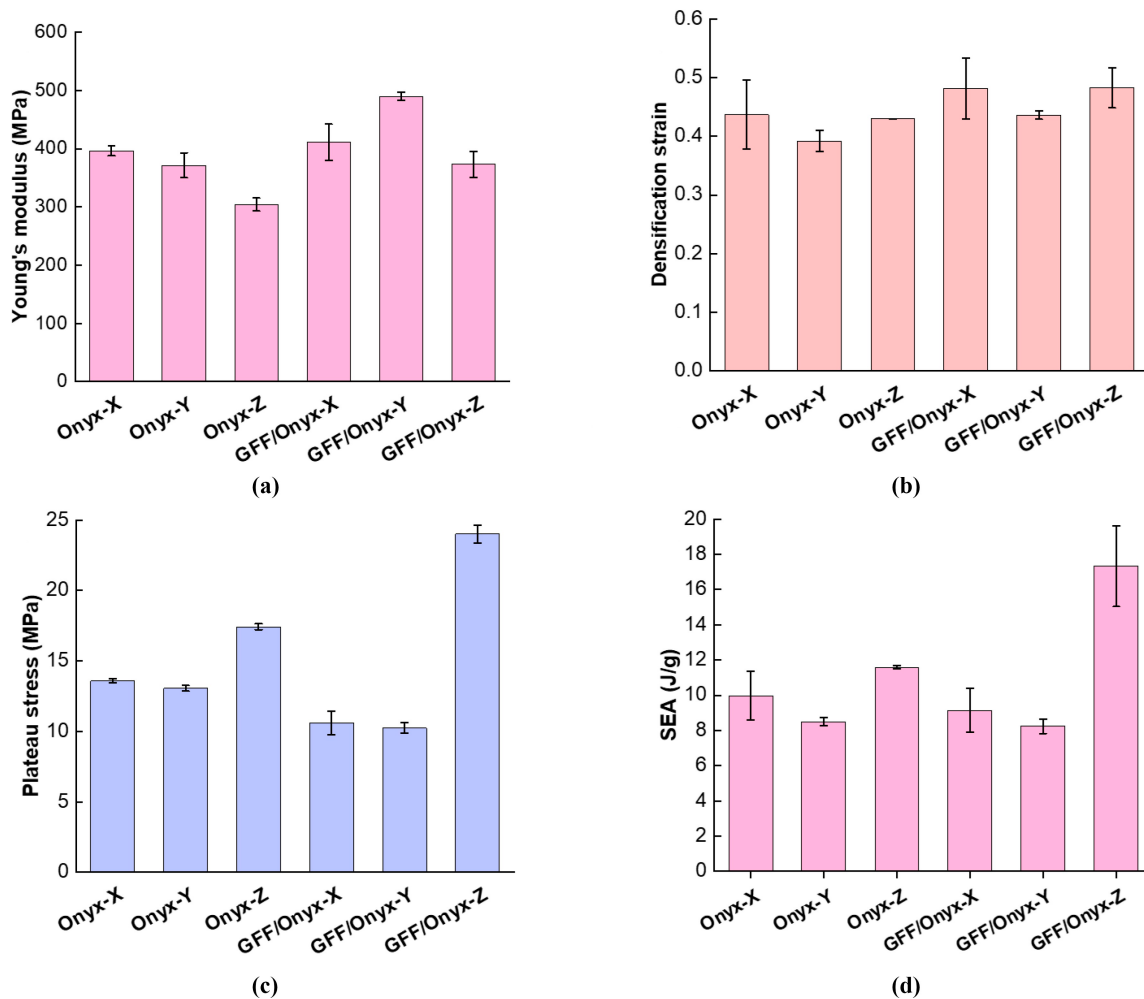
4. Conclusions

Gyroid structures were successfully fabricated using CFRCs via FFF, and their print quality, including fiber placement and void distribution, was systematically examined using X-ray CT. Quasi-static and dynamic compressive tests were conducted to evaluate the mechanical performance of gyroid structures manufactured from Onyx, GFF/Onyx, KFF/Onyx, and CFF/Onyx, with particular emphasis on the effects of loading direction and strain rate on deformation mechanisms, load-carrying capacity, and energy absorption.

X-ray CT analysis of 3D printed specimens revealed the presence of considerable process-induced voids in both Onyx and GFF/Onyx gyroid structures. In Onyx specimens, voids were predominantly located within the infill regions and aligned with the bead deposition paths, especially along $\pm 45^\circ$ infill directions, with a higher void concentration observed in the mid-height regions of the structures. Despite this, strong interlaminar bonding was observed between the infill and the outer wall layers. In contrast, GFF/Onyx gyroids exhibited voids primarily at the interfaces between the continuous fiber filaments and highly curved wall layers, which can be attributed to the placement of flattened fiber filaments in complex geometries. These observations underscore the challenges of minimizing void formation and achieving uniform interlaminar bonding in the AM of architected structures with complex curvature.

The deformations of 3D-printed gyroid structures under compression were found to be strongly dependent on both the loading direction and the strain rate. Under quasi-static loading, Onyx and GFF/Onyx gyroids loaded in the *X* and *Y* directions exhibited interlaminar failure due to weak interlayer

Figure 10 Comparison of (a) Young's modulus; (b) densification strain; (c) plateau stress; and (d) SEA of the Onyx and GFF/Onyx gyroid structures in the three principal directions



Source: Authors' own work

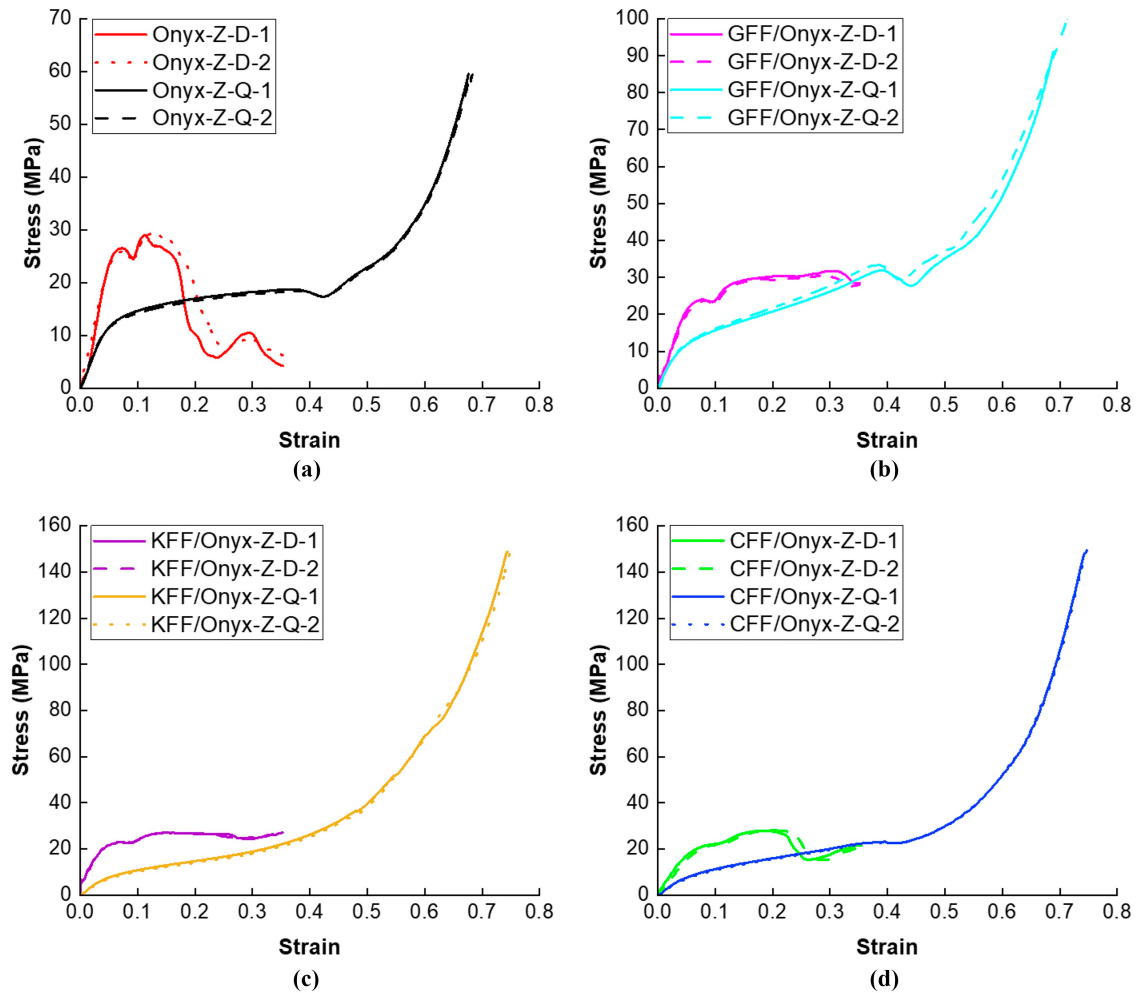
bonding and the presence of voids, whereas loading in the Z direction resulted in more stable deformation characterized by lateral shearing and progressive folding of the gyroid architecture. Under dynamic loading, Onyx gyroids experienced early failure, with rapid buckling and fragmentation occurring beyond approximately 15% strain. In contrast, fiber-reinforced gyroid structures maintained structural integrity under dynamic compression, as the continuous fibers facilitated effective load transfer, delayed crack propagation, and prevented catastrophic collapse.

The nominal stress-strain responses of all gyroids under quasi-static compression displayed the characteristic elastic, plateau and densification regions across all loading directions. Higher initial stiffness was observed in the X and Y directions due to the alignment of printed beads with the loading axis, while Z direction loading produced enhanced plateau stress and strain-hardening behavior due to the perpendicularly aligned printed beads to the loading directions. Compared with Onyx,

GFF/Onyx gyroids exhibited higher Young's modulus and densification strain in all directions, though reduced plateau stress and SEA were observed in the X and Y directions, likely resulting from interlaminar failure. Dynamic loading led to increased plateau stress levels in all materials; however, Onyx gyroids experienced a sharp stress drop associated with structural disintegration. In contrast, fiber-reinforced gyroids preserved their load-bearing capacity through fiber bridging, thereby maintaining structural integrity. Among the reinforced materials, GFF/Onyx exhibited the highest plateau stress under both loading regimes, while KFF/Onyx demonstrated the greatest strain-rate sensitivity with DIFs of 67.43% in plateau stress and 84.00% in SEA.

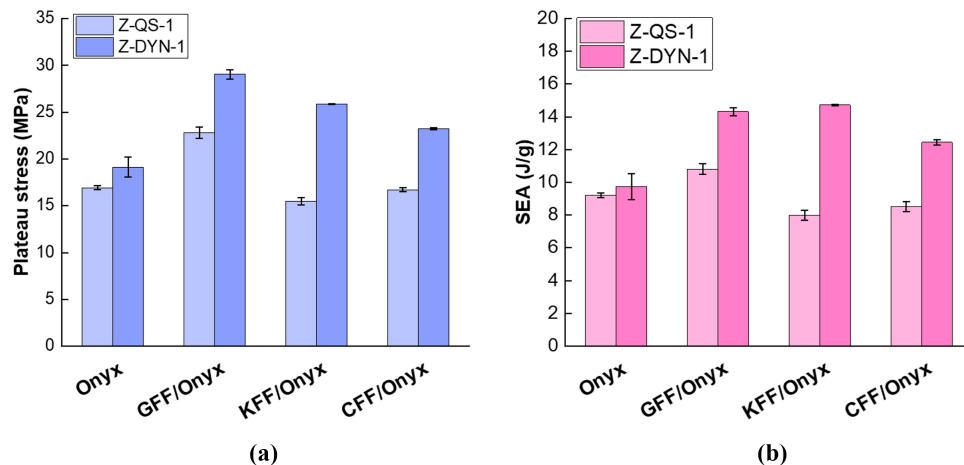
Overall, this study demonstrates the feasibility of manufacturing complex gyroid cellular structures using CFRCs and provides a comprehensive understanding of their mechanical behavior under varying loading directions, strain rates, and fiber types. The results highlight the significant role

Figure 11 Stress–strain curve of gyroid: (a) Onyx; (b) GFF/Onyx; (c) KFF/Onyx; and (d) CFF/Onyx subjected to compression at quasi-static (2 mm/min) and dynamic (4 m/s) loading velocities



Source: Authors' own work

Figure 12 Comparison of: (a) plateau stress and (b) SEA of the gyroid structures printed out using Onyx and different fiber reinforcements



Source: Authors' own work

of continuous fibers in enhancing mechanical strength, deformation stability, and energy absorption, particularly under high-rate loading, thereby establishing the potential of fiber-reinforced gyroid structures for impact-resistant and crashworthiness applications in aerospace, automotive and civil engineering sectors.

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Further reading

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