3D printed stretching-dominated micro-trusses

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HIGHLIGHTS
• Stretch-dominated and bending-dominated micro-trusses are fabricated by FDM-based 3D printing with 100 micrometers in strut diameter.
• Stretch-dominated octet micro-truss is mechanically programmed by 3D printing with rigid and soft materials.
• 3D printed CFRP truss shows strengthened mechanical properties resulted from shear-induced alignment of fibers along the 3D printing direction.

Abstract
Micro-architectures, such as truss structures, enhance the mechanical properties of structural materials while ensuring that they are lightweight in nature. Among others, stretching-dominated truss structures are known for their high modulus and yield strength, which makes them the best choice for lightweight structural applications. Finite element analysis of octahedral vs. octet structures is used to compare the differences in stress distribution in the stretching-dominated deformation of such trusses. Both octahedral and octet stretching-dominated structures were fabricated by fused deposition modeling (FDM)-based three-dimensional (3D) printing. These micro-architectures are printed with different polymeric materials, such as polylactic acid or polylactide (PLA), nylon 618, and a carbon fiber reinforced composite of PLA (CFRPLA). In addition, the CFRPLA filament with randomly suspended carbon fibers in PLA undergoes shear-induced alignment along the strut direction of the 3D printed micro-trusses, which leads to an improved Young’s modulus as compared to the other materials. The properties of the 3D printed stretching-dominated micro-trusses are evaluated by compression testing, finite element analysis (FEA), and thermal analysis. The 3D printed octet structure of CFRPLA with fiber alignment exhibits the highest modulus and yield strength of 0.6 GPa and 17 MPa, respectively.

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Keywords:
Architected material
Micro-truss
3D printing
Stretching-dominated structures
Compressive stress and strain

1. Introduction
High modulus-to-density materials can be realized by using a controlled cellular architecture [1], which feature cannot be achieved using a bulk sample of the same material [2]. Cellular structures are abundant in nature, where most of the structural components are polymers or organic-inorganic composites formed by the arrangement of hard ceramic particles in a hierarchical structure to yield strong materials, such as tree trunks and bones [3]. The development of these lightweight 3D structures is of particular interest to the aerospace and automotive industries, where weight savings directly leverages the
product performance [4,5]. In the past, the high costs associated with the manufacturing of truss structures limited their engineering applications, but the development of the additive manufacturing (AM) technology has recently sparked interest in using AM for more efficient material utilization, lowering the processing cost, and controlling the mechanical properties [6–8]. By varying the microstructure itself, the elastic properties of the object can be altered using a given composition for the applications such as 3D printed soft robotics [9], involving actuation of lightweight, flexible components. For example, employing different materials in a 3D printed composite can result in a phononic crystal metamaterial for controlling wave propagation, as demonstrated by Matlack et al. [10].

Different unit cell geometries can be chosen for trusses as the building blocks of macro-scale structures with hierarchical order, such as the building blocks for the Eiffel tower [11,12]. A 3D lattice can be formed by repeated stacking of the basic building block in the 3D space [2] and varying the cellular architecture in order to achieve the necessary structural properties. 3D hierarchical structures enable the formation of structural materials with high strength to volume ratio, while the high surface area per unit volume (due to decreased porosity) allows different functionalization approaches [13]. With specially arranged 3D structures, it is also possible to obtain mechanical metamaterials, such as auxetic materials, which exhibit a negative Poisson’s ratio. In addition, the use of nanoscale materials in 3D architecturing has been reported to achieve ultra-high strength-to-weight ratio beyond what is achievable at the bulk length scale [13].

3D structures comprised of strut-like members can be classified by their most prominent deformation mechanism, either strut bending or stretching. A bending-dominated structure will experience bending of its constituent struts while a stretching-dominated structure deforms primarily by the stretching or compressing of individual struts under loading, thus leading to a larger overall structural load bearing capability [14,15]. Foam is a common cellular material and is a bending-dominated structure, while crystallographic unit cell geometries, such as octahedral, octet, and Kagome, are examples of stretching-dominated structures [16]. The modulus of the cellular structure is given as \( E_{\sim}/E_i \approx (\rho_{\sim}/\rho_i)^3 \) in the case of bending-dominated materials, whereas in the case of a stretching-dominated structure, the behavior is linear and is indicated by \( E_{\sim}/E_i = \rho_{\sim}/\rho_i \), where \( \rho_{\sim} \) is the density of the cellular structure, \( \rho_i \) is the density of the solid, and \( \rho_{\sim}/\rho_i \) is the relative density; \( E_i \) is the bending modulus of the solid from which the strut is made. The modulus of a stretching-dominated structure is linearly proportional to its relative density and can be described as \( E_{\sim}/E_i \approx (\rho_{\sim}/\rho_i)^1 \) [17].

The modulus and initial yield strength of a stretching-dominated cellular solid are typically much greater than those of a bending-dominated cellular material of the same relative density, which makes the former attractive for lightweight structural applications [15]. The condition under which a structure will primarily deform by stretching is given by Maxwell's stability criterion, \( b - 3j + 6 = 0 \; \& \; 0 \), where \( b \) and \( j \) are the number of struts and nodes, respectively, in the unit cell [18, 19]. The node connectivity of the 3D structure plays an important role in defining its deformation mechanism [2]. The node connectivity “2” of an octet truss unit cell with a face centered cubic (fcc) arrangement is \( Z = 12 \) (see Fig. 1(a)) [15,18]. This type of connectivity offers the most effective load bearing or stretching-dominated deformation. The node connectivity of an octahedral unit cell consists of 8 equilateral triangles composed of 12 members and 6 joints. Two unit cells designs displaying stretching-dominated deformation behavior were explored in this study - the octet and octahedral trusses with struts of the same lengths [20]. The octet structure can be divided into two components as shown in the inset of Fig. 1(a); the eight tetrahedron units (shown in blue) join the octahedral unit cell (shown in red) to form the octet structure. Dong et al. showed that the design for assembly (DFA) model of an ideal octet truss structure deforms by stretching the individual struts with minimal bending of the octahedral structure in the interior [15,21]. On the other hand, the octahedral structure, although not in a fcc-like arrangement, is known to be stretching-dominated even though it can exhibit a combination of stretching- and bending-dominated deformations. The relative density of a unit cell is determined by the thickness of each octet truss and the number of octet trusses located within the cell is defined by \( \rho_{\sim}/\rho_i = \frac{1}{3} \cdot 12\pi R^2 / \left( \frac{l}{2} \right)^3 \) (1)

\( \rho_{\sim}/\rho_i = \frac{1}{3} \cdot \frac{l}{2} \cdot \frac{6\pi R^2}{\left( \frac{l}{2} \right)^3} . \) Elastic loading occurs according to the modulus and reaches an elastic limit when one or more sets of the struts yield plastically, buckle, or fracture.

In this investigation, the objective is to manufacture a stretching-dominated truss using 3D printing and achieve enhanced mechanical properties with different material choices for octahedral and octet truss structures. Further, uniaxial compression results and FEA results of all the structures are evaluated and analyzed. The filaments are also studied by scanning electron microscopy (SEM) and thermal analysis. Using a combination of material and structural designing, this work demonstrates the creation of lightweight and stiff structures with tailored mechanical properties. Overall, these open cell micro truss structures, processed by the versatile 3D printing technology, have significant potential to be used as both structural and functional materials.

2. Materials and methods

2.1. Fabrication of 3D printed architected micro trusses

A computer-aided design (CAD) software tool, Solidworks, was used to generate the octet and octahedral lattice structures, as shown in Fig. 1(a) and (d). Each model contains a basic unit cell with dimensions of 5 mm × 5 mm × 5 mm, made of square cross-sectional struts with a 1 mm diagonal. 3D spatial repetition of these unit cells leads to the creation of bulk 3D truss structures with external dimensions of 30 mm × 30 mm × 30 mm, which is further cut into reduced dimensions of 7 mm × 7 mm × 10 mm for compression experiments, as illustrated in Fig. 1(b) and (e). The specimen geometry was kept the same in both experimental and numerical analyses for easy comparison. The 3D truss structures were printed using a SeeMeCNC Rostock Max printer, which is based on the fused deposition modeling (FDM) printing technology. The filaments used for printing were commercial grade 1.75 mm diameter filaments from different vendors, as listed in Table 1.

During 3D printing, the material flows through a heated nozzle and forms 3D structures layer-by-layer. Because of the exceptional geometry adaptability offered by 3D printing, complex shapes can easily be fabricated in a single process by simply changing the CAD drawing file [14]. We employed 3D printing, and exploited its simplicity and effective rapid manufacturing features to create the octet and octahedral micro-truss structures shown in Fig. 1(a) and (d). 3D printing was performed with a layer thickness of 100 μm resolution in the vertical (z) direction; subsequently, the printed layers were directly bonded to each other and a one-body truss structure was formed. Fig. 1(a) and (c) show the CAD model and printed sample of a 3D arrayed truss structure, respectively. The strut thickness of these structures was fixed to
the thinnest possible printable size to achieve the smallest features. The structures follow the designs shown in Fig. 1(b) and (e) and maintain a cellular structure with hollow areas. Because these structures are fabricated layer by layer, the diagonal struts are not continuously uniform but have steps at the boundaries and the stacking of each layer can be clearly seen near the node in a representative optical image (Fig. 1(f)). The top and bottom faces of the structure are kept flat in the design for easier printing and adhesion to the printer bed. The horizontal struts are smooth and well-bonded at the nodes. A better view can be obtained in the SEM images of the printed layers of polylactide (PLA) and carbon fiber reinforced composite of PLA (CFRPLA), which can be used to study the surface and fiber alignment within the polymer matrix.

In this study, different material filaments were used to make two types of stretching-dominated structures. Thermoplastics, which are cheap and abundant in nature, are the default materials for FDM based 3D printing [22]; the printing parameters used for each material were altered depending on their printability. PLA is a biodegradable thermoplastic polymer and is known to be strong yet brittle. Nylon 618, on the other hand, is more compliant and soft, and is modified in comparison to the standard nylon material chain, resulting in a new co-polymer with dramatically enhanced bonding. CFRPLA composite material was also used to print 3D structures but its printing was more challenging as this filament is prone to grinding in the feeder, more easily than the plain PLA filament, due to its brittle nature. Carbon fiber PLA was made from NatureWorks 4043D PLA resin compounded with 15% (by weight) of carbon fibers. All the truss structures were printed assuming isotropic behavior in all directions; the same loading direction ([001] plane) was used for all the printed structures in the compression tests as well as the simulations and the response of each sample was analyzed.

2.2. Finite element analysis (FEA) of the stretching-dominated architected materials

FEA was carried out using ANSYS 17.0 software to compare the stress fields developed under uniaxial compression in octahedral and octet structures developed from different materials in their elastic ranges. Numerical simulations were conducted using a static structural analysis system to study each structure. The geometries of these structures were imported from the Solidworks database as step files. The octahedral and octet geometrical models had the same dimensions as the printed experimental structures (height = 10 mm, thickness = 7 mm, and width = 7 mm), although there may be slight differences between the exact size of the CAD models and the actual printed structures. For linear static structural analysis, the displacements (x) were solved using the matrix equation [K][x] = [F]. The elastic components given in Table 1 were used as the input parameters for the simulation of each material using a linear elastic material model, which includes the density, Young’s modulus, and Poisson’s ratio; these were sourced from the vendor’s specifications. The structures were meshed using a path conforming method to form a fine mesh, with the octahedral structure consisting of 91,978 tetrahedral elements and the octet structure consisting of 86,076 elements. Fig. 2(a) shows the meshed octahedral structure, with a zoomed-in view of the node in the inset (Fig. 2(b)). The mesh quality was checked by a refinement study, in which meshes of assorted sizes were compared. The dimensions of the elements were not uniform throughout the model and the default minimum element

<table>
<thead>
<tr>
<th>Material</th>
<th>Young’s modulus (GPa)</th>
<th>Poisson’s ratio</th>
<th>Density (g/cm³)</th>
<th>Manufacturer</th>
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<tr>
<td>PLA</td>
<td>3.5</td>
<td>0.38</td>
<td>1.25</td>
<td>SeemeCNC</td>
</tr>
<tr>
<td>CFRPLA</td>
<td>4.7</td>
<td>0.30</td>
<td>1.3</td>
<td>Proto-pasta</td>
</tr>
<tr>
<td>Nylon 618</td>
<td>2.95</td>
<td>0.36</td>
<td>1.10</td>
<td>Taulman</td>
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</table>
size settings was used for both the structures. The structures were compressed by applying boundary conditions, where the bottom face was fixed and the top face of the structure was free to move in the normal direction under the action of a displacement that increased linearly over 50 sub steps up to a strain of 0.06. The stress location for the both the structures seems relevant, because it is where failure will be initiated during mechanical testing. FEA was performed to study the stress distribution in the elastic range and hence an isotropic elastic behavior was assumed for the entire system; the resulting stiffness is then compared with respect to each material.

A static structural analysis was performed for the elastic mechanical analysis of the structures and therefore strains till the elastic limit were applied. The effective modulus of each structure was obtained from the stress-strain curve derived from the data generated by the FEA model. A displacement ranging from 0 to 0.6 mm was applied on the top face of the structure within the elastic deformation limits and the corresponding reaction force was evaluated at the bottom fixed support. The force-displacement data was then used for post-processing. Due to the idealized loading conditions assumed in the simulations, some deviations are to be expected from the experimental results.

2.3. Characterization of the architected materials

2.3.1. Uniaxial compression testing

To identify the changes in the mechanical behavior of different unit cell structures, compression tests were conducted using a MTS compression tester with a 500 N load cell. A uniaxial compressive stress was applied on the 3D trusses. We initially fabricated 30 mm × 30 mm × 30 mm structures by 3D printing and then cut them into smaller samples with dimensions of 7 mm × 7 mm × 10 mm for compression testing. The compression displacement rate was 2 mm/min, which translates to a strain rate of $3 \times 10^{-3}$/s. This loading rate follows the test conditions specified in the ASTM polymer compression test standard. Step loading in terms of the uniaxial displacement was imposed on the top surface while the bottom surface was fixed. The load-displacement data are then converted to stress-strain responses, from which the modulus of the truss structures can be determined. The tests were performed up to strain of ~50% for the PLA, CFRPLA, and nylon structures. Careful alignment between the sample and the plate is required to obtain a reliable loading slope, which is comparable to the known values of modulus for the corresponding material.

2.3.2. Scanning electron microscopy

The cross-sectional and surface morphologies of the filaments and structures were investigated by SEM (Nova NanoSEM, FEI Company) at room temperature. The samples were coated with a conductive layer of gold using a vacuum sputter coater (Hummer 6.2, Anatech USA) prior to imaging.

2.3.3. Differential scanning calorimetry (DSC)

The thermal behavior of the polymers was analyzed using a DSC Q2000 V24.9 Build 121 thermoanalyzer. The test temperature was varied in the range of 25–270 °C at a heating rate of 10 °C/min in nitrogen atmosphere. Four models, including the pre- and post-printed PLA and CFRPLA samples, were studied using DSC. And each model was analyzed twice. Approximately 3 mg of the samples were first heated to 270 °C in
aluminum boats and then cooled back to room temperature at a rate of 20 °C/min. Subsequently, two runs at a heating rate of 10 °C/min (25–270 °C) were carried out and the thermal parameters, such as glass transition temperature (Tg), cold crystallization temperature (Tcc), melting point (Tm), and melt enthalpy (ΔHm), were recorded from the third DSC heating run.

3. Results and discussion

3.1. Deformation behavior of octet vs. octahedral micro-trusses

Finite element models, shown in Fig. 2, were used to simulate the compression of 3D micro-truss structures. Fig. 2(c) and (d) describe the stress distribution in the CFRPLA octahedral and octet structures, respectively. From the simulation images, it can be seen that the stress is concentrated at the nodes, which makes them the weak points at which fracture is initiated; the maximum stress value at the nodes is higher in the octahedral structure than in the octet for the same displacement of 0.1 mm in the downwards direction. This can be attributed to the fact that in the octet structure, the horizontal struts also undergo tensile deformation at the same time, thus transmitting less load to the nodes. The horizontal struts in the octet experience tension while the angled struts undergo compression during loading, and therefore, in Fig. 2(d), the stress distribution is broadened at the nodes, unlike in the case of octahedral structures; thus, the octet structure exhibits a better resistance to the applied load.

To determine the effect of micro-architecture on the mechanical performance of the 3D printed structures, we performed uniaxial compression tests on each of the six samples. The stress-strain compressive response of the octet and octahedral structures was measured twice and summarized in Fig. 3(a) and (f). The two experimental runs showed equivalent results with ~3% error. The PLA and CFRPLA octahedral structures initially exhibited elastic deformation, where the stress increased linearly up to the yield point. Typically, the peak stress at strut failure was first observed, followed by a plateau, during which buckling of the structures was observed, as shown in the plot in Fig. 3(a). Following
the plateau region, the compressive stress increased steeply due to hardening, which occurred as the deformed struts came into contact with each other when the lattice structure densified. A similar behavior was noticed in the case of the PLA and CFRPLA octet structures, but the latter exhibited a significantly higher yield point before the stress reached the plateau region (Fig. 3(f)).

In a stretching-dominated structure, the struts experience stretching upon the application of a load. Because the strut members are stretching, a higher load bearing capability or yield point is expected in the stretching-dominated structure in comparison to a simple deformation of the truss geometry with a minimal strain imposed on the individual struts. As the structure is compressed further, the stretching strut members will have limited strain to failure and this can then cause a drop in the stress after the yield point as the stretching members fail due to local tensile straining. Once most of the stretching members fail, the octet structure will experience buckling of the lattice, in a manner similar to the octahedral structure which experiences buckling deformation in the plateau region of the stress-strain curve. The higher yield point in the octet structure agrees well with the simulations, which indicate higher stresses in an octet structure for a given structural density.

The FEA simulation results are also plotted in the stress-strain curves for comparison. In the case of the octahedral structures, the curves do not exactly overlap with the experimental curves; a percentage difference of ~30% in the PLA and CFRPLA results and ~150% in the nylon results is observed. However, the trend in the slopes of the three materials is similar to that of stiffness, i.e., CFRPLA > PLA > nylon. This is because the simulation considers an ideal stretch-dominated octahedral structure but the actual experiments indicate that it follows a buckling-dominated deformation instead, which has a different curve response. On the other hand, in the case of the octet structure, the elastic region curves of PLA and CFRPLA almost overlap with the experimental curves with ~10% deviation from the experimental results but nylon still exhibits dissimilar curves. This persistent trend shown by nylon may suggest that more properties need to be specified in the simulation apart from defining its Young’s modulus and Poisson’s ratio, which can predict its actual behavior.

In general, octahedral structures demonstrated higher Young’s modulus, as determined from the loading slopes of their stress-strain curves, than the octet structures. The PLA, nylon, and CFRPLA octahedral structures exhibited moduli of 0.45, 0.11, and 0.58 GPa, respectively, and the corresponding octet structures for the same materials exhibited moduli of 0.29, 0.08, and 0.37 GPa, respectively (Table 2). It should be noted, however, that the octahedral and octet structures have different relative densities, which should be taken into account. When compared to the FEA results, in the case of the PLA structures, the simulated Young’s moduli vary by about 40% in the octahedral and about 18% in the octet structures, from the experimental Young’s moduli values. However, the trend in Young’s modulus is similar to that of stiffness, i.e., CFRPLA > PLA > nylon, in both octahedral and octet structures. The models used in the simulation studies to input the material properties take into account the material elastic properties. In order to make the simulation better fit the experiments, a model with more number of input parameters, such as the fiber nature in CFRPLA and the soft elastic nature of nylon, may be used.

The volume and weight of the 3D truss structures were used to determine the densities of the octahedral and octet trusses and normalized by the reference densities of the corresponding solid material. The relative moduli were then determined by using the normalized solid reference modulus of PLA, nylon, and CFRPLA. The log scale plot of relative modulus vs. relative density in Fig. 4(a) exhibits two slopes - slope 1 and 2 (red lines), which refer to ideal stretching-dominated and ideal bending-dominated deformation behaviors, respectively. The CFRPLA structure exhibited greater bending-dominated deformation. Similarly, for a given material of given structural density, octet structures generally display a higher stretching-dominated relative modulus than the octahedral structures. The dependence of moduli on the material selection will be addressed in more detail in the following sections.

### 3.2. Material selection for 3D architecture: nylon, PLA, and CFRPLA

After analyzing the mechanical properties as functions of the type of structure, the effect of different material choices was studied. Elastomeric foams always fail by buckling and rigid polymers buckle before they yield when $\frac{\rho}{\rho_s} \leq 0.05$ [14]. A lattice structure made from a brittle solid will collapse when the struts start to break. Depending on the desired application, a strong polymer may be preferred even at the expense of ductility or a compliant structure may be preferred at the expense of strength. The two printable polymer choices of nylon and PLA are examples of soft and compliant vs. hard and stiff materials; they were both 3D printed into octet and octahedral structures for comparison. In addition, the functionalization of polymer-based 3D structures may be possible with additives (for example, addition of carbon-based materials to achieve conductivity) and thus a commercially available carbon fiber reinforced polymer was investigated for its mechanical properties, which improved significantly depending on the fiber orientation distribution in the final products.

For a given structure (octet or octahedral), the Young’s modulus was the highest for CFRPLA, followed by PLA and then nylon. The enhancement in the modulus of CFRPLA to 0.58 GPa can be attributed to the reinforcement of the polymer matrix due to the alignment of the carbon fibers. Fig. 3(f) shows the stress-strain plots of the octet structures. The PLA and CFRPLA strusses exhibit stretching-dominated characteristics; a clear yield point can be observed followed by a drop in the stress before it reaches a plateau. Nylon, however, did not exhibit a high yield point, indicating a more bending-dominated deformation. This is due to the low modulus and strength of nylon, which may not contribute as significantly to its load bearing capacity. Consider the octahedral structure shown in Fig. 3(a) - all three materials, PLA, nylon, and CFRPLA, showed bending-dominated deformations without pronounced yield points.

As seen in Fig. 3(g) and (h), failure is initiated by partial stretching in the struts at 20% strain. The compression results show that the PLA and CFRPLA octet and octahedral strusses exhibit similar mechanical behavior (Fig. 3(a) and (f)). The stress-strain curves of the PLA and CFRPLA octet truss samples exhibited a sharp drop in the stress after achieving the ultimate strength, which means that these lattice structures were brittle, resulting in a sudden collapse of the struts unlike the nylon lattice structure, in which the struts bend due to the high elasticity of the

### Table 2

<table>
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<th>Parameters</th>
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<th>Octet</th>
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<tr>
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<td>PLA CFRPLA nylon</td>
<td>PLA CFRPLA nylon</td>
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<tr>
<td>Experimental Young’s modulus (GPa)</td>
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<td>FEA Young’s modulus (GPa)</td>
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<td>Relative density ($\rho/\rho_s$)</td>
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<td>Relative Young’s modulus ($E_{tr}/E_s$)</td>
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<td></td>
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<td>0.08</td>
</tr>
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M. Kaur et al. / Materials and Design 134 (2017) 272–280

277
material [23]. In the case of nylon, the maximum stress of the octahedral structure is less than that of the octet structure and the stress distribution in both cases is similar. The elasticity of nylon dominates the structural mechanical properties of nylon-based trusses, as was also observed in the simulations, where the stress distribution is over the whole truss structure rather than being concentrated at the joints alone.

Furthermore, a relative modulus vs. relative density plot was constructed to accurately compare the Young’s moduli and the mechanical deformation behavior, as shown in Fig. 4(a). A nylon truss, regardless of its unit cell structure, displays a slope associated with bending-dominated behavior. On the other hand, PLA and CFRPLA octet and octahedral trusses exhibit a slope in between the stretching- and bending-dominated behaviors, leading to the development of a stretching-bending varied deformation behavior. A CFRPLA octet truss displays superior stretching-dominated behavior compared to a PLA octet truss as the former displays deformation behavior closest to the ideal stretching-dominated behavior represented by slope 1 in the density-modulus graph. The energy absorptions of these structures are also compared by measuring the areas under their respective stress-strain curves in Fig. 3(a) and (f). A bar chart is plotted from these values (see Fig. 4(b)). The key to energy absorption efficiency lies in the post-yielding response, which corresponds to the plateau region in the stress-strain curve and is limited well before the densification of the structure. When the absorbed energies of the octet and octahedral structures are compared, nylon shows the least absorption while the CFRPLA’s total absorption being slightly higher than PLA. The octet and octahedral bar graphs are not compared with each other as they do not have the same density.

These carbon fibers experience shear from the nozzle during extrusion, which leads to their alignment along the printing direction. When the filament is melted and confined to squeeze through the nozzle area, the viscoelastic interaction between fused PLA and the fibers, along with the shear forces induced during printing, helps the fibers to align along the direction of printing. This alignment along the printing direction is more pronounced in the 3D printing process and could not be observed in the CFRPLA melt, where fibers spontaneously assemble into randomly distributed long-range anisotropic domains within the plane of the solution-cast films [24]. During printing, the molten fiber-PLA mixture is extruded through a 250 μm brass nozzle. The fibers are oriented in the extrusion direction and this fiber alignment is dramatically higher in printed samples than in filament samples, which emphasizes the inherent characteristic of high orientation in FDM 3D printing. Thus, the FDM technique not only produces samples with higher fiber orientation, but also with higher molecular orientation in thermoplastics [25].

The orientation and crystallinity of CFRPLA were further confirmed using DSC. The thermal properties of PLA and CFRPLA, before and after printing, are studied using DSC thermograms. The DSC curves exhibit three thermal transitions, namely glass transition temperature (Tg), cold crystallization temperature (Tcc), and melting temperature (Tm). These values along with the melt enthalpy (ΔHm) are listed in Table 3. Glass transition occurs over a range of temperatures; therefore, Tg is typically defined as the point of inflection of the DSC curve [26], as illustrated in Fig. 5(e). PLA filament exhibits Tg, Tcc, and Tm of 59.86, 125.04, and 149.42 °C, respectively, while the CFRPLA filament exhibits a slightly higher Tg of 60.06 °C due to reinforcement by the carbon fibers. Note that when comparing the before and after printing conditions, the values of the thermal parameters (Tg, Tcc, and Tm) decrease, while ΔHm increases. Furthermore, we find that the cold crystallization peak of the printed filaments shifted to lower temperatures in the thermograms of the printed PLA and CFRPLA filaments. This shift in Tcc indicates that crystallization was faster in the printed samples. In addition, the alignment of carbon fibers in printed CFRPLA lowers its Tcc to below that of printed PLA, which suggests that carbon fibers also act as nucleating agents for PLA crystallization [27]. To understand the effect of carbon fibers on the crystallinity of PLA, the relative percent crystallinity (Xc, %) (of carbon fibers in PLA) is calculated using the enthalpy obtained from the DSC curves, using the following equation

\[ X_c(\%) = \frac{\Delta H_c + \Delta H_m}{\Delta H_m(100\%)} \times 100 \]  

where, \(\Delta H_c\) is the heat of crystallization (J/g), \(\Delta H_m\) is the heat of fusion.  

Fig. 4. (a) Data plot of the experimentally tested stretching-dominated truss structures. The relative Young’s modulus is plotted against the relative density on an Ashby chart and (b) energy absorption comparison for different samples calculated using the area under the curve of the respective compression stress-strain curves.

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(J/g), and ΔH_m (100%) is the enthalpy of melting of 100% crystalline PLA (93 J/g) [28]. In this investigation, PLA and CFRPLA filaments were found to exhibit X_c values of 26.18% and 22.87%, respectively, while the X_c values of printed PLA and CFRPLA samples were 29.03% and 28.83%, respectively, suggesting that PLA and CFRPLA are almost identical in terms of crystallinity. The presence of fibers has been shown to accelerate the nucleation of PLA [29]. The DSC results are in agreement with the results of the SEM and mechanical analyses, which shows that the 3D printed structures made from CFRPLA filaments show better stretching-dominated behavior due to the inclusion of reinforcing carbon fibers closely packed in PLA without any phase separation. These fibers align themselves during printing, making them better energy absorbers.

<table>
<thead>
<tr>
<th>Sample</th>
<th>T_g (°C)</th>
<th>T_cc (°C)</th>
<th>T_m (°C)</th>
<th>ΔH_m (J/g)</th>
<th>ΔH_c (J/g)</th>
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<td>147.05</td>
<td>13.96</td>
<td>13.04</td>
<td>29.03</td>
</tr>
<tr>
<td>CFRPLA filament</td>
<td>60.06</td>
<td>124.65</td>
<td>147.91</td>
<td>10.54</td>
<td>10.73</td>
<td>22.87</td>
</tr>
<tr>
<td>Printed CFRPLA</td>
<td>59.23</td>
<td>122.79</td>
<td>147.24</td>
<td>13.71</td>
<td>13.1</td>
<td>28.83</td>
</tr>
</tbody>
</table>
4. Conclusions

We studied the deformation of 3D printed stretching-dominated structures made of different polymer materials using compression testing and FEA simulation methods. Elastomeric materials, irrespective of their structure, yielded bending dominated stress-strain curves due to their dominant elastic properties. The octahedral and octet structures of nylon exhibited similar stiffness moduli in the range of 0.08–0.1 GPa. This phenomenon is attributed to its bending-dominated elastic behavior, which can be observed in the simulations as well. Rigid plastic micro-truss structures showed relatively higher Young’s moduli compared to elastic nylon-based micro-truss structures, with octahedral truss structures of PLA and CFRPLA exhibiting moduli in the range of 0.45–0.6 GPa. A higher modulus and energy absorption are observed for CFRPLA in both octahedral and octet structures. 3D printing yields carbon fiber-based PLA structures with a high degree of fiber alignment along the printing direction due to the shear forces acting on the polymer melt while extruding, which makes the structures mechanically more stable. This capability can be readily extended to create a broad range of composite architectures and materials with programmable reinforcement along given directions, which can exhibit tailored responses to an applied mechanical load. Octet structures exhibit greater stretching-dominated behavior than octahedral structures; the CFRPLA octet structure shows the highest stiffness due to the alignment of fibers during printing and this observation is confirmed by the SEM and DSC results as well. Thus, by varying the material composition and structural design, it is possible to create lightweight and sustainable functional composites. Structural composites with tailored mechanical properties can be produced by the versatile and highly efficient 3D printing technology, which is capable of fabricating cellular structures.

Acknowledgements

This work received financial support from the Discovery Accelerator Supplement Grant 493028-2016, funded by the Natural Sciences and Engineering Research Council of Canada (NSERC), and also supported by the National Research Foundation of Korea (NRF) funded by the Korea government (MSIP) under Grant NRF-2016R1A2B3011473.

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