Is Cubic + Octet an Ideal Material Geometry for Impact Resistance?

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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Introduction

With the evolution of football, helmets have evolved to become safer with the increasing physicality of the game. A football helmet consists of four major components: a polycarbonate outer shell, energy-absorbing structures, comfort padding material, and a strap system (Bustamante et al, 2019). Plenty of research has gone into the energy-absorbing structures used in helmets to make them more effective. The research explored in this report intends to show how cubic + octet foam structure competes with a current lattice structure used in football helmets by testing, obtaining data, and analyzing the results to compare the two structures. By calculating the stress vs. strain distribution, the data will reveal how these materials behave under compression which allows insight to the energy-absorbing capabilities these materials have. Through literature review, previous research will describe complex material geometries and how using them in combination with each other can help optimize their properties. The implications of this research may help helmet manufacturers improve the lattice structures implemented in the liners within helmets to ensure a safer energy-absorption system. This can further protect players from potential concussions and other traumatic head injuries when experiencing helmet-to-helmet impacts, helmet-to-ground impacts, or helmet-to-body impacts.

Background

Six cellular material geometries have been identified by researchers to observe their elastic stiffness. These include cubic, octet, cubic + octet, quasi-random, octet truss, and isotropic truss (Berger et al., 2017). For this research, the cubic + octet geometry was chosen because it combines the first two material geometries intended to maximize its material potential. According to Berger et al. (2017), cubic + octet can inherit the maximum strain energy storage of each parent geometry, can be isotropic, and is able to reach the Hashin-Shtrikman upper bounds (strain energy storage) on isotropic elastic stiffness (Berger et al., 2017). These characteristics allow for cubic + octet to present as a possible geometry to be implemented in a lattice structure for sports applications. Other advantageous properties that these low-density mechanical metamaterials provide is the ability to facilitate large crushing strains with high energy absorption and high thermal insulation which are beneficial for sports applications (Berger et al., 2017).

Lattice structures are commonly known as structures consisting of repeating patterns that are connected to form 3D shapes. The goal for these lattices is to optimize compression performance while simultaneously minimizing the overall weight of the structure (Santiago et al., 2020). Due to the presence of 3D printing and additive manufacturing, more complex shapes and parts have been able to be created which expands the potential benefits and applications of lattice structures. It is noted that expanded polystyrene foams have been widely used as energy-absorbing liners in helmet applications due to cost efficiency (Fernandes et al., 2019). Polystyrene foams are appealing due to their features of being lightweight, good thermal insulation, moisture resistance, and durability (Chen et al., 2015). Other materials that have been explored for multi-impact loading include agglomerated cork which is a more general geometry. Research conducted by Fernandes et al. (2019) varied the thickness of the agglomerated cork to optimize the liner and compare its performance under double impact. Research conducted by Begley & Zok (2013) presents a methodology for identifying constitutive responses of crushable, linear-softening materials intended to reduce the severity of brain injuries caused by head impact. This source ties perfectly into the research being explored in this report due to its applications to sports collisions. Head injury criterion (HIC) was established by the National Highway Traffic Safety Administration for assessing the risk of brain injury in vehicle collisions but was later adopted to assess the success of protective equipment, such as helmets, in sports applications (Begley & Zok, 2013). This research used perfectly plastic foam material.

Plenty of research has been conducted that implements different geometries varying from bio-inspired geometries to more complex geometries and their performance under compression testing. This is a well-researched topic, but what is yet to be established is a material geometry considered to be the best for energy-absorbing systems. My research will compare a cylindrical geometry lattice to the cubic + octet material geometry through compression testing to observe how each sample deforms under pressure.

Methods

Previously created CAD Files of a variety of pucks, all cubic + octet geometry, were drafted using SolidWorks Software (*Figure 1)*. *Table 1* outlines the differences in the chosen puck's dimensions and differing characteristics such as the presence of a wall. Four pucks were 3D printed one by one using a LulzBot Taz 6 3D Printer (*Figure 2)*. The filament used for each puck was NinjaFlex, a flexible material characterized as having vibration-dampening properties and its ability to mold into different geometries makes it ideal for sports applications. Once the pucks were chosen, each puck was uploaded into Cura-LulzBot which is a software program that prepares the puck file for printing. This allows for changes in size and orientation along with ensuring the printing properties of the respective filament, such as extruder temperature, platform temperature, and print speed. For NinjaFlex, the extruder temperature is set to 225°C-250°C, the platform temperature is set to 50°C room temperature, and the printing speed can vary. Once the filament is loaded into the printer, an SD card loaded with the puck's information is inserted into the printer. After checking the print settings, a puck is now ready to be printed, and depending on the size of the four pucks, these prints took anywhere between 2 to 7 hours.

Figure 1 – SolidWorks CAD Puck Model Example

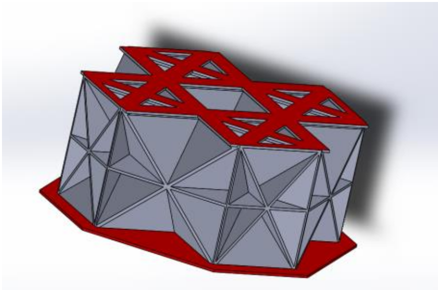
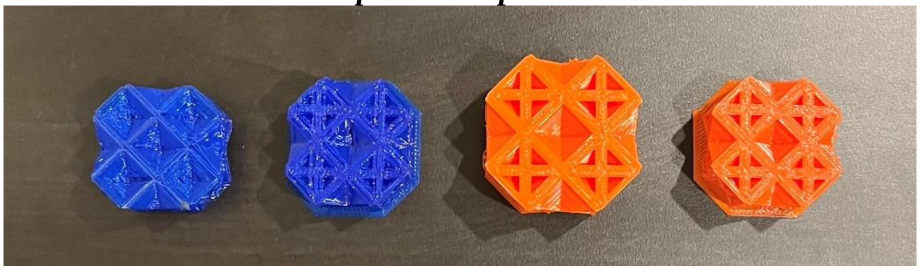


Table 1 – Puck Dimensions

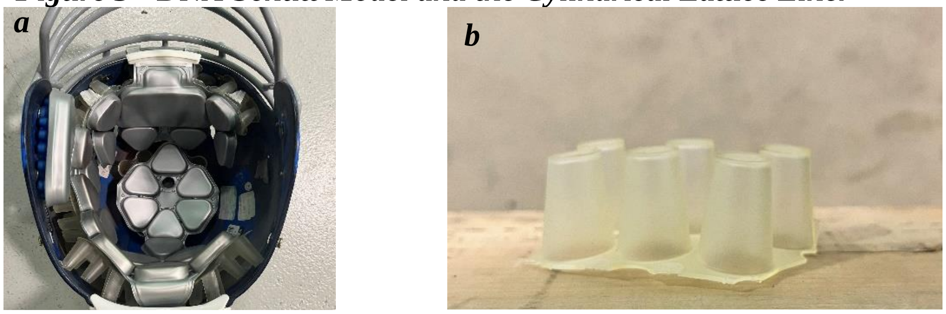
Blue 1	50 x 25 x 0.5 mm thickness
Blue 2	50 x 25 mm, raft 0.75 mm wall
Orange 3	30 x 60 mm, raft 0.5 mm wall
Orange 4	50 x 25 mm, raft 1 mm wall

Figure 2 – 3D Printed Puck Samples in Respective Order to the Puck Dimensions



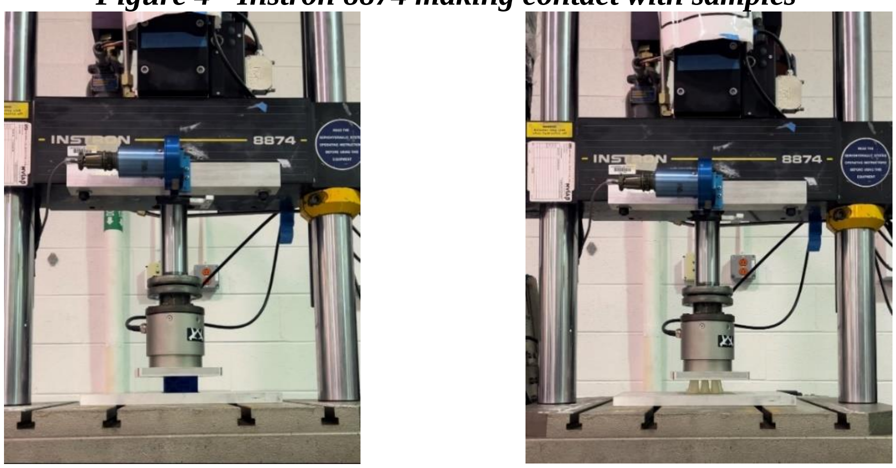
To determine if the cubic + octet material geometry can compete with the current lattice of a football helmet liner, a model Schutt DNA football helmet (*Figure 3a*) was obtained to remove a section of the plastic liner that rests inside the shell. The liner was cut out of the helmet's energy-absorbing system to match the size of the pucks so that the area of material being compressed was similar between all samples. The liner consisted of a cylindrical lattice which is used to absorb energy (*Figure 3b*), and is connected to polystyrene foam padding, which is used for comfort.

Figure 3 - DNA Schutt Model and the Cylindrical Lattice Liner



Prior to testing the four pucks and helmet liner, the speed of the Instron head was changed to get a “slow” and “fast” test setup on a test puck. These two different test speeds are reflected in the data collected. Displacement and force limits were set on the Instron software, so the head did not crash and break the load cell. Each sample was tested on an Instron 8874, a compact tabletop biaxial servo-hydraulic testing system, using a 10 kN load cell. Time (s), force (kN), and displacement (mm) data were recorded at 100 Hz. Each sample was positioned directly below the traveling head of the Instron 8874 prior to testing. The Instron head was moved downward until it made contact with the top of a sample (*Figure 4*).

Figure 4 - Instron 8874 making contact with samples

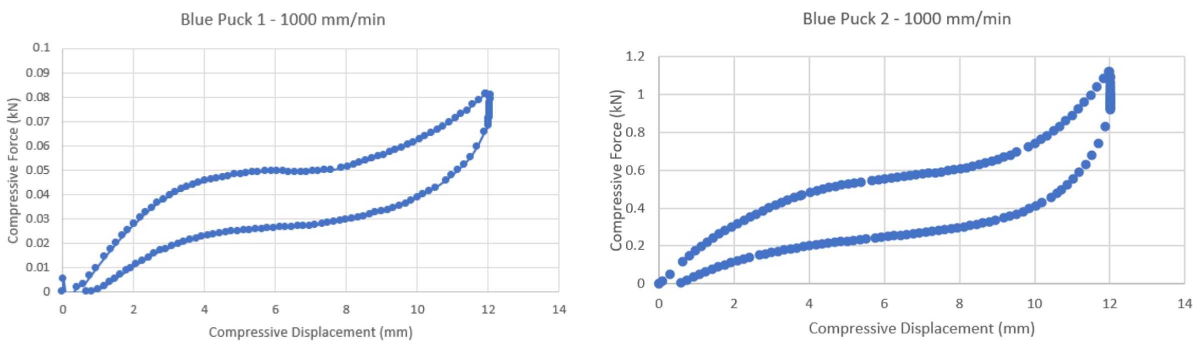


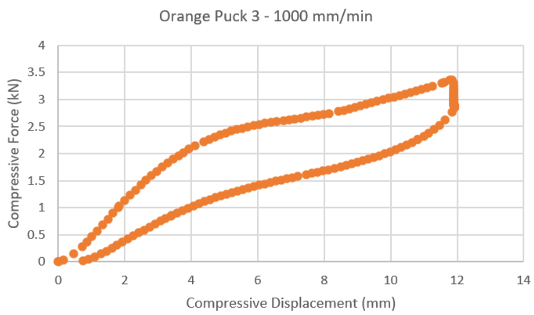
The displacement location displayed on the software was used as the starting point of the compression in each test. With all test parameters in place, one “slow” and one “fast” compression test was performed on each puck and the helmet liner sample. The traveling head would move into the previously defined start condition over 5 seconds and the head displaced downward at a rate of 100 mm/min or 1000 mm/min for 12 mm. Then the head traveled upwards at the same rate (100 mm/min or 1000 mm/min) during compression for 12 mm, bringing the head back to the initial compression starting point. Finally, the head is displaced upwards to a predefined endpoint over 5 seconds. This process was repeated for four pucks varying in density and the sample of the helmet liner was similar in size to the pucks. Once the data is manipulated to reflect compressive displacement (mm) vs. compressive force (kN), calculations for stress and strain can be performed for each sample to analyze their behavior during displacement caused by a force being applied.

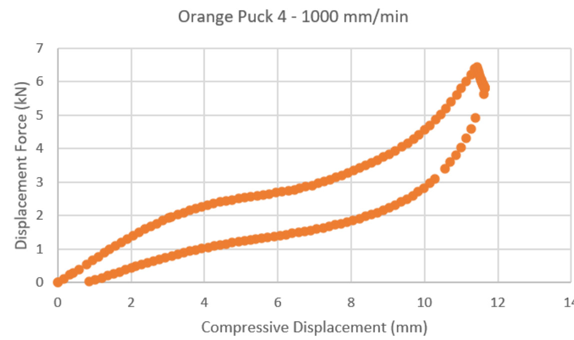
Data & Results

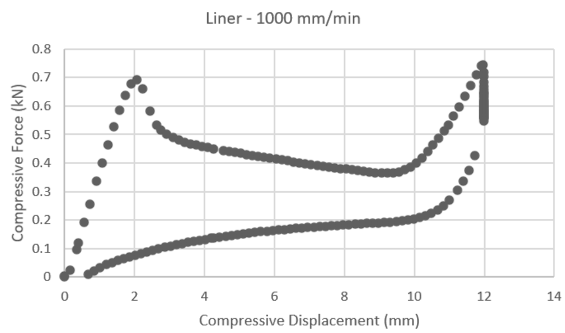
Testing the pucks and helmet liner produced data that outlined four steps: the device getting into the initial position, the loading phase (12 mm compression), the unloading phase, and the device returning to the original position. This research focuses on the data in steps two and three, the loading and unloading phase. The data collected during these two phases were manipulated to reflect Time (s), Displacement (mm), and Force (kN) that were transformed into graphs that reflect compressive displacement (mm) vs. compressive force (kN). *Figure 5* shows each sample tested at the slower speed of 1000 mm/min. The first points of each graph represent the sample in its initial position while the last points are the sample returning to its original position. The area between the curves represents the energy lost in the system during the loading and unloading phases.

Figure 5 – Servo-hydraulic Testing Results 1000 mm/min ("slow")



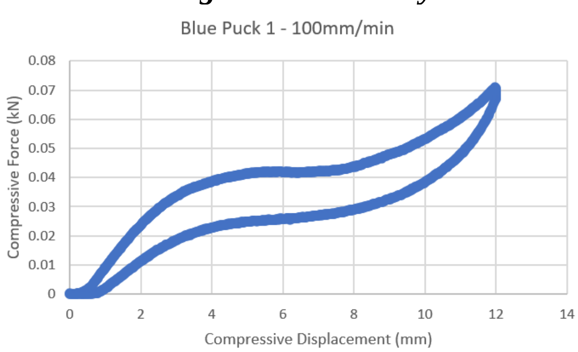


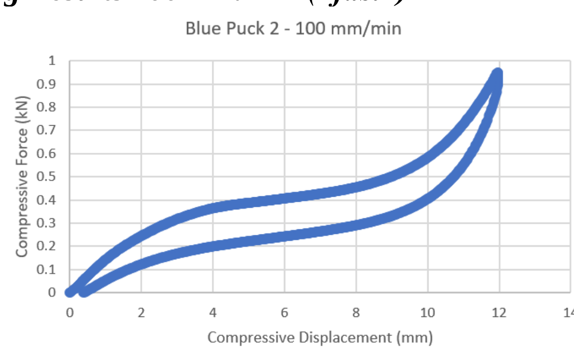


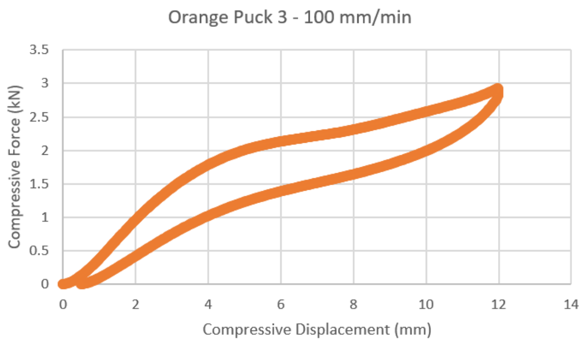


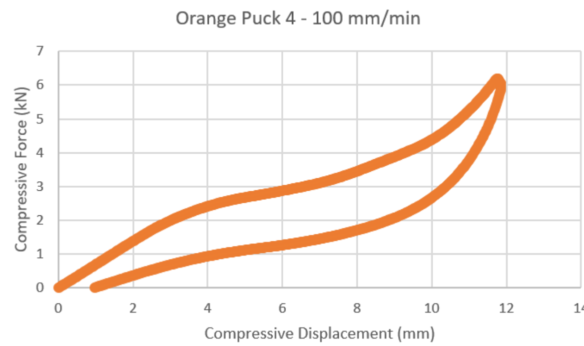
The same process was used to manipulate the data from the Servo Hydraulic Testing at 100 mm/min or at a faster speed. This can be seen in *Figure 6* with similar characteristics to the 1000mm/min graphs. Both sets of tests reveal differences in compressive displacement vs. compressive force of each sample at varying speeds.

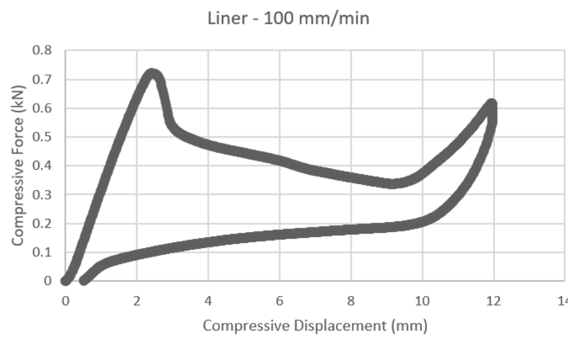
Figure 6 – Servo-hydraulic Testing Results 100 mm/min ("fast")











Comparing each graph created from the Servo-hydraulic Test data under the slow and fast speeds, none of the pucks behave in the same manner as the helmet liner. As stated before, the area between the curves represents the energy lost in the system during the loading and unloading phases. The graphs produced by Blue Puck 1, Blue Puck 2, and Orange Puck 3 showed less energy loss going from the “slow” test to the “fast” test while Orange Puck 4 and the liner experienced either an increase in energy loss from the “slow” test to the “fast” test or stayed the same. More points were needed to create the graphs at the “fast” speed which explains the fluidity of points in the 100 mm/min graphs compared to seeing some individual points in the 1000 mm/min graphs.

To obtain the relative density of the puck samples and liner, the mass of a fully solid sample will be its volume multiplied by the density of the polymer. The relative density is the ratio of sample mass to solid sample mass. NinjaFlex 3D Printing Filament is listed as having an approximate density of 1.2 g/cm^3 determined at 20°C. The mass of each sample was obtained using a digital scale and to get the relative density, each sample was then divided by the approximate density (*Table 2*). The closest sample to the helmet liner in relative density is Blue

Puck 1, which was characterized early on as being low in density. This similarity can be a baseline for further research using cubic + octet geometry to replicate the size and mass of current helmet liners.

Table 2 – Relative Density of Samples

	Mass (g)	Relative Density g/cm^3
Blue Puck 1	10.37	8.64
Blue Puck 2	20.55	17.13
Orange Puck 3	50.12	41.77
Orange Puck 4	35.16	29.30
Liner	8.99	7.49

The stress experienced during the Servo-hydraulic Testing was calculated by dividing the force by the bearing area. The strain experienced by each sample can be quantified by dividing the displacement by the height of the sample. A sample calculation of the stress at a specific point can be seen in *Equations 1* using data from Blue Puck 2. The stress was calculated using the maximum force experienced during the 100 mm/min testing speed of Blue Puck 2 and the bearing area of the flat face of this puck. The strain was calculated using the initial height of Blue Puck 2 (h_0) and the total compression during the loading face which was 12 mm (δ). Both equations can be repeated at each point on their respective graph to create a visual representation of the stress vs. strain experienced by each sample.

Equations 1 – Stress and Strain Example Calculations

$$\text{Stress}, \sigma = \frac{\text{Force (kN)}}{\text{Area}}$$

$$\text{kN} = 0.9623$$

$$\text{Area} = 4\, in^2 = 2580.64\, mm^2$$

$$\sigma = \frac{0.9623}{2580.64} = 372.892\text{ kPa}$$

$$Strain, \varepsilon = \frac{\delta}{h_0}$$

$$h_0 = 25mm, \delta = 12\, mm$$

$$\varepsilon^{\circ} = \frac{d\varepsilon}{dt} = \frac{1/60}{h_0} = \frac{1}{60 * 25} s^{-1}$$

$$\frac{1}{1500} s^{-1} = \frac{1}{1.5} 10^{-3} s^{-1}$$

$$\varepsilon^{\circ} = 0.67 * 10^{-3} s^{-1}\ for\ 1\ mm/min$$

$$\varepsilon^{\circ} = 0.67 * 10^{-1} s^{-1}\ for\ 100\ mm/min$$

$$\varepsilon^{\circ} = 0.67 s^{-1}\ for\ 1000\ mm/min$$

Discussion

Head injury criteria (HIC) is known as a measure of the likelihood of a head injury stemming from an impact. This criterion can be applied to vehicle crashes, protective gear, and sporting equipment. The brain damage guidelines are based on the head injury criteria which is considered a coefficient based on the resultant linear acceleration in the head's center of gravity (Dymek et al., 2021). According to Dymek et al. (2021), helmets certified by the National Operating Committee on Standards for Athletic Equipment (NOCSAE) cannot exceed a threshold severity index which is based on linear acceleration like HIC. The head injury criteria number is calculated by the acceleration experienced by the head in the event of an impact. For this research, tests were performed at 1000 mm/min and 100 mm/min while actual football hits happen at a much faster speed. In real-time, the force of a hit is dependent on several factors like the weight of a player, how fast they are going, and how fast they can stop moving. These factors can change the severity of an impact.

For future work, this research can be enhanced by making a complete lattice liner using the cubic + octet geometry, implementing it within a helmet, and adding the foam inserts back in. This would produce a cubic + octet geometry much smaller than the dimensions used in this research and the density can also be adjusted to replicate the ideal mass and density of a liner. Tests can then be performed on a different impactor system that would apply a quick force to the helmet in various areas simulating a hit or tackle. This would allow for different impact locations that align with NOCSAE standards to be tested and HIC values to be recorded. Extending this research to those parameters would allow for a more conclusive representation of how well the cubic + octet material geometry can work as a helmet liner as opposed to the cylindrical liner currently being used within a DNA Schutt model helmet.

Application

3D printing and additive manufacturing can provide multiple benefits to sports applications due to the ability to create form-fitting products with different geometries for biomedical devices, sports equipment, prosthetics, and much more. The conversation surrounding the implementation of 3D printed parts into not only sports but football helmets is not new. According to a review by Santiago et al. (2020), a proposed sensor system was developed consisting of unjacketed wires strung through two layers in a lattice that formed a complex capacitor. As the capacitance increases as the lattice is compressed, the complex capacitor can detect lattice deformation. This is one example of how 3D printed lattices can be used in a wearable application while also collecting impact data. The collection of this data can connect medical professionals to these sports applications due to the presence of concussions and their connection to helmet impacts. Additive manufacturing and CAD software have made producing lattices consisting of complex geometries with varying densities easier to produce than traditional methods (Santiago et al., 2020). With this improved technology, these lattices could be implemented into future football helmet designs by helmet manufacturers intending to produce the safest helmets. A review done by Tomin & Kmetty (2021) presents the energy-absorbing applications of polymeric foams in sports due to deformation mechanisms of foams that resemble cell structures. Unlike other sources, Tomin & Kmetty (2021) recognized that an unexplored field of research is the detailed study of multilayer sandwich foam structures. The implications of this research can lead to the combining of multiple material geometries to optimize energy-absorbing capabilities. It is evident that 3D Printing and Additive Manufacturing are present in sports applications and it seems that the presence will only increase as the recognized benefits can change the safety of sports equipment. With this technology making these complex lattices easier to produce, it is only a matter of time before they can be implemented on a larger scale and used by different helmet manufacturers.

Conclusion

This research combined the use of 3D printing and additive manufacturing, servo-hydraulic testing, and stress vs. strain to analyze the performance of the cubic + octet material geometry against an existing football helmet cylindrical lattice. Plenty of evidence shows the potential that 3D printing more complex material geometries such as cubic + octet can have on impact mitigation applications. As observed in the compressive displacement vs. compressive force graphs, none of the pucks acted in a way like the liner sample, which could be a good thing. Through testing, the cubic + octet structure is effective at dispersing force over an area which is ideal for application in sports equipment. Extensions of this research could include obtaining multiple existing liners, varying in geometries, and comparing their behavior with a more sports-based testing apparatus designed to simulate quick hits in different locations outlined by NOCSAE standards. For determining the success of this material geometry in future work, it is a matter of combining the cubic + octet material geometry in a uniform lattice structure with a specified density for it to show its capabilities in real-life scenarios such as within a new helmet model.

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