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Impact Resistance of 3D Cellular Structures for Protective Clothing

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Abstract

3D-printed cellular structures have attracted increased attention in recent years due to the many advantages of additive manufacturing technology. However, much of the current research is focused on the use of rigid or combined rigid and soft materials. In this study, the impact resistance of 3D cellular structures manufactured by Stereolithography (SLA) additive manufacturing technique using flexible photopolymer resin was investigated. Six different types of cellular structures were designed and manufactured by a photo-polymerizing 3D printer using two different types of flexible photo-curable resin materials. The resistance capacity of these structures against impact force was examined experimentally by using a customized free fall "impact drop test" where impact forces transmitted through the impacted structures were captured using a capacitive force sensor underneath the structure, in the form of real-time impact force vs time plot. The results indicate that the reentrant honeycomb (AU) cellular structure experienced the lowest peak impact force 2.73 N and 2.64 N made from Liqcreate and Prusa flexible materials respectively, and it has the best impact resistance performance among all developed 3D structures.

Keywords: 3D printing, flexible cellular structure, impact resistance, low speed impact, stereolithography (SLA), flexible photo-curable resin

1. Introduction

The role of impact-resistant equipment is to protect the body segment being struck by an object by absorbing the energy from impact, reducing or preventing damage.[1] Impact-resistant materials are those that can withstand extreme force or shock applied to them over a short period of time. Conventional impact protection materials are heavy, rigid, and inflexible, which limit their wider end user applications, causing wear discomfort and restriction of movement. Although impact protection materials have been extensively used in sporting goods, medical and military equipment and industrial protection, existing literature focuses on their protection effectiveness, and hence wear discomfort still remains a major unsolved problem with protective clothing and equipment. [2, 3]

Impact protective equipment and clothing are generally made up of padding materials embedded in specially designed clothing for particular requirements.[3] Foams, in the form of padding have been

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widely used as energy absorbing materials.[4] Generally, impact protective clothing possesses bulky pads and semi-rigid material insertions, which limits the breathability, comfortability and mobility of sports people, causing decreased performance during sporting activities.[5, 6] Current high performance materials such as shear-thickening gels, impact-hardening synthetic polymers and auxetic metamaterials are likely to take the lead being impact protective materials over the next decade. Recent advancements in additive manufacturing have acquired significant attention that enabled users to accurately develop 3D objects economically. 3D printing can provide complete freedom and ease in the fabrication of highly complex structures, which are difficult, time-consuming and very expensive to produce by conventional methods.[7-10]

Several additive manufacturing techniques are currently utilized to fabricate complex auxetic metamaterial cellular structures like Fused Deposition Modelling (FDM), PolyJet, StereoLithography (SLA), Selective Laser Sintering (SLS), Selective Laser Melting (SLM) and Electron Beam Melting (EBM). PolyJet is one of the most popular additive manufacturing techniques adopted by researchers for constructing cellular structures in which the outlines of jetting photosensitive inks are polymerized and then cured under ultraviolet (UV) light. The SLA 3D printing method has also been adopted to fabricate 3D cellular structures as it follows similar principle of curing photosensitive resin polymers. The fabrication of 2D planar cellular structures using the FDM technique has been effectively used for both rigid and flexible thermoplastic materials such as polylactic acid (PLA) and thermoplastic polyurethane (TPU) respectively, as printing materials.[7]

The 3D printing process depends on CAD data and information for substrate depositing in consecutive layers. The range of different infill patterns used to fill the interior of an object in most 3D printers are similar to porous materials such as in parallelogram, rectangular and hexagonal shapes.[11] Both the architecture and composition of cellular materials are important in determining the properties of printed items.[12] It is vital to provide a wide range of stiffness in cellular structures that can be optimized through interactive design techniques by tuning the topology of the cellular structure. Such requirements can be achieved by introducing the so-called ‘multi-material concept’ into the cellular structures.[13]

Critchley et al. [14] conducted a study of examining the fabrication of conventional 3D re-entrant auxetic foam by using pliable polymer materials. The 3D lattice foam structure was fabricated with Stratsys TangoBlack and Tango-Black8 polymers using an Objet 350 Connex, Stratasys 3D printer. The results of the study revealed that almost all geometric features achieved dimensional precision between 0.5% and 5% of the original design. However, it was observed that, support material was deposited throughout the samples and during cleaning process, structure was swelled. As a result, it caused cracking and fracture within the lattice structure.

Utilizing the ‘two materials concept’ in developing cellular auxetic structures, Wang et al. [15] designed and constructed auxetic metamaterial cellular structures having elastic joints and stiff beams/walls without any buckling issue. They investigated the influence of material selection and stiff material fraction on Young’s Modulus, Poisson’s ratio, and volume reduction, through experiments and FE simulations. All samples were 3D-printed using a Connex350® 3D printer. Two materials, VeroWhitePlus® and TangoBlackPlus® from Stratasys Polyjet Polymers were selected for printing the stiff and elastic regions of samples respectively. The results indicated that the auxeticity and mechanical properties of this dual-material auxetic metamaterial (DMAM) were noticeably different from those of traditional single-material auxetic metamaterials (SMAMs). Moreover, it has been suggested that the unique properties of DMAMs could be valuable to various engineering applications as shock-resistant equipment. However, DMAMs may not be suitable for protective clothing application as the structures were mostly made up of stiff materials.

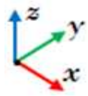
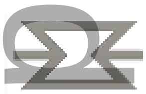
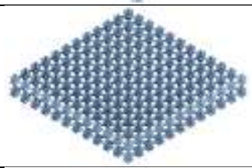
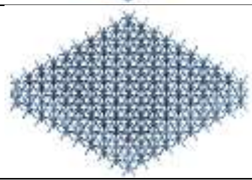
It is evident that most of the research related to cellular structures has been conducted theoretically in the form of analytical modelling and simulation evaluations, but with the advent of additive manufacturing technology, experimental research has been made possible to validate the theoretical studies based on some assumptions. However, despite the ability of experiments, research work on cellular structures made by the single flexible material concept is still very limited. Therefore, intensive experimental and analytical research is needed for the development of flexible impact resistant 3D cellular structures. The current study focuses on engineering design and evaluation of novel 3D cellular structures with a single flexible material using Stereolithography (SLA) additive printing, that can offer impact resistance, and flexible enough to adopt the body contours while being bent.

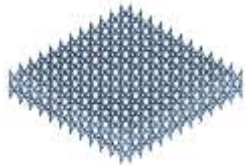
2. Materials and Methods

2.1 Design of cellular structures

A range of cellular structures were computationally designed using Autodesk® Fusion 360 (64 bit). The modeled cells were initially produced as 2D structures, then merged to form symmetrical 3D unit cells. An appropriate cell size was achieved after some preliminary experiments. These unit cells were repeated horizontally and vertically to create larger models. **Table 1** provides a summary of how CAD models were created and converted into various 3D printable models.

Table 1: Summary of CAD cellular structures with specific dimessions.

S. No.	Design Name	2D Unit Cell	Unit cell Dimensions (mm)	3D Unit Cell	 Complete cellular structure CAD Design Dimensions (mm)	
1	AU		Width = 4.166 Height = 2.88 Wall Thickness = 0.4 Angle = 45°			X = 49.73 Y = 52.37 Z = **5.35**
2	HC		Width = 2.97 Height = 2.88 Wall Thickness = 0.4 Angle = 60°			X = 55.84 Y = 52.48 Z = **5.36**
3	MA		Width = 2.68 Height = 2.68 Wall Thickness = 0.4			X = 50.92 Y = 50.92 Z = **5.36**
4	NA1		Width = 2.68 Height = 2.68 Wall Thickness = 0.4 Angle = 45°			X = 50.92 Y = 50.92 Z = **5.36**

5	NA2		Width = 2.88 Height = 2.88 Wall Thickness = 0.4 Angle = 45°			X = 52.48 Y = 52.48 Z = **5.36**
6	NA3		Width = 2.88 Height = 2.88 Wall Thickness = 0.4 Angle = 45°			X = 52.48 Y = 52.48 Z = **5.36**

In order to compare impact resistance performance of cellular structure pads with conventional materials found in comparable applications, the thickness of cellular structure pads was controlled to 5.36 mm, in line with conventional paddings material for protective assemblies, which are usually thicker than 5 mm.[2, 5] Wall thickness of unit cells (strut diameter) was also kept constant at 0.4 mm. Previous study[14] used a minimum strut diameter of 0.6 mm for 3D printed cellular structures.

2.2 Materials

Two different commonly used pliable photopolymer liquid resin materials with different shore hardness values were selected as base materials for making the cellular structure pads. They were flexible blue resin manufactured by Prusa® Research s.r.o., Czech Republic and premium flex resin manufactured by Liqcreate®, Netherland. Prusa flexible blue resin was the most appropriate resin with shore hardness value around 70A, as this material was fully compatible with the Prusa SL1 3D printer. The printing profile of this resin material was built in the printing slicer utility. The other resin Liqcreate premium flex with shore hardness value of 65A was open-sourced, and was also compatible with the Prusa SL1 3D printer. The printing profile of this resin was created in the Prusa slicer utility to achieve appropriate printing performance. A commercial foam Ethylene-Vinyl Acetate (EVA) with thickness around 6 mm was sourced from Intecfoam UK.[16] This conventional foam is widely used in personal protective equipment such as sports equipment, gloves and shoes. In this study, EVA foam was used as a reference material to compare the impact resistance performance with the newly developed flexible samples with cellular structures.

2.3 Additive manufacture of cellular structures

The cellular structures generated in CAD were required to be converted into STL file format to enable 3D printing. These STL file models were processed through a 3D printing slicer utility (i.e. PrusaSlicer® 2.3.1) and their printing parameters were modified and tuned accordingly. During this process, printing instructions were written in G-code scripts for the samples to be printed. To achieve high quality of printing, the printing parameters were further adjusted by careful visual inspection of individual samples being printed to detect any faults. Support material was used only for AU and HC models as both designs involved horizontal beams that require supporting material. The two models were printed at a 45° angle to achieve smooth printing. The rest of the models were printed without any support material. The 3D printer used to manufacture all cellular structures is shown in **Figure 1**. In the beginning, the printing platform was almost in touch with the bottom of the tank in the presence of liquid resin where UV light cures the first layer by exposure. During the printing process, the platform moves in upward direction for the repeated layering process till the whole structure is completed. For washing and curing of all printed samples, Prusa® CW1 washer was used, where the printing platform along with the newly printed structures were placed in the washing tub filled with isopropyl alcohol to remove the uncured extra resin residue from the structures. After washing, the washing tub was taken out of the washer first, and then, the printed structures were carefully removed from the platform to avoid any damage. The washed structures were then dried and UV-cured in the washer for testing and evaluation.

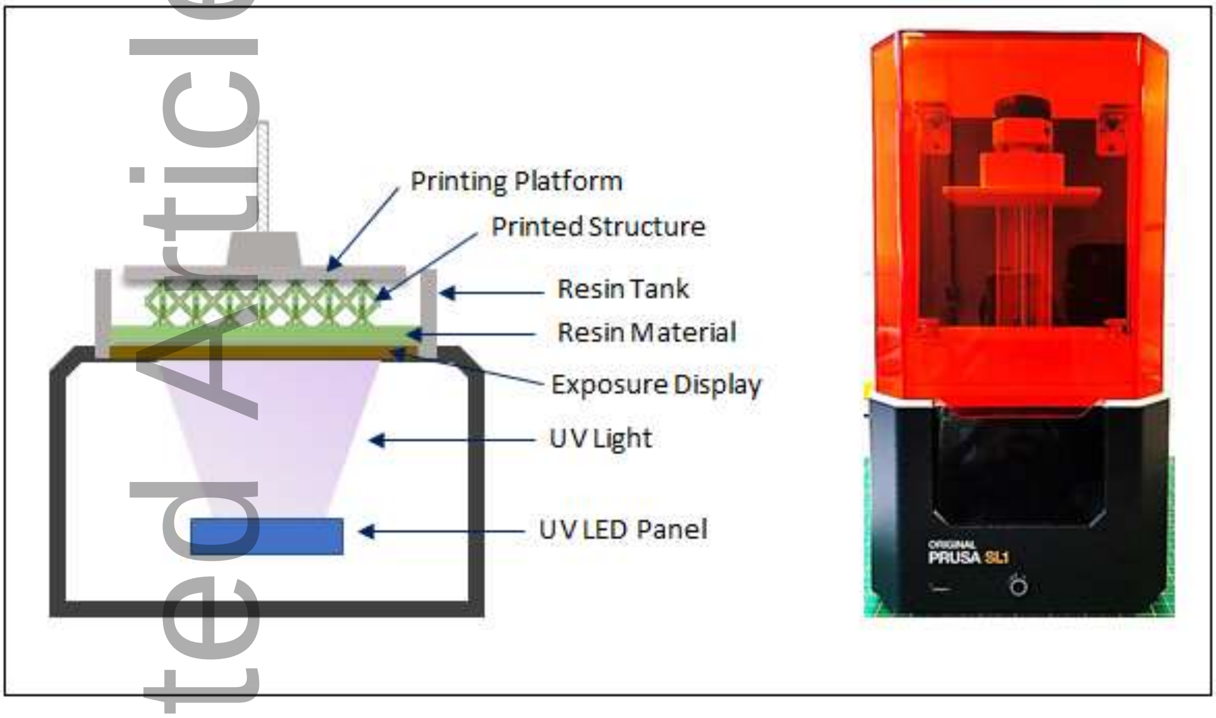


Figure 1: The Prusa® SL1 3D Printer (right) and a schematic diagram of the masked SLA process of Prusa® SL1 3D printer.

2.4 Impact performance test

To investigate the impact resistance properties of the 3D printed cellular structures, a range of test methods were considered. One is BS EN 1621-2: 2014 (Part 2)), which was developed for evaluating the motorcyclist back protectors against mechanical impact. In this test a material to be tested is impacted by a 5 kg bar shaped impactor with 50 J impact energy. The other is BS EN 13954-2015, which was established for testing motorcycle protective gloves against impact by a 2.5 kg flat face impactor to impact on a test sample, placed on a convex curvature anvil. Both methods were not suitable for assessing the peak impact force underneath the 3D-printed samples under a low velocity impact setup required in this study. Therefore, a similar free fall drop test method previously used[5] was adopted for this research. It is able to represent the human body impact injury by falling.

In this impact force attenuation test, a customized test rig was setup to simulate the free fall shown in **Figure 2**. A 0.028 kg steel ball with a diameter of 19.05 mm was used as impactor being attached to an electromagnetic magnet connected to an on/off switch controller. A 3D-printed socket/cap was mounted on the magnet in order to maintain the center position of the steel ball when attaching/detaching is needed.

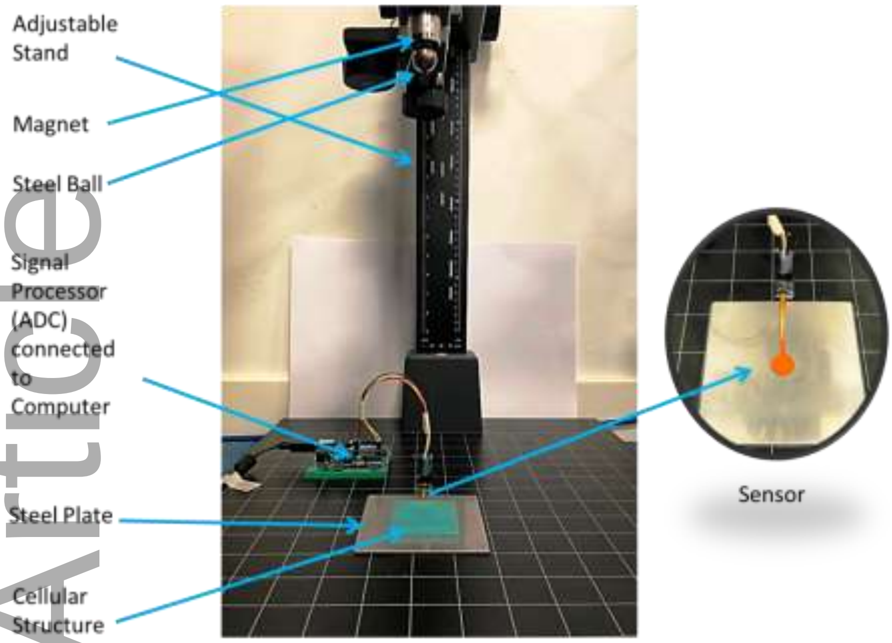


Figure 2: Customized impact test setup.

A smooth steel plate with dimensions of 100x100x4 mm was used as sample holder. It was glued on a large thick wooden board which was fixed on the floor. A thin capacitive force sensor with 45 N load capacity (Single Tact®) was sourced from Pressure Profile Sensors UK. It was mounted in the centre of the steel plate and was connected to an open-sourced Ardino Uno circuit board. **The circuit board was** linked to a computer to record the real-time impact force transmitted through a cellular structure during a simulated impact event. Open-sourced software provided by PPS, UK, was used to record the output signals/values vs time data sets. The output values were then converted into impact force using the following equation.

$$F = \text{Output values} \times \text{Rate (Hz)} / 512 \quad (1)$$

Where F is the force in N, and the frequency rate is in Hz.

The data set can create different impact energy profiles by using steel balls of different diameters and different heights of free fall. In this study, the free fall height of the impactor was set at 0.25 m based on the sensor capacity and the size of cellular structure specimen. The corresponding impact velocity of 2.23 m/s was calculated from the following equation.

$$v^2 = 2gh \quad (2)$$

Where, v is the impact velocity in m/s, g = 9.8 is the gravity in m/s^2 and h is the impactor free fall height in m.

For this research, the impact energy was 0.07 J according to equation (3).

$$E = mgh \quad (3)$$

Where, E is the impact energy in J, m = 0.028 is the mass of the impactor in kg and h = 0.25 is the height of the impactor free fall in m.

Three specimens from each cellular structure design were tested; the peak and median impact forces were recorded. Each specimen was tested only once. Statistical analysis was performed using MicroExcel® 2010 to assess the repeatability of the tests in the form of standard deviation among tested specimens.

3. Results and discussion

3.1 Factors may affect the performance of cellular structures

All designed cellular structures were printed using two resin materials Liqcreate® green and Prusa® blue, separately. Though all structures were printed smoothly as per CAD models, some damages occurred during post-processing operations, such as removal of printed samples from the printing platform and removal of support material. It is most critical when the flexible resin materials are used compared to tough resins, because the flexible resins are stickier than tough resins. The other cause of possible damages was made by the removal of support material. Due to the fine nature of the designed cellular structures, the support material was difficult to be removed. Small pieces of support material in the form of hanging struts may still remain inside the structures. These may affect the performance of the developed novel structures and any variations of results.

3.2 Impact resistance

To assess the impact force attenuation properties, all cellular samples were impacted by the steel ball at an impact velocity of 2.23 m/s, with equivalent impact energy of 0.07 J. The conventional EVA foam (EVAF) was used as a control material to compare the impact performance of the new cellular structures. **Figure 3** shows the median impact forces of the cellular structure pads manufactured. L5AU had the lowest peak impact force of 2.73 N, while L5MA and L5NA3 had a much higher peak impact force of 8.20 N. This indicates that L5AU absorbs 3 times more impact force then L5MA and L5NA3. This is mainly caused by the reentrant honeycomb geometry of L5AU,[14, 17] designed in an unique symmetrical repeat arrangement from 2D to 3D unit cell in both horizontal and vertical directions (**S. No. 1 in Table 1**). All the struts of the unit cells were positioned in horizontal axis. Such a unique design feature allows the structure to contract during impact loading and to expend while being bent. The second candidate with a low impact force of 5.08 N was L5HC with a honeycomb structure. The unit cell of L5HC was designed similarly to L5AU. However, due to its hexagonal shape, it would contract outwardly when being pressed, therefore absorbs less impact energy than L5AU with a reentrant honeycomb structure. This finding is also supported by research work reported by Critchley et al.[14] and Yang et al.[17] Another study conducted by Saxena et al.,[12] observed similar results with additively manufactured 2D reentrant honeycomb cellular structures for wearable application. Furthermore, Saxena found cellular structures adopted dome-shaped curvature when subjected to out-of-plane loading, an attribute suitable for wearable applications due to its ability to better fit body curvatures. In comparison, structures were made from a combination of stiff and flexible materials (bi-material concept) are less suited for clothing applications.

L5MA and L5NA3 were designed based on truss and vertical column principles (**S. No. 3 and 6, respectively, in Table 1**). When being impacted, the stress increases on the vertical columns of the structures, less impact energy is absorbed by the structures, so more impact force is transmitted through the structures.

The conventional EVA foam experienced the highest impact force of 9.38 N, presenting a sharp peak and relatively less impact duration than all the newly developed cellular structures. This is because, during the impact event, a higher force speed makes sharper and steeper peak, and the harder surface of EVA is unable to slow down the force, resulting in decreased impact duration. Conversely, the softer and porous surface of the cellular structures can slow down the high impact force and increase the duration of impact. This clearly indicates that developed open-cell cellular structures, particularly reentrant honeycomb structures, are more advantageous than the commercial foam with closed cell structure.

Similar to L5AU, PB5AU made from Prusa® material also shows the lowest impact force of 2.64 N, while PB5MA models present a higher impact force of 7.32 N. This evidently confirms that PB5AU with a reentrant honeycomb structure absorbs approximately 3 times more impact force than PB5MA due to its reentrant geometry. All the cellular structures fabricated from Prusa® Blue have better impact resistance performance than the structures fabricated from Liqcreate® Green and conventional EVA foam as shown in **Figure 4**.

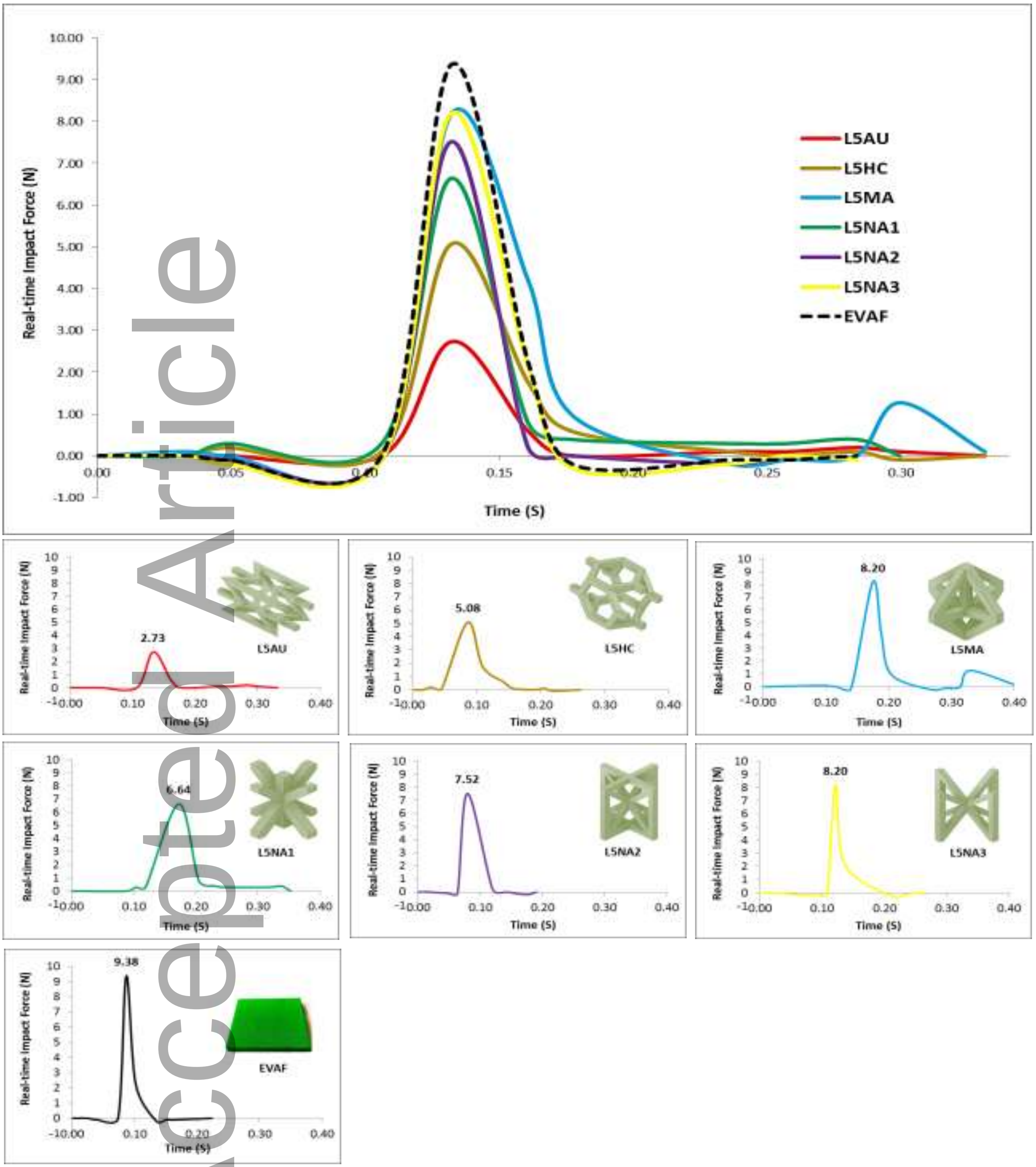


Figure 3: Real-time impact force of cellular structures fabricated from Liqcreate®, Green material.

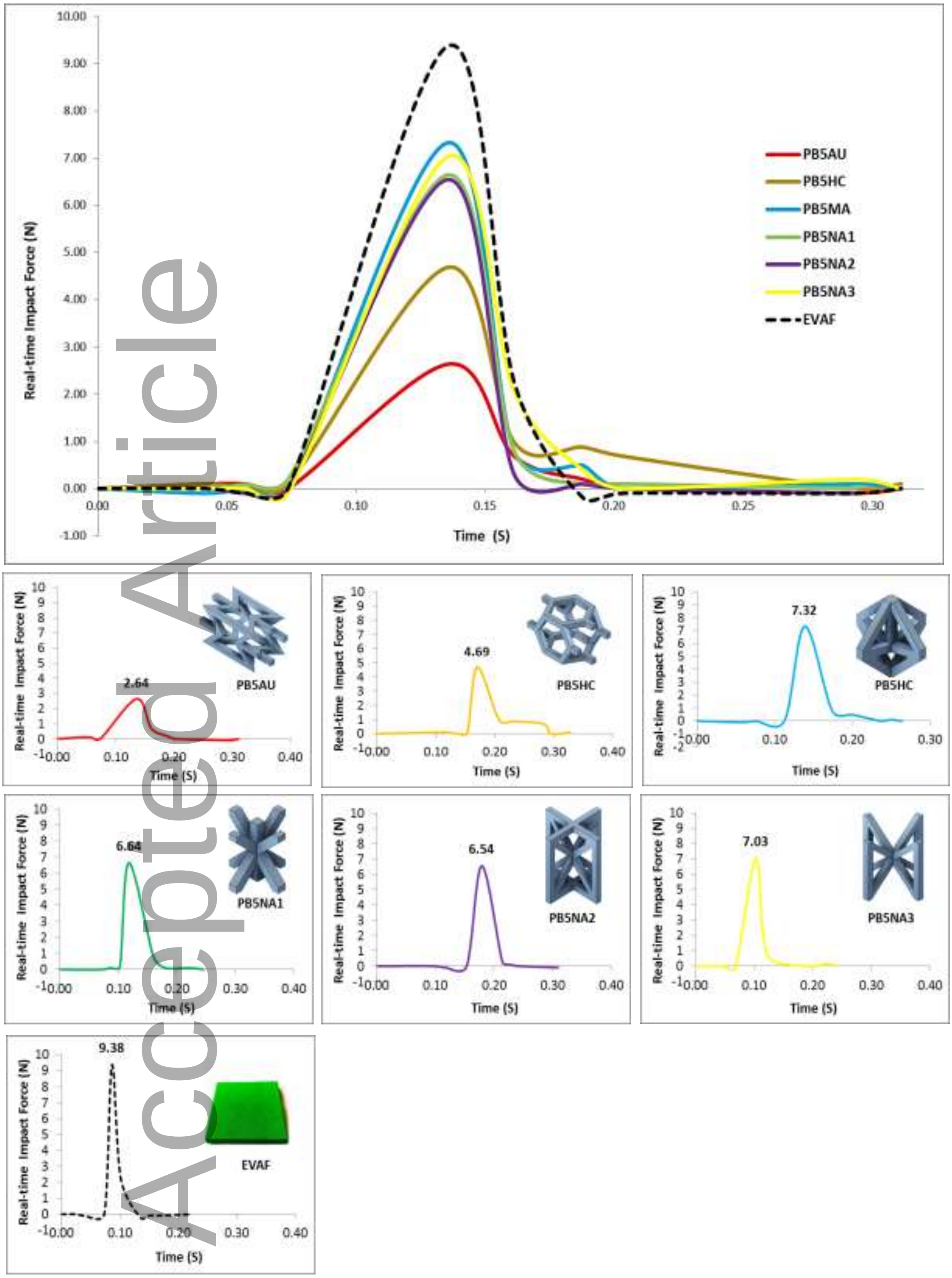


Figure 4: Real-time impact force of cellular structures fabricated from Prusa® Blue material.

To assess the repeatability of the impact test on cellular structures made from the two resin materials, the standard deviation of impact force obtained from three tested results for each structure was performed using Microsoft Excel® 2010. To eliminate the influence of weight and thickness differences caused by varied porosity among different structures, the impact force was normalised by their densities for all structures, including the conventional EVA foam. **Figures 5** and **6** show the repeatability of the impact test on the cellular structures made of Liqcreate® and Prusa® resin materials. The higher standard deviation values represent damages in the corresponding structures due to fabrication process limitations explained in Section 3.1. All structures were fabricated without any support material, except AU and HC. Because the PRUSA SL1 printer cures every single layer at a time, it may cause layer separation if the object involves bridging elements and is printed without support. Both AU and HC cellular structures involved bridging in their geometrical patterns; therefore, they were printed at a 45^o tilted position under support for smooth printing. However, the removal of support material was difficult and could cause damage to the cellular structures.

Cellular structures MA, NA1, NA2, and NA3 printed without any support material had minimal damages, as the removal of the cellular structures from the printer platform was performed with a sharp spatula that could cause only some damage to the cellular structure.

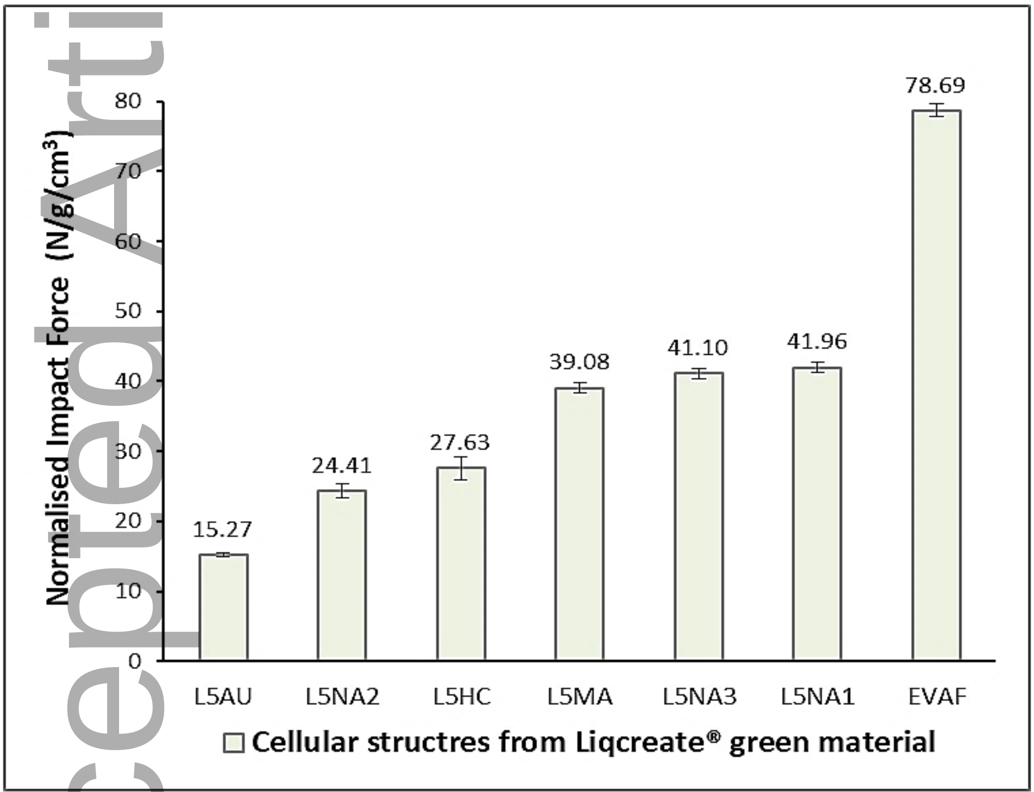


Figure 5: Deviation of impact forces among the cellular structure fabricated from Liqcreate® material.

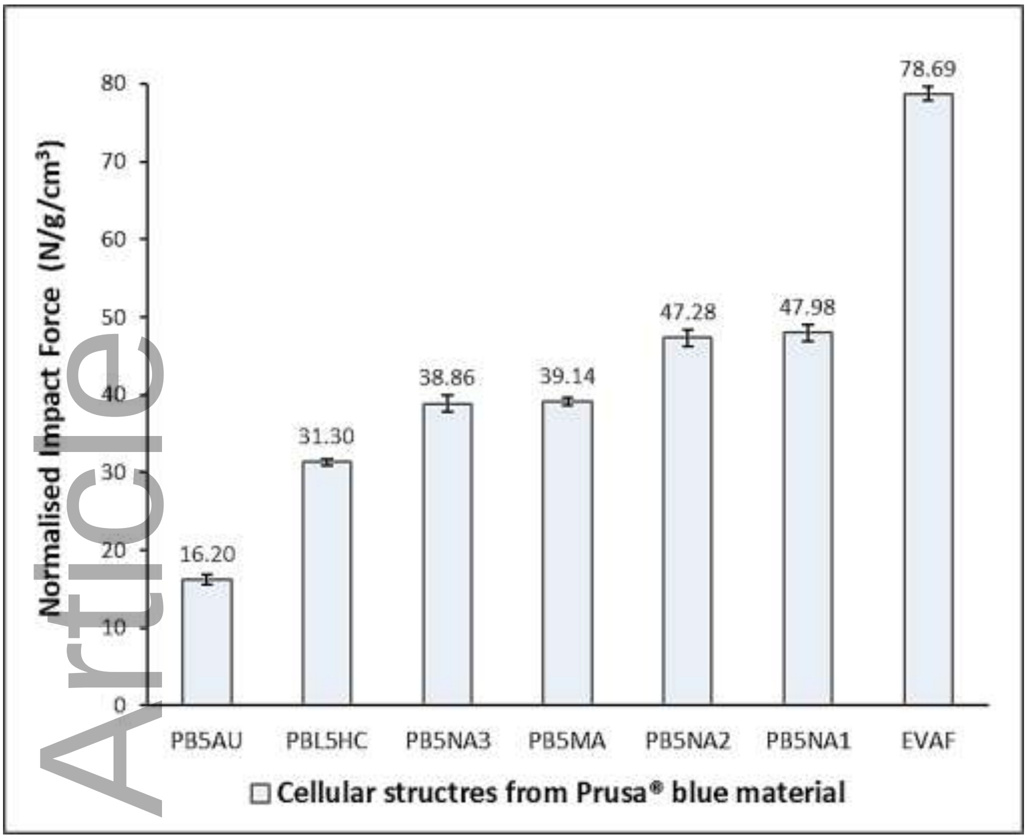


Figure 6: Deviation of impact forces among the cellular structure fabricated from Prusa® material.

All structures made from Prusa® flex resin with a shore hardness value of around 70A, show lower peak impact forces compared to the structures made from Liqcreate® flex resin with a shore hardness value of 65A. This indicates that slightly stiffer cell walls can provide better impact resistance performance while remaining soft and flexible.

Most impact protective equipment is made from traditional foams or various combinations of foams and rigid materials that are often thick, rigid, and inflexible. These materials restrict the movement of body parts of wearers while performing various activities. Results of this study however, clearly indicate that the 3D-printed cellular structures with unique geometrical pattern designs, such as reentrant honeycomb, made from single flexible material have great potential to be used as personal protective equipment (PPE) for protection of knees, hips, elbows, and shoulders from impact injuries. These structures will not only provide with impact resistant solution, but also facilitate body movements and enhance wear comfort.

4. Conclusions

In this research, six flexible and pliable micro-cellular structures were designed and manufactured using two different flexible photo-curable resin materials separately. An SLA type additive manufacturing printer was used to produce the structures. Free-fall drop impact tests were carried out for all six types of structures to investigate their impact resistance capacity under low-velocity impacts. The following conclusions can be made.

- All structures have better impact resistance performance than a type of conventional material currently used for protective textiles.
- All structures have shown reduced peak impact force, however, the reentrant honeycomb cellular structure (AU) experienced the lowest peak impact force made from both Liqcreate® and Prusa® flexible materials. This indicates that the reentrant honeycomb cellular structure (AU) has the potential to be used for protective clothing against slow speed impact.
- Because the material hardness factor has significant impact on impact performance, more work needs to be done to compare the performance of the developed novel structures to be printed using more material with different hardness.
- The geometrical shape and dimension of unit cell have major influence on the impact resistance properties of the cellular structure because they can affect the duration of an impact event. Further reduction in the thickness of cellular structure pad may be further investigated through parametrical studies.
- Support material left within the structure and damages caused by the removal process affect the impact resistance performance of the cellular structures.
- In future, wear resistance can be assessed when these cellular structure pads are embedded in protective assemblies.

Conflict of Interest

All authors have no financial/commercial Conflict of Interest.

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Table of Contents

Saadullah Channa[1, 2], Danmei Sun [1, *], George K. Stylios [1]

ToC text:

In this research, newly designed reentrant honeycomb 3D printed cellular structure made from flexible material experienced the lowest peak impact force. The results indicate that the soft, flexible and lightweight reentrant honeycomb cellular structure is suitable and has the potential to be used for impact protective clothing.

ToC figure:

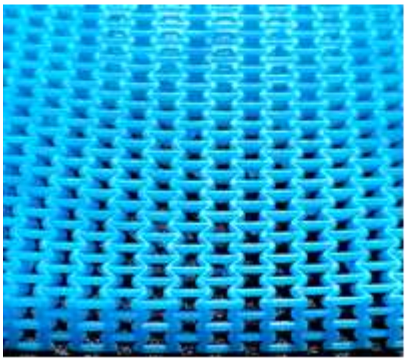

Figure: 3D printed reentrant honeycomb cellular structure made from Prusa® material (@ Saadullah Channa 2022)