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Mechanical behaviour of gel-filled additively-manufactured lattice structures under quasi-static compressive loading

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ABSTRACT

The worldwide incidence of traumatic brain injuries (TBIs) is on the rise. Helmets are one of the best technologies available to prevent TBIs from impacts to the head during recreational and occupational activities. The most commonly used material for helmet liners is expanded polystyrene (EPS) foam. However, while EPS can reduce linear accelerations from impacts, it does not perform as well at reducing rotational accelerations which are considered to be the most harmful to brain tissue. Recently, prismatic lattice structures have shown promise in reducing these harmful rotational accelerations. Here, a new structure for energy dissipation applications is presented that is hypothesised to improve the energy dissipation of the prismatic lattice by filling it with a gel. To test this hypothesis, 3D printed prismatic lattices fabricated from PLA, PET-G, and ABS were filled with 5 wt% and 10 wt% agar and tested to failure under quasi-static compression. Compared to the unfilled control group, it was found that PLA lattices filled with 10 wt% agar had the best performance demonstrating a 46.1% increase in energy absorbed and 57.4% increase in displacement to failure. These results demonstrate the superior energy dissipation properties of gel-filled prismatic lattices compared to unfilled prismatic lattices during quasi-static compression.

1. Introduction

The worldwide incidence of traumatic brain injuries (TBIs) is on the rise and is most prevalent in people younger than 25 and older than 75 years [14]. TBIs lie on a continuum from transient symptoms to fatal haemorrhages with mild TBI (mTBI) being the most common type of TBI [17]. According to global estimations 42 million people sustain a mTBI each year [4]. TBIs are also a major concern in the younger population with an estimated 1.6–3.8 million sports related cases reported each year in the USA. The incidence of sports related TBI is an ever–rising concern with increasing evidence linking repetitive concussive and sub-concussive head impacts with chronic traumatic encephalopathy (CTE), a progressive degenerative brain disease [11,18]. CTE in American Football has received widespread coverage in the lay press and academic literature, and has also been documented in players of other sports more popular in the EU and UK (e.g., soccer and rugby) [1,11]. CTE has a prolonged duration to symptom onset, sometimes up to decades after retiring from sport [7]. Currently there is no effective treatment for CTE and it is unknown how many people who sustain a sports–related TBI will progress to develop CTE [18]. Therefore, the best available solution to reduce the burden of TBI and CTE is to reduce their incidence by mitigating the transmission of harmful impact energies to

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the brain.

Helmets are the gold standard technology to prevent the occurrence of TBI from impacts to the head during recreational and occupational activities [9]. Typical helmets on the market today use expanded polystyrene (EPS) foam as the material for the helmet liner (i.e., the part of the helmet responsible for dissipating harmful energies away from the head). However, while EPS is a good choice of material for reducing linear accelerations from impacts, it does not perform as well for reducing rotational accelerations [5,9,12]. Rotational accelerations are hypothesised to be the most harmful to brain tissue, causing physical and functional damage to neurons and other neural cells [3,5,9,12,21]. There are few available products on the market that specifically target reducing rotational accelerations due to impacts such as Multilayer Impact Protection System (MIPS®; MIPS AB, Täby, Sweden), SHRED.® Rotational Energy System (SHRED., Venezia–Mestre, Italy), Kali Protectives Low Density Layer (Kali Protectives, CA, United States), Leatt Turbine (Leatt, NV, United States), and POC's SPIN pads (POC Sweden AB, Stockholm, Sweden). However, these solutions are additional components to conventional helmet designs and do not alter the helmet liner material.

Recently, Khosroshahi et al. [8,9] demonstrated the potential use of 3D printed prismatic lattice structures to reduce rotational accelerations during head impacts. Through computer simulations of head impacts, it was found that a 40 mm thick hierarchical prismatic helmet liner could significantly reduce rotational accelerations of the head. It has also been demonstrated that composite lattice structures filled with foams [2,15] and shear thickening fluid [19] can enhance the energy absorbing properties of lattice structures. Therefore, it is hypothesised that filling prismatic lattices with a gel-based material will further improve their energy absorbing properties. Here, the fabrication process and mechanical behaviour of such 3D printed unfilled and filled prismatic lattice structures under quasi–static compression is presented.

2. Theory

A crashworthiness analysis was performed to compare the energy absorbing effectiveness of filled versus unfilled prismatic lattice structures adopting the approach of Prajapati et al. [16].

The energy absorbed (EA) is defined as the area under the experimentally recorded force-displacement curve and is given by:

$$EA = \int_0^{d_{\max}} F(x)dx \tag{1}$$

where x is the displacement, F is the reaction force, and d_{max} is the maximum displacement.

The addition of a filler material incurs an increase in the total mass of the specimen. Therefore, it is necessary to determine the energy absorbed per unit mass for each composite. This specific energy absorbed (SEA) is given by:

$$SEA = \frac{EA}{m} \tag{2}$$

where m is the mass of the specimen. Specimens with higher SEA values have superior crashworthiness compared to specimens with lower SEA values [16].

Crash force efficiency (CFE), a measure of a structure's energy absorption efficiency, was calculated using the following equation:

$$CFE(\%) = \frac{P_{mean}}{P_{\max}} \times 100 \tag{3}$$

where P_{max} is the maximum recorded force, and P_{mean} is given by:

$$P_{mean} = \frac{EA}{x} \tag{4}$$

Specimens with higher CFE values possess more stable force fluctuations during deformation than those with lower CFE values [16].

3. Materials & method

3.1. Fabrication of 3D printed lattices and agar gel

The main geometry investigated in this study is a 20 × 20 × 20 mm lattice with struts of 2 × 2 mm square cross section creating a total of four voids per face with a 7 × 7 mm square cross section (Fig. 1) which was designed in SolidWorks (DS SolidWorks Corp., MA, USA). The dimensions were chosen based on typical bicycle helmet liner thickness of approximately 20 mm which was used as the cube edge length. The lattice strut edge width of 2 mm was used as lattices fabricated with 1 mm strut edge width were found to fail during handling and preparation. The prismatic lattice structures were 3D printed with Ultimaker 3 3D printers (Ultimaker, Utrecht, Netherlands) using common 3D printing materials: polylactic acid (PLA), polyethylene terephthalate glycol (PET–G), and acrylonitrile butadiene styrene (ABS). All lattices were printed with a resolution of 0.1 mm and 90% infill. For the gel fill material, agar with two different weight–percentages were prepared by premixing the agar powder (Tryptone Soya Agar (Casein soya bean digest agar) EP/USP/JP/BP, Thermo Fisher Scientific) with water, using the appropriate amount of each to achieve 5 wt% and 10 wt% agar, respectively. In particular, water was poured into a beaker and placed on a hot plate magnetic stirrer (IKA, RH basic 2). When the temperature reached 70 °C, the desirable amount of agar powder was added and constantly mixed with a PTFE cylindrical stirrer at a speed of approximately 10,000 rotations per minute until the solution became transparent. Following complete homogenisation, the solution was poured into PLA moulds containing 3D printed polymer lattices and allowed to cool at room temperature for 1 h. The setting of the agar took place under refrigerated conditions at 3–4 °C for 12 h prior to removal from the mould. Excess agar was carefully removed from the lattice using a scalpel so that only the agar that filled the void space remained (Fig. 1c and Fig. 1e).

3.2. Heat treatment of polymer lattices

A separate set of 3D printed lattices for each material group were subjected to a heat treatment cycle by placing the specimens in an oven set at 70 °C for 1 h followed by an initial quenching in air for 1 h at room temperature (22 °C) and then refrigerated for 12 hat 3–4 °C, similar to the temperatures and durations as the lattices submerged in agar (Section 2.1). These lattices, referred to as the 'heat treated' group, were not filled with agar gel. Given the glass transition temperature of PLA is in the range of 50–80 °C, a further group of PLA lattices were embedded in 10 wt% agar gel that was subsequently removed following cooling and solidification to investigate the effects of embedding the lattice structures in 70 °C agar on their mechanical properties. Sample numbers, nozzle temperature, print temperature, and sample mass (mean ± standard deviation) for each group are shown in Table 1. Note: the mass of each group was calculated from four samples per group, and Unfilled (heat treated) and 10 wt% agar fill then removed were assumed to have the same mass as the Unfilled (control).

3.3. Compression testing

A Zwick Testing Machine (Zwick Roell, Worcester, UK) equipped with a 5 kN load cell was used to compress each sample (Table 1) to failure under a constant velocity of 1 mm/minute. A small subset of samples were tested with 3D printed filaments aligned horizontally and vertically to determine if there was mechanical anisotropy, see Figs. 1a and 1b (data not shown). Subsequently samples were tested with fibres aligned horizontally only as these provided a markedly stiffer mechanical response compared with the vertically aligned fibres.

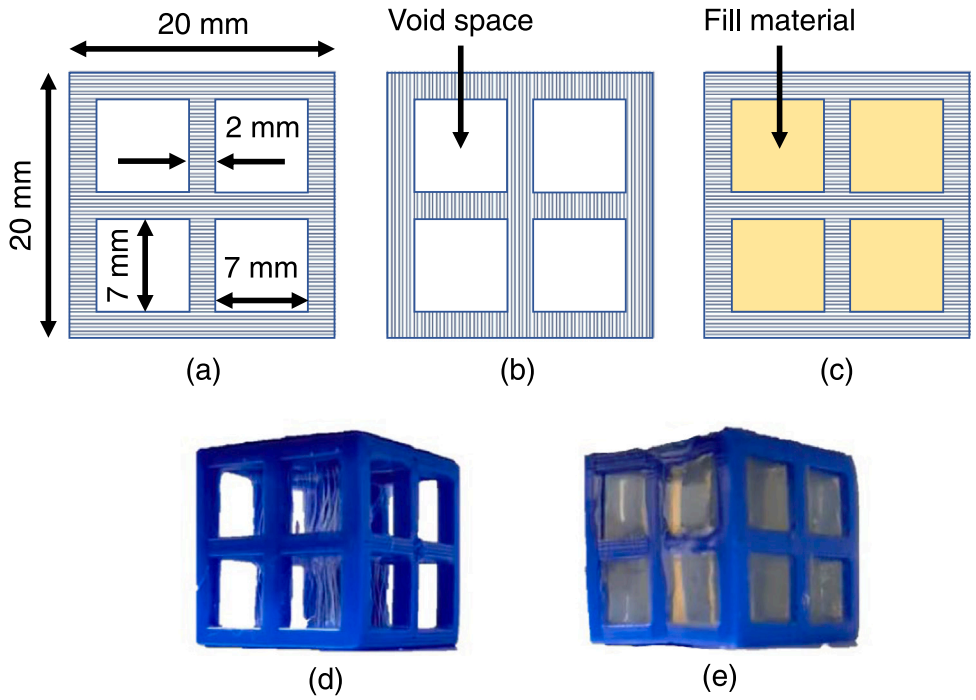

Fig. 1. (a) Unfilled lattice structure with horizontally aligned filaments, (b) unfilled lattice with vertically aligned filaments, (c) filled (agar shown in yellow) lattice structure with horizontally aligned filaments, (d) sample image of 3D printed lattice structure, and (e) sample image of 3D printed lattice structure filled with agar.

Table 1
Samples fabricated for testing, their respective print temperatures and masses.

Lattice and fill material	Number of samples	Nozzle temperature (°C)	Print bed temperature (°C)	Mass (g)
PLA				
Unfilled (control)	9	210	65	1.95 ± 0.02
Unfilled (heat treated)	6			1.95 ± 0.02
5 wt% agar fill	10			7.86 ± 0.14
10 wt% agar fill	10			8.77 ± 0.23
10 wt% agar fill then removed (sham control)	9			1.95 ± 0.02
PET–G				
Unfilled (control)	10	245	85	1.93 ± 0.04
Unfilled (heat treated)	6			1.93 ± 0.04
5 wt% agar fill	9			7.88 ± 0.19
10 wt% agar fill	9			8.48 ± 0.04
ABS				
Unfilled (control)	10	240	80	1.93 ± 0.03
Unfilled (heat treated)	7			1.93 ± 0.03
5 wt% agar fill	10			7.75 ± 0.28
10 wt% agar fill	10			8.83 ± 0.31

4. Results

4.1. Failure behaviour of unfilled and filled lattice structures

The filled and unfilled lattices displayed distinct failure behaviour under quasi-static compression. As shown in Figs. 2a and 3a, the unfilled lattices undergo a combination of elastic buckling, plastic deformation, and brittle fracture of the struts. Whereas the filled lattices (Fig. 2b, Fig. 3b) demonstrated more plastic deformation and fewer complete lattice fractures.

The areas in the red circles in Fig. 3 highlight regions in the lattices that have fractured. Typically, the unfilled lattices contain more fractures than the filled lattices. Interestingly, the filled lattices undergo more plastic deformation and contain fewer fractures than the unfilled lattices. Figs. 2b and 3b also demonstrate the flow of liquid out of the agar gel as time progresses (Fig. 2b) and can be seen collecting around the base of the compressed filled lattice (Fig. 3b yellow ellipse).

4.2. Force–displacement behaviour of unfilled and filled lattice structures

The force–displacement curves for each individual test, material, and fill configuration are presented in Fig. 4. For PLA, the unfilled (Fig. 4a), heat treated (Figs. 4b), 5 wt% agar filled (Fig. 4c), and 10 wt% agar filled (Fig. 4d) lattices reached maximum displacements of 2.88 ± 0.56 mm, 1.39 ± 0.14 mm, 4.14 ± 0.32 mm, and 5.20 ± 0.96 mm, respectively, before complete failure (Table 2). The mean ± standard deviation for the maximum reaction forces for unfilled, heat treated, 5 wt% agar filled, and 10 wt% agar filled lattices were 2394 ± 161 N and 1807 ± 281 N both peaking at approximately 1 mm, 2214 ± 71 N peaking at approximately 1.5 mm, and 1944 ± 196 N, peaking at approximately 2.2 mm, respectively (Table 2). Therefore, filling the PLA lattice with 5 wt% and 10 wt% agar gel enhanced the maximum failure strain by 30% and 45% compared with the unfilled lattice, respectively. However, this increase in failure strain was accompanied with a reduction in peak reaction force of 7.5% and 18.8% for the 5 wt% and 10 wt% agar solution compared with the unfilled lattices, respectively.

For PET–G, the unfilled (Fig. 4e), heat treated (Fig. 4f), 5 wt% agar

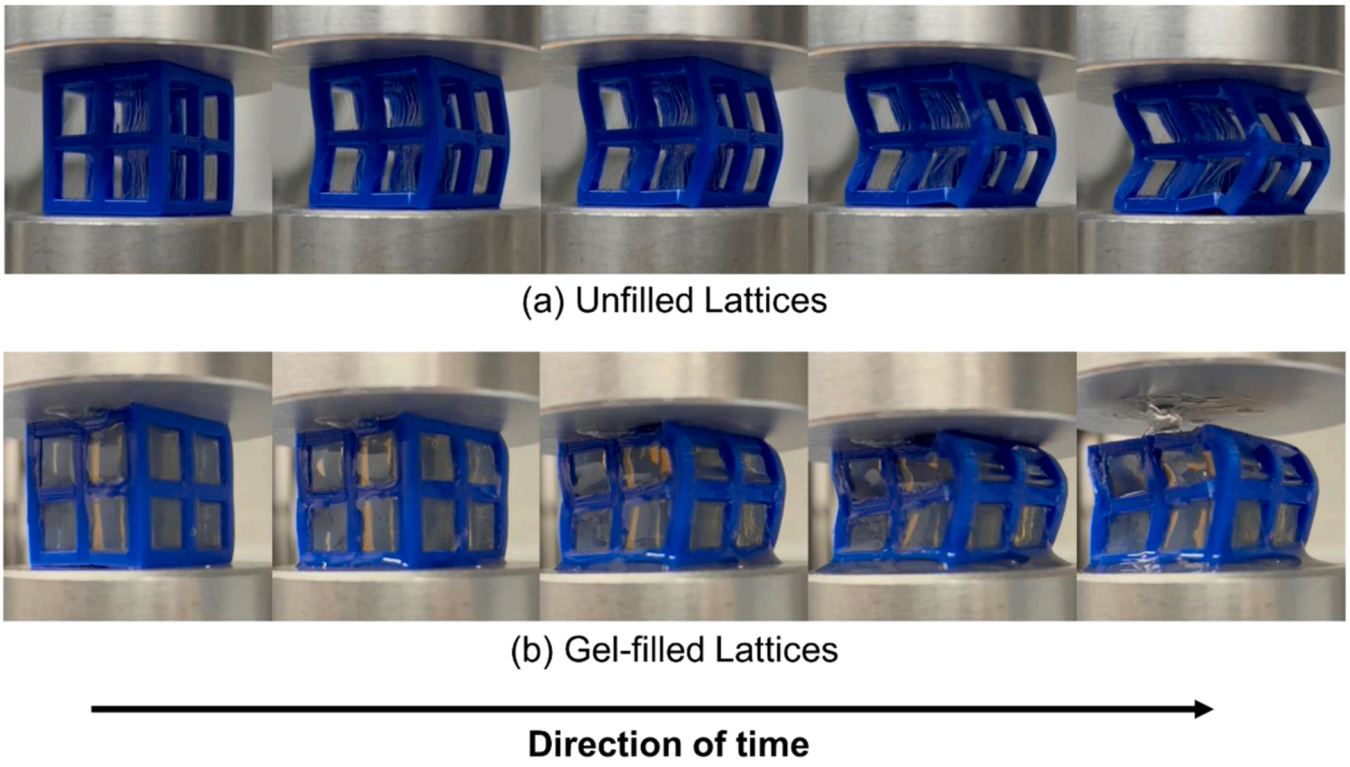

Fig. 2. Details the typical progression of the compression test and mechanical behaviour of the (a) unfilled and (b) gel-filled lattices as time progresses from left to right. It should be noted that time is not evenly spaced in this sequence instead images were taken at the initiation of failure at different locations within the lattices.

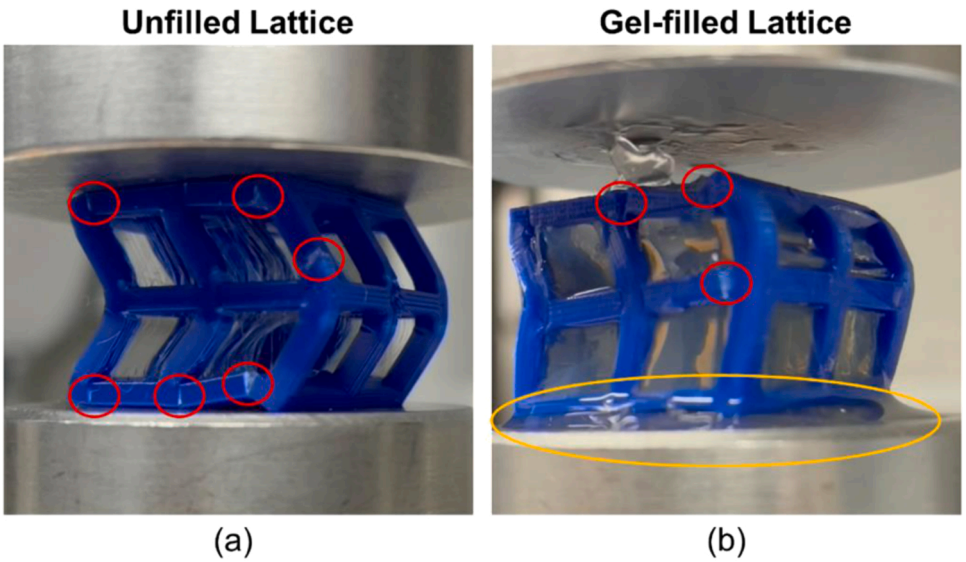

Fig. 3. The (a) unfilled and (b) gel-filled lattices at maximum deformation detailing points of failure within the structures. Red circles identify fractures of the polymer lattice. The yellow ellipse (right image) shows a pool of liquid which flowed out of the gel under compression.

filled (Fig. 4g), and 10 wt% agar filled (Fig. 4h) lattices reached maximum displacements of 2.11 ± 0.31 mm, 1.65 ± 0.21 mm, 3.13 ± 0.72 mm, and 2.10 ± 0.35 mm, respectively, before complete failure. The average maximum reaction forces for PET–G unfilled, heat treated, 5 wt% agar filled, and 10 wt% agar filled lattices were 1618 ± 88 N at a displacement of 1.5 mm, 1227 ± 97 N at 1.1 mm, 1619 ± 105 N at 1.9 mm, and 1601 ± 127 N, at 1.5 mm. Therefore, by filling the PET–G lattice with 5 wt% agar gel increased the maximum failure strain by 33% compared to the unfilled lattices. Conversely, filling PET–G lattices with the higher 10 wt% agar gel lead to a reduction of 0.5% of the maximum failure strain. Even if the addition of both 5 wt% and 10 wt% agar gel affected the failure strain there was a negligible change in reaction force when compared with the unfilled PET–G lattices. It should be noted that there is an outlier curve for the PET–G lattices filled with 5 wt% agar solution. If this data was excluded from analysis the change in maximum failure strain compared to the unfilled lattices would be an increase of 18% instead of 33%.

The ABS unfilled (Fig. 4i), heat treated (Fig. 4j), 5 wt% agar filled (Fig. 4k), and 10 wt% agar filled (Fig. 4l) lattices reached maximum displacements of 3.02 ± 0.76 mm, 1.26 ± 0.22 mm, 3.01 ± 0.79 mm,

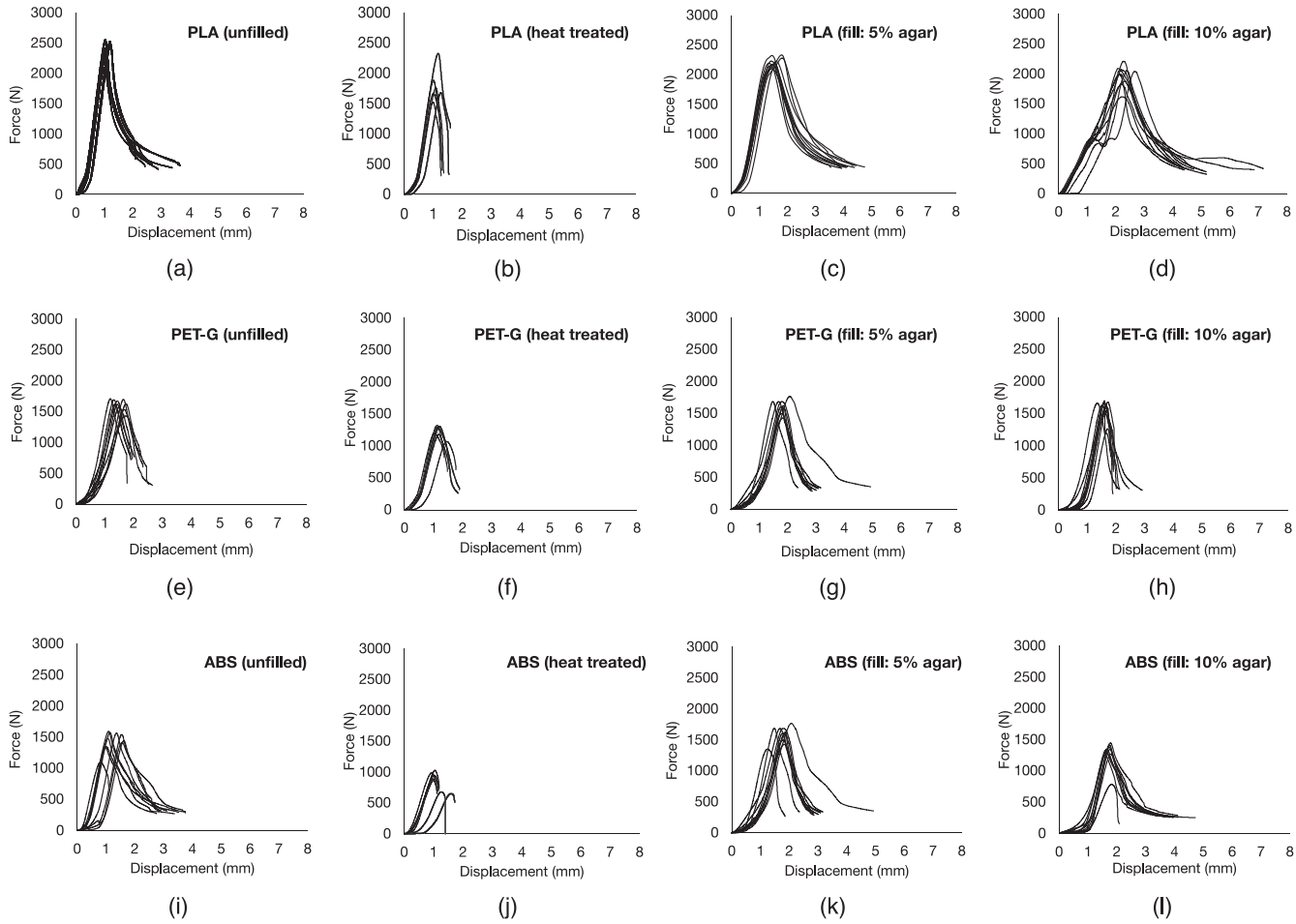

Fig. 4. Force–displacement curves for filled and unfilled PLA (a–d), PET–G (e–h), and ABS (i–l) lattice structures. The (heat treated) curves were not filled with agar.

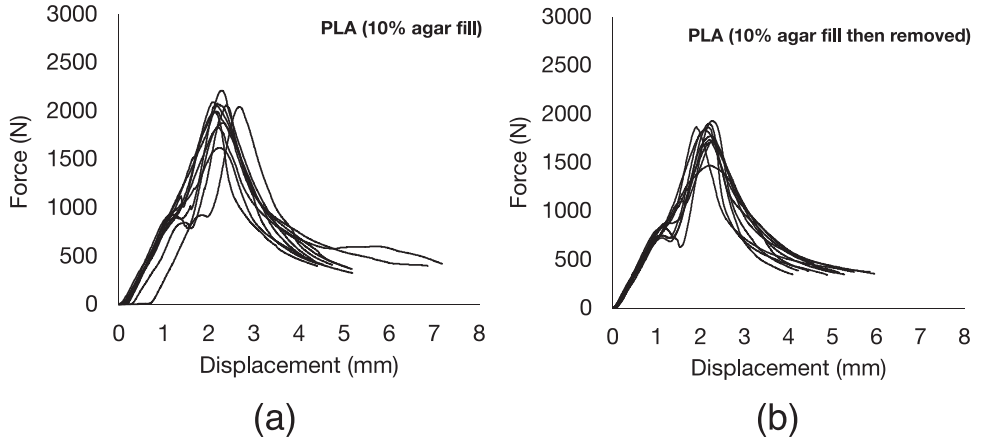

Fig. 5. (a) Force–displacement curves for PLA lattices filled with 10 wt% agar, and (b) filled with 10 wt% agar which was subsequently removed prior to compression testing.

and 3.80 ± 0.67 mm, respectively, before complete failure. The average maximum reaction forces for ABS unfilled, heat treated, 5 wt% agar filled, and 10 wt% agar filled lattices were 1441 ± 149 N, 866 ± 147 N, 1592 ± 129 N and 1289 ± 188 N, peaking at a range of displacements. Therefore, by filling the ABS lattice with 5 wt% agar gel increased only the peak reaction force by achieving a force of 1592 N while there was virtually no change in maximum failure strain compared to the unfilled lattices. However, the ABS lattices filled with 10 wt% agar gel affected both maximum failure strain (e.g., 21% higher than unfilled lattices) and peak reaction force (e.g., 10.5% lower than unfilled lattices).

There was no consistent behaviour of the mean maximum reaction force for the different type of lattices (i.e., ABS, PLA and PET–G groups) filled with 5 wt% agar compared to the unfilled lattices. In particular, the addition of 5 wt% agar led to an increase in the mean maximum reaction force for the ABS group, while the PLA and PET–G groups presented a decrease and virtually unchanged values, respectively. All

Table 2
Mechanical behaviour of unfilled and filled lattice structures. Max values for each material are shown in bold text. CFE = crash force efficiency.

Lattice and fill material	Max. reaction force (N)	Max. displacement (mm)	Energy absorbed (mJ)	Specific energy absorbed (mJ/g)	CFE (%)
PLA					
Unfilled (control)	**2394 ± 161**	2.88 ± 0.56	2764 ± 362	1417 ± 186	40.7
Unfilled (heat treated)	1807 ± 281	1.39 ± 0.14	1127 ± 292	578 ± 150	44.4
5% agar fill	2214 ± 71	4.14 ± 0.32	4097 ± 396	521 ± 50	**44.6**
10% agar fill	1944 ± 196	**5.20 ± 0.96**	**4418 ± 767**	504 ± 87	43.2
10% agar fill then removed (sham control)	1816 ± 75	5.04 ± 0.64	3922 ± 442	**2011 ± 227**	43.1
PET–G					
Unfilled (control)	1618 ± 88	2.11 ± 0.31	1511 ± 147	783 ± 76	44.5
Unfilled (heat treated)	1227 ± 97	1.65 ± 0.21	940 ± 135	487 ± 70	**46.6**
5% agar fill	**1619 ± 105**	**3.13 ± 0.72**	**2008 ± 521**	**1041 ± 270**	39.4
10% agar fill	1601 ± 127	2.10 ± 0.35	1200 ± 326	622 ± 169	35.2
ABS					
Unfilled (control)	1441 ± 149	3.02 ± 0.76	1821 ± 426	**943 ± 221**	42.4
Unfilled (heat treated)	866 ± 147	1.26 ± 0.22	467 ± 73	242 ± 38	**43.8**
5% agar fill	**1592 ± 129**	3.01 ± 0.79	**1918 ± 563**	248 ± 73	39.9
10% agar fill	1289 ± 188	**3.80 ± 0.67**	1681 ± 410	190 ± 46	33.6

groups exhibited a decrease in the mean reaction force when the lattices were filled with 10 wt% agar compared to when they were filled with 5 wt% agar and the unfilled lattices. However, the decrease in reaction force for PET–G groups is within one standard deviation. Whereas, the ABS groups see a more marked decrease in reaction force between the 5 wt% and 10 wt% filled lattices but both are within one standard deviation of the unfilled lattice. It is hypothesised that these differences in reaction force are due to the accuracy and precision of the fabrication process, which may result in imperfections in the bonding between the deposited filaments [13]. Another factor may be that the 10 wt% agar is stiffer but also more brittle with a lower failure strain than the 5 wt% agar.

The failure displacement of the lattices was improved with the addition of the agar. For the PLA lattices there was a monotonic increase in failure displacement with agar concentration. Whereas, for PET–G the failure displacement was increased with the addition of 5 wt% agar but decreased with the addition of 10 wt% agar. On the other hand, for ABS the failure displacement did not increase with the addition of 5 wt% agar (although the maximum reaction force did), but failure displacement did increase with the addition of 10 wt% agar. A continuous increase of the failure displacement of PLA groups was observed leading to an increase of 35.9% and 57.4% with the addition of 5 wt% and 10 wt% agar, respectively. Comparing ABS and PET–G lattices it can be seen that the ABS group performed better with 10 wt% agar providing a 22.9% increase in failure displacement while the failure displacement of PET–G increased by 38.9% with the addition of 5 wt% agar.

4.3. Effects of heat treatment on the mechanical behaviour of the lattices

Considering that the polymer lattices were submerged in 70 °C liquid agar solution to fabricate the filled polymer lattices it was necessary to investigate the effects of heat on their mechanical behaviour. Two methods were employed to investigate the effects of heat on the lattices: (i) investigating the effects of heat alone on the 3D printed polymer lattices (PLA, PET–G, ABS) by placing them in a 70 °C oven for one hour, and (ii) by removing the solidified agar (10 wt%) from 3D printed lattices (PLA only) that had been submerged in the 70 °C liquid agar. Both methods were initially cooled at room temperature before being placed in a fridge (3–4 °C) overnight (12 h). Following cooling, each specimen was subjected to compression testing as outlined in Section 2 Materials & Methods.

The resulting force–displacement curves for the PLA, PET–G, and ABS lattices heat treated in the oven are shown in Figs. 4b, 4f, and 4j. The heat treated groups saw a marked reduction in both the maximum displacement and force compared to the other groups (control, 5 wt% agar fill, 10 wt% agar fill) demonstrating that subjecting the polymer lattices to 70 °C followed by quenching at room temperature for 1 h then 12 h at 3–4 °C has deleterious effects on the mechanical properties. Interestingly, the same deleterious effects were not displayed for the filled lattices that were submerged in 70 °C agar and underwent the same quenching process. Furthermore, for some filled lattices there was an improvement in the maximum displacement (PLA, PET–G, ABS), maximum force (PET–G, ABS), and energy absorbed (PLA, PET–G, ABS).

The force–displacement graphs for the PLA lattices with 10 wt% agar gel removed are shown in Fig. 5b. These lattices reached a maximum displacement of 5.04 ± 0.64 mm before complete failure, and the average maximum reaction force was 1782 ± 133 N peaking at approximately 2.3 mm displacement. Therefore, filling the PLA lattice with 70 °C agar solution appears to effect the mechanical properties of the PLA, but not as much as subjecting the lattices to 70 °C dry heat. Comparing the force–displacement curves in Fig. 5, there is a decrease of 3.1 % in the maximum displacement and 8% in the maximum reaction force upon removal of the gel material from the lattice. However, the group with the agar gel removed retains an increase in maximum displacement of 43% over the unfilled lattice (Fig. 4a). Moreover, the trends in the force–displacement curves remain remarkably similar between the groups filled with 10 wt% agar gel (Fig. 5a) and the group with the gel material removed (Fig. 5b), and are distinctly different from the force–displacement behaviour of the unfilled lattices (Fig. 4a) and those filled with 5 wt% agar gel (Fig. 4b).

4.4. Crashworthiness of unfilled and filled lattice structures

A crashworthiness analysis was performed to compare the energy absorbing effectiveness of the filled versus unfilled prismatic lattices structures [16]. The area under the curve was calculated for each individual force–displacement curve for all tests to estimate the energy absorbing properties of unfilled and filled lattice structures. These values were then used to calculate the specific energy absorbed (SEA) and the crash force efficiency (CFE) for each sample group. The results of these calculations are presented in Table 2.

Total EA of the PLA lattices under compression to failure for unfilled, heat treated, filled with 5 wt% and 10 wt% agar gel, and filled with 10 wt% agar which was subsequently removed was 2764 ± 362 mJ, 1127 ± 292 mJ, 4097 ± 396 mJ, 4418 ± 767 mJ, and 3922 ± 442 mJ, respectively. These results represent a 38.9% increase in EA between the unfilled PLA lattices and those filled with 5 wt% agar gel, and a 46.1 % increase in EA between the unfilled PLA lattices and those filled with 10 wt% agar gel. Upon removal of the 10 wt% agar there was an 11.9% decrease in EA compared to the 10 wt% filled lattice. However, there remained a 34.6% increase in EA over the control unfilled lattices. Whereas, the heat treated PLA lattices had an 84.1% reduction in EA.

Compared to PLA lattices, the PET–G group provided lower total EA

under compression to failure for unfilled (1511 ± 147 mJ), heat treated (940 ± 135 mJ), filled with 5 wt% (2008 ± 521 mJ) and 10 wt% (1200 ± 326 mJ) agar gel. These results represent a 28.2% increase in EA between the unfilled PET–G lattices and those filled with 5 wt% agar gel, and a 22.9% decrease in EA with those filled with 10 wt% agar gel. Whereas, the heat treated PET–G lattices had a 46.6% reduction in EA.

The ABS lattices provided a total EA under compression to failure 1821 ± 426 mJ for unfilled, 467 ± 73 mJ for heat treated, 1918 ± 563 mJ for 5 wt% agar filled and 1681 ± 410 mJ for 10 wt% agar gel filled. These results represent a 5.2% increase in EA for the lattices filled with 5 wt% agar gel compared with the unfilled lattices. There is an 8% decrease in EA between the unfilled lattices and lattices filled with 10 wt % agar gel despite the 21% increase in failure strain for the lattices filled with 10 wt% agar gel compared to the unfilled lattices. This is due to the decrease in peak force between the unfilled lattices and lattices filled with 10 wt% agar gel. Whereas, the heat treated ABS lattices had a 118% reduction in EA.

For each specific material group, the SEA was greatest in the PLA filled with 10 wt% agar that was subsequently removed (2011 ± 227 mJ), unfilled ABS (943 ± 221 mJ), and PET-G with 5 wt% agar fill (1041 ± 270 mJ). The CFE was greatest for PLA filled with 5 wt% agar (44.6%), unfilled heat treated PET-G (46.6%), and unfilled heat treated ABS (43.8%) in their respective material groups.

A summary of results is provided in Table 2.

5. Discussion

5.1. Mechanical performance of filled and unfilled lattices

Previously, Khosroshahi et al., [9] investigated the mechanical performance of tetrahedral and prismatic lattice structures as helmet liners for dissipating energy in helmeted head impacts, and Ling et al., [10] investigated the mechanical performance and energy dissipating potential of octet–truss lattices. Khosroshahi et al., [9] found that a hierarchical prismatic topology and lower relative densities decreased head accelerations, brain strain, and brain strain rate due to the prismatic structure's lower resistance to shear deformation. Motivated by this work, we hypothesised that the energy dissipation of prismatic lattice structures could be further improved by filling the void space with an agar gel. Indeed, it has been demonstrated that composite lattice structures filled with foams [2,15] and shear thickening fluid [19] can generate structures with enhanced energy absorbing properties compared to unfilled lattices. For the first time ever, we demonstrated that this novel design increased the energy absorbed of additively manufactured prismatic lattice structures by filling the void space with either 5 wt% or 10 wt% agar. The energy absorbing properties of these structures was measured by performing quasi–static compression tests on filled and unfilled PLA, PET–G, and ABS lattice structures and calculating the EA, SEA, and CFE for each sample. Overall, the PLA lattices filled with 10 wt% agar had the best EA performance (4418 ± 767 mJ), the largest displacement to failure (5.20 ± 0.96 mm), demonstrating a 46.1% increase in EA and 57.4% increase in failure displacement for complete failure of the structure compared to the unfilled (control) lattices. The addition of the agar gel improved the mechanical performance of the PET–G and ABS groups, with the highest EA values obtained from the addition of 5 wt% agar in contrast to the PLA lattices. However, the addition of the gel filler material resulted in lower SEA values for PLA and ABS lattices compared to the unfilled lattices.

5.2. Effects of heat and heat treatment

The effects of heat from submerging the lattices in 70 °C liquid agar on the resulting mechanical behaviour was investigated using two methods: (i) heat treating the polymer lattices in an oven and (ii) removing the agar once cured from the lattice (sham control) structures before performing the compression tests. There is an apparent annealing effect on the PLA lattices from being submerged in the 70 °C liquid agar resulting in a 54.5% increase in maximum displacement between the control and sham control lattices (Table 2). Indeed, Jayanth et al., [6] have shown that heat treating PLA up to 100 °C can result in increased ductility and tensile fracture strength due to the formation of very fine crystals and a reduction in the internal stresses caused by the fused deposition additive manufacturing process [6,20]. However, our results demonstrated a decrease in the maximum reaction force, maximum displacement, and EA compared to all other test groups when the polymer lattices were heat treated in a 70 °C oven. Interestingly, the sham control specimens that were submerged in 70 °C agar, which was subsequently removed, did not experience this marked reduction in mechanical behaviour. It is not clear why this is the case, but our conjecture is that the heat is transferred and dissipated differently to the polymer submerged in 70 °C liquid agar compared to a dry 70 °C heat from the oven. Indeed, the lattices submerged in 70 °C liquid agar are immediately subjected to the heat from the agar and are placed on the lab bench at ambient temperature. Whereas, the heat treated lattices are placed in a constant 70 °C dry oven for one hour before allowing to cool at room temperature. Furthermore, it may be possible that during the setting process, some agar may have bonded to the polymer lattice and filled surface pores, microcracks, and other vacancies created during the fabrication processes, thus improving the mechanical performance of these lattices.

5.3. Limitations

There are limitations associated with this work that should be noted. Firstly, the mechanical properties of bulk agar and bulk lattice material were not measured. This data would be useful for computational modelling of the unfilled and filled lattice structures. The effects of submerging the PET–G and ABS lattices in 70 °C liquid agar were not investigated here as the glass transition temperature for these materials is significantly higher than for PLA. However, as the heat treated lattices have shown, submerging PET–G and ABS in 70 °C liquid agar may also influence the mechanical behaviour of these structures. Future work will be conducted on the effects of heat treatments on all lattice materials. Only two concentrations of agar were investigated in this study. Other fill materials may provide further improved energy dissipation properties for filled lattice structures and will be investigated in future work. The mechanical behaviour of the filled lattice structures were investigated under quasi–static compressive loading. However, this may be inadequate for certain applications such as in helmet liners to reduce the rotational accelerations from impacts. Moreover, these tests were performed without any lateral confinement which may be present in the cases for helmets and other PPE and could lead to a strengthening effect in the compressive response. However, this work has demonstrated the validity of the concept that filling prismatic lattice structures with a gel improves their energy absorbing properties. Future work will investigate the dynamic compressive and dynamic oblique compressive and shear behaviour of filled lattice structures to investigate their potential use in head protection applications. Topology and material optimization should also be performed to determine optimal properties to increase the SEA while maintaining high EA and CFE values.

6. Conclusion

For the first time ever, we present a novel design to improve the energy dissipation of prismatic lattice structures by filling the void space with agar gel and subjecting the test samples to quasi–static compressive loading. Overall, there was an improvement in the energy absorbed but not the specific energy absorbed by these structures through the addition of a gel material. The main conclusions of this work are:

- Filling lattices with agar had an overall positive effect in improving the energy absorbed by the lattice structures but reduced the specific energy absorbed in all groups except PET-G with 5 wt% agar fill.
- PLA lattices filled with 10 wt% agar had the best mechanical performance (failure strain, energy absorbed) of the materials tested in this study.
- PLA is sensitive to the annealing effects when filling the lattices with agar.
- 5 wt% agar fill increased the amount of energy absorbed in PET–G and ABS lattices, whereas 10 wt% agar fill reduced the amount of energy absorbed.
- Heat treating the polymer structures in a dry oven had deleterious effects on their mechanical performance. However, the heat treatment from the wet environment from being submerged in agar during the setting process appears to have improved the mechanical performance of the lattice upon removing the agar.

CRediT authorship contribution statement

Samuel Black: Validation, Formal analysis, Investigation, Data Curation, Writing – Review & Editing. **Antzela Tzagiollari:** Validation, Formal analysis, Investigation, Data Curation, Writing – Review & Editing. **Subrata Mondal:** Validation, Formal analysis, Investigation, Data, Curation, Writing – Review & Editing. **Nicholas Dunne:** Resources, Writing – Review &, Editing, Supervision, Project Administration, Funding acquisition. **David B. MacManus:** Conceptualization, Methodology, Validation, Formal analysis, Resources, Data Curation, Writing – Original Draft, Writing – Review & Editing, Visualization, Supervision, Project, Administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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