DYNAMIC COMPRESSIVE RESPONSE OF 3D PRINTED THERMOPLASTIC POLYURETHANE HONEYCOMBS WITH GRADED DENSITIES

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ABSTRACT

Fused filament fabrication (FFF) 3D printing of thermoplastic polyurethanes (TPUs) offers a unique capability to manufacture tailorable, flexible cellular structures which can be designed and optimised for specific energy absorbing applications. This paper describes the manufacture and dynamic compressive analysis of 3D printed cellular structures with graded densities. An optimised 3D printing procedure was developed which allowed the manufacture of high quality structures, with low internal voidage, which were capable of undergoing repeated cyclic loading to densification without failure. The honeycombs produced all had an average relative density of 0.38±0.01 and were graded in density either in a continuous manner or with discrete step changes in density within the structure. After analysing their quasi-static compressive response, all arrays were subject to sinusoidal compression over a range of amplitudes (5%-45% strain peak-peak) at a frequency of 0.5Hz. It was found that by grading the structural density in different ways, mechanical damping may be tailored. Cyclic compressive testing also showed how strain softening of the TPU parent material could lead to reduced energy absorption and reduced damping over the course of 50 cycles; to what degree of this behaviour occurred was found to be dependent on the strain history. All samples were also subject to impact loading with a flat steel plate at strain rates of up to $45s^{-1}$ and specific impact energies of up to $270mJ/cm^3$ using a drop weight tower. Under high energy impact loading which caused significant densification in the uniform density structure, all samples with an element of grading transferred lower peak loads than the uniform density structure revealing the potential of density grading of TPU structures to provide superior impact protection in extreme environmental conditions.

1 INTRODUCTION

Cellular structures can be formed from most solid materials including polymers, metals, ceramics, glasses and composite materials [1] and are utilised in many structural applications as energy absorbing materials due to their low density and high energy absorbing capability. Polymeric foams and honeycombs are particularly attractive as passive protection systems as they are relatively cheap, easily formed into complex geometries and can effectively dissipate the energy of repeated impact events if formed from elastic materials [2, 3]. Large amounts of energy is dissipated in such structures via cell wall buckling, through viscous losses in the movement or compression of fluid in the structure, via plastic deformation and by fracture [1]. Despite their merits, there is only a narrow range of energies which the typical, single density cellular structure is optimised to absorb and this can be understood by analysing the typical compressive stress-strain behaviour of a cellular structure as shown in Figure 1. The ideal amount of energy which a cellular structure will absorb is indicated by the shaded region under the stress strain plateau. Larger compression energies would densify a structure, transferring high stresses and lower compression energies could be more efficiently absorbed by a lower density structure, which would transfer a lower peak stress. To better visualise what energies are most efficiently absorbed by a cellular structure, energy absorption diagrams and efficiency diagrams can be formed from the stress-strain diagram.

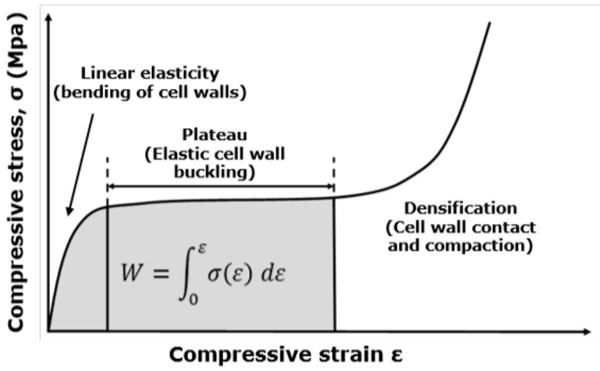
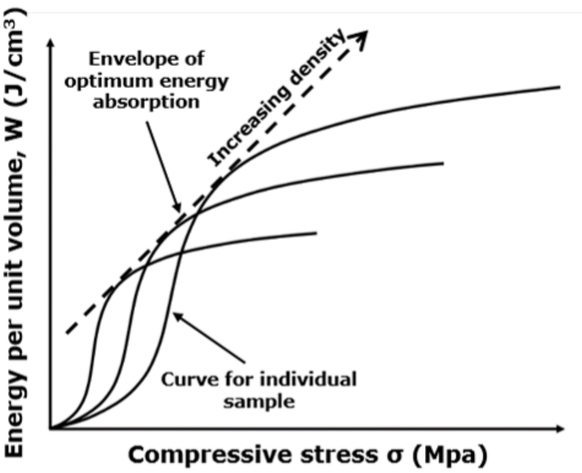


Figure 1: Schematic illustrating the typical compressive stress-strain response of a cellular structure under compression.

Figure 2a shows a typical energy absorption diagram formed by taking the cumulative area under the stress-strain curves of three foam structures with different densities. There exists a shoulder point on each of the curves which indicates the energy which those structures are optimised to absorb [1], allowing an envelope of optimum energy absorption for a class of cellular structure to be drawn. To give a numerical value to the efficiency of energy absorption of each structure, the energy absorbed may be divided by instantaneous stress to give an "Efficiency" parameter [4], and this can be plotted against stress to form an efficicncy diagram for a class of cellular structures as shown in Figure 2b.



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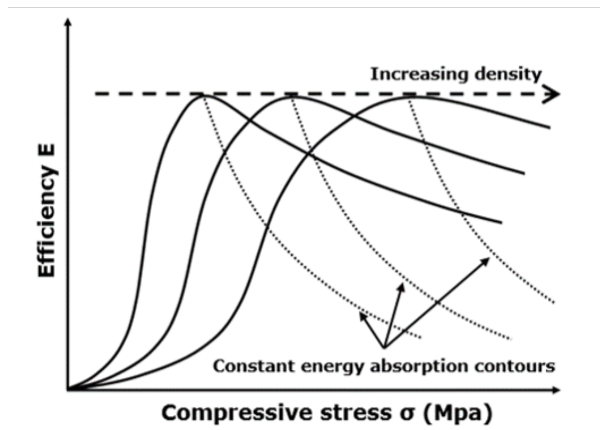

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Figure 2: a) Typical energy absorption diagram for a class of cellular structures with a range of densities and b) the efficiency diagram for a class of cellular structures with a range of densities.

In real world applications, energy absorbing structures are likely to be subject to a large range of vibrational loads and therefore it would be advantageous if multiple points of maximum energy absorbing efficiency could be designed into a cellular structure. Since a single density structure has one maximum efficiency peak, it should follow that a structure with multiple densities should have multiple efficiency peaks when compressed. It is the aim of this work therefore to explore how functionally grading the density of cellular structures can be used to manipulate their energy absorbing response in this way. Density grading of polymeric foams which are formed in a bulk process is not possible and it was desired that the structure formed should not require adhering in multiple parts. 3D printing however, provides a geometric design freedom that not achievable via any other means [5] making it the ideal method of manufacture to consider for the creation of these tailored cellular structures. Although there have been a number of attempts to create 3D printed cellular structures with tailorable stress-strain and energy absorbing behaviour [6–8], much of the work has focused on the printing of brittle structures and attempts to create structures with hyperelastic behaviour via polyjet 3D printing produced samples fragile in nature which fractured during the removal of support material [9]. In this work, in order to create hyperelastic, durable structures, fused filament fabrication (FFF) 3D printing is used which allows the use of thermoplastic polyurethane (TPU), a material known to have excellent impact properties and abrasion resistance [10]. This work builds on previous experimental analysis of 3D printed cellular structures which took the form of single density TPU honeycombs, carried out by the authors at the University of Bristol [3]. In this work the quasi-static behaviour of the density graded TPU honeycombs structures is reviewed along with their dynamic compressive response in both sinusoidal compressive and drop tower impact tests.

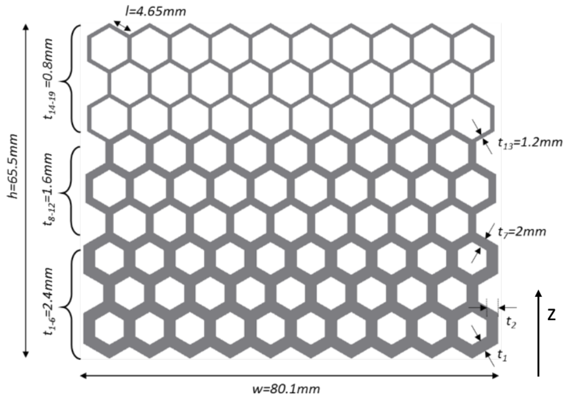
2 Cellular arrays

All specimens produced in this work were manufactured via 3D printing of Ninjaflex TPU on an Ultimaker Original 3D printer. The Ninjaflex TPU was produced by Fenner Drives and has a tensile modulus of 12MPa, ultimate tensile strength of 26MPa and elongation to break of 660% according to the manufacturer [11]. Four specimens with graded density through their structure were produced along with three specimens of constant density for reference. All graded cellular arrays were designed with wall length, l=4.65mm and an average cell wall thickness, t_a=1.6mm. The wall thicknesses were graded through the structures from t=0.8mm to t=2.4mm; Figure 3a and 3b show a design schematic and a manufactured specimen respectively and 3c details the wall thicknesses of, from left to right, the continuously, 5-stage, 3-stage and 2-stage graded structures. The low, medium and high density reference samples were designed with wall length, l=4.65mm and thicknesses of t=0.8, 1.6 and 2.4mm respectively.

Table 1: Dimensional properties of the cellular arrays measured after manufacture

Specimen details	**Number of rows**	**Height, h (mm)**	**Width, w (mm)**	**Depth, d (mm)**	**Relative density, $\rho^*_{\mathbf{RD}}$ (-)**
High density	19	66.2	81.7	29.8	0.50
Medium density	19	65.5	81.1	29.7	0.37
Low density	19	64.5	80.7	29.6	0.26
Continuous grading	19	65.4	81.1	29.7	0.39
5-stage grading	21	72.5	81.2	29.7	0.37
3-stage grading	19	65.5	81.1	29.6	0.38
2-stage grading	21	72	81.7	29.8	0.37

The relative density for a hexagonal array with constant wall length and thickness is equal to ρ_{RD}=(2/3-2)(t/l) [1] and for a graded structure designed, it holds that the average relative density, $\rho_{aRD} = (2/3^{-2})(t_a/l)$. The measured relative density, ρ^*_{aRD} of the final 3D printed specimens were calculated such that $\rho_a/\rho_s = \rho^*_{aRD}$ where ρ_a=specimen mass/the cuboidal area which it occupies and ρ_s=the parent material density. The wall thickness of the produced parts were measured to be accurate to within $\pm$0.2mm of the design values. Table 1 provides details of the topological properties of the manufactured specimens.



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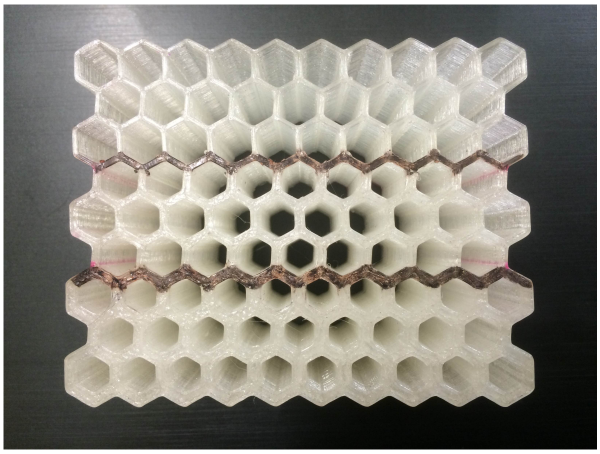

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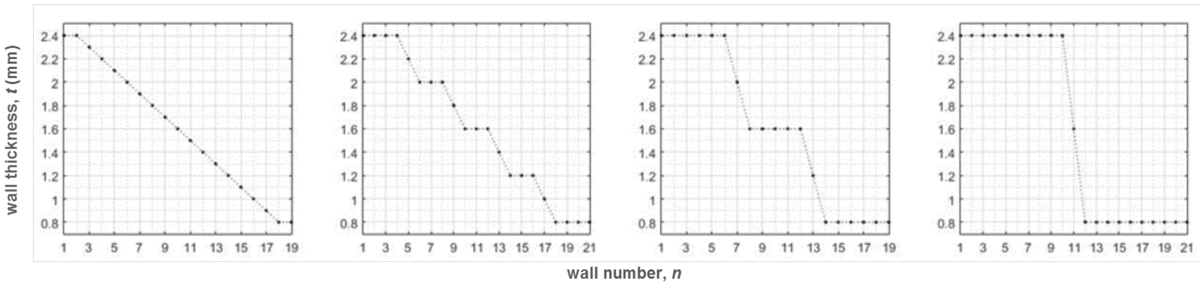

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Figure 3: a) Design details of the 3-stage graded hexagonal structure. Cell walls are numbered n=1-19 from the base of the structure and corresponding thickness values, t_n are indicated; b) the test specimen produced by FFF 3D printing from TPU; the walls of intermediate thickness are indicated in black; c) graphical representation of the wall thickness of, from left to right, the Continuous, 5-stage, 3-stage and 2-stage graded specimens.

3 Experimental Methods

Flat-plate, quasi-static compression tests of the hexagonal arrays were carried out using a Shimazu AGS-X static test machine with a load cell with $\pm$10kN load cell. All samples were compressed in the -z direction as indicated in Figure 3a under displacement control at a strain rate, $\dot{\varepsilon}$ =0.03 up to a maximum load of 5kN to ensure complete densification. All samples were loaded and unloaded under these conditions for 5 cycles with data shown here being captured on the 5th compressive cycle.

Samples were subsequently compressed sinusoidally at 0.5Hz between flat plates using an Instron hydraulic test machine to analyse their damping behaviour. All arrays were compressed to a strain of 5% and then cycled for 50 cycles to a designated peak strain. Each sample underwent 5 tests which corresponded to the 5 peak strains of 10, 20, 30, 40 and 50%.

Finally, all specimens were subject to flat plate impact testing using an Instron Dynatup 9250HV drop tower; the boundary conditions of the drop testing mimicked those of the quasi-static and cyclic testing. Each specimen was subject to a range of impacts of increasing specific impact energy from 30 to 270mJ/cm^3 by increasing the height from which the 7.03kg mass was dropped. The stress-strain behaviour of the samples was recorded for the graded density samples and compared to the uniform density samples. The key parameter in these tests to note was the peak stress transferred.

4 Results and discussion

4.1 Quasi-static testing

In Figure 4a-d, the stress-strain curves are plotted for the four graded structures with the stress-strain curves for the three uniform density structures included for reference. The uniform density structures exhibit the predicted characteristic profiles with initial linear behaviour, flat plateaus and then sharp increase in stiffness to densification. With increasing density there is an associated increase in stiffness of the linear section and the flat plateau sections occur at higher stresses. The onset of densification occurs at a lower strain with increasing density with the strain at which the structures being defined as the point where the structure has been compressed to its maximum energy absorbing efficiency; these points will be precisely defined later. The onset of the plateau shall be approximated here as 0.1 strain which corresponds to the theoretical collapse stress for regular hexagons [1] and the plateau stress, σ_p defined as stress at the median plateau strain. With these definitions the low, medium and high density structures have plateaus which span 0.43, 0.38 and 0.31 strain and have plateau stresses of σ_p= 0.05, 0.19 and 0.56MPa respectively. Beyond strains of 0.47, 0.6 And 0.78 the low, medium and high density structures respectively approach a common stiffness profile and at this point they are regarded to have reached "full" densification.

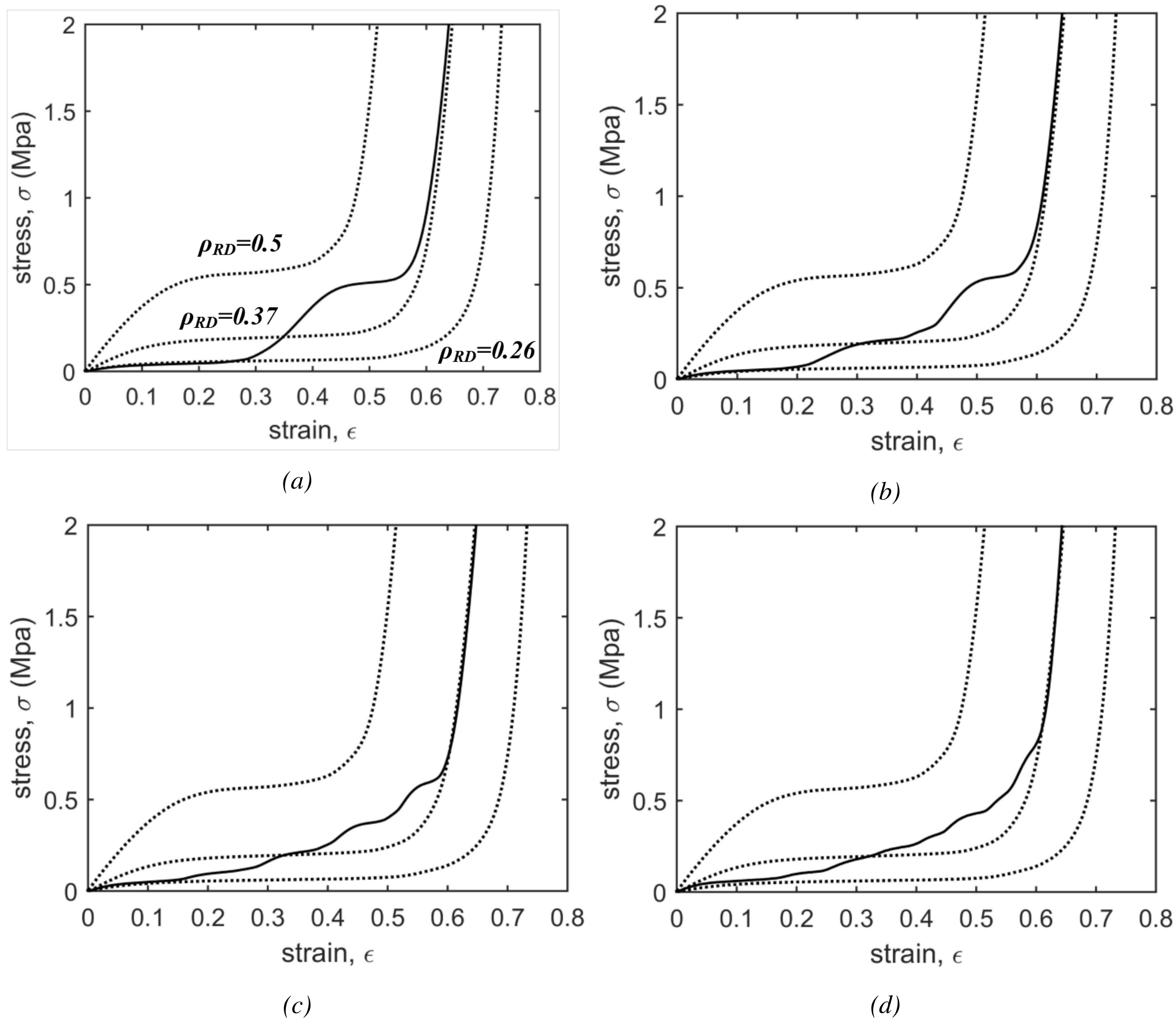


Figure 4: Stress strain behaviour of the a) 2-stage; b) 3-stage; c) 5-stage and d) continuously graded structures. The stress strain behaviour for the low, medium and high density structures are included for reference with the relative density, ρ_{RD} indicated in a).

Clear plateau regions can be observed in the stress-strain profiles of the 2-stage and the 3-stage graded arrays indicating a staggered collapse of regions with increasing density within the structure during compression. The clearly defined plateaus are an indication that each density region undergoes linear deformation, collapse and densification before the succeeding, higher density layer undergoes significant deformation. The 5-stage and continuously graded structures have less well defined plateau regions which occurs due to the onset of significant deformation of the successive, higher density layers before the previous region has undergone full densification. In all the graded arrays, the length of the individual plateaus decrease as the densities of the layers being compressed increases.

Improtantly, the strain to densification in all the graded examples is higher than that of the equivelent uniform density sample and it is likely for this reason that the graded structures absorbed approximately 10% more energy when compresed to a σ=1Mpa than the equivalent uniform density sample. Similar favourable enregy absorbing behaviour was found for rigid, density graded lattices analysed in [12], when compared to the equivalent uniform density structures.

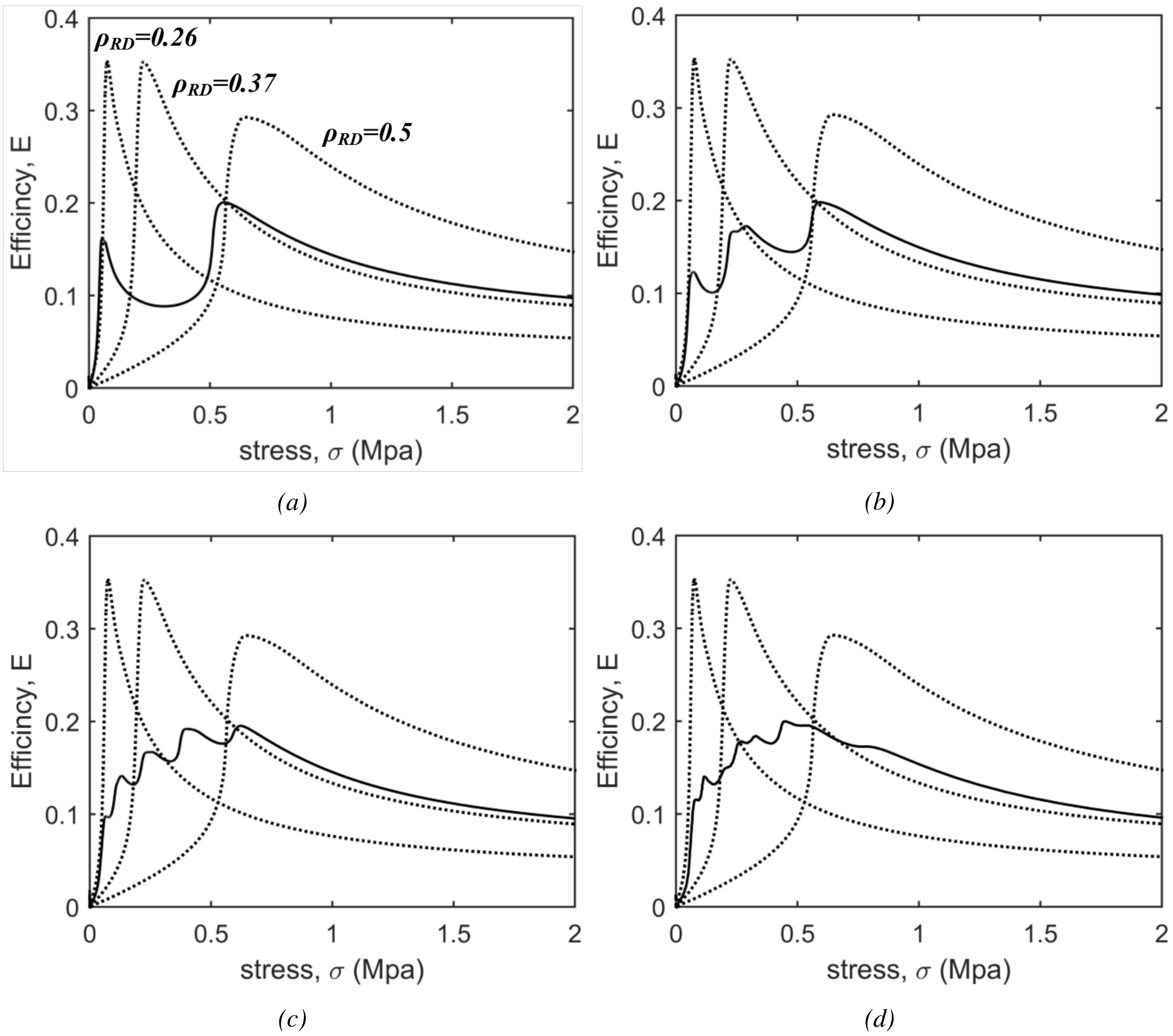


Figure 5: Efficiency-stress diagrams for a) 2-stage; b) 3-stage; c) 5-stage and d) continuously graded structures with the efficiency absorption profiles for low, medium and high density uniform structures included for reference.

In Figures 5a-d, efficiency-stress curves are plotted for the four graded structures with the efficiency-stress curves for the three uniform density structures included for reference. The efficiency parameter plotted here against stress has maxima at points just before the point where the increase in energy is exceeded by the increase in stress [2]. The uniform structures all possess a single maxima, with the low and medium density structures operating at a maximum efficiency of 0.35. The efficiency of the high density structure is significantly lower at 0.29 which is due to the compressive stress-strain profile exhibiting a less well defined plateau; a result of the deformation mechanisms becoming less buckling dominated due to the high t/l ratio within the array.

The efficiency curve for each graded structure has a number of peaks and it is clear that all the graded structures are more efficient at absorbing low and high energy loads whilst intermediate loads are better absorbed by the equivalent uniform structure. It can be seen that the 2-stage graded array is the most efficient out of the graded arrays at absorbing low energy loads with a peak efficiency of 0.16 at a stress of 0.055MPa however there is a large trough in efficiency at intermediate compression energies. The continuously graded structure does not exhibit the same trough in efficiency, exhibiting higher efficiency over a wider range of compression energies, with the lowest fluctuation in energy absorbing efficiency. It can also be observed that the magnitude of the efficiency peaks increases successively with the compression of the successive, higher density layer in all the graded structures. To summarise the quasi-static analysis of these structures, by density grading grading, we were successful in absorbing a higher total energy in compression than the equivalent uniform array and the graded structures were also more efficient than the equivalent uniform array at absorbing low energy compression loads. The continuously graded array performed most efficiently over the widest range of compression energies however the equivalent uniform density array had the highest peak efficiency.

4.2 Cyclic compressive behaviour

Figures 6a-e show the cyclic compressive stress-strain behaviour of uniform, 2-stage, 3-stage, 5-stage and continuously graded structures respectively. Each plot shows the cyclic compressive behaviour from the 50th cycle of 5 separate tests; the samples were pre-strained to 5% and then cycled to either 10, 20, 30, 40 or 50% compressive strain in each of the tests. The loading and unloading cycle in each case occurs in the clockwise direction and the loading portion of each curve takes on a similar profile to that of the quasi-static tests. Due to the presence of layers of high relative density, at large compressive strains, the stresses transferred by the graded structures far exceed that of the uniform structure. As the TPU parent material is viscoelastic, so too is the response of each of the structures, with the unloading portion of the cycles tracking lower stress values than the loading. Further, since the TPU parent material also undergoes a strain-softening response which is dependent on the magnitude of the compressive strain to which it has been subject [3, 13], the samples appear softer (have lower plateau stresses) the higher the maximum strain to which they were cycled. This effect should behaviour should be considered in the design of practical energy absorbing systems.

The damping of a structure is proportional to the area within the closed hysteresis loop which is formed during cycling [14]; for a stress-strain plot the area gives the specific energy dissipated in a single cycle in J/cm^3. Figure 6f shows the specific energy dissipated in each compressive cycle for each structure in each of the 5 tests with unique maximum strains, ε_{max}. The energy dissipated by the uniform density structure increases in a linear manner with increasing maximum strain. The energy dissipated by the structures with an element of density grading increased in a non-linear manner, with increasing gradient. This non-linear increase can be attributed to the fact that, at low strains, only the lower density part of the structures are being compressed and therefore less material is deforming. The damping capacity of all the structures is lower than that of the uniform density structure in all but the case where they are compressed to ε=0.5. At high strains, the graded structures provide greater damping as well as absorbing more energy; these properties may be advantageous in certain energy absorbing applications. Further, by varying the type of density grading, it can be seen here that the peak stress, energy absorption an damping behaviour may be modified. There is therefore great potential to further explore how density grading may be modified in order to tune these parameters to suit different energy absorbing applications.

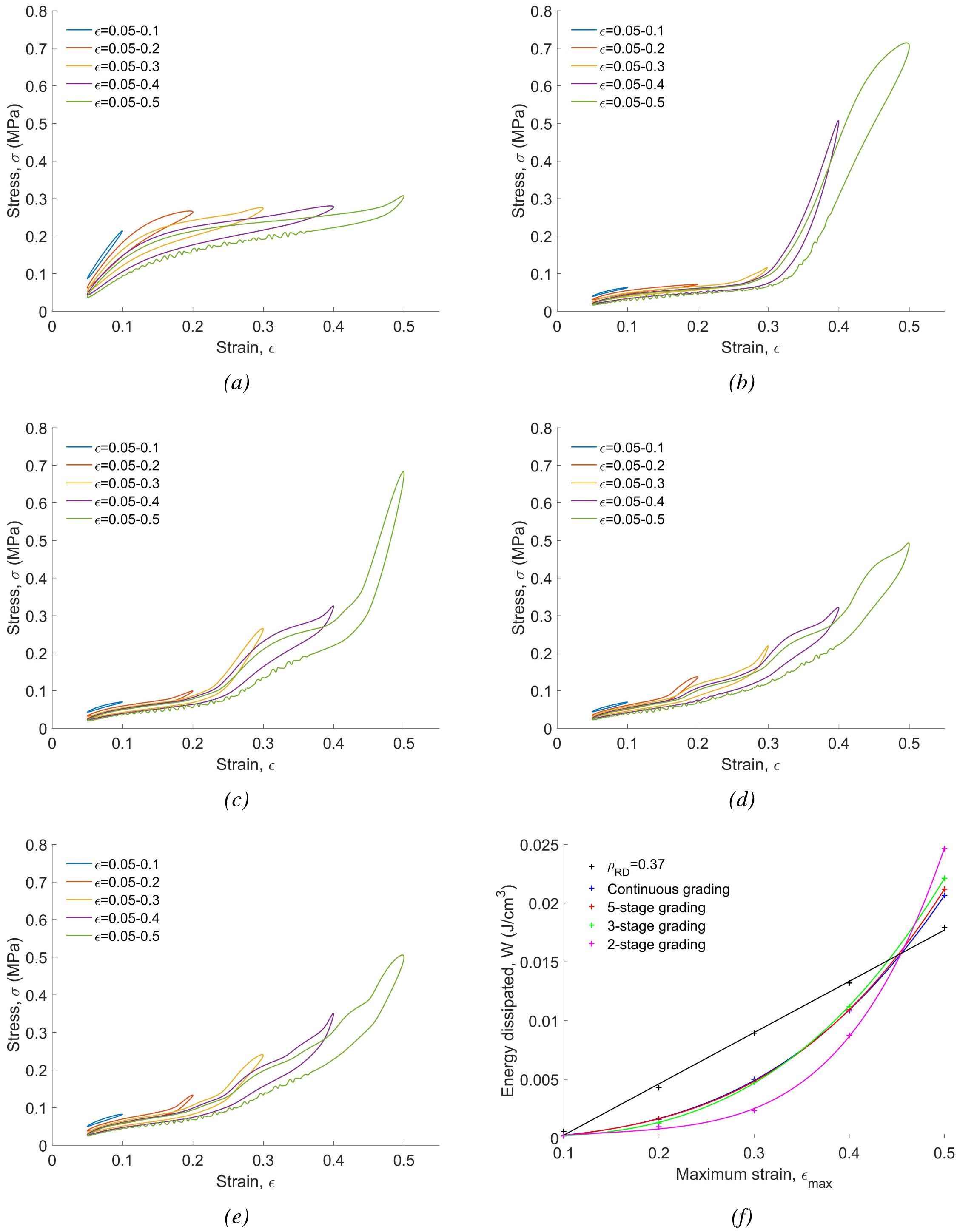
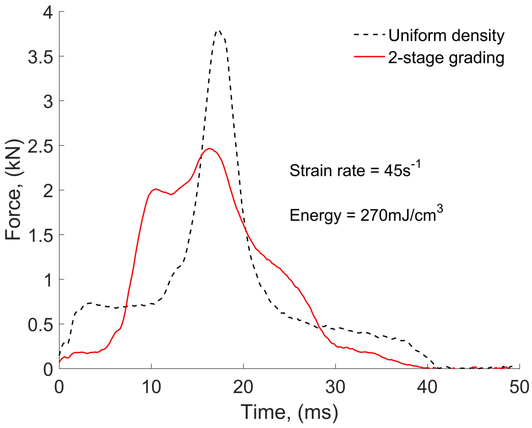


Figure 6: Cyclic compressive stress-strain response of a) uniform density, b) 2-stage graded, c) 3-stage graded, d) 5-stage graded and e) continuously graded structures compressed between 5% and 10, 20, 30, 40 and 50% compressive strain. f) The specific energy dissipated in each compressive cycle for each structure in each of the 5 tests with unique maximum strains, ε_{max}.

4.3 Impact behaviour

Figures 7a-d show the force-time plots for 2-stage graded, 3-stage graded, 5-stage graded and continuously graded subject to a flat plate impact with the specific energy (total energy normalised by specimen volume) of 270mJ/cm^3. In all cases the graded structures transfer a lower peak force than the equivalent uniform density specimen which has undergone significant densification. The lower peak force can be attributed to the graded specimens densifying at a higher strain than the uniform specimen and therefore absorbing more of the energy in the plateau regions; an observation also made in [12] for the compressive behaviour of density graded lattices. It should be noted that for lower energies which did not cause significant densification in the uniform density sample, the uniform density sample transferred lower loads than the graded specimens. This behaviour is consistent with the quasi-static results which showed that the graded specimens absorbed large compression loads more efficiently than the uniform density specimen. As a result of these findings, for the limited impact cases and designs explored here, it would appear that the density graded structures would be useful for absorbing extreme load cases which would otherwise densify the equivalent uniform structure. In particular, the 2-stage graded specimen significantly outperformed the uniform density specimen under extreme impact loading. The effect of different grading designs should be further explored in order to optimise structures for given impact cases however these preliminary studies clearly show the potential for density graded structures to outperform uniform density structures when subject to certain loading cases.



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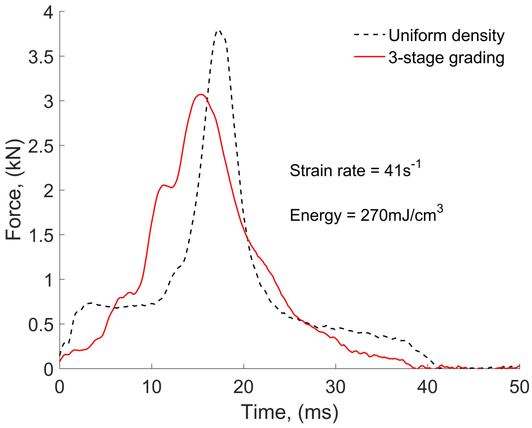

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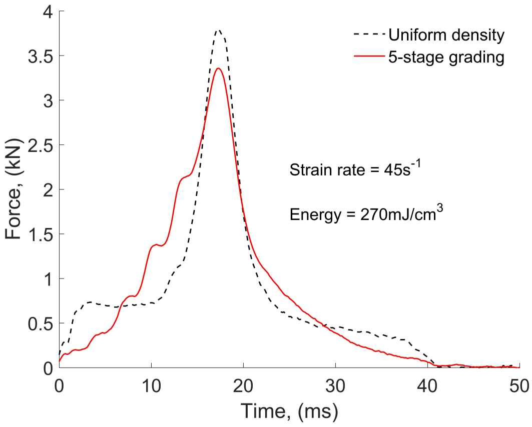

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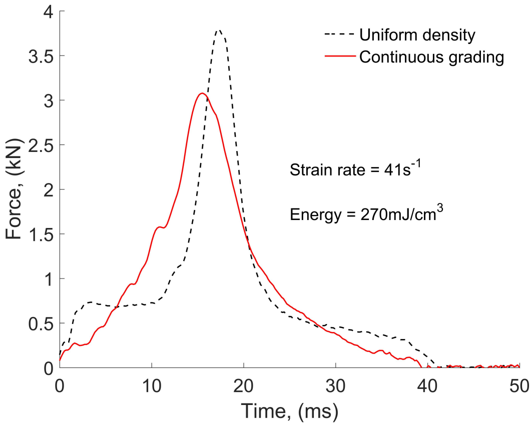

(d)

Figure 7: Force-time plots showing the response of a) 2-stage graded, b) 3-stage graded, c) 5-stage graded and d) Continuously graded TPU honeycombs subject to a specific impact energy of 270mJ/cm^3 compared to a uniform density structure.

5 Conclusions

In this work we have shown that it possible to produce hyperelastic, recoverable TPU honeycombs with graded densities via FFF 3D printing. By utilising commercially available thermoplastic polyurethane as a parent material it was possible to form structures which could be repeatedly compressed to densification without fracture. By grading the density of the structures from ρ_{RD} =0.26-0.5 in different ways, the quasi-static, cyclic compressive and impact behaviour of the structures were significantly altered. It was shown in quasi-static tests that grading the structures resulted in a compressive stress-strain response with a number of stress plateaus. Graded structures reached densification at higher strains than the equivalent uniform density structure and were more efficient at absorbing low and high load cases that the uniform density equivalent. When subject to cyclic compressive testing, no failure was seen in any of the specimens after 250 cycles. The damping response of the graded structures was heavily dependent on the type of grading and increased non-linearly with maximum compressive strain. All the graded structures exhibited greater damping properties than the uniform equivalent when compressed sinusoidally between 5-50% strain and dissipated less energy when compressed to peak strains of 40% or less. Further, by carring out a number of drop tower impact tests, it was shown that there is a clear potential for graded structures to protect against extreme impact cases which would usually lead to significant densification in the equivalent uniform density structure. In future work, the effect of different density grading parameters on mechanical properties such as minimum and maximum density and multiple density gradients should be explored. Other structural modifications such as structural hierarchy and cell wall pre-buckling should also be explored as other means for tailoring the mechanical response of these novel, hyperelastic 3D printed structures.

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