Using 3D printing to realise ball-and-spring metamaterial designs

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Abstract. A new method of realising ball-and-spring metamaterial designs has been developed to allow for their fabrication using low-cost, hobbyist grade 3D printers. This realisation method uses a tapered beam design which is shown, though computational simulation, to be a suitable approximation of ball-and-spring models. The low-cost of the method allows for the fabrication of metamaterials to be more easily accessible to academics. This realisation method is then used to fabricate the first true, three-dimensional mechanical topological insulator. Through the development of the method, a new technique for supporting intricate lattice-like structures during 3D printing has been conceived. This new support technique, named "hybrid support", makes use of a common 3D printing problem, stringing, to provide horizontal support and systematically generated, tree-like structures to provide vertical support. The resulting support architecture uses minimal material and is easily removed in post-processing. Hybrid support allows sparse thin structures to be printed at heights and overhangs previously unachievable using hobbyist grade 3D printers.

1. Introduction

Mechanical metamaterials are a type of material showing novel mechanical properties not found in nature. Designing these materials has been done using simple ball-and-spring models[1–4]. Ball-and-spring models use infinitesimally thin central-force springs to connect point masses, which act as hinges. Translating these designs into reality is often difficult, time-consuming and expensive. Finding a method to quickly and cheaply realise these metamaterial designs would allow researchers to easily test hypotheses about the behaviour of metamaterials. It would also allow for the application and feasibility of metamaterials designs to be demonstrated helping to generate further support for this field from the industrial sector.

In this report, a method is presented to cost-effectively translate these ball-and-spring designs into real working models using a hobbyist grade 3D printer. Using thermoplastic polyurethane (TPU) a tapered beam design is shown to replicate the predicted behaviour of a test model (a mechanical topological insulator (MTI)) using low-cost 3D printing. Through this process, this report also describes the first realisation of a true three-dimensional MTI and an important new support method which allows small-scale lattice designs to be printed on hobbyist grade 3D printers.

1.1. Mechanical metamaterials

Metamaterials are specifically structured materials that are designed to possess properties not found in their constituents or other, natural materials [5]. Having first been developed in the field of electromagnetism to display exotic properties such as microwave cloaking [6], these types of materials were then adopted by other fields including thermodynamics, acoustics and mechanical physics [7]. These materials are commonly constructed out of small-scale metaatoms, identical building blocks which, only when stacked on top of one another to form a large-scale structure, display the desired properties [8,9].

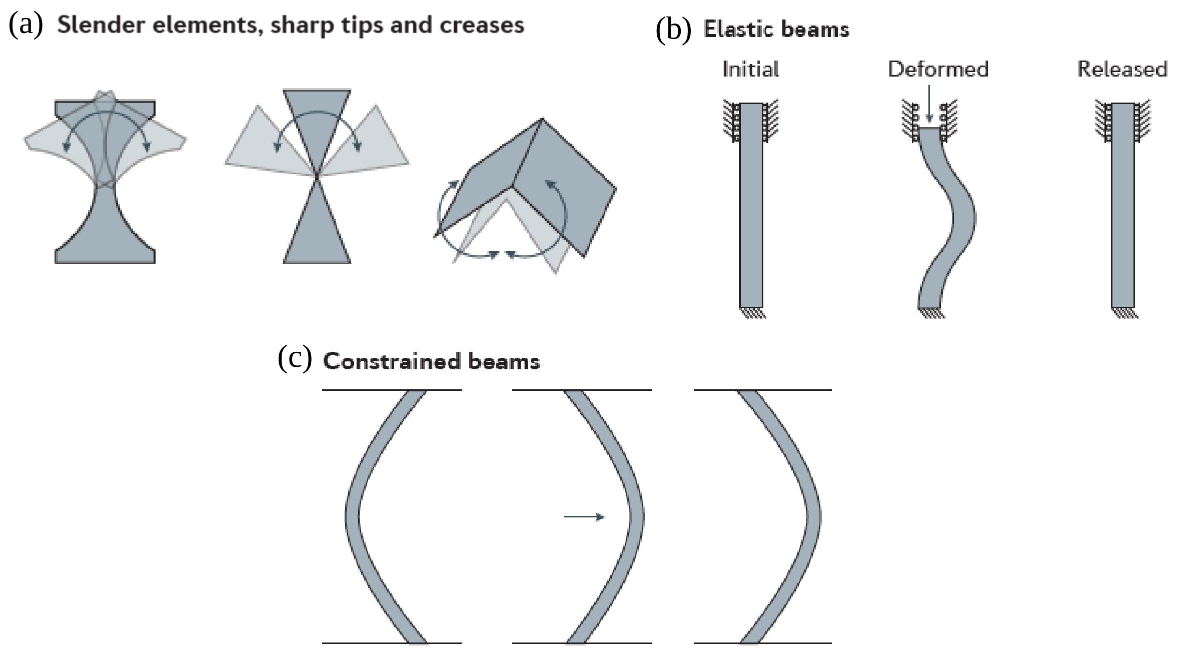

Figure 1. Figure showing three types of mechanisms used in metamaterial design: slender elements (a), which localise bending, elastic beams (b), which undergo buckling when compressed, and constrained beams (c), which snap between two equilibrium states. Figure adapted from [5].

Mechanical metamaterials are materials that aim to control properties including the deformation, stress, and storage of energy in a material via its macroscale structure [10]. This is done using different mechanisms including those shown in figure 1 [5]. Materials have been designed to show many different mechanical properties such as negative Poisson's ratios [11] (the ratio of transverse strain to lateral strain) and programmable elasticities [12]. The ability to control the behaviour of a material in this way gives rise to many applications such as pre-programmed buckling in structures [4], energy storage [13] and stretchable lithium-ion batteries [14].

1.2 Maxwellian Frames

One set of mechanisms utilised in the design of mechanical metamaterials are Maxwellian frames. These are frames (or lattices) consisting of hinges connected by rigid beams or springs such as the ball-and-spring models mentioned previously. These frames were first investigated by James Clerk Maxwell in an 1864 paper [15]. In this paper it was demonstrated that the stiffness of a frame could be changed by altering the number of degrees of freedom, N_f, and constraints, N_c. The number of degrees of freedom is equal to the number of hinges multiplied by the dimension of the frame and the number of constraints is given by the number of beams. This work was later expanded upon by Calladine to give the equation

$$N_f - N_c = N_0 - N_S \tag{1}$$

where N_0 is the number of zero modes, soft sections of the frame that can move freely without a restoring force, and N_S is the number of states of self-stress, sections of the frame where the beams are under stress but the hinges are not [16]. By constructing metamaterials from these frames, this equation allows areas of softness to be pre-programmed.

Equation 1 can be viewed as analogous to the conservation of electrical charge law by interpreting the zero modes and states of self-stress as positive and negative quanta of mechanical charge. When the number of constraints is equal to the number of degrees of freedom a frame is known as isostatic. Equation 1 then requires that the number of zero modes is equal to the number of states of self-stress making the frame mechanically charge neutral. Kane and Lubensky found that these isostatic frames can be described using a topological polarisation vector [17]. Much like an electrically polarised material can have opposing charges localised on opposite surfaces despite its net charge being zero, a topologically polarised frame can localise degrees of freedom and states of self-stress on opposing surfaces despite its net mechanical charge being zero. This allows the properties of mechanical metamaterials constructed from Maxwellian frames to be pre-programmed in unique ways.

1.3. A mechanical topological insulator

An MTI is a material that displays softness on one of its surfaces, but rigidity on the opposing surface and in its bulk. This is called surface softness asymmetry (SSA). It is constructed as an isostatic lattice with a net mechanical charge of zero but has a topological polarisation which gives rise to this SSA. In this lattice, zero modes are localised on one face, giving rise to the soft surface, and states of self-stress are localised on the opposite face, giving rise to the rigid surface. This material displays topological protection, which means that cutting or damaging its surfaces will not affect the SSA as shown in figure 2(a) and (b). There is interest in this material as it has many potential applications. For example, a hard hat, a hat worn to absorb any impact to the head, consists of a hard, exterior shell and a soft, interior cushioning. Once this interior wears down, it must be replaced or repaired to continue to provide protection. However, if a hard hat was constructed using an MTI, with its soft surface facing inward

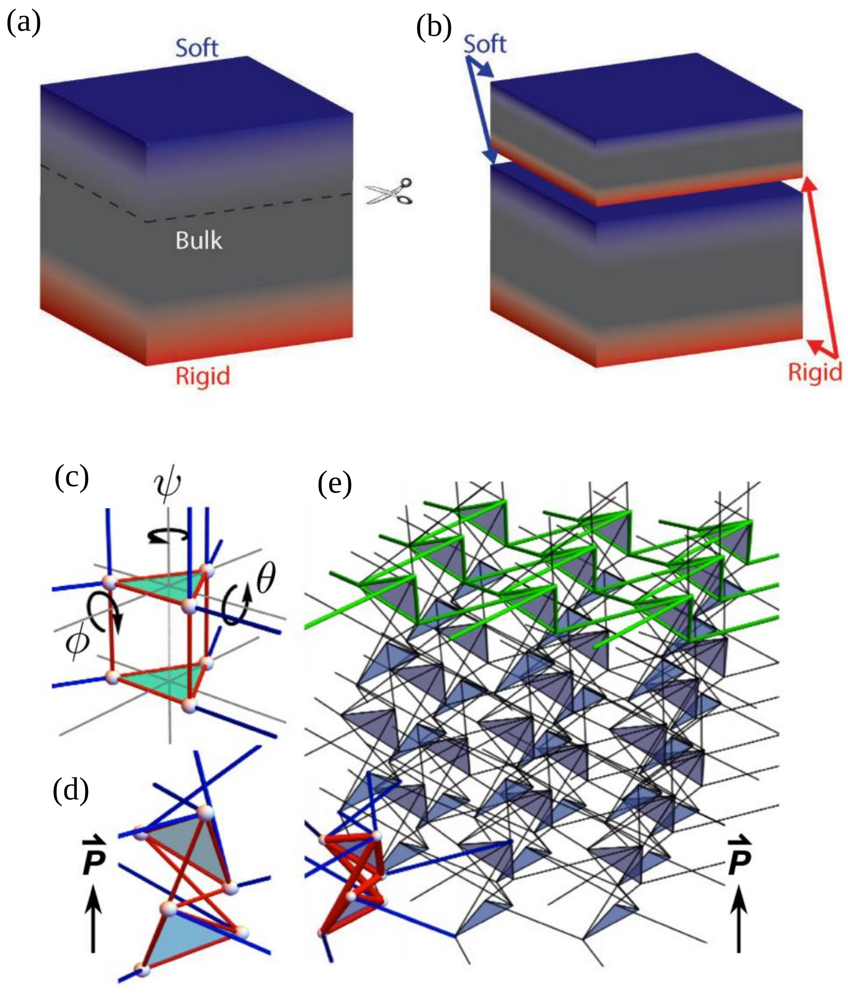

Figure 2. Figure showing the design and properties of the MTI. (a) and (b) show how the SSA of the material is topologically protected when cut. (c) and (d) show a unit cell of an untwisted and twisted kagome lattice respectively. (d) shows the unit cell of the MTI that is realised in this paper. (e) shows the lattice structure of the MTI made up of many unit cells. In (d) and (e) the polarisation vector of the lattice structure, $\vec{P}$, is shown. (a) and (b) are adapted from [18]. (c), (d) and (e) are adapted from [1].

and its hard surface facing out, as the soft surface wore down it would still provide cushioning and protection to the user.

In 2018 Baardink et al. presented a design for an MTI [1]. This was the first time a design had been presented that did not contain Weyl lines, soft deformation lines that appear in the bulk, making it the first published design of a true, three-dimensional mechanical topological insulator. This design was based on a ball-and-spring system in the form of a three-dimensional kagome lattice, one of the simplest three-dimensional isostatic lattices. The lattice was then twisted by changing the length of the springs and positions of the lattice points as shown in figure 2(c) and (d). Using computational simulations, the model was probed for the desired SSA during the twisting process. This was carried out systematically until an orientation was discovered that displayed the desired properties. The final structure is shown in figure 2(e). This was the test model used in developing a method for 3D printing ball-and-spring metamaterial designs in this report.

1.4. 3D printing

3D printing is a process of building three-dimensional objects by fusing layers of material upon one another. This process can create complex models that cannot be fabricated using any other method. 3D printers have surged in popularity over the past decade, especially in the hobbyist sector, and the price of these printers has greatly reduced. This makes this method of fabrication far more accessible to academics. Therefore, developing a method of realising metamaterials designs using a low-cost 3D printer would allow for widespread experimentation and realisation.

The printer that was used in this project was the Prusa i3 Mk3s with the MMU2 upgrade installed. This is a fused deposition modelling (FDM) printer, also known as a fused filament fabrication (FFF) printer, with a 0.4mm nozzle. FDM printers work by feeding a continuous filament of thermoplastic into an extruder. This extruder melts the thermoplastic which is ejected through to a nozzle. This nozzle is used to “draw” the first layer of the model onto a print bed – the flat surface on which an object is constructed. The printer then draws a second layer which fuses to the first as it cools. Layers are continually printed upon one another until the object is fully formed as shown in figure 3. This method of 3D printing has been adapted to print many different materials, from chocolate and pasta, to concrete and living tissue [19–21]. The Prusa printer used in this project prints with thermoplastics that melt below three hundred degrees Celsius. The MMU2 upgrade installed on the printer allows up to five materials to be used in a single print by replacing the material fed to the extruder.

This printer was chosen because of its price point. The printer costs approximately 700 GBP and the multi-material upgrade a further 270 GBP. At this price, it is foreseeable that many academics could purchase one of these printers for printing metamaterials. Another reason this printer was chosen is the low-cost of print materials, costing approximately 30 GBP for 500g of flexible TPU. This allows for models to be printed cheaply and many iterations to be produced letting prints be refined and honed without a large cost.

To print a model on a 3D printer an STL file of the design must first be created. This is a file that describes the fully enclosed surface of the model and is often created using computer-aided design (CAD) software. This file is then input into a slicer, a program used to split the model into layers that

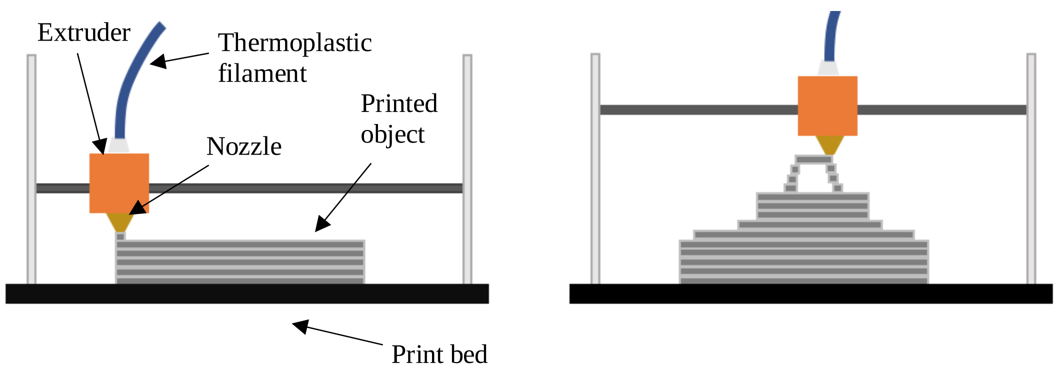

Figure 3. Figure showing the layer by layer build process of an FDM 3D printer.

can be printed. The software then determines the extrusion path of the nozzle and outputs it as G-code, a type of code that can be understood by the printer. This code can then be input into the printer and the model can be fabricated.

2. Soft spheres and rigid beams

To translate the ball-and-spring model of the MTI into a real-world object is a challenge. This is, in part, due to the theoretical model consisting of infinitesimally thin central-force springs that do not allow bending and point masses which act as perfect hinges. This means that the realised object will deviate from the design. However, the design of the MTI gives some scope in the realisation process as it is topologically robust. This means that the design must be changed considerably for it to lose its properties. Even with this topological robustness, if the fabricated model strays too far from the theoretical design it will cease to show the desired SSA. Therefore, a balance must be found and steps must be taken to ensure that the realisation process does, in fact, preserve these properties.

As a foundation for this realisation process inspiration was taken from “Intrinsically Polar Elastic Metamaterials” [18], a paper published in 2017 by Bilal et al., in which a ball-and-spring metamaterial was designed and realised. In this paper, a metamaterial design was translated from a theoretical model by replacing each point mass with a soft elastic sphere, to act as a hinge, and each spring with a rigid beam. This was realised using a Polyjet 3D printer and was shown to demonstrate the properties predicted by the theoretical model. This model and the realisation can be seen in figure 4(a) and (b).

As accessibly and affordability are important parts of this project, a Polyjet printer could not be used as they are expensive. However, this realisation process was attempted using the multi-material upgrade on the low-cost Prusa printer. To begin, three printing materials were obtained: polylactic acid (PLA) for use as a rigid material, TPU with a shore hardness of 98A for use as a soft, elastic material and polyvinyl alcohol (PVA), a water-soluble polymer, for use as a support material. These are materials that are cheap and easy to obtain with PLA being a highly popular filament among hobbyists.

2.1. Push-fit models

To transfer the model described in Baardink’s paper to an STL file, the lattice points and connectivity matrix are input into a MATLAB script. This generates CSV files containing the lattice coordinates and bond positions of a single unit cell. A CAD program called OpenSCAD then uses the CSV files to create two STL files: the first to define the spheres of the lattice and the second to define the beams. To test if it would be feasible to print this design on the Prusa printer, preliminary “push-fit” models were fabricated. These models were printed entirely from rigid PLA. The spheres and beams were printed individually and were assembled together by pushing the beams into specifically positioned holes in the spheres.

Initially, a single unit cell was printed as seen in figure 4(c)(left). This model is very large due to small angles between springs in the theoretical design. These small angles are not a problem in an idealised model as the springs are infinitesimally thin. However, in the physical realisation, this cannot be the case and these small angles can cause the beams to intersect with one another. To avoid this the beams must be made very thin in comparison to the sphere radius. By making these beams thin, the whole model must be made large in order for them to retain their rigidity. This brings it up to sizes that are not feasible when printing multi-celled lattices.

To reduce the size of the unit cell, the angles and positions of several beams were altered; moving them further apart from one another but keeping them connected to the spheres. By doing this it allowed the size of the unit cell to be reduced by half whilst retaining the beam thickness and rigidity as seen in figure 4(c). The model can be altered in this way without affecting its properties due to its topological robustness. With the reduced unit cell size, a 2x2x2 lattice was printed and constructed using the push-fit method as shown in figure 4(d). This was the first realisation of the lattice structure but as it was constructed using completely rigid components in did not exhibit the desired SSA.

2.2. Multi-material printing

This method of push fitting the models together was long and laborious taking about 40 hours to print and construct a 2x2x2 lattice. After being deemed unfeasible to construct larger lattices it was concluded that the MTI would have to be printed as one piece using the three materials mentioned previously. The

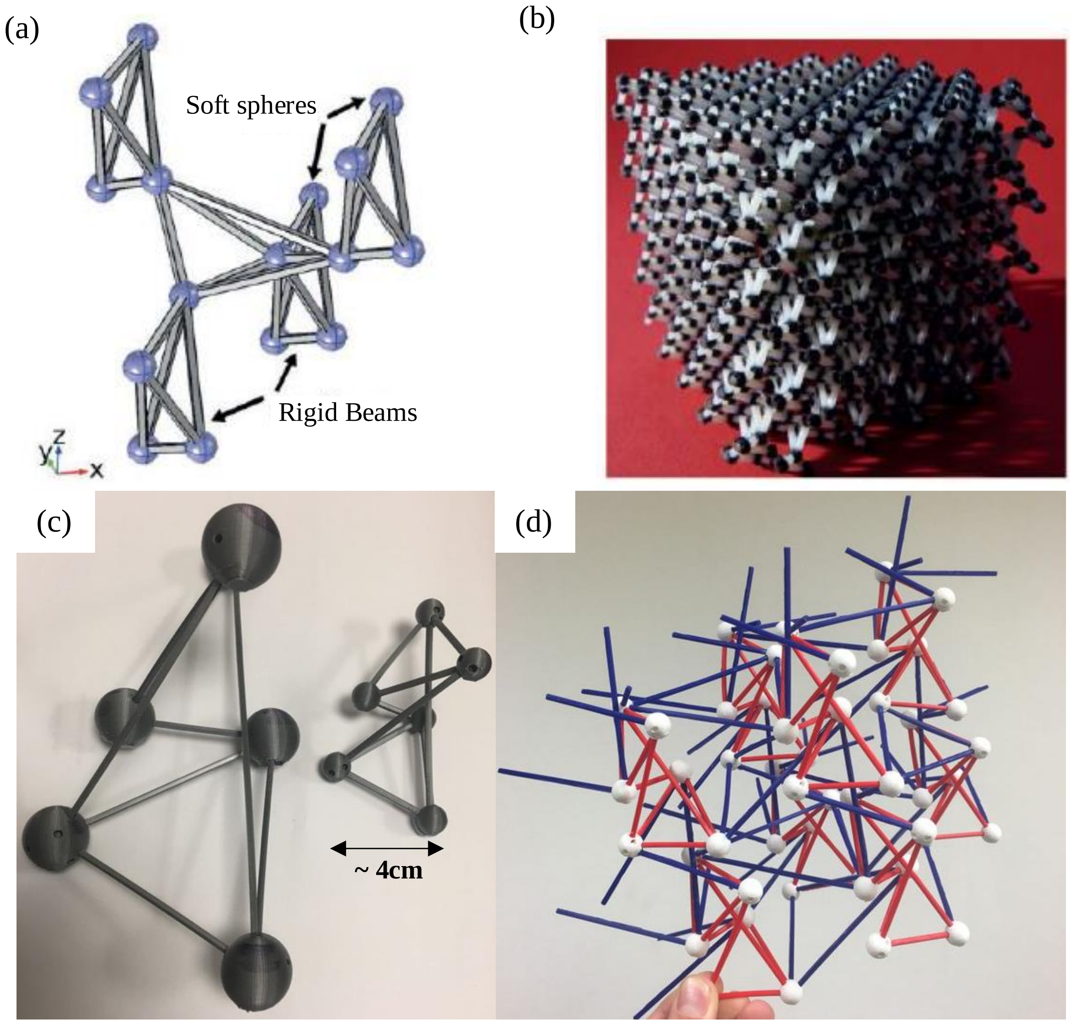

Figure 4. (a) and (b) show the design and realisation of the metamaterial model produced by Bilal respectively. (c) shows the sizes of the first 3D printed unit cell of the MTI and the second smaller unit cell where the beam positions have been shifted slightly. (d) shows a colour coded PLA model of a 2x2x2 MTI lattice. The white indicates the spheres at each lattice point, the red indicates the internal beams of each unit cell and the blue indicates external beams between unit cells (cf. figure 2(c)-(e)). (a) and (b) are adapted from [18].

PLA and TPU were to be used for the beams and spheres respectively and the PVA was to be used as a support material.

After multiple attempts, several problems were found. Firstly, before transitioning between different materials the printer must purge the nozzle of the current material. This is done by extruding it in a purge block, an area of the print bed reserved for purging the nozzle. This process takes a long time and wastes large quantities of material: up to 80% of the total print.

As well as this the motor used to feed the different filaments to the nozzle can often get jammed due to the differing hardness of each material. For example, PVA is very hard and brittle compared to TPU. This means it becomes difficult to tune the “gripping strength” of the motor. If it is too tight, the gears used to feed the materials to the nozzle will crush the TPU filament and jam but, if it is not tight enough it will be unable to grip the PVA filament. This requires the printer to be under constant supervision to rectify these issues when they occur.

Another problem with this printing method is that the angle at which objects are printed affects their strength. Previously all the rigid beams were printed flat on the print bed giving each the same stiffness in the horizontal and vertical directions. However, due to the vertical adhesion between PLA layers not being as strong as the horizontal print strength, bonds that are printed at different angles will have different rigidities. This is not ideal when printing lattice structures. As well as adhesion between a single material, adhesion between different materials can also be also problematic. FDM printing requires each layer to strongly adhere to one another or the model will fall apart as it is printed. Unfortunately, the materials being used fail to adhere well and proved that the structure could not be fabricated using this printer in this way. So, a method was devised to print the whole structure with a single material.

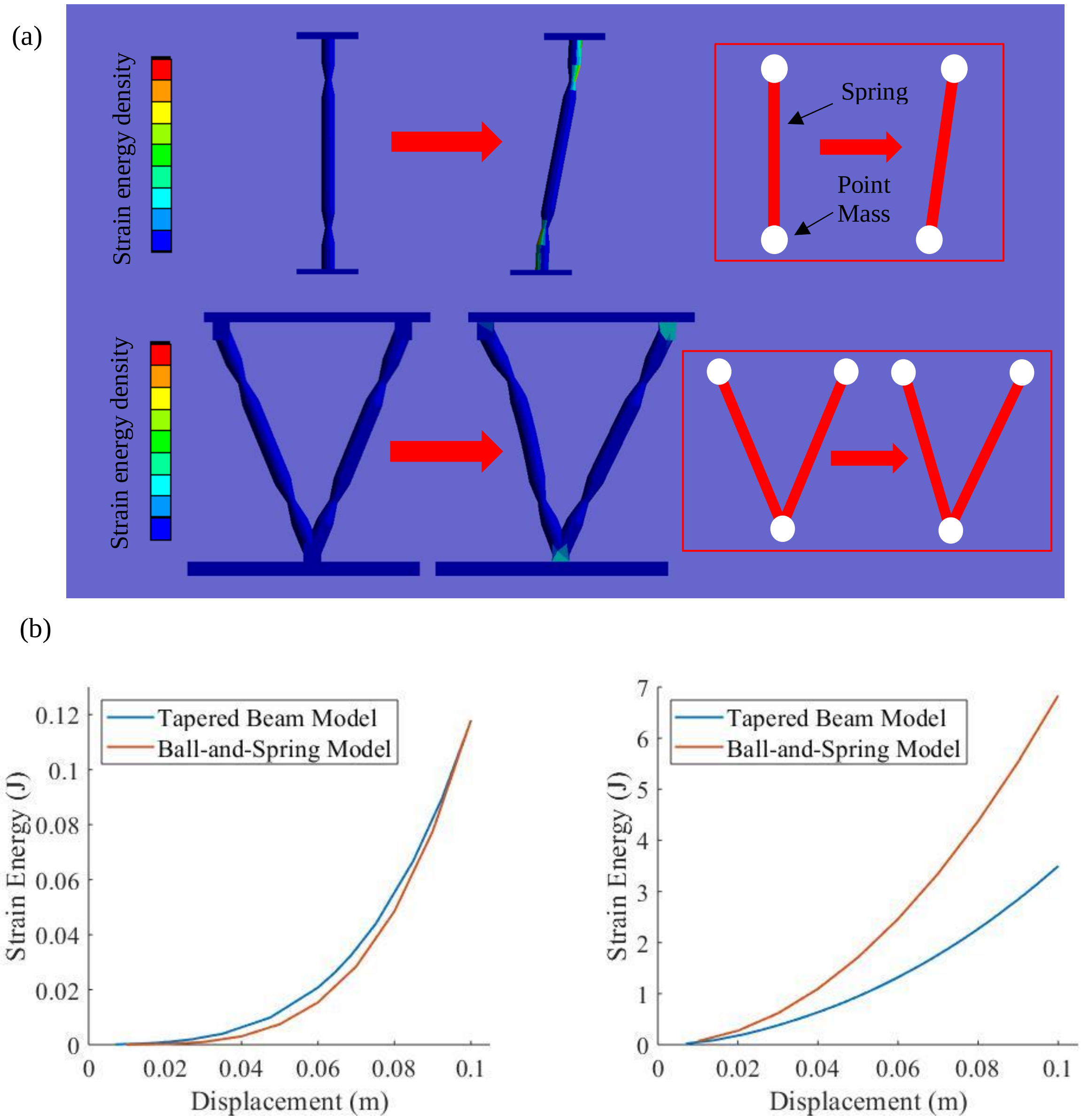

Figure 5. Figure showing the strain energy of the tapered beam design for two different models as they are deformed. (a) shows the computational simulations carried out in ANSYS using both a single beam (top) and a double beam (bottom) model. The localisation of strain energy is indicated with red being high strain energy density and blue being low. The red inserts show the ball-and-spring equivalent of each model. (b) shows a comparison between the strain energy of the modelled tapered beam design and the ideal ball-and-spring model as they are deformed. The graph on the left shows the data for the single beam model and the graph on the right shows the data for the double beam model.

3. A single material design

3.1. Tapered Beams

After some consideration, a new realisation method was developed. This method involved the use of a tapered beam design and printing the whole model and its support structure from 98A TPU. This material has excellent interlayer adhesion giving a very similar vertical and horizontal print strength and by fabricating the model out of a single material, all the issues of multi-material 3D printing mentioned previously were resolved.

The springs in the original theoretical model are replaced by beams, intersecting at the lattice nodes. The beams are tapered near the intersections to localise bending as shown in figure 5(a). Having these tapers slightly displaced from the vertices of the lattice avoids problems with intersecting beams whilst also increasing the maximum angle each beam can pivot. This better resembles the theoretical design in which the infinitesimally thin springs can pivot freely without intersecting with one another.

To test if this was a viable way of realising the ball-and-spring model, simple pivoted beam structures were modelled using the engineering simulation software ANSYS. The energy stored in these structures as they are deformed (the strain energy) was compared to ideal ball-and-spring models. This can be seen in figure 5. To effectively compare these models the spring constant used in the ball-and-spring model had to be found. To do this, a single beam simulation was used to estimate a spring constant for the ball-and-spring model. This was carried out by matching the final strain energy of the ball-and-spring model to that of the tapered design as seen in figure 5(b)(left). This spring constant was then used to compare a double beam simulation with its ball-and-spring counterpart as seen in figure 5(b)(right). This graph shows that for small deformations the models resemble one another. However, as the deformation becomes larger, the strain energy diverges, and the models stop being similar. This means that this method of realising the ball-and-spring mechanism is a good approximation for small deformations. Because of this, the tapered beam architecture was deemed to an acceptable approximation of the original design.

The OpenSCAD program was then modified to produce a model with this tapered design as seen in figure 6(a). To print this model using a single material, a new method of supporting the structure during fabrication, which could be easily removed after the print, had to be devised.

3.2. A new support method

The supports generated by PrusaSlicer, the Prusa printer's native slicer, enclose the tapered lattice structure as shown in figure 6(b). This is not a viable support method for single material printing as the main structure and supports are difficult to discern from one another. Therefore, a different support method had to be devised. To create a new form of support the CAD program Meshmixer was employed. The support generator in this program uses an algorithm to place tree-like structures on the model, as shown in figure 6(c). This allows for the generation of supports which are easily removed and material efficient. Supports were optimised by varying the overhang angle, a parameter determining how large an overhang needs to be to be supported. A single unit cell and its supports were generated and then successfully printed. This print took under 2 hours, a large reduction from the previous methods. The print was then repeated to optimise the infill parameter, a parameter that defines how

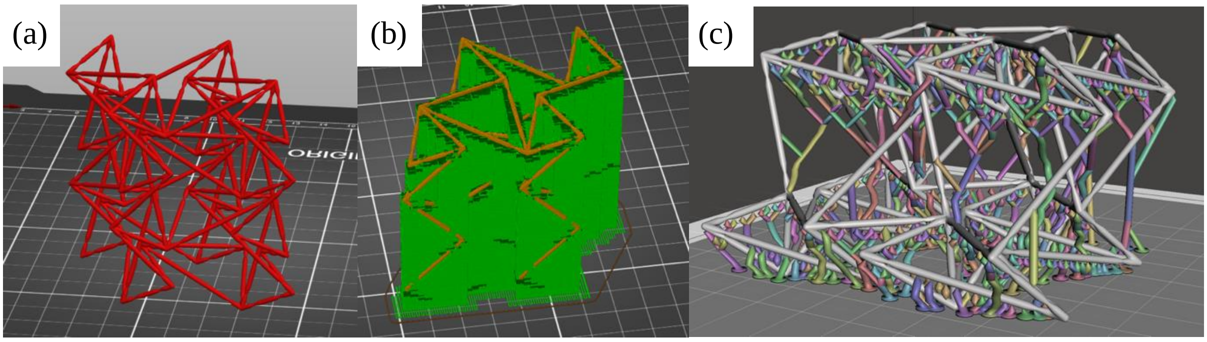

Figure 6. A figure showing a 2x2x2 lattice with tapered beams (a) and the support structures generated by PrusaSlicer (b) and Mesh-mixer (c).

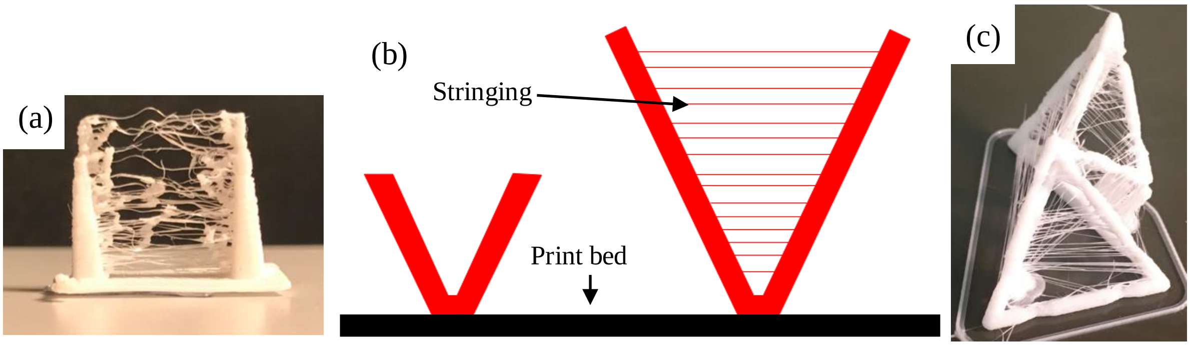

Figure 7. A figure showing stringing in 3D printing. (a) shows stringing on a 3D printed “stringing test”, a model printed to clearly display the amount of stringing created when printing. (b) shows a diagram displaying how stringing allows a print to self-support and achieve larger heights and overhangs. (c) shows a flexible unit cell printed using the hybrid support method.

much of the hollow space inside of an STL file is filled with material when printed. The ideal infill parameter was found to be 90%. Using this support method, an attempt was made to print a 2x2x2 tapered lattice. After 13 hours it was noted that the print quality had reduced considerably causing the print to fail. This was due to the tree supports providing vertical support but very little horizontal support. To overcome this problem, a little ingenuity had to be invoked by making use of a problem that plagues many 3D printers: stringing.

3.3. Stringing

Stringing is a phenomenon caused when the nozzle of the 3D printer moves from printing in one area of the print bed to another. If there is any molten material on the nozzle it will stretch it between the two locations creating a “string” as seen in figure 7(a). This is seen as a nuisance as it reduces the quality of the print and increases the amount of post-processing that must be done. This effect is especially apparent in soft materials such as TPU. This can be reduced by altering the print settings and considerable time was initially spent optimising these settings.

Despite this, it was discovered that, when printing intricate lattices, this stringing acted as a horizontal “self-support” much like tensioned ropes connecting the lattice beams to one another. By encouraging this effect prints were found to retain horizontal stability at larger heights and overhangs, as shown in figure 7(b). After a print is finished this stringing is easily removed using scissors. One advantage of using stringing for support is that, even if it cannot be completely removed in post-processing, it does not greatly impact the properties of the final structure. This is due to the strings being thin in comparison to the metamaterial structure resulting in a negligible effect on the material properties, providing the majority of them are removed.

By combining increased stringing with the tree-like supports of mesh mixer, a new support method, named “hybrid support”, was birthed as seen in figure 7(c). This provided both horizontal and vertical stability when printing and allowed for the fabrication of much larger, more detailed structures than possible using only vertical supports.

3.4 Printing an MTI

A smaller nozzle was installed on the Prusa printer with a diameter of 0.25mm. By taking advantage of the hybrid support method, this allowed the size of the unit cell to be reduced to approximately 1.5 by 1.5 by 4 cm. This reduction in size allowed for a large 4x4x2 lattice to be printed taking a total of 40 hours to print. After post-processing, this model was qualitatively tested to see if it displayed the desired SSA. As shown in figure 8, when compressed, the model displays the predicted softness properties with a clearly identifiable soft face in contrast to the opposing rigid face. This makes it the first demonstration of a realised MTI.

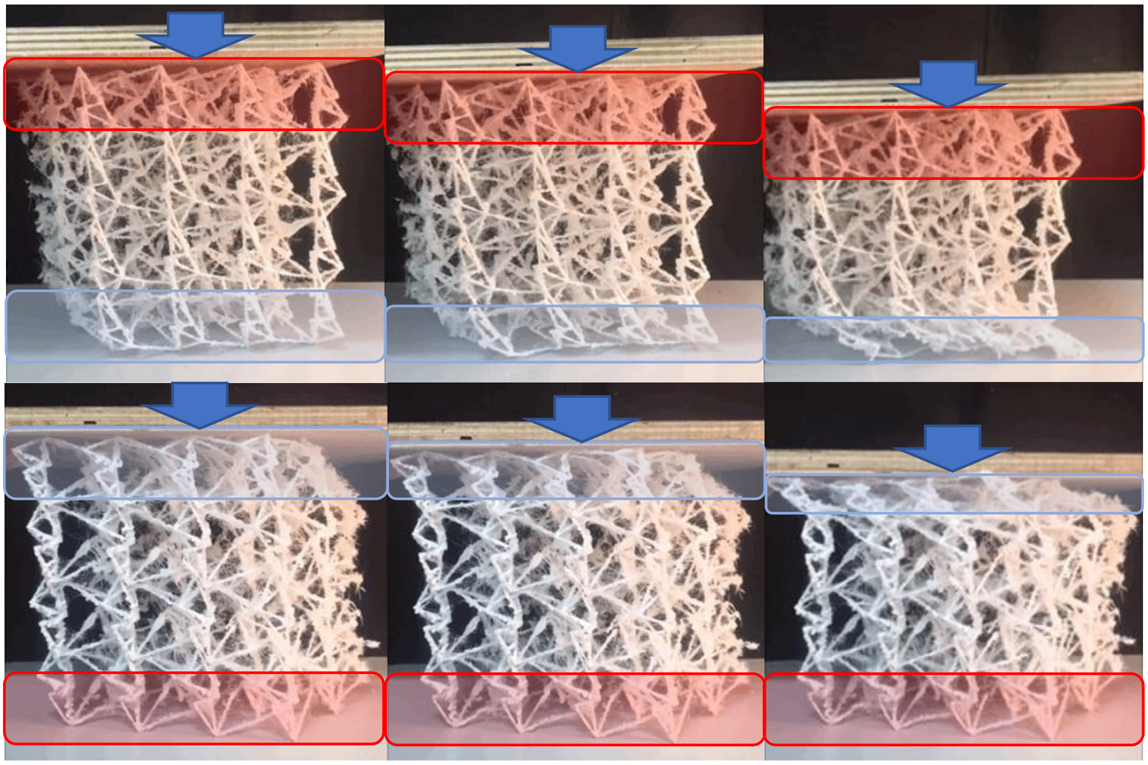

Figure 8. A figure showing a 4x4x2 MTI under compression. The soft edge (blue) can be seen to deform and the rigid edge (red) can be seen to remain stiff as pressure is applied as shown by the arrow. The top and bottom sections show the same material but inverted.

4. Discussion

By fabricating a material that correctly displays the properties predicted by a theoretical ball-and-spring model, the validity of the tapered beam design has been demonstrated. It has also been shown that, by using the developed hybrid support method, this complex, intricate design can be successfully constructed using a low-cost 3D printer.

This realisation technique has the potential to be easily and quickly adapted by researchers for other metamaterial designs. Due to the simplistic nature of the tapered beam design, it is easy to both understand and reproduce in CAD software. Very little modification to the geometry of the original ball-and-spring model is required. The spring positions are maintained and the point mass positions continue to be the vertices of the structure. This leaves the realised structure recognisable as the original design aiding the intuitive nature of the realisation process. This realisation process can also be easily modified by moving the taper position. For example, if tight angles and intersecting beams are not an issue, the tapered sections can be moved closer to the vertices giving a better approximation of the ball-and-spring design. The low cost of the realisation process allows structures to be iteratively prototyped and for modifications to metamaterial designs to be easily tested. This could help accelerate metamaterial research as it is possible for many people to access to fabrication facilities utilised in this process.

One success of the realisation process is the development of the hybrid support system. Using stringing to support a print has not been documented before and, when printing small detailed lattice structures, is extremely helpful. This support method allows for complicated, soft structures to be printed on low-cost FDM 3D printers without the need for an additional support material which was not possible beforehand. This method could be useful for printing many other lattice or mesh-like structures, not just metamaterials. By developing the hybrid support method, printing complex structures has been made more accessible as they can now be printed on more affordable 3D printers.

This method, however, also has failings. During the project, a large 4x4x4 print was attempted. Even with the hybrid support, the print failed on the third layer of unit cells. This is due to the supports being printed using a flexible material. As the height of the model is increased, this flexibility causes the stability of the supports to decrease until eventually, the print fails.

Whilst the stringing provides support for the print it can also cause a build-up of plastic around the nozzle. Whilst this was not an issue when printing the models in this report, this build up had to be carefully removed at the end of each print. There is concern that if larger prints were carried out this build-up could cause the nozzle to become clogged and the print to fail. To avoid this, the print could be paused every 24 hours to allow for the nozzle to be cleaned before resuming.

5. Looking forward

This realisation method has been shown to work qualitatively for the case of the MTI. However, in order to fully characterise the success of the method the properties of the printed model must be quantitively probed. To do this, compression testing apparatus must be used to determine the softness response of each face of the MTI. This will allow the realisation to be compared to the original model and to quantify the success of the realisation technique.

The realisation process has been shown to be successful for one ball-and-spring metamaterial design. It could now be applied to other designs to discover whether it produces the same results. A good starting point could be a previously realised metamaterial such as the example produced by Bilal [18]. This would allow the realisation techniques to be critiqued against each other.

The current method of removing the stringing utilised in the hybrid support method is simple. However, if this were to be carried out on many models it could become tedious. As a possible alternative to using scissors, a short burst of intense heat could be applied to the model. This burst of heat should be hot enough to disintegrate the stringing but short enough to leave the rest of the model intact. This alternative post-processing technique would first have to be tested and optimised before use but could increase the usability of the hybrid support method.

The hybrid support method could also be improved by further optimising the printer and support parameters. More experimentation could be carried out printing other, small lattice structures to find the optimum balance between stringing and vertical supports. This may allow taller structures to be printed without failure further increasing the impact of this new support method on low-cost 3D printing.

6. Conclusions

It has been shown that Bilal’s method of realising ball-and-spring metamaterials is not easily reproducible using a low-cost 3D printer. To overcome this a new method of realising ball-and-spring metamaterials has been developed which can be carried out on a hobbyist grade printer accessible to many academics. This allows both iterative prototyping and cost-effective experimentation due to low fabrication costs. The tapered beam design used in this method has been shown, using computational simulations, to be a suitable approximation of a ball-and-spring system. Using the new realisation process the first MTI has been fabricated and its SSA has been demonstrated exhibiting previously unseen mechanical properties. This structure is yet to be quantitively probed and doing so would allow for a more accurate understanding of the effectiveness of the realisation technique.

In the creation of the realisation technique, a new method of supporting highly detailed structures during FDM 3D printing has been developed. This allows for structures to be printed on hobbyist grade 3D printers that could not have been previously. Because of this, hybrid support could foreseeably be used to print many different detailed metamaterial designs at a low-cost not just ball-and-spring examples. There is still room for further optimisation and experimentation of hybrid support in what could be a very useful technique for the future of metamaterial fabrication.

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References

[1] Baardink G, Souslov A, Paulose J and Vitelli V 2018 Localizing softness and stress along loops in 3D topological metamaterials *Proc. Natl. Acad. Sci. U. S. A.* **115** 489–94
[2] Gatt R, Mizzi L, Azzopardi J I, Azzopardi K M, Attard D, Casha A, Briffa J and Grima J N 2015 Hierarchical auxetic mechanical metamaterials *Sci. Rep.* **5** 8395
[3] Paulose J, Chen B G G and Vitelli V 2015 Topological modes bound to dislocations in mechanical metamaterials *Nat. Phys.* **11** 153–6
[4] Paulose J, Meeussen A S and Vitelli V 2015 Selective buckling via states of self-stress in topological metamaterials *Proc. Natl. Acad. Sci. U. S. A.* **112** 7639–44
[5] Bertoldi K, Vitelli V, Christensen J and Van Hecke M 2017 Flexible mechanical metamaterials *Nat. Rev. Mater.* **2** 17066
[6] Schurig D, Mock J J, Justice B J, Cummer S A, Pendry J B, Starr A F and Smith D R 2006 Metamaterial electromagnetic cloak at microwave frequencies *Science* **314** 977–80
[7] Kadic M, Bückmann T, Schittny R and Wegener M 2013 Metamaterials beyond electromagnetism *Rep. Prog. Phys.* **76** 126501
[8] Kadic M, Bückmann T, Stenger N, Thiel M and Wegener M 2012 On the practicability of pentamode mechanical metamaterials *Appl. Phys. Lett.* **100** 191901
[9] Overvelde J T B, Shan S and Bertoldi K 2012 Compaction through buckling in 2D periodic, soft and porous structures: effect of pore shape *Adv. Mater.* **24** 2337–42
[10] Christensen J, Kadic M, Kraft O and Wegener M 2015 Vibrant times for mechanical metamaterials *MRS Commun.* **5** 453–62
[11] Sun K, Souslov A, Mao X and Lubensky T C 2012 Surface phonons, elastic response, and conformal invariance in twisted kagome lattices *Proc. Natl. Acad. Sci. U. S. A.* **109** 12369–74
[12] Schumacher C, Bickel B, Rys J, Marschner S, Daraio C and Gross M 2015 Microstructures to control elasticity in 3D printing *ACM Trans. Graph.* **34** 136
[13] Shan S, Kang S H, Raney J R, Wang P, Fang L, Candido F, Lewis J A and Bertoldi K 2015 Multistable architected materials for trapping elastic strain energy *Adv. Mater.* **27** 4296–301
[14] Song Z *et al.* 2015 Kirigami-based stretchable lithium-ion batteries *Sci. Rep.* **5** 10988
[15] Maxwell J C 1864 L. on the calculation of the equilibrium and stiffness of frames *Philos. Mag.* **27** 294–9
[16] Calladine C R 1978 Buckminster Fuller’s “tensegrity” structures and Clerk Maxwell’s rules for the construction of stiff frames *Int. J. Solids Struct.* **14** 161–72
[17] Kane C L and Lubensky T C 2014 Topological boundary modes in isostatic lattices *Nat. Phys.* **10** 39–45
[18] Bilal O R, Süsstrunk R, Daraio C and Huber S D 2017 Intrinsically polar elastic metamaterials *Adv. Mater.* **29** 1700540
[19] Godoi F C, Prakash S and Bhandari B R 2016 3d printing technologies applied for food design: status and prospects *J. Food Eng.* **179** 44–54
[20] Marchment T and Sanjayan J 2020 Mesh reinforcing method for 3D concrete printing *Automat. Constr.* **109** 102992
[21] Mironov V, Boland T, Trusk T, Forgacs G and Markwald R R 2003 Organ printing: computer-aided jet-based 3D tissue engineering *Trends Biotechnol.* **21** 157–61