The design of impact absorbing structures for additive manufacture

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Abstract. Additive manufacturing (AM) is increasingly becoming a viable manufacturing process due to dramatic advantages that it facilitates in the area of design complexity. This paper investigates the potential of additively manufactured lattice structures for the application of tailored impact absorption specifically for conformal body protection. It explores lattice cell types based on foam microstructures and assesses their suitability for impact absorption. The effect of varying the cell strut edge design is also investigated. The implications of scaling these cells up for AM are discussed as well as the design issues regarding the handling of geometric complexity and the requirement for body conformity. The suitability of AM materials for this application is also discussed.

1. Introduction

This paper details work on the design of lattice structures for energy absorbing applications as well as methods to conform them, with the ultimate aim of manufacturing body protection tailored to an individual’s body. The complexity of such parts means that Additive Manufacturing (AM) is likely to be one of the few processes that can realise these designs.

1.1. The potential of AM lattice structures in conformal body protection

The geometric freedom afforded by additive manufacturing processes allows the design of products of a complexity not achievable through any other means [1]. Without the need for physical tooling (such as the moulds used in injection moulding or the machine tool used in CNC machining) a product does not need to be designed with compromises to facilitate removal from the tooling. Parts of previously unattainable complexity can be fabricated through AM, utilising the complexity to consolidate assemblies into the minimum number of necessary components, or building assemblies of parts when necessary. Weight and size can be minimised, and products can be designed purely with function in mind [1].

Although covering a wide range of technologies, AM processes are united through the method in which parts are built: material is deposited, fused or cured in a succession of two dimensional slices, stacked and combined with the layer below to form a three dimensional shape. As AM parts are fabricated layer-by-layer, the material deposition mechanism (such as a print head, nozzle or directed laser) never encroaches on the part as it is being built. One particularly novel avenue that is opened by this is the fabrication of lattice structures, with physical properties that can be tuned to a particular application. Lattice structures as defined by this work are a tessellation of a unit cell, itself composed.
of struts, as shown in figure 1. When a lattice structure is deformed in some way to fit a shape, it is then termed a conformal lattice structure.

![Figure 1. Naming conventions for a conformal lattice structure.](image)

By utilizing body scan data of an individual’s body, personalized body-fitting apparel can be designed. Personal protective equipment (PPE) used in sport in particular is an area that tailored lattice structures could be of use, and were the driving force behind the work detailed in this paper.

1.2. Suitability of AM processes for conformal body protection

The materials available for processing in AM are currently fairly limited and are specific to each AM process. It was determined that due to the relative strength and resilience of the range of polymers available, laser sintering would be the process used to build conformal lattice structures for this application. Laser sintering uses a reflected laser to selectively fuse layers of powdered material together. The part is supported by the surrounding un-sintered powder as it is being built, which is removed once the build is finished with a compressed air source, shot blast or water bath. This support mechanism is also advantageous to lattice structures; most other AM processes require an actual support structure to be built alongside the part, which would be difficult and time-consuming to remove from a lattice structure.

2. The design of conformal energy absorbing AM lattice structures

Conventional materials were first investigated as a basis for the design of AM lattice structures. As the most commonly used material in energy absorbing applications, polymeric foams in particular were the focus of study.

2.1. The structure of foam

Foams are suited to absorbing energy due to a low density, cellular structure that deforms readily under load [2]. There are two broad categories of foam: open cell and closed cell. A closed cell structure consists of walls and struts, forming isolated cells of gas, while an open-cell structure consists solely of struts. Open cell foam absorbs energy through strut buckling and the work done in pushing air out of the weaving structure. Closed cell foams absorb energy through strut buckling, cell wall bending and the compression of trapped gas. Foams generally undergo compressive behavior of three regimes. Initially, the foam exhibits a linear elastic region where very little energy is absorbed. A wide plateau region follows, with a densification phase where stress rises steeply [2].

During the manufacture of foams, the foaming process generates a three-dimensional cellular structure that is controlled by the principle of minimal surface energy [2,3]. Thomson (later Lord Kelvin), investigating the minimum surface qualities of aqueous foams, developed a repeatable unit cell for a perfectly ordered, regular foam. This later became known as the ‘Kelvin cell’. The Kelvin cell is a modified truncated octahedron (a polyhedron composed of six square and eight hexagonal faces) and has been used extensively more recently in simulations of foam behavior [4-7].
2.2. Implications of scale

While foams can consist of individual cells less than a millimetre in diameter, a key constraint of current laser sintering technology is resolution. Laser sintering is limited to a minimum feature size of 0.4mm [8]. In terms of lattice structure design, this means that practically the smallest feasible strut diameter imposed is 0.4mm. With this as a consideration, cell diameter must be roughly an order a magnitude higher than strut diameter, making minimum cell diameters in the order of 5 to 10mm. Another constraint of laser sintering is the removal of un-sintered powder after fabrication. The lattice structure design must facilitate this. For a structure inspired by foams, only an open cell foam could be replicated by AM.

As Closed-cell structures cannot be manufactured, the bending of cell walls and compression of trapped air that contribute to energy absorption in closed-cell foams cannot be replicated. Also, the scale possible in AM is an order of magnitude higher than the micro-scale of conventional foam cellular structure. Air flow will not be significantly impeded by an AM structure at the macro scale like a micro-scale foam, so will not contribute to energy absorption to any useful level. This leaves cell strut bending as the only remaining mechanism for energy absorption in an AM lattice structure.

2.3. AM lattice structure designs

As a regular representation of the cellular structure of foam, the Kelvin cell makes a promising candidate for the basis of energy absorbent AM lattice structures. Two such designs are shown in figures 2 and 3. The first is a straight strut, triangular cross-section design, with fillets between the nodes to imitate the natural structure of foam. Both have a cell diameter of 15mm, and at two cells thick are approximately 30mm in height (geometric features of the struts slightly increase overall height). Five samples of the first design were manufactured in a blend of 50% virgin / 50% recycled PA 2200 material (nylon-12) from EOS on a Formiga P100 laser sintering machine.

![Figure 2. Straight strut structure (inset: SEM image of open cell polymeric foam [6])](image1)

![Figure 3. Helical strut structure (inset: helical strut)](image2)

When compressed, the samples exhibited the characteristic three stage compression seen in foams. Samples were compressed on an Instron 3366 Dual Column Testing System at a strain rate of 100mm/min. Figure 4 shows an initial linear increase in stress as the samples were compressed (A), followed by a wide plateau observed (B) before another sharp increase as the structure compresses to the point that struts start to make contact with each other (C).
Taking advantage of the geometric freedom that AM provides, the second design was augmented with helical struts. The helix is constrained to a ‘law curve’ that reduces the radius of the helix to zero at each end. This allows helical struts to connect without intersecting each other. The reasoning behind this helical design was that increasing the overall length of each strut would allow more deformation within the structure (both for struts in tension and compression) and thus increase energy absorption.

As shown in figure 5, the helical strut samples exhibited a different compressive response to the straight strut samples. A two stage compression is apparent, an approximately linear region (A) followed by a steep densification region (B) where stress quickly rises. Again, this is due to struts starting to make contact. The helical struts store or absorb more energy than the straight strut alternative, but due to the more bulky design, the densification stage starts slightly earlier (at around 70% strain rather than 75%).

3. Conformal methods for fitting a lattice structure to the human body

There are several methods that have been identified of fitting a structure to shape, i.e. generating a conformal structure. Two dimensional examples of these methods are shown in figure 6 for comparison.
The ‘trimming method’ trims or cuts a regular tessellation to fit a particular conformal shape. The structure retains its orientation, and only the cells at the boundary of the structure are affected by the conformal method. Mullen *et al* use trimming to generate lattice structures for medical applications [9]. A structure can be trimmed to any shape, although there is no guarantee that the result will be useable. The ‘sweeping method’ deforms a structure to follow a surface of the conformal shape and as such is only suitable for use on sheet-like shapes, as used by Chu *et al* [10]. Mesh-based methods are a two-step process where a finite element meshing algorithm is used to generate a volumetric mesh of, for example, tetrahedral elements. This mesh is used as a skeleton to map lattice structure struts to (for example, see Gervasi *et al* [11]). Although a robust method, the structure will usually exhibit variation in cell size and shape. Finally, a randomised structure can be applied to a conformal shape, such as a 3D Voronoi tessellation. However at the macroscopic scale that cellular structures can be replicated by current laser sintering technology, the ratio between cell size and part size is such that a randomised structure only serves to randomise its properties.

Each of these methods deform a structure in some way to fit a conformal shape. The sweeping and mesh-based methods consider the surface of the conformal shape as the basis of the structure generation, and 'fill in' the volume with a warped structure. As a result, these methods form 'closed' structures of intact (but varied) cells. In contrast, the trimming method populates a volume with structure and cuts it to fit the surface of the conformal shape. This results in a perfectly regular structure with 'open' and incomplete cells at the boundary.

The trimming method is compatible with any three dimensional tessellation. With this greater variety of tessellations brings a wider range of structure types, each with potentially different physical properties when manufactured. The trimming method is the most viable method of conforming a structure to a shape as it is robust and flexible.

### 3.1. Skinning a conformal structure

The main disadvantage of the trimming method is that the boundary regions of the structure are weakened where cells have been cut. A common method of strengthening the boundary of a trimmed structure is to wrap the structure (or a portion of the structure) with a sheet of solid material, commonly termed a ‘skin’. This is shown in figure 7. A solid skin such as this can also provide some added rigidity for a lattice structure in weight-saving applications, and may provide some useful spreading of an impact in an energy absorbing role, but a different type of skin was developed by the authors to retain the flexibility of an energy absorbing structure. This skin type was termed a ‘net skin’ and is also shown in figure 6. Unlike a solid skin, the topology of a net skin is defined by the underlying lattice structure; cut cells are connected with skin struts to reconnect trimmed struts.
4. Handling geometric complexity

Additive manufacturing allows the fabrication of complex lattice structures, however conventional computer aided design (CAD) software becomes a limiting factor to size and complexity. Conventional CAD utilises a method of boundary-representation (b-rep) to represent three-dimensional geometry [12]. ‘Solid’ models are actually represented as a ‘watertight’ shell of zero-thickness surfaces. If the model is not watertight, it is usually not possible to tell what is ‘inside’ and ‘outside’, making the part a challenging proposition to manufacture.

While this is an elegant way to represent conventional products or components, this model structure is not suited to representing lattice structures. A single strut may only be comprised of a few surfaces, but even a moderately sized lattice structure of a few thousand struts becomes so computationally demanding that it makes the use of b-rep unfeasible. Additionally, the sheer number of struts increases the risk of non-manifold errors occurring; gaps between polygons or intersecting or overlapping polygons can compromise the watertight boundary [12].

Other geometry representation methods have been investigated for the fabrication of lattice structures. Voxels – a 3D analogy to pixels – are a volume representation that describes a model as a series of discrete cubes [13]. Function representation, developed by Pasko et al uses functions to implicitly describe geometry and has been used to great effect to represent a range of lattice structures [14].

Slice files represent a model as a sequence of 2D cross-sections and are used by AM processes to build parts. A CAD model must be converted to a slice file as this is the format that an AM machine reads data. Each slice of the model corresponds to a built layer. A novel method developed by the authors processes slice files to generate trimmed structures on a layer by layer basis. This is both a less computationally expensive method of generating trimmed geometry and also forgoes any need for further format conversions required by other geometry representations. A concept conformal chest protector designed by the author and built through the process developed is shown in figure 8. As well as a net skin, it contains in excess of 50,000 helical struts.

Figure 8. Chest protector concept

Figure 9. Functionally graded structures
The method developed also allows for functionally graded lattice structures, where structure geometry varies across the part. The base tessellation must remain the same, as one tessellation cannot morph into another without severe warping, but strut geometry can be varied as required. Example layers of functionally graded structures are shown in figure 9.

5. Conclusions
A methodology for generating conformal lattice structures based on the structure of polymeric foams has been discussed. The preliminary tests discussed in this paper have shown that AM lattice structures can be designed to exhibit similar compressive properties as conventional foams, as well as the ability to dramatically transform the compressive response by taking advantage of the geometric complexity AM affords. The tests conducted do not replicate an environment for sports PPE. A combination of both limited material options for laser sintering and the absence of many of the mechanisms of energy absorption available in foams mean that the energy absorption capabilities of the structures are limited. However, the tests do show the potential for tailored lattice structures, and as materials and processes improve so too will the potential for energy absorbent AM lattice structures.

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