Impact Absorbent Rapid Manufactured Structures (IARMS)

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Abstract

Rapid Manufacturing (RM) is increasingly becoming a viable manufacturing process due to dramatic advantages that it facilitates in the area of design complexity. Through the exploration of the design freedom afforded by RM, this paper introduces the concept and initial research surrounding Impact Absorbent Rapid Manufactured Structures (IARMS), with an application in sports personal protective equipment (PPE). Designs are based on the cellular structure of foams; the inherent advantages of the cellular structure are used as a basis to create IARMS that have the potential to be optimised for a specific impact absorbent response. The paper provides some initial results from compression testing.

Introduction

PPE is used in many sports to reduce the risk of injury to the athlete or player. Conventional PPE can be cumbersome and ill-fitting as the design is limited by their manufacturing processes. There is a need for customisation for the individual athlete to take into account variations in body size and shape; this not only serves to reduce potential injuries but also improve player performance. Utilising the design freedom and geometric complexity of Rapid Manufacturing (RM) techniques, the project aims to create customised PPE that is not only optimised for the specific impact forces and velocities involved within a particular sport but also the overall weight, flexibility and comfort perception of the PPE garment.

The Scuta Project

The research documented within this paper was conducted under an EPSRC/IMCRC funded Integrated Project conducted at Loughborough University; Tailored Injury Prevention & Performance Improvement for Protective Sports Garments (known as Scuta) [1]. The overall project aims are the optimisation and customisation of Personal Protective Equipment (PPE) utilising Rapid Manufacturing (RM) techniques for a number of test-case contact and ball sports: Tae kwon-do, Cricket and Association Football.

Within Scuta, Work Package 4 (WP4): *The Generation of 3D Conformal Data* is investigating both the specific design of IARMS and potential modelling strategies that allow the generation of conformal and body-fitting RM PPE to be realised. The work packages contained within the integrated project are responsible for investigating related issues as follows [1]:

* Work for this paper was undertaken at Loughborough University, however this author has now taken a position within the School of Art & Design, De Montfort University, Leicestershire, UK

WP1: *Determining Human-Related Impact Intensity During Contact Sports*
WP2: *Perception & Comfort of Personal Protective Equipment*
WP3: *Advanced Modelling of Personal Protective Equipment for Sports*
WP4: *The Generation of 3D Conformal Data*
WP5: *Materials Analysis*
WP6: *Instrumentation & Validation*

The research documented within this paper concentrates on the initial design and compression testing of IARMS manufactured using the Laser Sintering process. The Computer Aided Design (CAD) work was completed using NX5 and Magics.

Application and Aim of IARMS Design

The Tae kwon-do chest protector (known as a hogu) has been selected as an application to focus research. Tae kwon-do is a martial art that employs punches and kicks, with kicking accounting for 80% of strikes [2]. Kicks can be broadly characterised as swing or thrust kicks, delivering high-speed impacts to a contestant over the course of a match [2]. The aim for IARMS designs in development is to generate personalised, resilient structures tailored to this environment.

Design Research

WP5: *Materials Analysis* is responsible for investigating and developing new impact absorbent materials suitable for both additive manufacturing techniques and the actual manufacture of IARMS. However, as this research is being conducted concurrently, an initial constraint for IARMS design is the utilisation of commercially available materials. Given this initial design constraint, the design research has been directed at utilising the geometric freedom afforded by additive manufacture to provide the impact absorbent characteristics required, rather than the actual physical properties of the build material. To aid this design process, existing conventional impact absorbent materials, specifically foams, have been investigated.

Structure of Foam

A wide range of materials are utilised in engineering applications for impact absorption. In personal protection (e.g.: impact absorbing PPE) and product protection (e.g.: packaging), polymeric foams dominate the market [3]. The favourable impact characteristics of foam are derived mainly from its cellular structure which is classified as either open or closed-cell. A closed-cell structure consists of walls and struts, forming isolated cells of gas. An open-cell structure consists solely of struts – during manufacture, the cell walls formed between nucleating bubbles are pierced and shrink into the forming struts. This creates a structure where a fluid (ie: air) can flow freely through it [3]. Examples of open and closed-cell foam are shown in Figure 1.

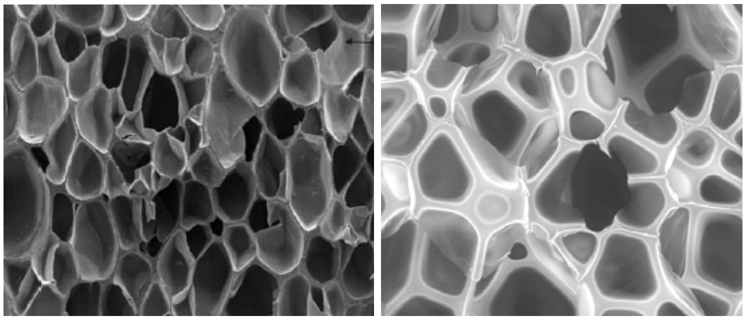


Figure 1: SEM photographs of open-cell (left) and closed-cell (right) structure of foam [3,6]

Compressive Behaviour of Foam

Foams are particularly good at dissipating the energy and reducing the peak force of an impact due to their low density, elastically deforming structure. The cellular structure also lends itself well to absorbing oblique impacts [3]. Foams have a characteristic three-regime compressive behaviour, shown schematically in Figure 2. 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 [4]. The energy absorbed by a foam, per unit volume is shown by the area under the curve in Figure 2. In regards to flexible foams, the manner in which energy is 'absorbed' in the elastic stages of compression is in potential energy stored by deforming the structure.

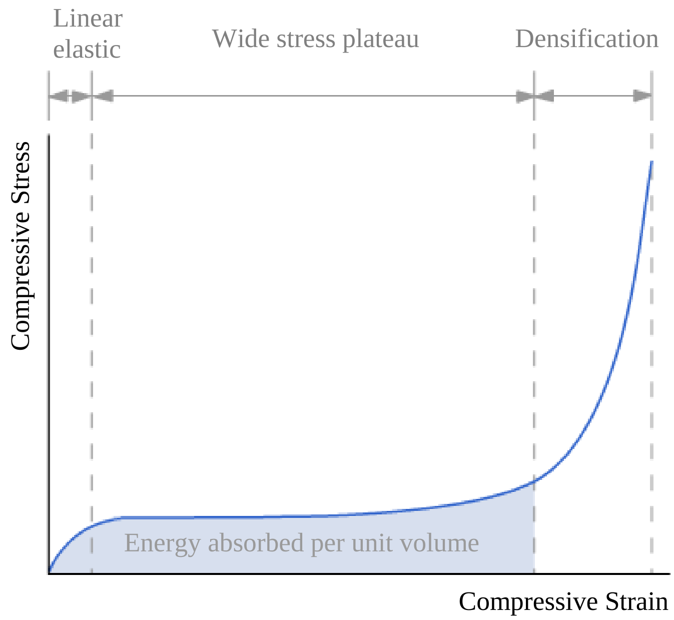


Figure 2 – Characteristic compressive behaviour of flexible foam (based on a diagram from [5])

The 'wide stress plateau' illustrated in Figure 2 is a characteristic of foams; the reason why they make such good energy absorbers. It is a stage of elastic, localised collapse where weaknesses in the structure buckle [6]. Further deformations will spread from these localised areas until the foam is completely compressed. The final regime of compression sees significant stiffening of the foam in a phase known as densification [6]. This stage is where plastic deformation of the foam occurs, reducing its capacity to absorb subsequent impacts. Cells have completely collapsed and the struts of the structure are compressed into contact. The structure now more closely approximates the properties of a solid block.

In open-cell foams, energy is absorbed through the bending of the structure's struts. Closed-cell foams will generally absorb higher impacts as compression of the gas trapped inside cells will contribute to its energy absorption mechanisms [7]. An ideal foam would have a stress plateau that ended at the maximum impact stress associated with the application [3]. The foam would not reach the densification phase during normal operating conditions. This would ensure that the product did not suffer fatigue, but it would also ensure that minimal impact energy is transferred to the object that it is protecting.

This criterion can be transferred to the design of tailored IARMS. The cellular structure of foam is a suitable starting point for the design of IARMS as it has been shown to be a fine energy absorber. The irregular structure of foam is difficult to replicate in the design of IARMS, so a simplification of the structure has been applied using a model known as the Kelvin structure.

The Kelvin Structure

The foaming process generates a three-dimensional cellular structure that is controlled by the principle of minimal surface energy [8]. Kelvin proposed a body-centred cubic lattice of a 14-faced polyhedral cell as a representation of an idealised foam structure [9]. The Kelvin structure is based on a modified truncated octahedron (a polyhedron composed of six square and eight hexagonal faces): the hexagonal faces have zero mean curvature, while the square faces are flat with outwardly curved edges, as illustrated in Figure 3.

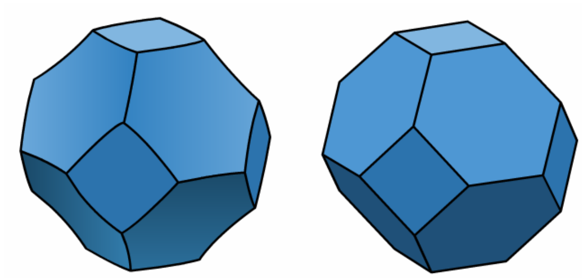


Figure 3 - A Kelvin cell (with curved faces) and the planar-faced truncated octahedron it is based on

The Kelvin structure has since been used as the basis for finite element analyses (FEA) of foam structures to better understand the relationship between structure and properties [10, 11, 12]. Although originally proposed as a model of the minimal surface energies characteristic of foams, the Kelvin structure has been shown to be a good model of its mechanical properties [10, 11, 12] and thus shows promise as the base for the design of IARMS.

Initial IARMS Design

The Kelvin structure is comprised of large, compressible polyhedra. Due the open, low relative density of the structure, it can be compressed to high percentage strains before structural elements come into contact. An open-cell structure has been adopted to facilitate the removal of un-sintered powder from samples created. The wide angles between meeting struts means the ‘node’ between them needs only be the same diameter as the struts. Minimising the node allows the structure increased compressibility; large nodes in structures like this are generally solid and reduce the structure’s compressibility. Using the Kelvin structure as a base, different geometries can be applied to it to generate a range of designs; one such design has been named the 'straight strut' design, as illustrated in Figure 4.

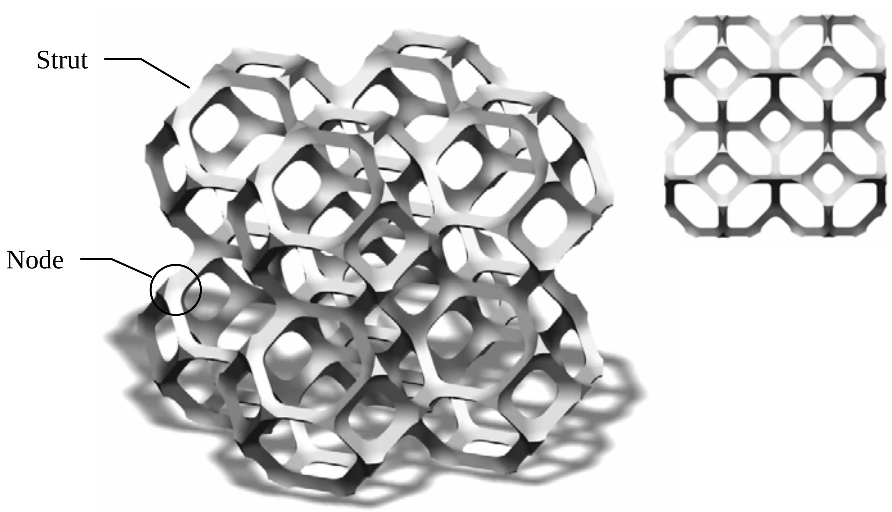


Figure 4 - 'Straight strut' IARMS design

A primary purpose of this design is the minimisation of file size. Minimal polygons required to represent struts to facilitate the generation of physically large structures. Each strut is essentially a triangular prism and is represented by twelve polygons in an .stl file, as illustrated in Figure 5. This compares very favourably to the number of polygons required to represent a cylinder (also illustrated in Figure 5) and significantly reduces file size.

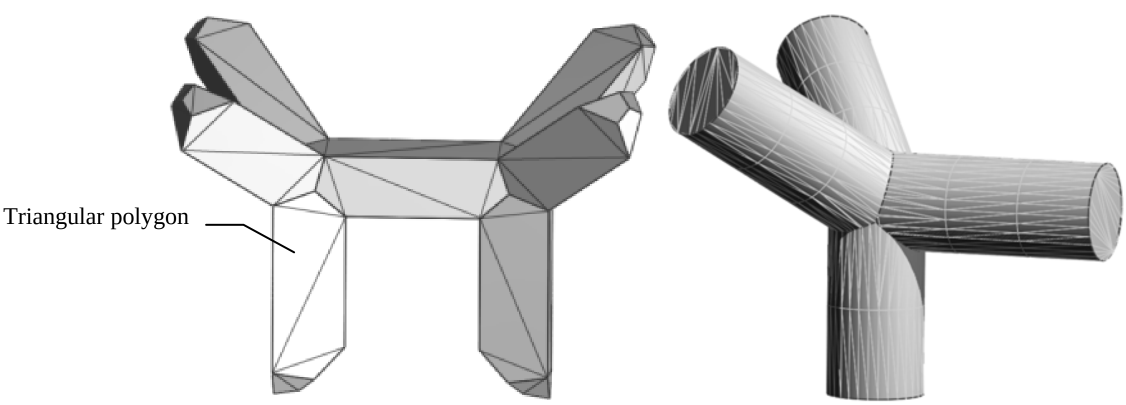


Figure 5 – Polygon representation of strut geometries

Each node of the structure has fillets applied to it to reduce the chance of crack formation, although the fillets can be removed. The addition of a set of fillets at each node does significantly increase the polygon count of the structure, although compared to that of a strut of circular cross-section the polygon count is still favourable.

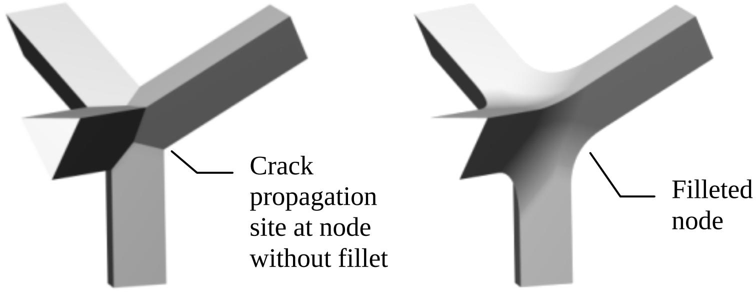


Figure 6 – Fillets applied to a node

By applying a more complex helix geometry to the Kelvin structure, a more flexible IARMS design is created. The 'helical strut' design is illustrated in Figure 7. The higher geometric complexity in comparison to the straight strut design significantly increases the .stl file size. The profile of the helix that comprises the strut follows a law curve, as shown in Figure 7. This allows multiple struts to meet at a node, ensuring contact only at the node.

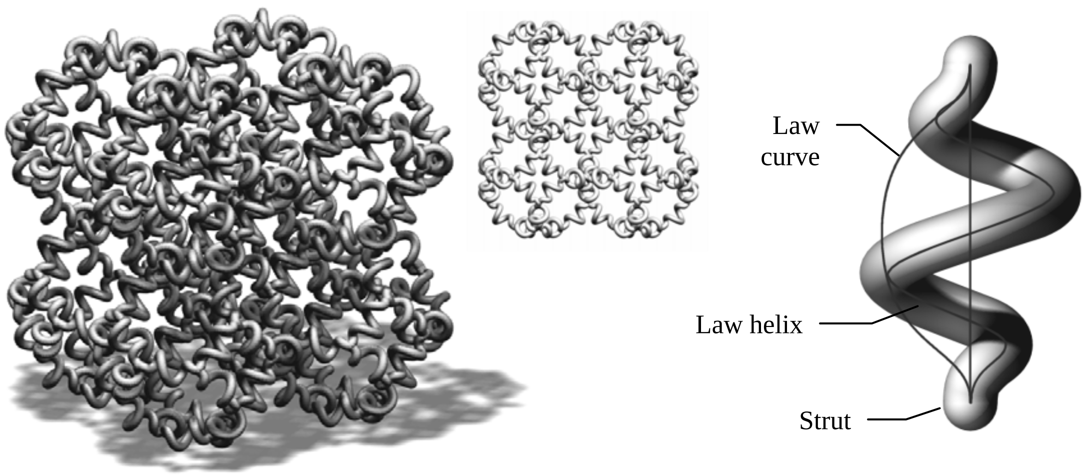
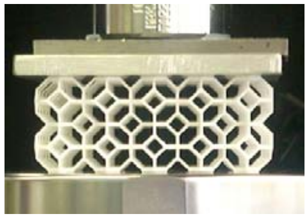
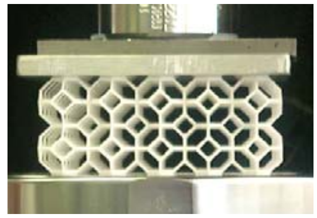
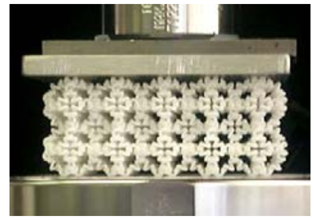


Figure 7 - 'Helical strut' IARMS design

Compression Testing of IARMS

Initial compression tests have been conducted on the two variants of the IARMS design, summarised in Table 1. Each variant was manufactured in a blend of 50% virgin/50% recycled PA 2200 material from EOS on a Formiga 100P, although for comparison, a set of straight strut samples were also manufactured in Duraform EX on a Vanguard with HiQ upgrade. Due to the unknown properties of these newly developed structures, low-rate compression tests were conducted on samples, rather than high-rate impact tests more representative of Tae kwon-do strikes.

Design Variant	Straight strut	Straight strut	Helical strut
Machine/ Material	Vanguard with HiQ upgrade / Duraform EX	Formiga 100P / PA 2200	Formiga 100P / PA 2200
No. of Samples Manufactured	5	5	5
.stl File Size	0.88 MB	0.88 MB	26.50 MB
Sample Dimensions	75 x 75 x 30mm	75 x 75 x 30mm	75 x 75 x 30mm
Compressive Extension	25mm	25mm	25mm
Strain Rate	100mm/min	100mm/min	100mm/min

Table 1 – Compression samples

Methodology

The IARMS samples were compressed on an Instron 3366 Dual Column Testing System at a strain rate of 100mm/min. Tests were controlled by extension and the load measured because the compressive strength of the structures were unknown. The test setup is shown in Figure 8 and summarised in Table 1.

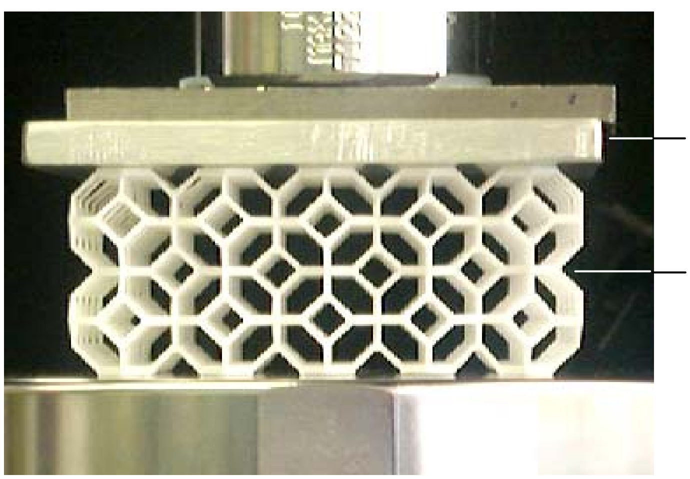


Figure 8 – Flat sample compression test setup

Each 30mm thick sample was compressed by 25mm once and the reaction force measured. From this, the compressive stress and compressive strain was calculated and plotted.

Results

Compressive Behaviour of the Straight Strut Designs

The three regimes of compression that are commonly associated with foam have been observed in the compression of the straight strut samples. As shown in Figure 9, the Duraform EX straight strut samples exhibit an initial, linear elastic response until approximately 15% strain when the structure softens. The structures deform significantly across a wide stress plateau with relatively minimal exertion. Finally, at around 75% strain the samples stiffen considerably as the struts that compose the structure come into contact during densification. This is where the peak stresses of these samples occur, between 25 and 30kPa.

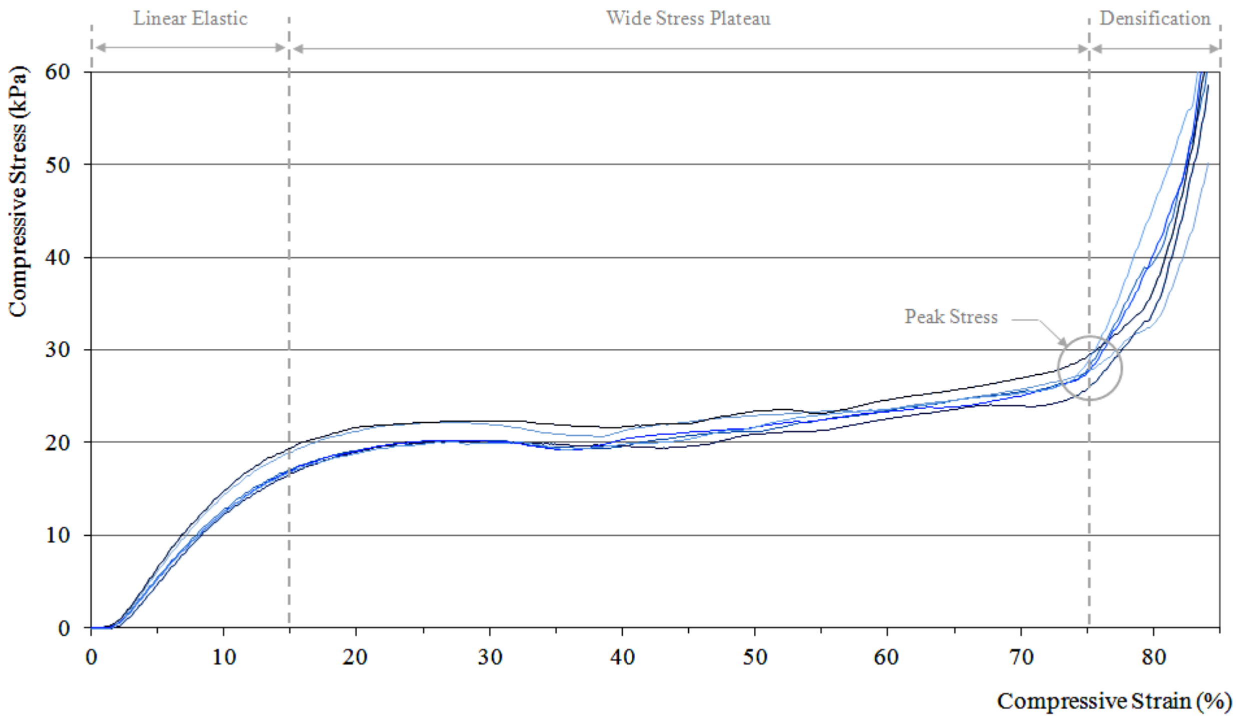


Figure 9 – Compressive response of straight strut samples (Duraform EX)

The PA 2200 straight strut samples exhibit a very similar compressive behaviour, shown in Figure 10. There is a greater variation between PA 2200 samples, however they perform similarly to the Duraform EX samples. Both sets of samples plateau at around 10 to 15% strain, with a compressive stress around 15kPa. Both sets of samples increase in stiffness as they enter the densification stage between 70 and 75% strain. The range of peak stresses of the PA 2200 samples is slightly lower than that of the Duraform EX samples, with the exception of one anomalous sample shown with a dashed curve in Figure 10.

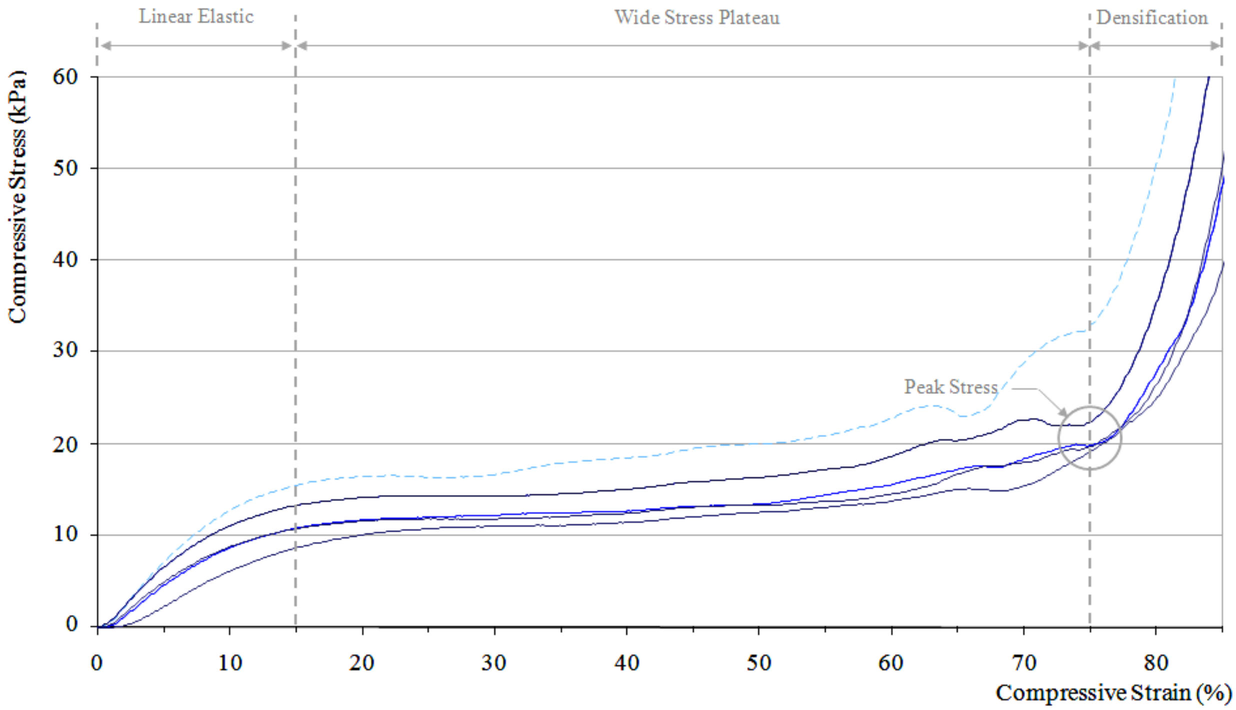


Figure 10 – Compressive response of straight strut samples (PA 2200)

It is during the densification stage that plastic deformation of the samples' structure begins to occur. The samples do not return to their original height, as shown in Figure 11. Plastic hinges have formed at the nodes of the structure, creating a largely regular deformation pattern throughout it. Figure 11 clearly shows that the plastic deformation has occurred at the nodes rather than in the struts, which remain relatively straight as the structure compresses. Some fracturing occurs around the nodes within the structure; struts have failed where the fillets on the nodes finish. The level of actual fracturing within the structure is minimal and is not a significant cause of the structure's loss of resilience.

Figure 11 – Compression of a straight strut sample

Compressive Behaviour of the Helical Strut Design

A different compressive behaviour is observed of the helical strut sample. The helical structure exhibits potentially linear stiffness, replacing the first two regimes of compression found with the straight strut samples, with a densification stage beginning at approximately 70% strain. This is shown in Figure 12.

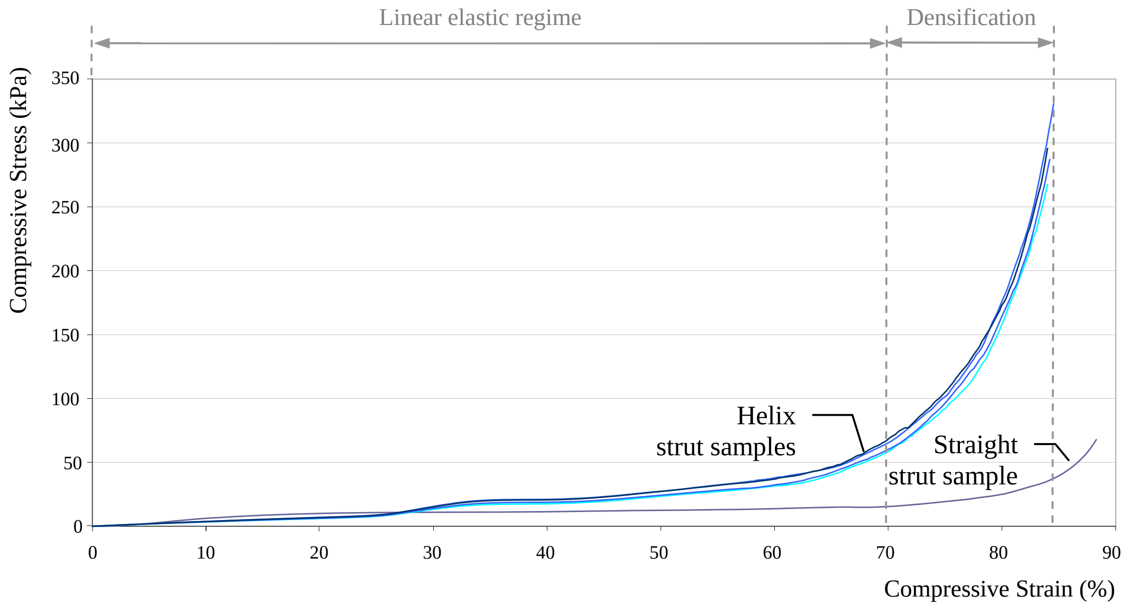


Figure 12 – Compressive response of helical strut sample, with the straight strut response shown for comparison

Densification in the helical strut samples occurs earlier than in the straight strut samples because the helical geometry of the struts make contact earlier than the straight struts.

Figure 13- Compression of a helical strut sample

This particular helical strut design absorbs significantly more energy than the straight strut design, an example shown in Figure 12 for comparison. The helical strut design did not recover to full height; as with the straight strut samples some plastic deformation occurred. It is less obvious where plastic hinges have formed throughout the helical strut samples due to the complexity of the structures.

Conclusions and Further Work

The research documented in this paper shows through physical testing that the Kelvin structure does approximate the compressive behaviour of flexible foams. The two structure designs tested exhibit very different properties. The straight strut samples exhibit a compressive response similar to that of conventional foams, with the characteristic three regimes of compression. By inserting a different strut geometry into the structure, a completely different compressive behaviour is observed; the helical strut sample displays a two regime compression; a linear elastic phase followed by densification. The helical strut sample absorbs significantly more energy than the straight strut design.

A major limitation in the generation of lattice structures (such as IARMS) for Rapid Manufacture are the file sizes required to represent them. Although the helical strut design is more resilient than the straight strut design, its .stl file is thirty times larger. It is currently unfeasible to generate a structure large enough to form a Tae kwon-do hogu or similar PPE of the helical strut design with conventional CAD. Additionally, the designs discussed in this paper are not capable of withstanding the forces associated with Tae kwon-do at this point. Designing a strut geometry with properties exceeding that of the helical strut design but with a minimised .stl file size is a key focus of this ongoing research.

The samples tested in this study have not been optimised for any particular environment – altering the strut parameters of the designs will effect the structure's compressive behaviour. A parametric study will be conducted to identify what these effects are and the design of other strut geometries is ongoing. The results suggest that it should be possible to tailor IARMS to specific applications, through the selection of optimised parameters. Additionally, strut parameters or designs could be varied throughout a structure to create functionally graded garments. Although they underwent some plastic deformation, i.e. they did not reform back to their original shape after compression, the samples did not break into pieces. With optimisation, these structures could potentially be much more resilient.

The loading rates applied to the samples in these compression tests are not representative of the impacts associated with Tae kwon-do. Further tests must be conducted in more representative conditions to determine the effects of strain rate on the structures' compressive behaviour. To generate conformal IARMS, a means to create body-fitting garments is being investigated. Although not covered in this paper, a key aspect of this research is the development of a modelling methodology to generate conformal samples of the structure that will fit to the curves of an individual's body.

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