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Citation:

URQUHART, Simon, CARTER, Emma, PLANT, Harry and DUNCAN, Oliver (2026). Application of Mechanical Metamaterials for Head Impact Protection in Recreational Snowsports. In: ISEA Sports Engineering Conference, Washington State University, 1 Jun 2026 - 4 Jun 2026. Washington Statue University, p. 1. [Conference or Workshop Item]

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Application of Mechanical Metamaterials for Head Impact Protection in Recreational Snowsports

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Introduction

The 2022 Beijing Winter Olympics reached an audience of over 2 billion worldwide, boosting participation in recreational skiing and snowboarding to over 120 million people [1]. Due to its high-speed and technical nature, injuries have been found to be as high as 3.49 injuries per 1000 participation days [2]. Head injuries can account for anywhere between 20-54% of all snowsports injuries and are the most common cause of snow-sport fatalities [3,4]. Helmets have been shown to reduce the likelihood of a head injury by up to 60% [5].

Helmets currently used in skiing and snowboarding act in the same manner as those used in other sports, such as cycling, climbing and motorsport, by using a crushable layer (typically expanded polystyrene (EPS)) that reduces peak acceleration of the head during an impact. This crushable layer is less effective when subjected to oblique impacts. This is due to the foam being relatively resistant to shearing, increasing peak rotational accelerations. Recent advances in manufacturing and computer simulations have led to the possibility of designing helmets made from mechanical metamaterials. Within the world of metamaterials lie auxetic materials; these display a negative Poisson's ratio and have previously demonstrated efficient impact energy absorption [6,7]. Additionally, the increased fracture toughness and synclastic curvature of auxetic metamaterials may be beneficial in sports helmets [8,9].

Head Injuries in Snowsports

The leading mechanism of head injury is contact trauma in the event of a collision with the ground, another ski slope users, or natural objects (e.g. trees, rocks, etc.) [3,10]. Each year in North America, around 600,000 ski and snowboard injuries occur, with head trauma accounting for up to 20% and TBIs responsible for 88% of fatalities [11]. Collisions can be direct or oblique/glancing, causing linear or rotational head acceleration [12].

Research in 2023 tested whether current helmet standards reflect head accelerations during impacts on snow [13]. Drop tests with an instrumented headform showed mean peak accelerations of 51g (± 6), 106g (± 29), and 170g (± 27) on soft, hard, and very hard snow at 6.1 m/s. While helmets reduced acceleration on all surfaces, their effectiveness declined as snow hardness increased. These findings highlight the need to consider snow-helmet interactions in future helmet design.

Mechanical Metamaterials and Their Properties

The performance of a mechanical metamaterial depends on both lattice design and material choice. 2D re-entrant hexagonal and arrowhead shapes reduce peak forces under impact [14,15], while auxetic chiral lattices can offer larger stress plateaus [16]. Anti-tetra chiral structures (i.e. those featuring four ribs connected at an offset from a central node) can be designed to efficiently absorb impact energy, minimising peak forces [17,18]. By systematically controlling parameters, these structures can be engineered to maximise energy absorption efficiency under specific loads [19-21].

This article will aim to select an optimised anti-tetra chiral geometry that seeks to minimise peak linear acceleration (PLA) in a snowsports-related incident. A baseline EPS helmet foam was used as a comparison.

Methods

Structure parameterisation

It was decided that an anti-tetra chiral structure offers a good baseline to work from due to their rotational deformation mechanisms [22,23]. Chiral structures are typically comprised of central rotating rings which are connected by ligaments (beams). Standard chiral central rings are tangentially connected, causing the connecting ligaments to rotate when the structure is compressed. Anti-chiral central rings are connected in a square [23]. Regardless of ligament, connection chiral structures may only exist with either 3,4 or 6 ligaments per central ring. In this study anti-tetra chiral (4 ligament) units will be assessed.

When constrained to a set cell height, an anti-tetra chiral structure can be parameterised by three variables: beam length (l), beam thickness (t) and central ring diameter (Φ). Each of these parameters can be changed independently, but other parameters do rely on them. Cell depth was set at 30mm (h) as this was deemed to be in line with current energy absorbing liners seen in snowsports helmets. Structure width was then kept at a constant 60mm to preserve continuity across all models. To maintain this thickness whilst keeping complete beam and central rings, the beam lengths were set at 3, 3.75, 5 and 7.5mm. This ensures that the structure will be between 2 and 5 cells high. To prevent impossible structures with central rings larger than the beams that connect them, the central ring size is to be defined as a multiplier of the beam length. This allows it to be scaled in relation to the beam length. Beam length was constrained by printer resolution.

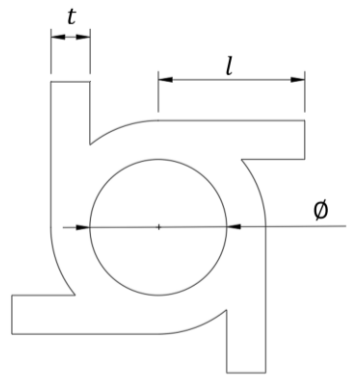


Figure 1 Structural parameters of the anti-tetra chiral cell

To design the experiments, four 'levels' were chosen for the 3 parameters. As previously mentioned, beam lengths were dictated by the cell height. Both the beam thickness and central ring upper and lower bounds were chosen to maximise design space whilst allowing for computable and manufacturable structures. Levels 2 and 3 were then set at equal spacings between the upper and lower bounds. All values can be seen in Table 1.

Table 1 Design Parameters of anti-tetra Chiral auxetic structures

Factor	Diameter (% of beam length)	Beam Length (mm)	Beam Thickness (mm)
Level 1	40	3	0.8
Level 2	80	3.75	1.2
Level 3	120	5	1.6
Level 4	160	7.5	2

For a design space with 3 parameters each with 4 levels, there are a possible 81 different structures. A Taguchi Array was used to reduce the number of structures tested while still capturing the effects of multiple factors and their interactions. In this instance it reduced the required structures to be tested to 16. This approach allows identification of factors that have the greatest influence on performance, and suggests which levels may give the best results (i.e. minimum peak acceleration) [24]. The array used in this study is set-up and processed in Minitab (Minitab LLC, US).

Each structure was generated in Autodesk's Computer aided design software, Fusion 360 (Autodesk, US). Each sample was then exported to OrcaSlicer (OrcaSlicer, US) as a .STL file and printed on a Bambu Lab P1S (Bambu Lab, China) fused filament fabrication (FFF) 3D printer. Samples were printed out of Bambu Lab's TPU 95A HF as per guidance from Bambu Lab Online. This material provided a flexible, fast-printing and hyperelastic base for the samples. EPS samples with external diameters similar to that of the chiral structures were taken from an off-the-shelf snowsports helmet; in total 5 samples were taken, which would allow for a new sample for each velocity.

Test Methods

Each chiral structure was tested on an impact test machine (IM10; Imatek, UK). Data was recorded with a 60kN force transducer (Kistler, Switzerland) at a rate of 80KHz. The tests were conducted using a flat anvil striker with a mass of 14.4 kg. Samples were impacted at velocities of 3.18, 3.66, and 4.50 m/s, corresponding to energy levels below, at, and above (73, 96 and 146J, respectively) that specified in helmet certification standards [25]. A 24-hour interval was given between tests to allow for inspection and full material relaxation.

Prior quasi-static compression tests on TPU 95A structures showed full recovery after approximately 16 hours. To ensure reliability and align with normal working hour a 24-hour rest period was given between tests. This adjustment allowed samples to recover before subsequent impacts.

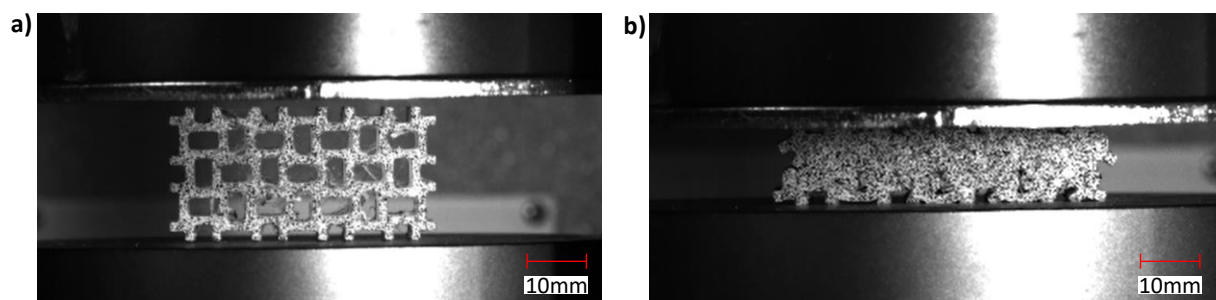


Figure 2 Unoptimised anti-tetra chiral structure a) prior to impact, b) at maximum deformation under impact

Results

Experimental Analysis

Each structure was consistently lighter than the modelled mass ($12.6\% \pm 8.6$). An example acceleration-time plot is shown from sample 12 across all 3 velocities (Figure 3a). The 3 best performing samples (lowest PLA) (sample 6, 7 and 16) and the EPS foam can then be seen plotted in figure 3b. Combining the 3 PLA values of each sample to generate a score, 12 out of the 16 samples performed better than the EPS Foam.

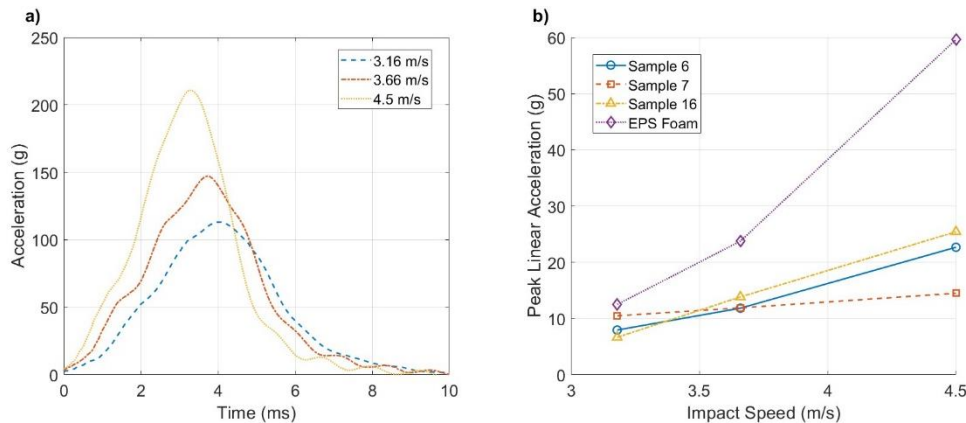


Figure 3 a) Acceleration-Time data of sample 12 across all 3 velocities,
 b) PLA of three best performing samples (sample 6,7, and 16) and the EPS Foam

Taguchi Array Analysis

As a demonstrative example of how this approach could then be extrapolated to tune the structures for use in helmets, weightings were chosen relating to each impact velocity. The three velocities were weighted in terms of likelihood of the incidence occurring. H. Ogawa et al. [26], states that of their nearly 20,000 injured snowsports participants, 32.8% were beginner, 47.4% were intermediate and 19.8% were either advanced or expert level. G. Ruedl et al. [27] then links these skill-levels to different impact velocities, which can be linked to the three chosen energy levels. This means a weighting system can be applied to create a Structure Performance Score (SPS) over the three velocities (Equation 1).

$$SPS = 0.328PLA_{3.16} + 0.474PLA_{3.66} + 0.198PLA_{4.5} \quad (1)$$

Each of the SPS results was then used as the result in the Taguchi Array, set up with the lowest SPS being the favoured response. From analysing the main effect of mean responses, beam length and beam thickness emerge as the dominant factors, while the central ring diameter has only a minor influence.

The optimal factor levels were identified as Level 2 for beam length and Level 4 for beam thickness, with diameter contributing negligible effects, but at a slightly more optimal point at 40 and 80% of the beam thickness. These findings highlight the structural importance of beam length and thickness.

Final Design

The chosen parameters from the taguchi array results can be used to generate an optimised design that should have the lowest theoretical SLS and PLA. With diameter having a small overall influence on the design outcome, it should be selected based on practical design considerations such as manufacturability and material efficiency. Therefore, the larger diameter of 80% is chosen due to printer resolution. This structure can be seen in Figure 4.

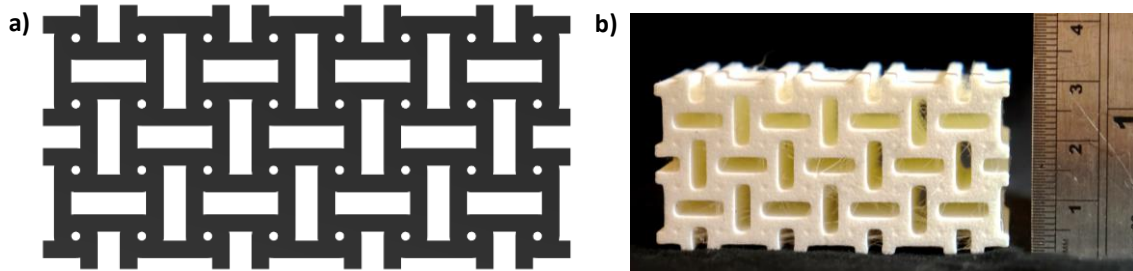


Figure 4 a) Orthographic view and, b) 3D printed sample of the optimum anti-tetra chiral design as selected by the Taguchi Array

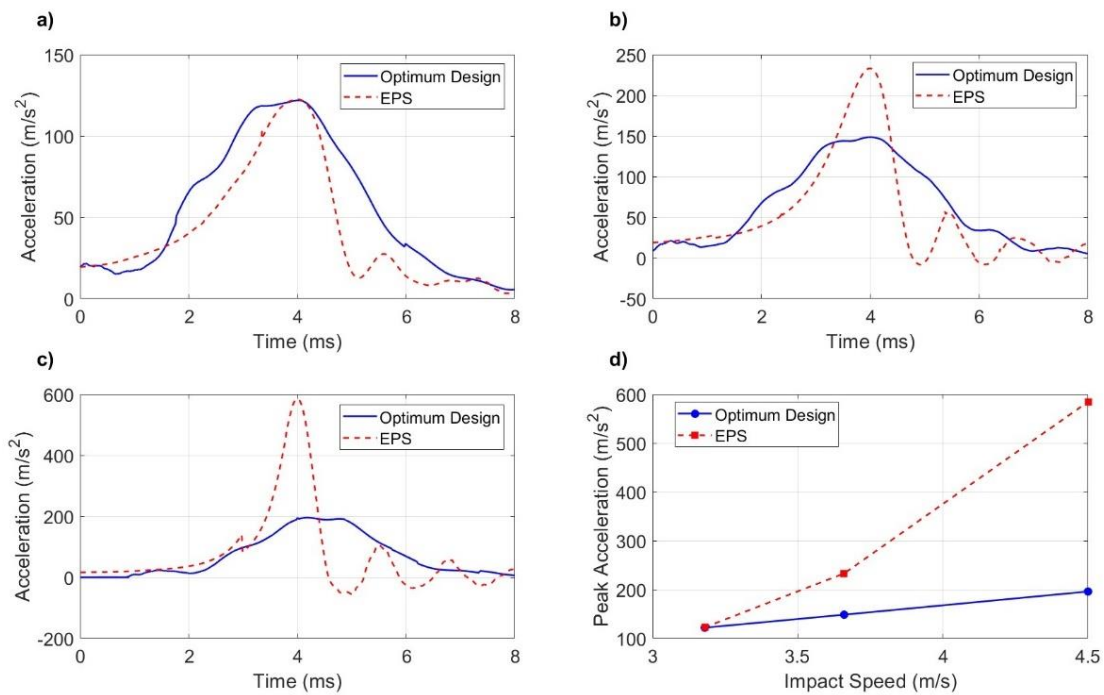


Figure 5 Comparison of acceleration-time plots of optimised structure and EPS Foam at, a) 3.18m/s, b) 3.66m/s and c) 4.5m/s. d) Comparison of peak accelerations across all velocities

The optimum design was then manufactured in the same manner as the previous structures, and tests following the same methodology were conducted to validate the Taguchi Array. Comparison to the EPS foam at the three separate velocities can be seen in Figure 5. The optimum design betters the EPS across all velocities with an improvement in SPS by 56.4%.

Discussion

The aim of selecting an optimised anti-tetra chiral geometry that seeks to minimise peak linear acceleration (PLA) in a snowsports related incident is met, with significant improvements found over the baseline EPS foam that is commonly found in snowsports helmets. A reduced peak linear acceleration is seen across all tested velocities; these improvements indicate the possible use of anti-tetra chiral structures in future sports helmets.

Use of the Taguchi Array provided an efficient and effective method of assessing a wide design space allowing for the assessment of as many anti-tetra chiral configurations as possible. From a possible 81, 16 structures were assessed, the results concluded that the beam length and thickness contribute the most to changes in the performance of the structure with the central ring diameter having a minimal effect on the result. This is likely due to the central ring only controlling the rotation of the beams, whereas beam deformation is the primary mechanism to store the energy.

Future Work

This article assesses structures in exclusively direct impacts, rather than oblique ones. In most snowsports head impacts, both linear and angular accelerations play a part in contributing to injury risk. As such, future work could also investigate how these structures perform in oblique impacts. Working towards optimising for linear and oblique impacts may lead to a departure from the Taguchi Array due to its limitations when dealing with multiple objectives. A genetic algorithm could allow for a continuous design space rather than a discrete one as used in this article, and may be able to cope with conflicting objectives.

Alternatively, work could be done to further improve the performance of the optimised structure with a greater number of parameters investigated. Recent literature [28,29] claims that graded auxetic structures consistently outperform their uniform counterparts under impact. Therefore, investigating this could unlock further performance gains in impact resistance. Video capture collected in this testing may also allow for future work to be completed on investigating the effect of wave propagation and Poisson's ratio on the energy absorption efficiency of each structure, and the EPS foam.

Conclusions

The anti-tetra chiral auxetic structure has demonstrated superior performance compared to EPS foam, commonly used in snowsports helmets, under direct impacts. These findings provide a foundation for further exploration of such structures, not only in snowsports helmets but also across a broader range of sporting equipment and related applications.

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