Adaptable Mechanical Metamaterial for Ice Hockey Helmet Liners

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I. INTRODUCTION

Ice hockey has one of the highest concussion rates in sport [1]. A challenge in preventing concussions and developing helmets is the range of common head impacts. Current ice hockey helmets are designed to protect during falls on the ice, as assessed in certification standards. However, more than 90% of concussions are caused by collisions between players that currently are not considered in certification standards [2]. Consequently, current helmets do not compress sufficiently for the primary energy-absorbing mechanisms to take place and therefore offer limited protection during collisions [3]. Due to the severity of injuries caused by rigid surface impacts, helmets need to work well in these impacts, and using lower stiffness liners is not feasible.

A helmet liner that can adapt its compressive properties, depending on the nature of impact, could improve helmets during collisions while maintaining high stiffness during rigid surface impacts. A strain rate-dependent mechanical metamaterial with tailorable buckling behaviour, as previously introduced by Janbaz *et al.*, could achieve such a switch in stiffness properties in a helmet liner [4].

II. METHODS

The mechanical metamaterial of unit cells is constructed from aligned and orientated bi-beams (Fig. 1 (A)). A bi-beam consists of two dimensionally identical beams manufactured in different hyperelastic materials, adhered laterally. One material is highly strain rate-dependent (i.e. visco-hyperelastic) while the other is largely strain rate-independent (i.e. hyperelastic) and, under quasi-static conditions, stiffer than the visco-hyperelastic side. A bi-beam will buckle towards the side with a higher instantaneous elastic modulus when compressed axially. Consequently, a bi-beam will buckle towards the stiffer hyperelastic side at low compression rates. Exceeding a threshold strain rate switches the order of stiffness and the direction of buckling (Fig. 1 (B) and (C)).

A unit cell is formed from two bi-beams positioned at a small distance from each other, with opposing orientation. Due to the orientation of the individual bi-beams in the unit cell, and the switch of buckling direction depending on the compression rate, two different loading conditions can occur.

1. Both bi-beams buckle in opposite directions (low compression rates) and thus do not restrict each other's buckling motion, causing a relatively compliant response (Fig. 1 (D)).
2. Both bi-beams buckle towards each other (high compression rates). Contact between the two beams mostly prevents further buckling, causing a rapid increase in stiffness (Fig. 1 (E)).

The strain rate-dependent switching of deformation increases the stiffness abruptly and multiple times more than the progressive increase due to the shear-thickening material behaviour alone.

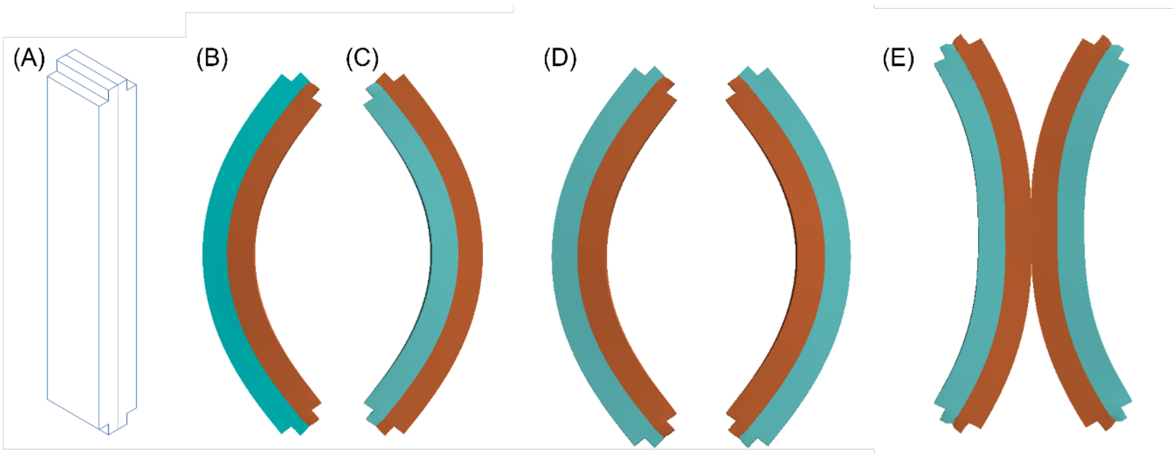

Fig. 1. (A) Bi-beam design. (B) Bi-beam buckling towards the hyperelastic side (turquoise) at low strain rates and (C) towards the visco-hyperelastic side (orange/brown) at high strain rates. (D) Unit cell buckling out and (E) in.

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A proof-of-concept study was undertaken, following a material characterisation study, to identify suitable materials (TPU 95A and Ninjaflex™) [5]. Strain rate dependence was not used as the switching mechanism, as TPU 95A possesses higher stiffness at all strain rates. Instead, bi-beam orientation was used to designate the buckling direction and response. An Instron universal test machine (Electropulse E3000, 5 kN load cell) was used to compress unit cells, arranged for both loading conditions, to a compressive engineering strain of 0.15 (5.76 mm displacement) at three different strain rates (0.83, 8.3 and 83.3 s^{-1}). Each testing condition was repeated five times and newly fabricated beams were used in each test. Force vs. displacement data were obtained from the test device and all tests were filmed (Phantom Miro R311, Vision Research Ltd., Bedford, UK) to record buckling direction.

III. INITIAL FINDINGS

In 90% of tests both bi-beams buckled in the predicted directions. The remaining tests were excluded from the analysis. Force vs. displacement traces differed depending on the loading condition. Traces where bi-beams buckled away from each other show a peak between 0.05 and 0.065 compressive strain while buckling in traces peaked between 0.1 and 0.12 strain at peak forces about 2–3 times higher. Additionally, compressive stiffness increased with increasing compression rate.

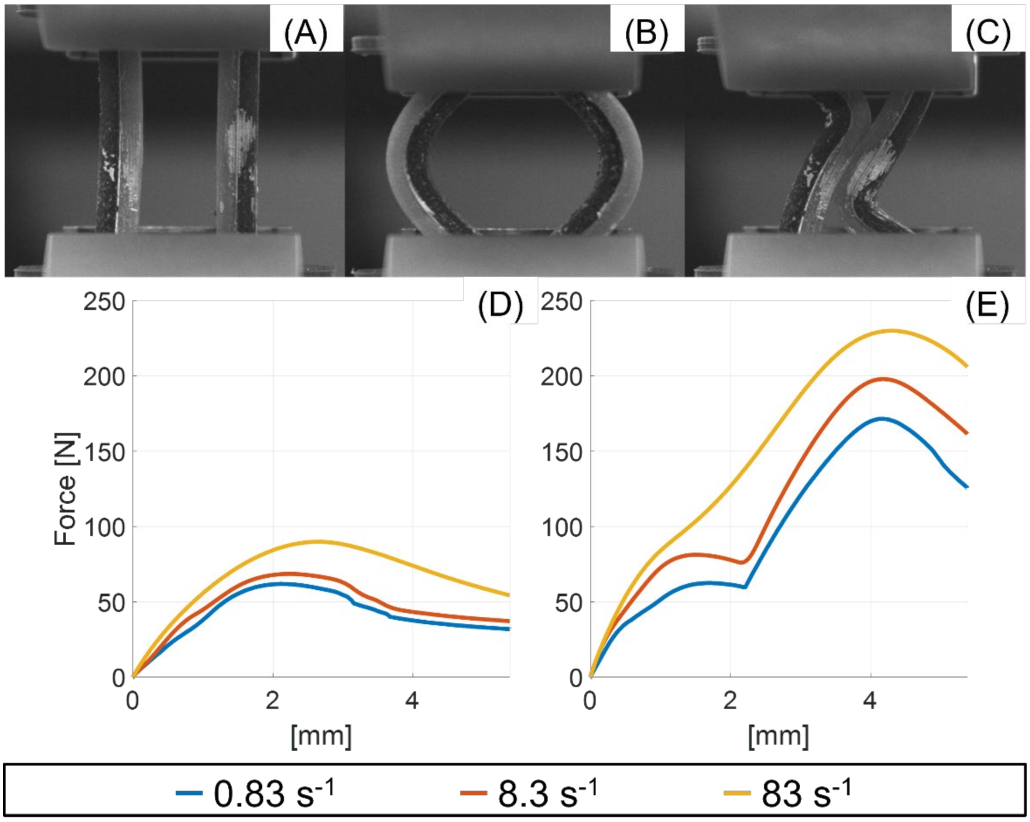

Fig. 2. Uniaxial compression test of bi-beam unit cells while (A) uncompressed, (B) buckling out, and (C) buckling in with force vs. displacement traces for (D) buckling out and (E) buckling in.

IV. DISCUSSION

A stark switch in compressive stiffness, clearer than a typical viscoelastic switch, is consistently achievable. Findings suggest that a metamaterial sheet produced from bi-beam unit cells could be programmed to perform well across a wider range of impact scenarios. Scaling geometries to helmet liner-appropriate size, increasing the number of unit cells compressed simultaneously, and material strain rate-dependence will be introduced in future studies to assess the metamaterial's feasibility as a helmet liner.

V. REFERENCES

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