Developing Elastomeric Cellular Structures for Multiple Head Impacts.

M. Robinson, S. Soe, G. McShane, R. Celeghini, R. Burek, M. Alves, B. Hanna, P. Theobald

Abstract Foam-based materials were originally incorporated into helmets in the 1970's, providing an effective method of absorbing impact energy and so protecting against severe head injury. Similar materials still exist in the majority of protective helmets today, indicating a need for an innovative approach that will achieve a step-change in energy absorption performance. This paper focusses on tailoring the Miura-Ori (MO), origami-derived geometry, as a method to achieve a material structure tailored to maximise impact energy absorption, whilst complying with existing product design constraints. This ambitious concept was then realised using an elastomeric, additive manufacturing powder, before being tested against foam derived from a commercially-available American football helmet. MO pads demonstrated comparable performance versus foam at relatively low impact velocities, though recorded a peak acceleration 15% less than foam at the highest impact velocity. This difference increased once the respective samples were exposed to their third impact, demonstrating the superior performance of MO over multiple impacts. The MO material demonstrated encouraging energy impact absorbing behaviour, with scope remaining to further optimise the geometry in order to further enhance performance. Furthermore, opportunities exist for achieving superior shear-energy performance than contemporary materials and, ultimately, for harnessing the benefits of additive manufacturing to fabricate person-specific headwear optimised for a given impact environment.

Keywords additive manufacture, cellular structures, impact, helmet, personal protection

I. INTRODUCTION

Activities which present a severe head injury risk injury typically utilise foam-lined helmets to provide enhanced protection. Foams represent a highly effective mechanism of energy absorption and are light-weight, meaning that they are ideal for personal protection applications. They absorb energy by deformation of the cell walls within the structure, achieving effective absorbing from linear impacts; however, foams are relatively poor at shear energy dissipation. Sports-related helmets typically use foams such as expanded polystyrene and vinyl nitrile for single- and multi-impact environments respectively; however, both are long-established materials that can probably be out-performed by new and novel solutions. Such advances could achieve greater energy absorption and so head protection, during impact scenarios.

Additive manufacturing (AM) has supported a surge in interest in impact mitigating cellular materials, with most current work focussing on prismatic (honeycomb), and strut -based periodic lattice, structures. The layer-by-layer fabrication of AM offers unprecedented access to novel geometries and material-geometry combinations, providing opportunity to manufacture structures with superior weight/performance ratios, versus contemporary materials [1-2]. Whilst investigation continues to explore the mechanical potential of these types of traditional cellular structures [3-4], their potential for achieving best-in-class performance in demanding applications, such as those with challenging material thickness constraints and complex load cases (including radial and tangential force), remains to be proven. In addition to the added complexity offered by AM, access is increasing to exotic material families, with the mechanical properties and processing parameters of AM elastomers being reported in literature [5-6]. The elastomeric nature of some of these materials allows the manufacture of a complex structure that can survive multiple impacts.

This paper evaluates a new and novel material structure, utilising AM, to out-perform a helmet-derived foam, during multi-impact scenarios. Here, we present a new class of impact attenuation structure, the stacked folded

M. Robinson and B. Hanna are PhD Students, S. Soe is a Senior Postdoctoral Researcher, and P. Theobald is an Academic (theobaldps@cardiff.ac.uk; +44 2920 874726), in the Department of Engineering at Cardiff University in Wales, UK. G. McShane is an Academic in the Department of Engineering at Cambridge University in England, UK. R. Celeghini and M. Alves are Academics in the Department of Engineering at University Sao Paulo in Brazil. R. Burek is President at Charles Owen, Inc, in GA, US.

cellular structure based on an origami fold pattern, as a novel solution for head protection. The concept has evolved from stacking nested, alternating layers of the Miura-Ori (MO) folded structure, to create a three-dimensional metamaterial with a tailored mechanical response [7]. When oriented such that the direction of stacking is perpendicular to the loading direction, the stacked folded cellular structure has a number of design parameters that enable tailoring of its buckling, and so energy absorption, for a particular impact scenario; hence, it is possible to select a MO configuration by varying the internal geometry in a similar manner to selecting polystyrene based on density [8]. The stacked MO structure has previously been numerically investigated for use in blast protection, though the use of traditional manufacturing techniques including etching and folding caused difficulties nesting and joining the layers [8]. Adoption of AM provides scope to overcome the limitations of traditional techniques.

This paper will now explore the design and manufacture of a novel MO structure, investigated for its potential use in personal protection applications. We will combine the MO structure - which affords a high degree of performance optimisation due to the scope in varying a high number of geometric variables, with AM – which enables the fabrication of such complex structures from high-performance, elastomeric materials. It is the aim that the final material structure out-performs established foam at a range of impact velocities, and over a series of multi-impact tests.

II. METHODS

Two internal foam pads were removed from opposite sides of a commercially available *Rawlings Impulse 2015* American football helmet. The comfort foam layer was removed from both pads to leave only the impact absorbing foam, which appeared consistent with vinyl nitrile, a material commonly used in American football helmets (Fig.1.). The 2D profile of the two foam pads were then measured (Fig. 2.).

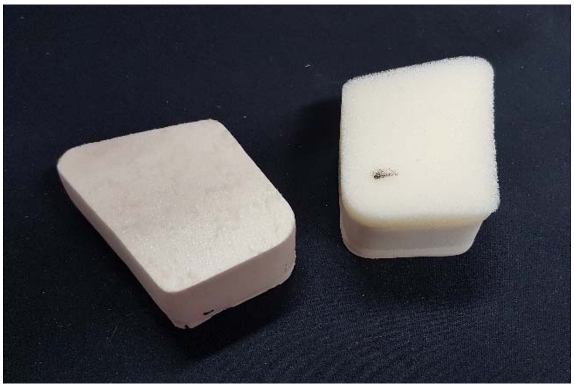

Fig. 1. The two foam parts removed from the American football helmet, one showing the comfort foam removed (left) and the other still intact (right)

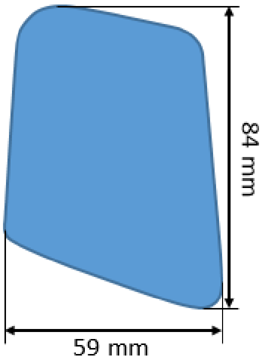

Fig. 2. Dimensions of the foam samples

Commercially available Computer Aided Design (Solidworks 2016) and Finite Element Analysis (FEA; Abaqus 6.14) software was used to develop a bespoke MO geometry, specifically for use in protecting against American football head impacts (Fig. 3). FEA was performed in an attempt to achieve a structure that was optimised to achieve minimal peak acceleration at an impact velocity 5.46ms^{-1}, correlating with the greatest impact performed in the experimental testing (described below). This MO configuration was additively manufactured from a commercially-available elastomeric powder, then manually trimmed to best replicate the foam sample dimensions (Fig. 4).

The thickness of the foam and MO pads were measured at three locations which, combined with the 2D profile of both materials (Fig. 2 & 4) and their masses, allowed for calculation of a relative density (ρ_{rel}), as described in the results section. The MO profiles differed subtly from the foam, predominantly due to the irregularity of the cellular structure.

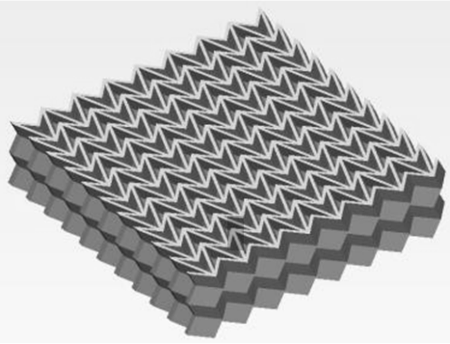

Fig. 3. Final MO design

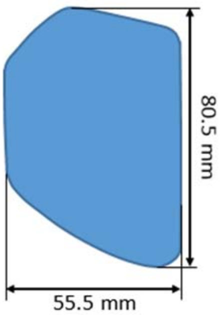

Fig. 4. Dimensions of the trimmed MO samples

Comparative impact testing was performed on a monorail shock absorption testing facility (model: 1002 MAU 1006/CF/ALU; AD Engineering, Bergamo, Italy). Data was measured via a single axis accelerometer (model: PCB 353/B17-1D, 500g maximum acceleration) located in-line with the centre impacting platen, and was recorded at 50kHz via a data acquisition system (model: 'DLS 9000/CM 625; AD Engineering, Bergamo, Italy). Data was filtered in accordance with ISO 6487 class 1000. Each pad was taped in place to the centre of the fixed lower platen of 130mm diameter, using electrical tape. A separate flat 4.7kg impacting platen of 130mm diameter was then wire-guided, under free-fall, onto the sample.

Each sample was subjected to 3 impacts, with a relaxation time of 75 s +/-10s between impacts [9], at 4 different velocities (3.46, 4.23, 4.88, 5.46 ms^{-1}; +3%/-0%) [10]. During preliminary testing, for the velocities investigated in this study, it was found that: (i) after 3 impacts, the foam samples demonstrated a 'stabilised' peak acceleration over future impacts; (ii) after being subjected to a series of impacts, being rested for 10 minutes and then impacted again, the samples produced similar peak accelerations to when initially impacted. The following methodology was, therefore, adopted:

1. Three impacts to each sample at the lowest velocity, with relaxation time of 75s +/- 10 s between tests.
2. Each sample was rested for at least 10 mins, and then subjected to a further 3 impacts at the next velocity.
3. Testing of each sample was performed at the lowest, and increased to the maximum, impact velocity.

   Each sample was then rested for at least 10 mins, before 10 impacts at 4.88 ms^{-1}, with a relaxation time of 75s +/- 10s between impacts. This velocity was selected to represent the worst case scenario, from this testing regime, whilst preventing damage to sensitive measurement equipment.

III. RESULTS

No variation was evident in the thickness of the MO samples, those these differed from the mean foam pad thickness (Table 1). Data presented in Table 2 then describes the percentage increase in peak g across three impacts of identical velocity, following a relaxation time of 75s +/- 10 s between each test. This measure was used to identify stability in material behaviour. Over three impacts the MO samples consistently increased by approximately 10%; however, the increasing percentages with increasing velocity indicates that the foam performance has not stabilised after three impacts. Subsequently, high velocity (5.48 ms^{-1}) impacts were not performed on the foam samples, to protect the testing equipment.

Table 1. Dimensions of the foam and MO pads

	Overall Pad Thickness (mm)		Mass (g)	Ext. Volume (mm3)	ρ_{rel} (kg/m3)
	Av.	*sd*			
Foam 1	21.58	0.17	8.85	83041	107
Foam 2	24.19	0.2	10.04	93084	108
MO 1	25.49	0.02	27.92	93574	298
MO 2	25.49	0.04	29.75	93574	318

Table 2. Increase in peak acceleration from first to third impacts, at increasing velocities

	3.46 m/s	4.23 m/s	4.88 m/s	5.46 m/s
Foam 1	19%	30%	42%	N/A
Foam 2	19%	32%	45%	N/A
MO 1	13%	9%	9%	6%
MO 2	11%	14%	9%	16%

Fig. 5 describes the peak acceleration during the first impact, across increasing velocities. Relative mean accelerations of the MO samples versus the foam are: +11g (3.46 m/s), +22g (4.23 m/s), +28.5g (4.88 m/s), and -67.5g (5.46 m/s). Fig. 6 then demonstrates how the material performance varies after the third impact, with the relative mean accelerations of the MO sample versus the foam as: +6.5g (3.46 m/s), -7g (4.23 m/s), -73g (4.88 m/s).

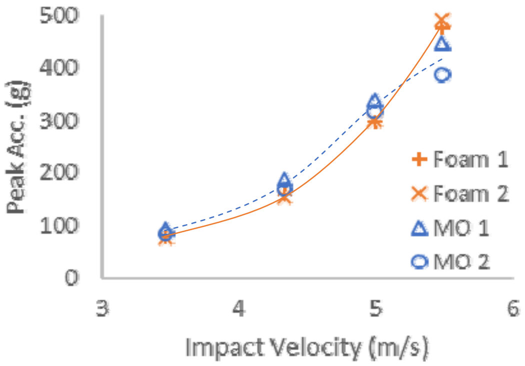

Fig. 5. Peak Accelerations for first impacts

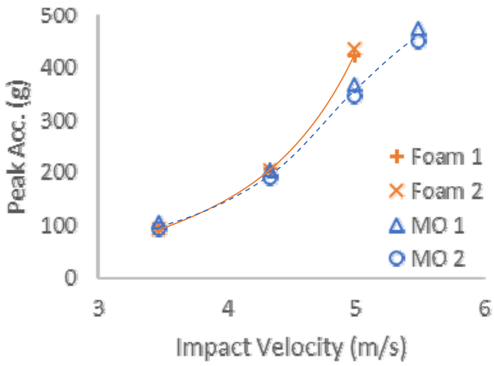

Fig. 6. Peak Accelerations for third impacts

The divergence in performance described in Fig. 6 is due to the relatively poor recovery of foam. Accelerometer (Fig. 6.) and high speed video data (Fig. 7.) appear to confirm that the foam sample reached full densification at the highest speed, unlike the MO (Fig. 8.).

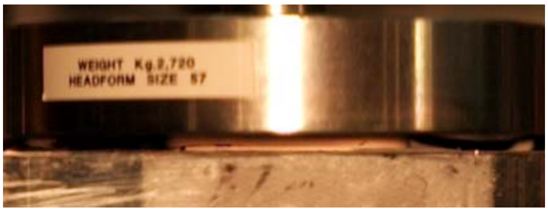

Fig. 7. First impact at 5.46ms^{-1}, demonstrating foam compression

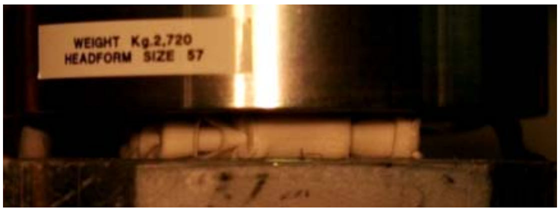

Fig. 8. First impact at 5.46ms^{-1}, demonstrating MO compression

Relative performance of the two materials during multiple impacts was then investigated at the highest velocity not presenting risk to the testing equipment (i.e. 4.88ms^{-1}). Fig. 9 describes the foam pads initially achieving a marginally lower impact acceleration than the MO samples then, following the third impact, consistently inducing peak acceleration values 16-22% higher than MO.

The acceleration-time traces (Fig. 10. & 11) demonstrate the variation between foam and MO samples at the third impact for 3.47 ms^{-1} and 4.88 ms^{-1} velocities. Traces for all impacts are included in the Appendix.

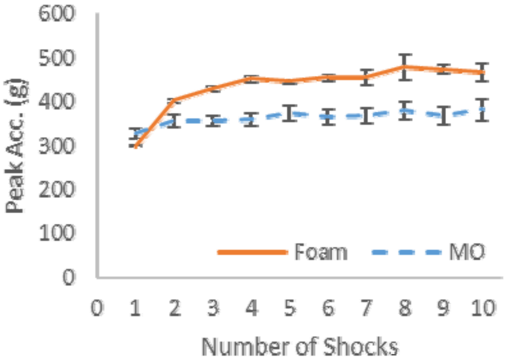

Fig. 9. Multiple impacts at 4.88 m/s on foam and MO samples (error bars show range)

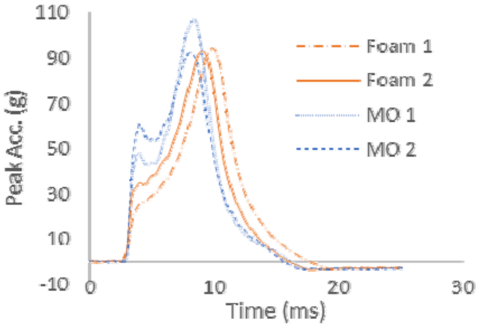

Fig. 10 Acceleration-time traces at 3.47ms^{-1} for the third impact.

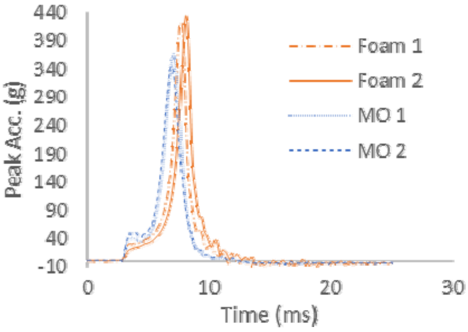

Fig. 11 Acceleration-time traces at 4.88 m/s for the third impact

IV. DISCUSSION

This study aimed to develop a new elastomeric structure for use in multi-impact scenarios, with potential to out-perform the contemporary foam material. The MO has been observed to achieve marginally greater peak acceleration in initial impacts, though has a 15% smaller peak acceleration than foam at higher velocities (Fig. 5). Higher velocity impacts would likely have further increased this difference, as the foam had already reached full densification (Fig. 7.); however, this was not investigated through risk of damaging the testing equipment. By contrast, the near-linear increase in peak acceleration measured by MO impacts would indicate that the material had not fully densified, with the extent of compression illustrated in Fig. 8 indicating the success of the FEA design optimisation process.

The superior performance of the MO material in recovering its absorption characteristics post-impact is measured in Table 2. The peak acceleration measured for three impacts on to foam increased by 19% at the lowest, and >40% at the highest, velocities. MO performance was favourable, demonstrating an approximate 10% increase in peak acceleration across the three impacts, at all velocities. Additionally, the performance of MO was observed to quickly stabilise given the consistency of results between the third and tenth impact (Fig. 9.). Further investigation using a greater number of cyclical impacts are planned, to better explore the potential for MO to be used within a multi-use, multi-impact environment. Of further reassurance are the similar time durations to the foam sample, as evidenced in Fig. 10 and Fig. 11.

Throughout the experimentation, it was noted that MO 2 demonstrated marginal, but consistently lower, peak acceleration values than MO 1. Table 1 details that MO 2 had a mass 94% that of MO 1, a difference probably due to a combination of the manual trimming of the samples and, potentially, due to subtle variations as a consequence of the manufacturing process e.g. wall thickness variation, retention of residual AM powder, etc. It is likely that these unintentional differences, and subsequent higher ρ_{rel} of MO 2, were the cause of the marginally superior performance. Future investigations will be designed to explore how to mitigate against these factors. For the first 5.48ms^{-1} impact, MO 2 displayed an acceleration 87% that of MO 1. As noted, MO 2 had a consistently lower peak acceleration; however, this is a more notable difference than that displayed at other velocities and impacts for the two samples (Fig. 5.), so it is likely this data point is anomalous.

The preliminary nature of this study focuses on the efficacy of a design process to develop a novel impact absorbing material, with success measured using peak acceleration as opposed to an injury criterion. A relatively small number of planar samples were investigated, with future work ultimately progressing towards incorporating MO in to a helmet design, to consider the need for compliance with geometry and subsequent boundary conditions. Extending this design process will also enable consideration of other helmet components, including the shell. Further work will also consider how the MO structure can be tailored to absorb shear energy, and whether this design process provides opportunity to develop a bespoke structure for a specific impact environment e.g. position-specific helmets.

V. CONCLUSIONS

This study has demonstrated an approach in using MO to create a novel material that appears, following preliminary investigation, to demonstrate superior impact energy absorption performance versus foam. Encouraging performance was evidenced during multi-impact scenarios, with MO out-performing foam by 15% over high velocity, multiple impacts. This study now provides a platform to further investigate optimisation of the MO structure for enhanced shear energy absorption, and ultimately to explore the potential to design bespoke head protection.

VI. ACKNOWLEDGEMENT

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VII. REFERENCES

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VIII. APPENDIX

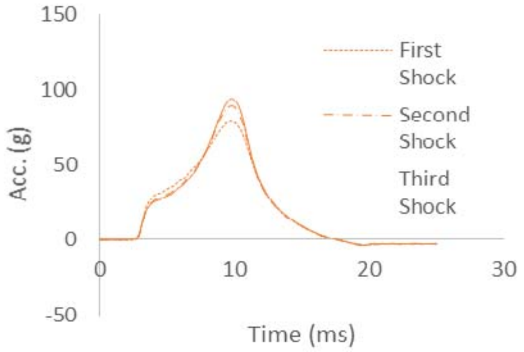

Fig. A1. Acceleration-Time History for 3 repeated impacts, at 3.47 m/s, on Foam 1

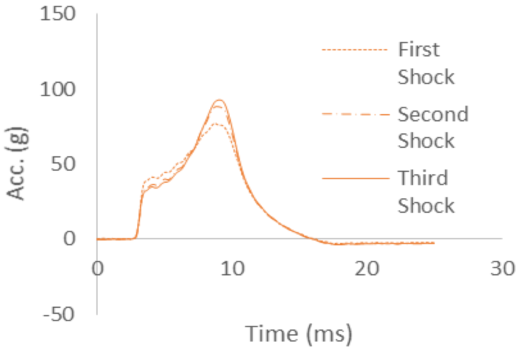

Fig. A2. Acceleration-Time History for 3 repeated impacts, at 3.47 m/s, on Foam 2

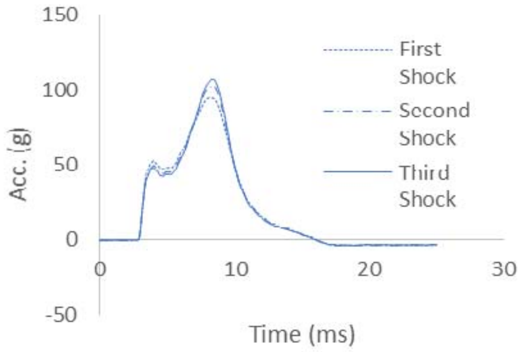

Fig. A3. Acceleration-Time History for 3 repeated impacts, at 3.47 m/s, on MO 1

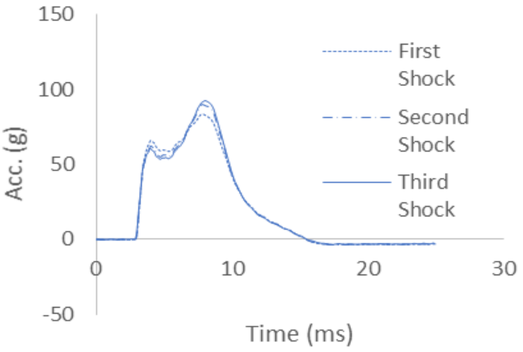

Fig. A4. Acceleration-Time History for 3 repeated impacts, at 3.47 m/s, on MO 2

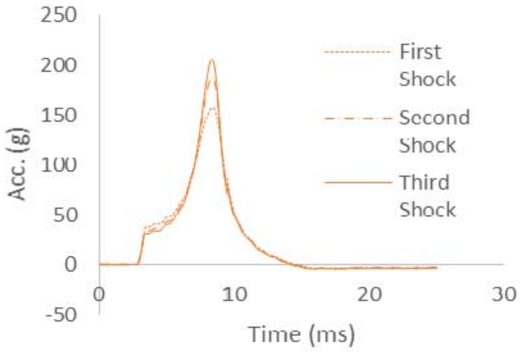

Fig. A6. Acceleration-Time History for 3 repeated impacts, at 4.23 m/s, on Foam 1

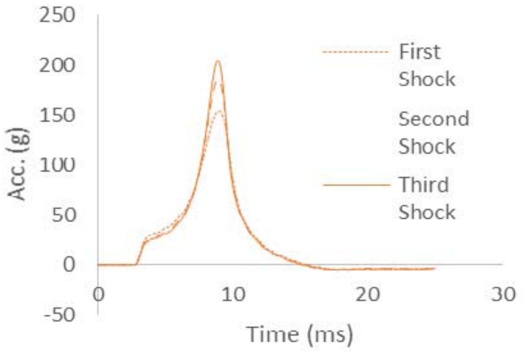

Fig. A5. Acceleration-Time History for 3 repeated impacts, at 4.23 m/s, on Foam 2

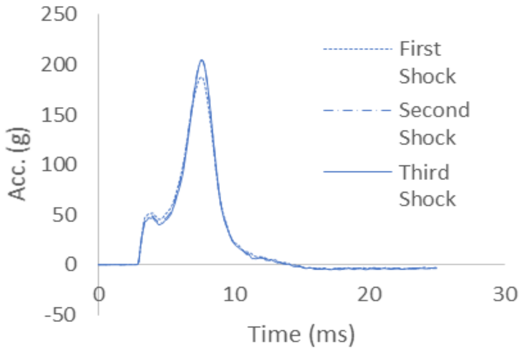

Fig. A7. Acceleration-Time History for 3 repeated impacts, at 4.23 m/s, on MO 1

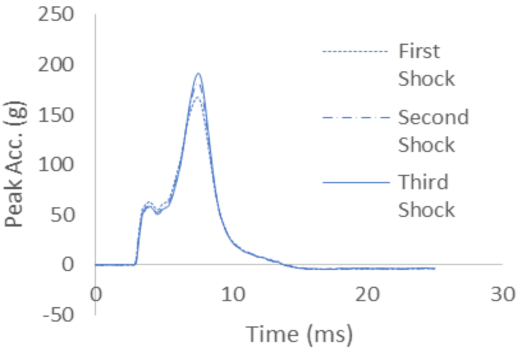

Fig. A8. Acceleration-Time History for 3 repeated impacts, at 4.23 m/s, on MO 2

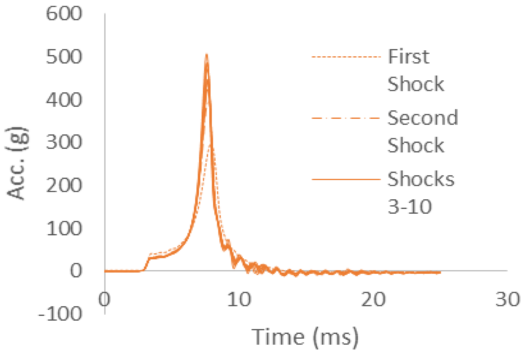

Fig. A9. Acceleration-Time History for 10 repeated impacts, at 4.88 m/s, on Foam 1

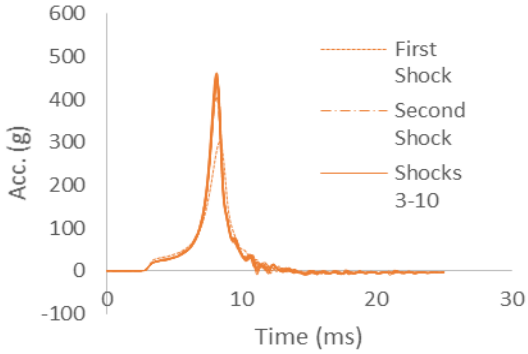

Fig. A10. Acceleration-Time History for 10 repeated impacts, at 4.88 m/s, on Foam 2

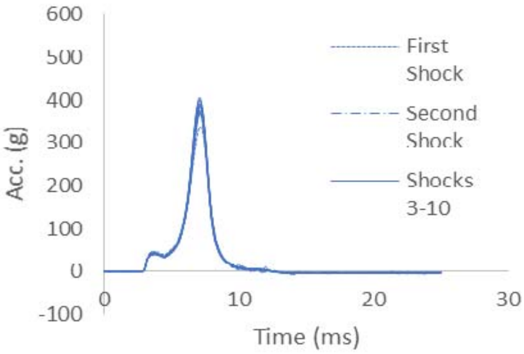

Fig. A11. Acceleration-Time History for 10 repeated impacts, at 4.88 m/s, on MO 1

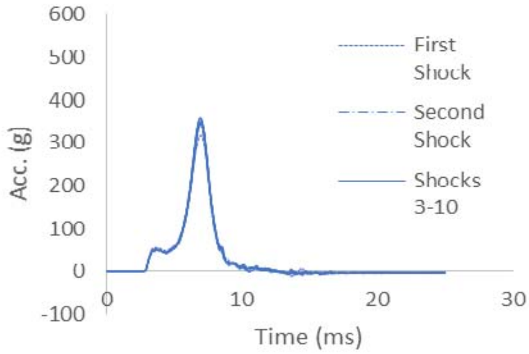

Fig. A12. Acceleration-Time History for 10 repeated impacts, at 4.88 m/s, on MO 2

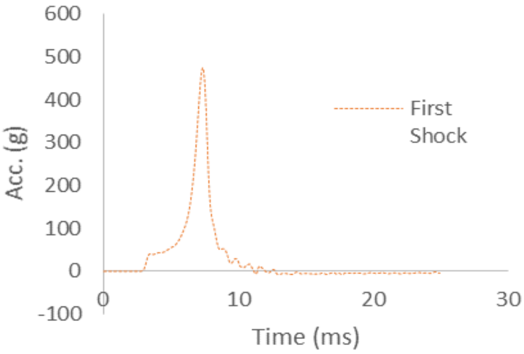

Fig. A13. Acceleration-Time History for 1 impact, at 5.46 m/s, on Foam 1

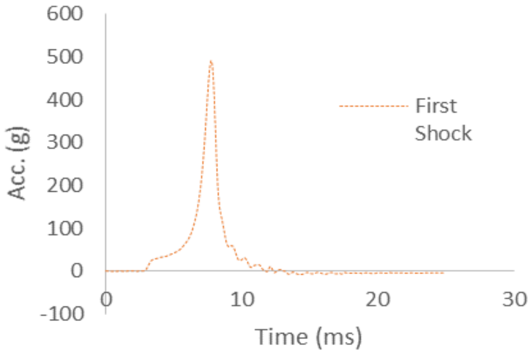

Fig. A14. Acceleration-Time History for 1 impact, at 5.46 m/s, on Foam 2

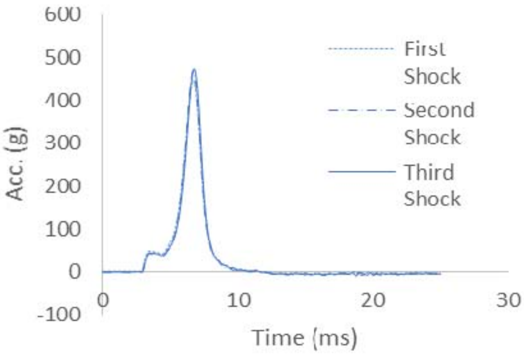

Fig. A15. Acceleration-Time History for 3 repeated impacts, at 5.46 m/s, on MO 1

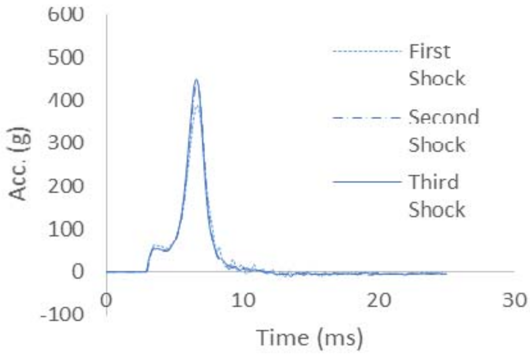

Fig. A16. Acceleration-Time History for 3 repeated impacts, at 5.46 m/s, on MO 2