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NEGATIVE STIFFNESS HONEYCOMBS FOR BLAST MITIGATION PANELS

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ABSTRACT

Midé Technology Corporation (Midé), a Hutchinson company, in collaboration with The University of Texas at Austin (UTA), have investigated the potential for novel negative stiffness (NS)-based structures as blast resistant vehicle panels. Protecting vehicles from blast shockwaves would ideally minimize added weight and maximize reusability. Homogenous metal panels provide such protection but without the benefit of reusability, absorbing energy via plastic deformation, while also adding significant weight to a vehicle, thereby sacrificing mobility. Although various emergent approaches, including the use of hexagonal honeycombs and auxetic materials, have proved promising in terms of higher energy absorption per unit mass, such approaches also rely on plastic deformation additionally suffering from the drawback of occasionally transmitting a higher peak force as compared to the incident.

1. INTRODUCTION

Protecting vehicles from blast shockwaves is vitally important for today’s military vehicles. Any solutions providing such protection would ideally minimize added weight to increase mobility. Furthermoe, a solution providing resuability or resettability, would be beneficial for reducing lifecycle cost and maintaining mission capability and readiness. While homogenous metal panels can provide blast protection, they are not reusable—absorbing energy via plastic deformation—while also adding significant weight to a vehicle.

Negative Stiffness (NS)-based vehicle panels are porous energy absorbing structures and therefore have the potential to be significantly lighter than thick homogenous energy absorbing metals. Furthermore, the proposed blast mitigation mechanism uses novel, low density, honeycomb structures that absorb energy elastically and are therefore inherently reusable. Such honeycombs can also be functionaly graded with the ability to spread the load providing the possibility of mitigating the detrimental effect of an increased transmitted peak force found in traditional honeycombs.

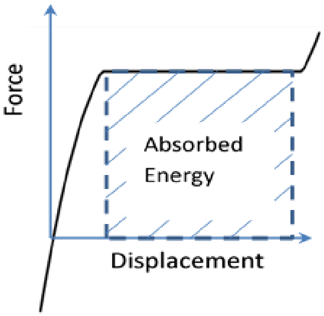

Figure 1: Ideal shock response of honeycomb/foam structures

The honeycomb panel is made from NS-based ideal shock isolator units, originally developed by UTA researchers [1]. Such an ideal shock isolator unit acts as a stiff structure until a threshold force is applied (such as the loading from a shock or blast event), at which point it provides a constant force response to the applied shock loading, absorbing a maximum amount of input energy for a given displacement and allowable force transmission or threshold. The ideal shock response is shown in Figure 1, where the force plateau represents the force threshold. The sequential effect of force application on the NS unit cell is shown in Figure 2.

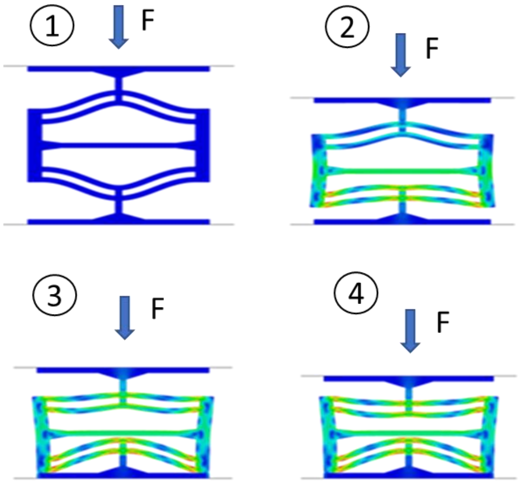

Figure 2: NS unit cell - effect of force application

This unit cell shock isolator is composed of pre-curved beams that buckle from one state to another upon application of a threshold force. The shock mitigation mechanism happens entirely within the elastic region of the material within the curved beam, absorbing energy much like a constant force washer spring. In contrast, solid metals, traditional honeycombs or auxetic materials absorb energy via plastic deformation of the constituent metals. Unlike these other materials, therefore, NS-based honeycombs absorb energy in a fully recoverable way.

A prototype NS-based unit cell made from 17-4 stainless steel specifically designed and fabricated for shock mitigation is shown in Figure 3a for illustration purposes. This particular unit cell was previously designed and fabricated for recoverable shock mitigation. The corresponding experimentally obtained shock response is shown in Figure 3b. The unit cell was experimentally tested at a strain rate on the order of 10^2/s, which approaches blast strain rates. The unit cell reduced the input acceleration of 12,000g to a transmitted acceleration of 800g in an instrumented drop test, which is the largest scale of testing conducted so far. The unit cell does not dissipate the energy but instead absorbs the energy during the original impact, storing it as potential energy, and then releasing it during the rebound over a much longer time period resulting in a significantly lower transmitted acceleration.

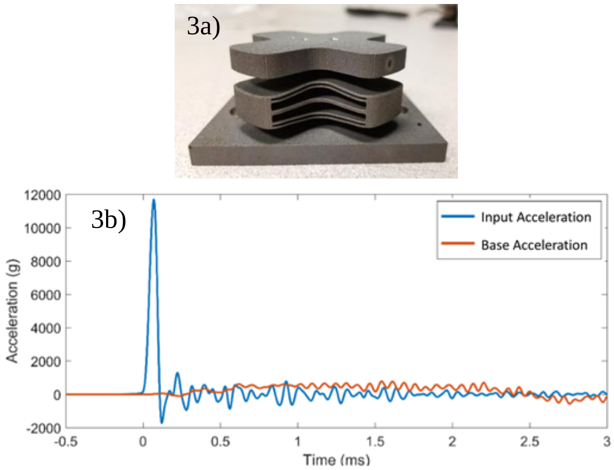

Figure 3: a) Prototype NS-Based unit cell manufactured using SS 17-4 and b) experimental shock response [2]

It is important to note that this specific unit cell is a 3D design, fabricated using additive manufacturing techniques, that is intended to conform to the underlying surface. This is in contrast to a 2D planar design that would be more suitable to a flat surface. Such a 3D design is meant to conform to a surface in an interlocking and modular manner.

Critical Dimension
Beam Thickness (t)
Center Thickness (ct)
Beam Length (L)
Bistability (Q)
Apex Height (h)
Beam Offset (off)
Stem Width (sw)

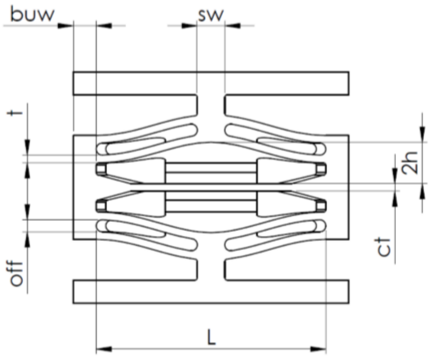

Figure 4: NS-Based unit cell design parameters

Important design parameters for the NS-based unit cell are shown in Figure 4. Beam thickness (t) denotes the thickness of the pre-curved beam. Center thickness (ct) denotes thickness of the center beam that stabilizes the unit cell and prevents outward buckling during shock loading. Beam length (L) denotes the horizontal length of the pre-curved beam. Apex height (h) is the free height between the apex of the curved beam and the center beam, dictating the amount of allowable travel of the pre-curved beam prior to bottoming out. Beam offset (off) is the offset between the negative stiffness beams. Stem width (sw) is the width of the stem through which the load is transferred to pre-curved beams. Bistability (Q) is a design parameter that affects the bistability of the unit cell and therefore the force threshold [2].

2. Unit Cell Blast Response

For the purposes of this study, an NS-based unit cell was designed and simulated in Abaqus/CAE 2018.HF1 finite element analysis (FEA) software [2] specifically to mitigate blast loading and to predict the response of the unit cell to such a loading. The blast load used in this study is shown in Figure 5. The blast load is based on CONventional WEApons (CONWEP) simulation approach obtained from Erdik *et al.* [3]. The blast profile assumes the use of 1kg TNT at a 0.5 m standoff. This particular blast profile has a peak incident overpressure of 3.9 MPa and a positive phase duration of 0.32 ms.

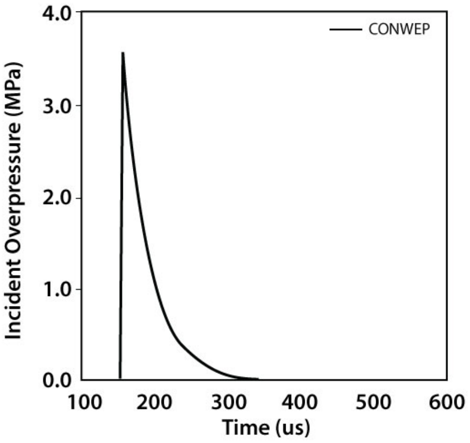

Figure 5: Representative blast load [3]

Prior to the Abaqus simulation, analytical equations [4] were used to optimize the energy absorbed by the NS honeycomb for a representative impulse and a fixed length, L = 40mm. The resulting design is based on the configuration shown in Figure 4 including four upward curving and four downward curving beams, each with dimensions of t = 0.3 mm and h = 1.3mm.

A combination of solid and shell elements was used to create the finite element mesh. A part with the shell thickness rendered is shown in Figure 6. The Abaqus S4R shell element, with enhanced hourglass control, was used to model the curved beams. The S4R element is a quadrilateral shell with reduced integration. The Abaqus C3D8R element, also with enhanced hourglass control, was used to mesh the remaining parts of the model, including the bumpers.

Figure 6: Shell/solid combination mesh [3]

The material assumed for this simulation is direct metal laser sintered (DMLS) SS 17-4 with a yield strength of 1 GPa, a yield strain of 0.00508, and a Young's modulus of 197 GPa. A dynamic explicit simulation was used with the entire model assigned a time-varying velocity dependent upon the desired integrated impulse acceleration. The bottom center node was constrained with respect to in-plane displacement.

The blast impulse and the corresponding acceleration of the top plate of the NS-based unit cell are shown in Figure 7. As can be seen from Figure 7 the input acceleration of 30,000 g's is significantly attenuated; as it absorbs the mechanical kinetic energy imparted by the blast, it slows the motion of the top (outer) plate, extending the duration of the impact and lowering the peak acceleration experienced by the outer plates of the NS-based unit cell. This unit cell was designed to maximize the amount of energy absorbed by the snap-through event given the fixed length of the unit cell. Further optimization is possible by absorbing energy progressively with unit cells placed in series.

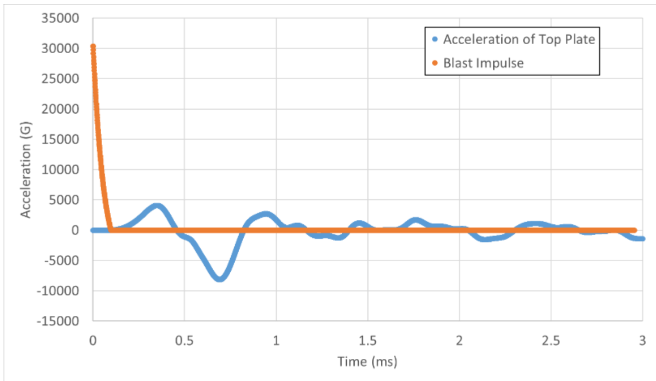

Figure 7: Simulated shock response of NS unit cell designed for blast mitigation

The force and stress thresholds of this particular design are 1,100 N and 0.85 MPa. Calculated energy absorbed is 2.55 J with a NS unit cell mass of 26 g (excluding the mass of potential top and bottom plates). This results in an as yet unoptimized energy absorbed per unit mass of ~0.1 J/g. This currently compares to on the order of 1J/g for hexagonal honeycombs [5] for a similar stress threshold configuration and ~0.5J/g for SS 17-4 PH (or precipitation hardened).

3. NS-Based Honeycombs

The honeycomb structure is built by layering these unit cells across the thickness of a panel while staggering the unit cells when moving from one layer to another. An illustration of such a honeycomb configuration is shown in Figure 8. While 2D planar unit cells are shown for illustration purposes, 3D conformal cells could be used in a similar manner.

The advantage of staggering unit cells in the honeycomb layout is that the shock is distributed across a wider and wider area activating more and more unit cells as the shock moves through the thickness of the panel. This is a significant advantage of the current approach in that it could avoid the “dishing” effect observed in traditional honeycomb shock absorbers [6]. Such an effect happens because the shock absorption is more localized resulting in a concave shape, much like a dish or bowl, which increases the input kinetic energy from the blast or shock.

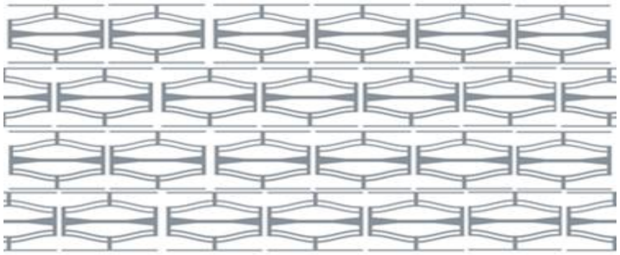

Figure 8: NS-Based honeycomb panel

In order to further mitigate “dishing” effects, NS unit cells at the front could be stiffer with unit cells getting progressively more compliant and absorbing less energy moving from the front to the back. Stiffer unit cells at the top would absorb a larger portion of the energy while ensuring the unit cells remain parallel to the applied force direction. In the case of loading at an angle the unit cells are significantly stiffer along the normal or transverse direction and should therefore only respond to the component of the loading parallel to the loading direction.

4. Application

This design approach can be integrated as part of up-armoring approaches in the near term for current platforms, or as part of a more integrated part of future vehicle structural designs. Figure 9 is a cartoon showing response of the honeycombs integrated into the underside of a vehicle. Red shading visualizes unit cells that could be activated from a localized blast, illustrating how the shock from the blast would be distributed over a progressively wider area as the shock moves upward towards the vehicle.

The proposed honeycombs are porous and therefore would be expected to be lighter than homogenous materials when fully optimized while potentially mitigating force amplification effects observed in traditional honeycombs. As such, the approach will continue to ensure soldier protection while improving ride quality. Additionally, the proposed honeycombs are resettable and could potentially be re-used.

While damage would be expected on the surface layer due to shrapnel and other ballistic loadings, the damage could potentially be absorbed with a properly designed front plate. Furthermore, the modularity afforded by the unit cell approach would allow for discarding of damaged cells while reusing the intact ones. Such an advantage would apply equally to both the 2D planar and 3D conformal unit cells.

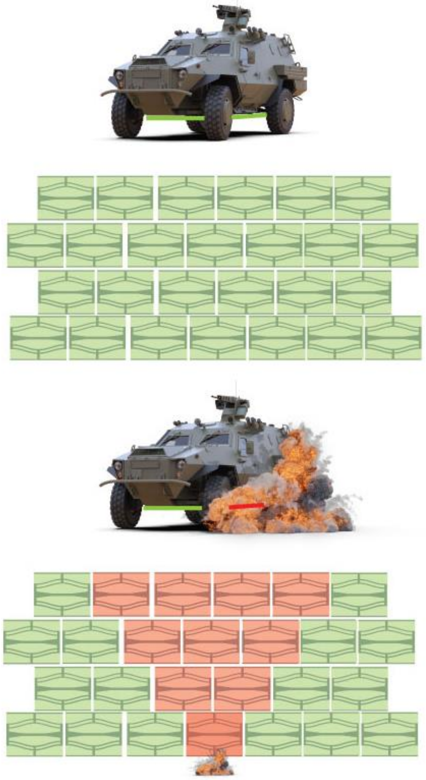

Figure 9: Blast mitigation honeycomb panel on underside of vehicle – illustrating shock propagation

Acknowledgements

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