

Auxetic Metamaterials under Direct Impact Loads in a Structural Health Monitoring Framework

**by James Ayers, Ben Chamish, Tzi-Kang Chen, Anindya Ghoshal, Chandan
Kittur, Michael Coatney, Natasha Bradley, and Tyrone Jones**

ARL-TR-6306

January 2013

NOTICES

Disclaimers

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

Citation of manufacturer's or trade names does not constitute an official endorsement or approval of the use thereof.

Destroy this report when it is no longer needed. Do not return it to the originator.

Army Research Laboratory

Aberdeen Proving Ground, MD 21005

ARL-TR-6306**January 2013**

Auxetic Metamaterials under Direct Impact Loads in a Structural Health Monitoring Framework

**James Ayers, Tzi-Kang Chen, Anindya Ghoshal, Chandan Kittur,
Michael Coatney, and Natasha Bradley
Vehicle Technology Directorate, ARL**

**Ben Chamish and Tyrone Jones
Weapons and Materials Research Directorate, ARL**

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188		
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.					
1. REPORT DATE (DD-MM-YYYY) January 2013		2. REPORT TYPE Final		3. DATES COVERED (From - To) 1 October 2011 to 30 September 2012	
4. TITLE AND SUBTITLE Auxetic Metamaterials under Direct Impact Loads in a Structural Health Monitoring Framework			5a. CONTRACT NUMBER		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) James Ayers, Ben Chamish, Tzi-Kang Chen, Anindya Ghoshal, Chandan Kittur, Michael Coatney, Natasha Bradley, and Tyrone Jones			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Research Laboratory ATTN: RDRL-VTM Aberdeen Proving Ground, MD 21005			8. PERFORMING ORGANIZATION REPORT NUMBER ARL-TR-6306		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSOR/MONITOR'S ACRONYM(S)		
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT Under direct impact from ballistic loads, acoustic waves typically propagate throughout a structural component causing damage to sensitive areas. For structures with intelligent embedded monitoring systems, such as mounted piezoelectric actuators, a direct impact between 150–200 m/s of small-caliber rounds has produced catastrophic results. This report focuses on redirecting acoustic waves using non-traditional structural configurations. The technical approach utilizes periodic and graded metamaterials (produced from auxetic cellular, lattice topology and material composition), which are lightweight and can be assembled for extreme anisotropy and phononic bandgaps, which can be exploited to alter the propagation path of high amplitude stress waves. This research focuses on the initial stage of understanding how to tailor periodic lattices for highly concentrated impact and blast loads, which generally produce a broadband frequency response and yield only partial bandgaps. Specific attention is given to square, hexagonal, re-entrant, and modified re-entrant topologies. As a baseline comparison, a solid aluminum plate is examined against uniform and graded re-entrant unit cell lattices. The plates are individually subjected to both in- and out-of-plane direct impact loading conditions of a 0.22-caliber fragment simulating projectile traveling at 300 m/s. A less than 10% marginal difference in peak stress amplitude exists between the loading conditions for a given single through-the-thickness unit cell.					
15. SUBJECT TERMS Auxetic, metamaterials, lattice, impact					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 26	19a. NAME OF RESPONSIBLE PERSON James Ayers
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (Include area code) 410-278-7650

Contents

List of Figures	iv
List of Tables	iv
1. Background and Motivation	1
2. Objectives and Technical Approach	3
3. Numerical Analysis	3
3.1 Numerical Setup	4
3.2 Numerical Results	7
3.2.1 Full-field Wave Propagation	7
3.2.2 In-plane Loading Quantitative Comparison	11
3.3.3 Out-of-plane Loading Quantitative Comparison.....	13
4. Experimental Investigation	14
4.1 Experimental Setup	14
4.2 Experimental Results.....	15
5. Conclusions	16
6. References	18
List of Symbols, Abbreviations, and Acronyms	19
Distribution List	20

List of Figures

Figure 1. Notional embedded structural health monitoring system for impact.	1
Figure 2. Finite element method (FEM) parameterization: (a) Hexagonal honeycomb (angle $\theta = 30^\circ$), (b) rectangular cell (angle $\theta = 0^\circ$), (c) re-entrant cell (angle $\theta = -10^\circ$), (d) hexagonal cell with linear variation of the cell thickness in Z direction, (e) hexagonal cell with gradual variation in X-Y plane, and (f) re-entrant cell with banded thick wall regions.	4
Figure 3. (a) View of projectile (green)-lattice (magenta) interface and (b) magnified view.	5
Figure 4. Loading conditions: (a) in-plane impact and (b) out of plane impact of the FSP impacting the periodic lattice.	6
Figure 5. Loading profile: (a) time domain and (b) frequency content.	6
Figure 6. Comparison of time history of wave propagation for in-plane loading: (a) solid plate, (b) uniform auxetic lattice, and (c) graded T-banded auxetic lattice.	8
Figure 7. Comparison of time history of wave propagation for out-of-plane loading: (a) solid plate, (b) uniform auxetic lattice, and (c) graded T-banded auxetic lattice.	10
Figure 8. Identified monitoring locations for (a) in-plane and (b) out-of-plane load.	11
Figure 9. In-plane loading comparison per spatial location for uniform auxetic lattice: (a) radial alignment and (b) vertically aligned points.	12
Figure 10. In-plane loading solid versus auxetic lattice configuration: (a) point 4 and (b) point 8.	12
Figure 11. Out-of-plane loading comparison per spatial location: (a) radial and (b) vertical points.	13
Figure 12. Out-of-plane loading solid vs. lattice configuration: (a) point 4 and (b) point 8.	14
Figure 13. Auxetic panel: (a) schematic and (b) plexiglass panel with bonded piezoelectric actuator.	15
Figure 14. Auxetic panel subjected to continuous harmonic loads: excitation frequency at (a) 35 kHz and (b) 65 kHz.	16

List of Tables

Table 1. Monitoring point location relative to an origin (0,0) at lower left corner.	11
---	----

1. Background and Motivation

Under direct impact from ballistic loads, acoustic waves will typically propagate throughout a structural component and may cause damage to sensitive areas. Sensitive areas may be defined as primary structural elements (PSE) that are critical for mission performance, i.e., embedded hardware such as avionic controlling devices or intelligent systems that allow for structural state awareness (figure 1). For structures with intelligent embedded monitoring systems, such as mounted piezoelectric actuators, a direct impact between 150–200 m/s of small-caliber rounds has produced catastrophic results (1). One way to reduce the wave propagation is to design a larger structure, which lowers the resulting localized stress, while increasing undesirable weight. Another design strategy is to guide the waves away from the critical areas by built-in energy arresters or lightweight structured materials. Air-based vehicles, such as airplanes and helicopters, generally require the weight to be minimized for range and endurance. This report focuses on redirecting guided waves using non-traditional structural configurations that are conventionally lightweight.

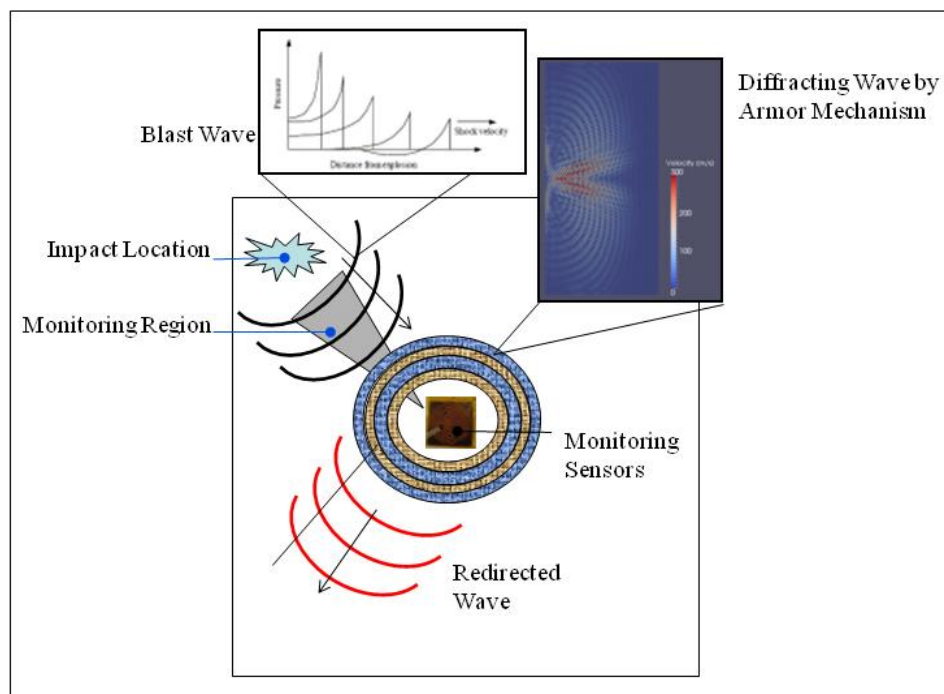


Figure 1. Notional embedded structural health monitoring system for impact.

Traditional passive armor platforms operate under two stages during a small arms ballistic event: (1) arresting the projectile and (2) energy dissipation. Extensive armor research has focused on ceramic materials, which are some of the most efficient armor materials to mitigate momentum

transfer of a small- or medium-caliber projectile (2). Ceramic recipes rely on stiffness from backing materials to work on arresting the projectile. These backing materials are usually bonded behind ceramics with low-density, low-impedance, and low shear strength adhesives. The backing is largely used to dissipate the kinetic energy in a ceramic armor system. As an example, experimental and modeling methods have been developed to investigate mechanical responses on sandwich composite panels subjected to the impact of explosively driven wet sand (3). Under high-intensity dynamic loading, sandwich panels suffered 30% less deflection than equivalent solid plates. One-dimensional studies were used to study the momentum and energy transfer to plates in air blasts (4).

Other work investigated the dynamic behavior of two types of sandwich composites composed of E-Glass Vinyl-Ester (EVE) face sheets and Corecell™ A-series foam with a polyurea interlayer (5). Using a shock tube apparatus to subject samples to high-intensity impulse loading, results show that the addition of polyurea interlayer improves the overall blast performance and maintains structural integrity. However, ceramic armor concepts can suffer due to parasitic weight. One method of reducing the energy is by redirecting a significant portion of the energy, i.e., shock waves, as the projectile impacts the armor, which improves the ballistic performance of passive armor systems (6). It is expected that the understanding and development of novel dynamic energy dissipation mechanisms for armor systems under high ballistic loading rates will forge the development of new and possibly improved solutions for protection (7).

Metamaterial research is an emerging area due to recent advances in additive manufacturing and has been broadly defined as materials that have properties associated with the structure as opposed to their inherent chemical composition. One researched metamaterial is a periodic lattice, which has the distinct structural advantage of redundancy for load paths and contact interface. One such periodic lattice is the auxetic configuration, which is characterized by a negative Poisson's ratio, where the lattice exhibits a dilatation under tensile loads and contraction under compressive loads. Continuous periodic structures with a cell structure smaller than a desired wavelength will attenuate and guide waves (8). Unit cells with negative internal angles have shown to reduce the angular range of wave propagation (9). In addition, auxetic topologies with angles between -30° and 30° have shown to propagate waves primarily in the vertical direction. The negative internal angle has the added benefit of having significantly less propagation in the horizontal direction. There is also a change in the directionality depending on the frequency of the excitation.

Other work focused on in-plane wave propagation in chiral lattices using Bloch analysis, with sets of parameters that affect the elasto-dynamic behavior, suggesting a class of lattice for designing novel photonic metamaterials (10). Periodicity has been exploited with resistive inductive (RL) shunted piezoelectric patches to control vibrations of a cantilever aluminum plate (11). Results indicate that the unit cell approach can predict the actual response of the system.

The auxetic lattice also exhibits anisotropy, which means a dependence on direction. Since the acoustic waves must follow a path along the structure, the energy is diverted in the path of least resistance. Functionally graded materials (FGMs) have been modeled to investigate propagation of large amplitude waves within layered and graded structures. Results illustrate that it involves complex coupling of elastic and viscoelastic responses (12).

2. Objectives and Technical Approach

The primary objective of this research is to understand how waves propagate in inorganic materials under direct impact loads. A secondary goal is to develop optimized structures that distribute energy and stress levels to specified locations. The approach is to utilize the anisotropic behavior of auxetic periodic lattices to redirect the energy, and then to fabricate and test the metamaterials under prescribed loading conditions that are parallel and perpendicular to the periodicity of the lattice. The developed configurations are evaluated against a baseline configuration, which is a simplified metallic plate.

3. Numerical Analysis

The models of three-dimensional (3-D) lattice structures are generated for finite element analysis using solid continuum elements. In order to build and update the structures models with different shape, size, and details of the cell, the models were generated using Abaqus/CAE with plug-in Python codes that generate the models with different parametric features. The following features were designed for variation, as shown in figure 2:

1. Model geometric dimensions: (X, Y, Z)
2. Shape of the unit cell (hexagon, rectangular, re-entrant)
3. Angles of the cell (θ)
4. Sizes of the unit cell (a, h)
5. Wall thickness in the unit cell (t_1 , t_2)
6. Linear variation of the cell wall thickness in model thickness direction (Z)
7. Variation of the cell wall thickness in model X-Y plane (gradually or banded)

After a geometric model is generated in Abaqus/CAE, the model is then exported as a Standard ACIS Text (SAT) format file. The consequent models are meshed in CUBIT and solved by the well known hydrocode Elastic-Plastic Impact Computations (EPIC).

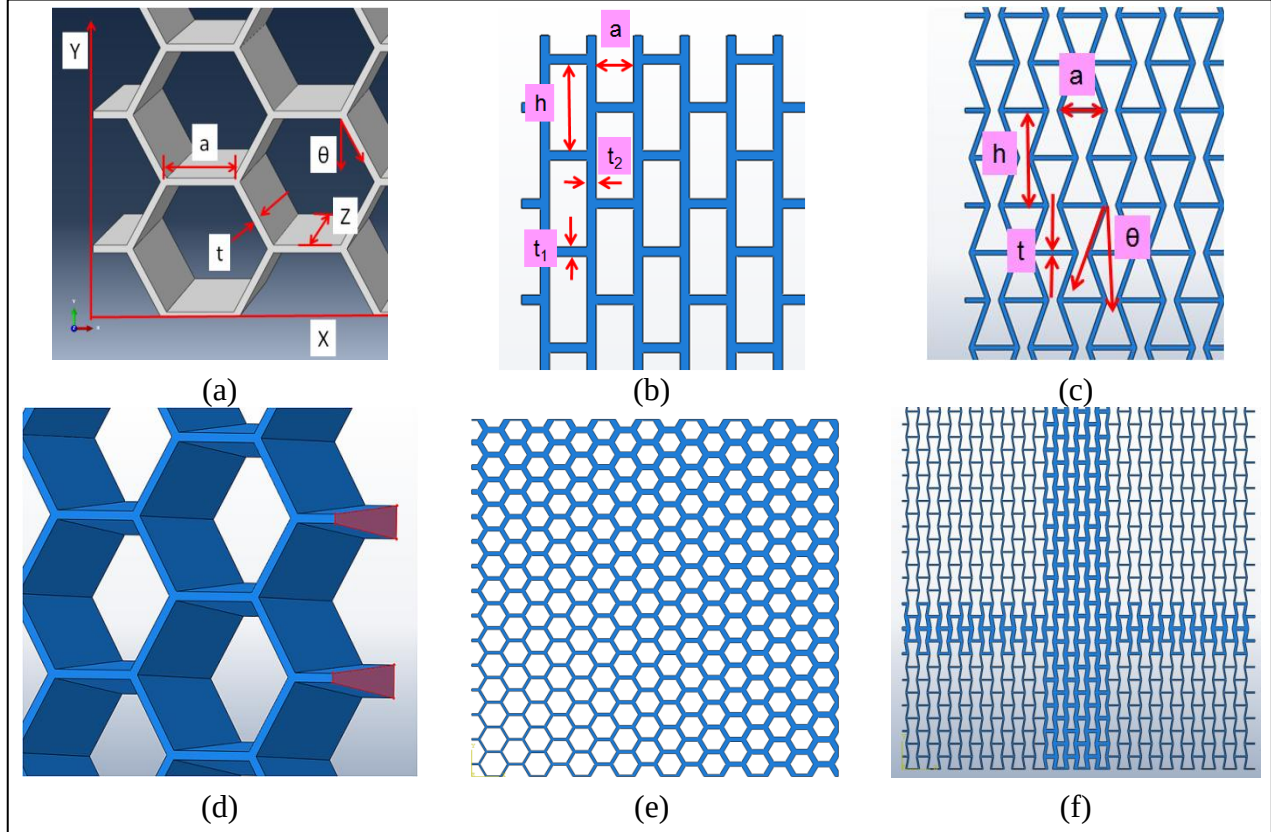


Figure 2. Finite element method (FEM) parameterization: (a) Hexagonal honeycomb (angle $\theta = 30^\circ$), (b) rectangular cell (angle $\theta = 0^\circ$), (c) re-entrant cell (angle $\theta = -10^\circ$), (d) hexagonal cell with linear variation of the cell thickness in Z direction, (e) hexagonal cell with gradual variation in X-Y plane, and (f) re-entrant cell with banded thick wall regions.

3.1 Numerical Setup

The analysis of the auxetic systems used an in-house military hydrocode, known as EPIC. EPIC is an explicit finite element code that is used to model material response under dynamic loading conditions (13). Developed in 1977, this code supports 1-, 2-, and 3-D calculations for a variety of ballistics applications. The high/hyper velocity projectile-target interactions capabilities were employed to aid with the lattice geometry. EPIC provides numerous material model options to facilitate the modeling of a wide range of materials, including ductile solids (e.g., metals and plastics), crushable solids (e.g., concrete and foam), liquids, brittle solids (e.g., ceramics and glass), fabrics (e.g., Kevlar and nylon), composites, soils, and explosives. In addition, EPIC's material library provides more than 175 sets of material model constants. Problems involving large deformations typically require the use of EPIC's element erosion/conversion options,

wherein finite elements are either eroded (eliminated) or converted to particles when their inelastic strains have exceeded a user-specified threshold level. EPIC's Generalized Particle Algorithm (GPA) is used to model the behavior of the converted particles. The solid model geometries discussed in section 3 were created in Abaqus/CAE then meshed externally with the software CUBIT. The meshed model was then transferred to the EPIC software. The discretization of auxetic panels was high enough to necessitate parallel processing, and the models were solved using EPIC on eight processors.

The auxetic plates were modeled as Aluminum 5083 using EPIC's proprietary library constants, which uses Johnson-Cook's (JC) strength and failure model (figure 3a). The fragment simulating projectile (FSP) was modeled with EPIC's 4340 Rolled Homogenous Armor (RHA) library constant also constructed with JC strength and failure model (figure 3b). In order to distribute the load at the impact location and reduce the projectile perforating the lattice, a secondary disk twice the size of the FSP (11.2 mm) in diameter wide and 2 mm thick is located on top of the lattice (seen in figure 3b). The intermediate disk provided successful results by spreading out the force applied by the FSP to the lattice and was included in subsequent simulations.

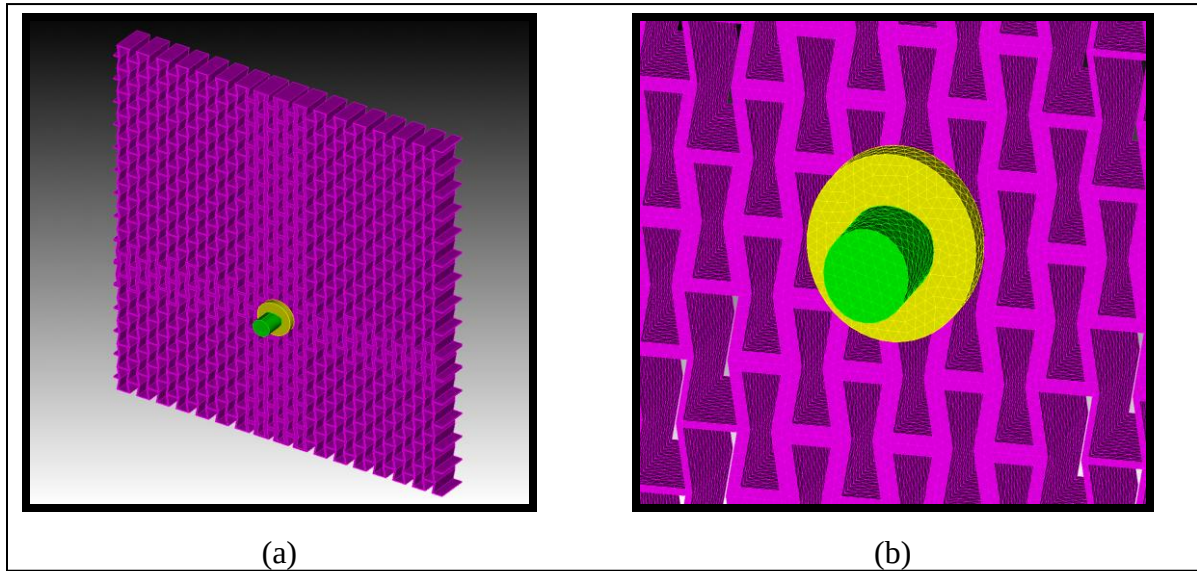


Figure 3. (a) View of projectile (green)-lattice (magenta) interface and (b) magnified view.

In order to understand the low velocity effects, the FSP travels at a prescribed impact velocity of 300 m/s. This velocity was determined after several iterations, where the structural response was above initial noise levels without perforating the structure. Both materials use a Mie-Gruneisen equation of state, which accounts for the relationship between the pressure and volume of a solid at a given temperature. Two impact locations were examined to understand the relative effect of the lattice periodicity in the x-y plane: an in-plane load located at the top surface of the panel and

an out-of-plane load whose impact was located where the T-banded horizontal and vertically graded unit cells intersect (figure 4).

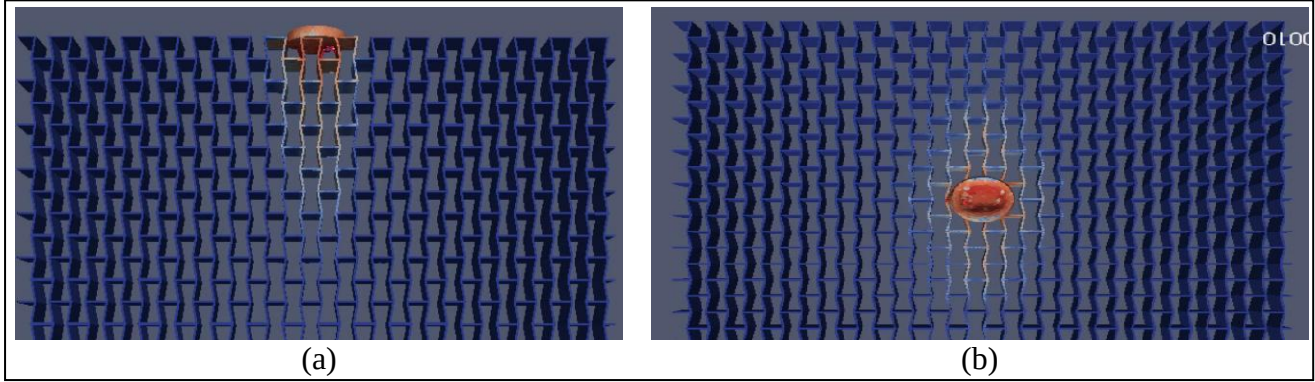


Figure 4. Loading conditions: (a) in-plane impact and (b) out of plane impact of the FSP impacting the periodic lattice.

The primary purpose of the loading study is to understand how the stress waves travel to exploit the in-plane periodicity and answer the fundamental question whether out-of-plane loading may be successfully directed by a periodic panel in the in-plane direction.

The loading profile from the impact was determined by summing the nodal forces at the point of impact throughout the time interval in which the load rapidly decays. The temporal and spectral profiles are provided in figure 5a–b. It can be seen that for the given FPS, the primary frequency lobe is between 10–50 kHz, which will be a consideration later in the design of the unit cell size and respective geometry selection per reference 9.

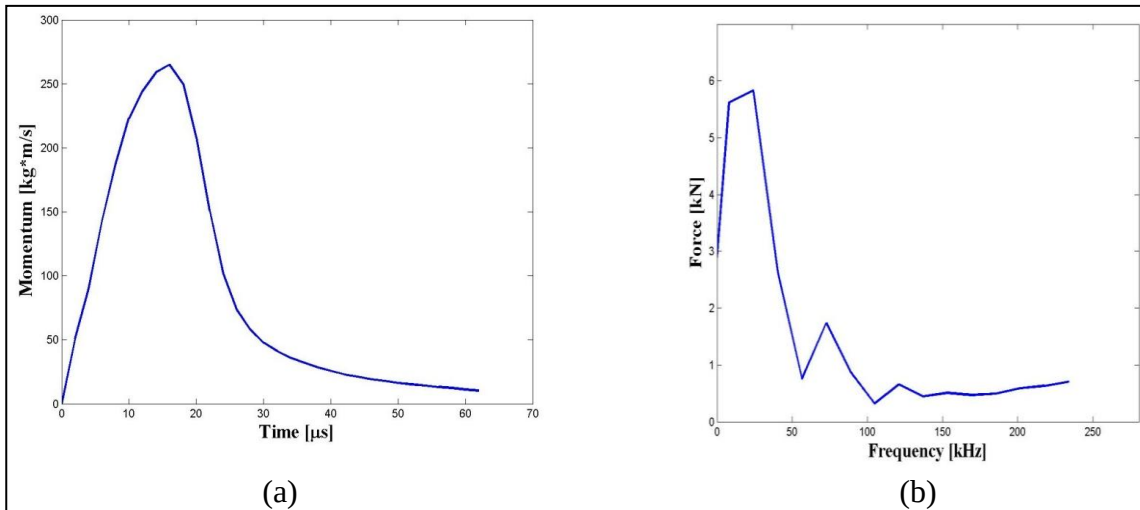


Figure 5. Loading profile: (a) time domain and (b) frequency content.

3.2 Numerical Results

Full-field wave propagation effects and single point analysis are compared for given plate configurations and loading conditions. A qualitative study of the wave propagation is performed on three different plate configurations. A quantitative study of individual points on the plates relative to the impact load is then provided.

3.2.1 Full-field Wave Propagation

As a qualitative comparison of the stress wave interaction within the periodic configurations, figure 6a–c shows sequential progression at 20 μ s intervals of three different plate configurations: a solid aluminum plate, a homogeneous plate with a re-entrant unit cell, and a T-banded graded plate with a re-entrant unit cell. For comparative purposes, each plate was designed with equivalent mass, where the length and width spatial dimensions were fixed, while the depth of each configuration is varied.

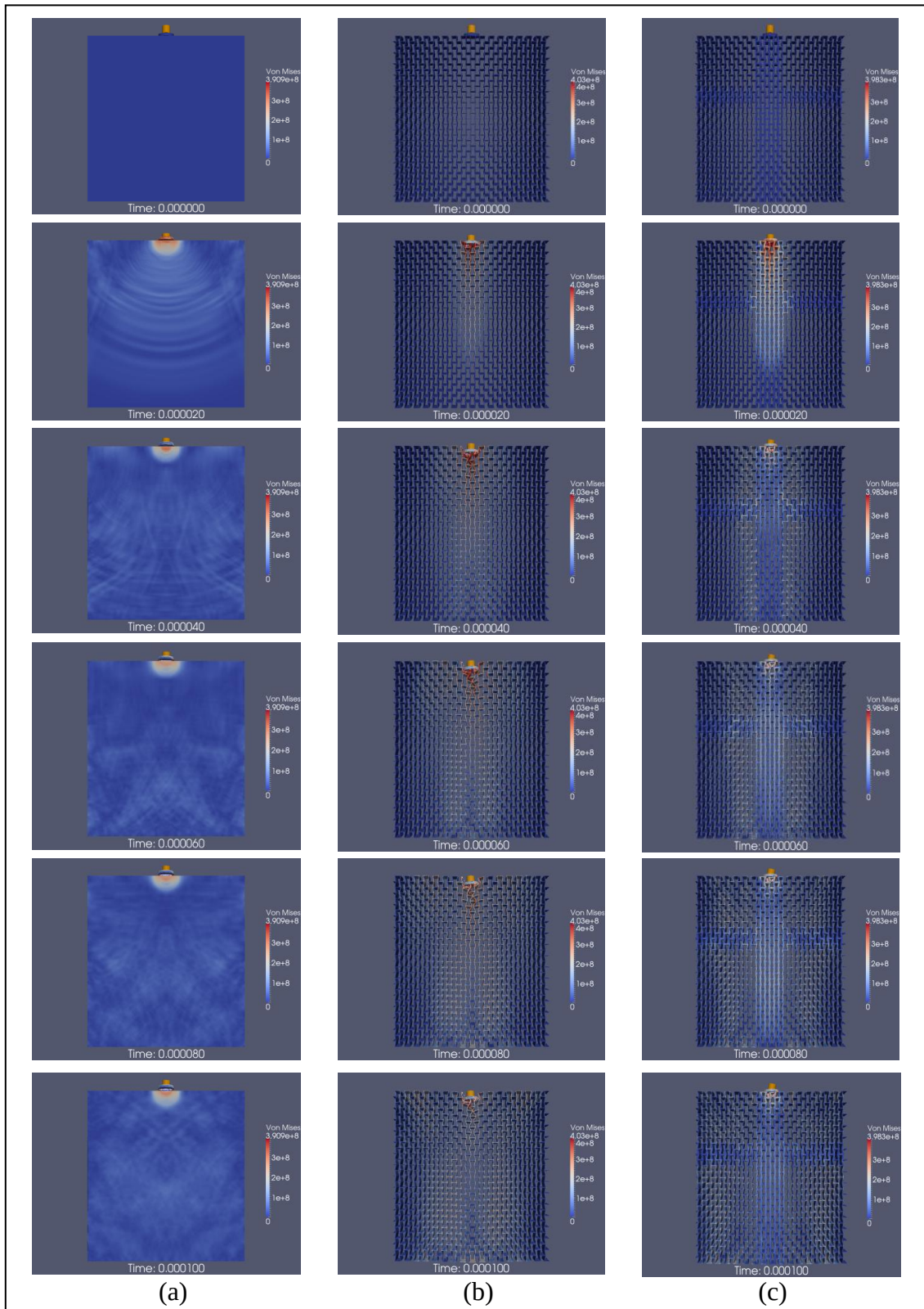


Figure 6. Comparison of time history of wave propagation for in-plane loading: (a) solid plate, (b) uniform auxetic lattice, and (c) graded T-banded auxetic lattice.

Qualitatively, from figure 6a, the solid plate exhibits radial waves, which are then reflected at the boundaries and a complex interaction exists between the incident and reflected waves after the 40- μ s time interval. The uniform and graded T-banded auxetic panels illustrate the apparent vertical anisotropic behavior of the panels, where the maximum stress field is clearly vertically oriented, particularly in the figure 6c. Rather than radial waves, this observed redirection of the energy is possible for in-plane impact loading due to the inherent in-plane unit cell periodicity. In contrast, figure 7a–c depicts the solid and auxetic plates under out-of-plane loading at the 80- μ s interval, such that the axis of the FSP is perpendicular to the mid-plane of the plate.

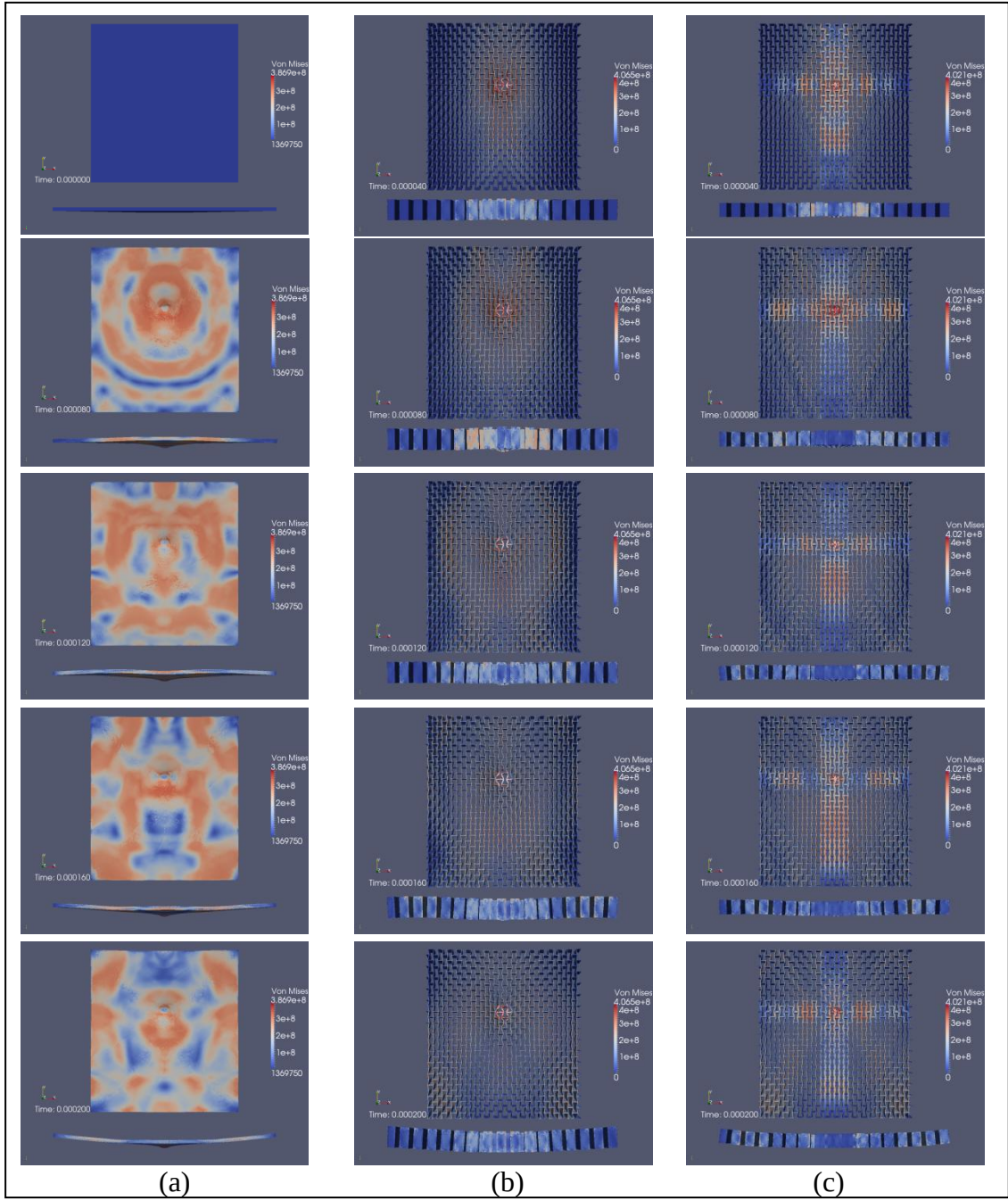


Figure 7. Comparison of time history of wave propagation for out-of-plane loading: (a) solid plate, (b) uniform auxetic lattice, and (c) graded T-banded auxetic lattice.

The circular-crested generated waves are qualitatively evident in the solid plate (figure 7a), whereas significantly less vertical redirection of the energy is apparent in figure 7b–c. This phenomenon may be attributed to the single through-the-thickness unit cell within the auxetic lattices. The anisotropy produced from the unit cell periodicity is not exploited, as observed in the in-plane loading conditions.

3.2.2 In-plane Loading Quantitative Comparison

For in-plane loading, the plates were monitored at specific locations to more fully understand the effect of the auxetic lattice, consequent grading effects, and the dependence on the loading direction. Figure 8 identifies the eight monitoring points, and table 1 provides the (x,y) locations relative to the origin at the lower left corner. Eight points were identified for each plate configuration: four radially aligned (numbered 1–4) and four vertically aligned (numbered 5–8).

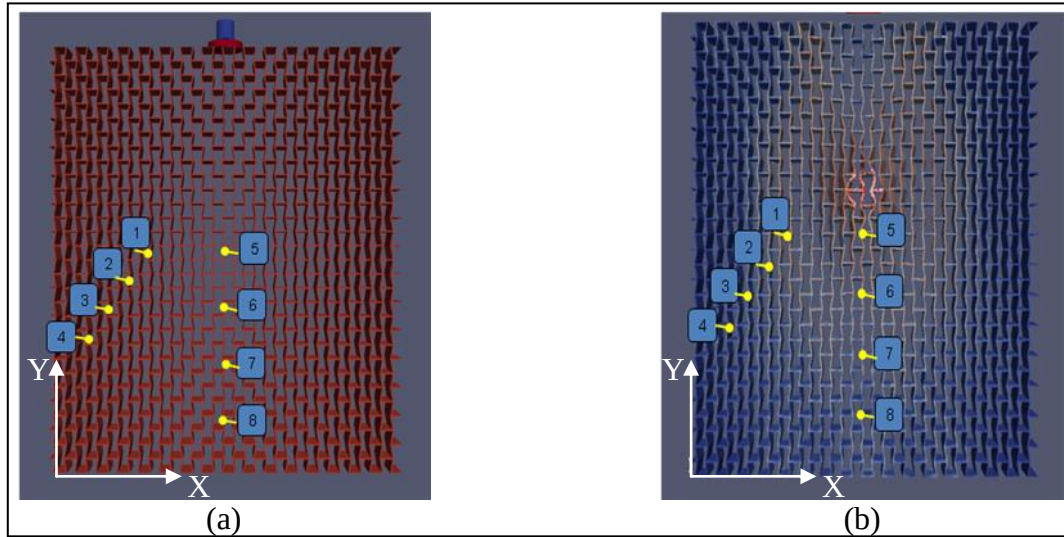


Figure 8. Identified monitoring locations for (a) in-plane and (b) out-of-plane load.

The monitoring points (table 1) were spatially identical for each plate configuration, solid and auxetic, for subsequent quantitative comparisons.

Table 1. Monitoring point location relative to an origin (0,0) at lower left corner.

Point	X [mm]	Y [mm]
1	32	52
2	25	44
3	19	36
4	12	28
5	55	52
6	55	36
7	55	20
8	55	4

Figure 9a–b compares the radial and vertically aligned points as a function time and von Mises stress for the uniform auxetic lattice.

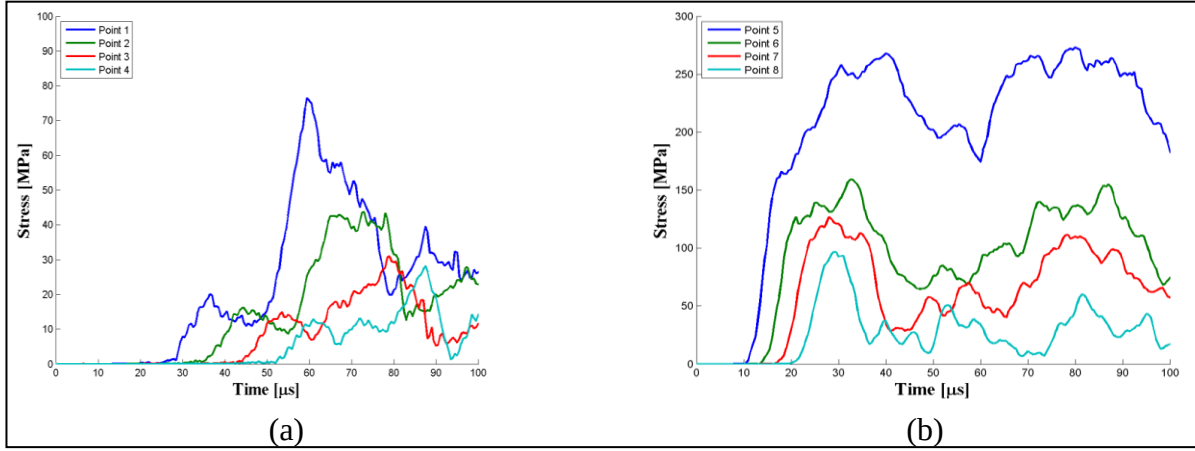


Figure 9. In-plane loading comparison per spatial location for uniform auxetic lattice: (a) radial alignment and (b) vertically aligned points.

From figure 9a–b, it is observed that the maximum Von Mises stress occurs at Points 1 and 5, which is expected due to their proximity to the impact location. For the radially aligned points, the relative peak stress is reduced by 62.5% from Point 1 to Point 4, which is approximately equivalent to the vertically aligned stress reduction of 64.5% from Point 5 to Point 8. Potential reasons for the dramatic reduction are wave attenuation through material damping, boundary interaction, and distribution of the energy through the periodic ligaments.

A comparison between the solid, uniform auxetic, and graded auxetic are shown for selected points in figure 10a–b.

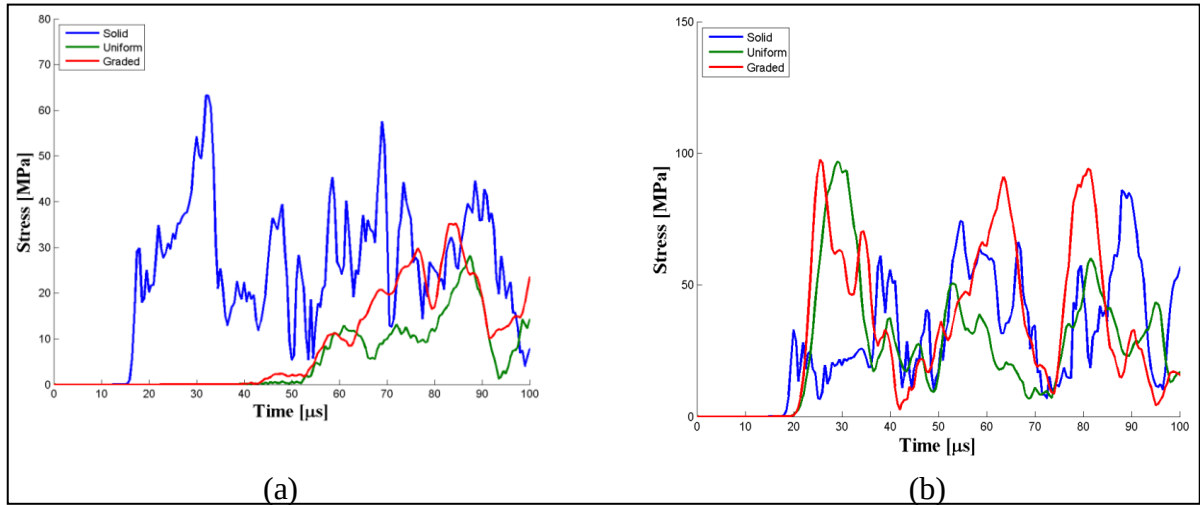


Figure 10. In-plane loading solid vs. auxetic lattice configuration: (a) point 4 and (b) point 8.

From figure 10a, the incident arrival time of the wave is a factor of 2.9 faster in the solid plate than the auxetic lattice at radial Point 4, and a factor of 1.9 larger in peak stress amplitude. This significant discrepancy highlights the effectiveness of the auxetic lattices to directionally orient the energy per the designed anisotropy of unit cell. In figure 10b, the initial arrival time of the solid plate is 9.2% faster than the auxetic configurations at the vertical Point 8, whereas the initial peak amplitude decreases by 36.3%. These results further confirm the premise that the energy is steered vertically as the loading remains in-plane to the periodicity, while the wave speeds are approximately equivalent.

3.3.3 Out-of-plane Loading Quantitative Comparison

The identical eight monitoring points are compared for out-of-plane loading conditions, as shown in figure 8b. Figure 11 presents a comparison of the uniform auxetic lattice for the radial and vertical points, and gives specific attention to comparing the solid to auxetic lattice configuration.

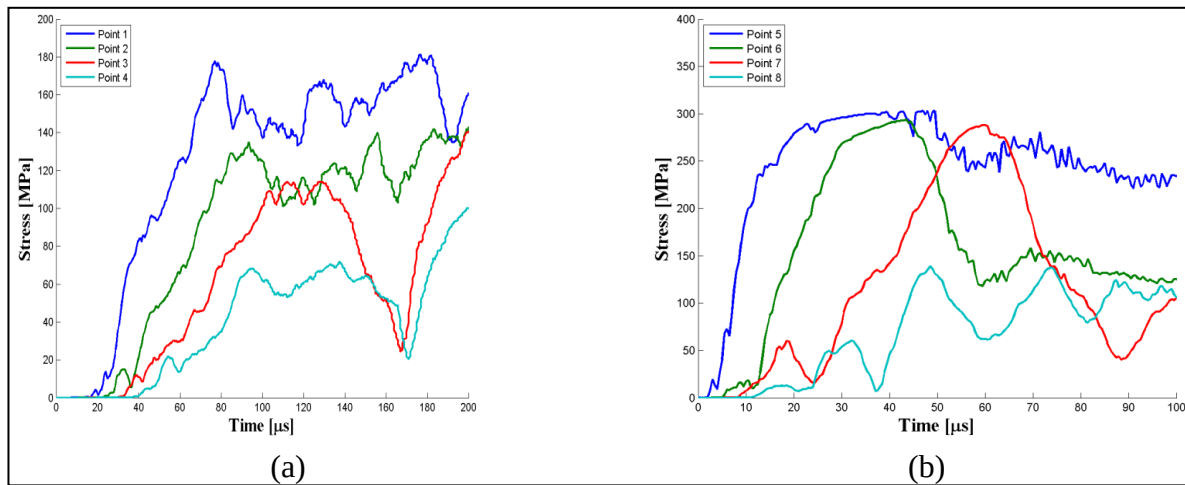


Figure 11. Out-of-plane loading comparison per spatial location: (a) radial and (b) vertical points.

From figure 11a, the peak amplitude ratio is an estimated 3:1 ratio of radial locations Point 1 and Point 4, whereas the peak amplitude of the vertical locations Points 5–7 are within 5%. The distinct variation between the radial and vertical points may be attributed to anisotropy of the auxetic lattice configuration. Figure 12a–b illustrates the solid to lattice variation as a function of time for Point 4 and Point 8.

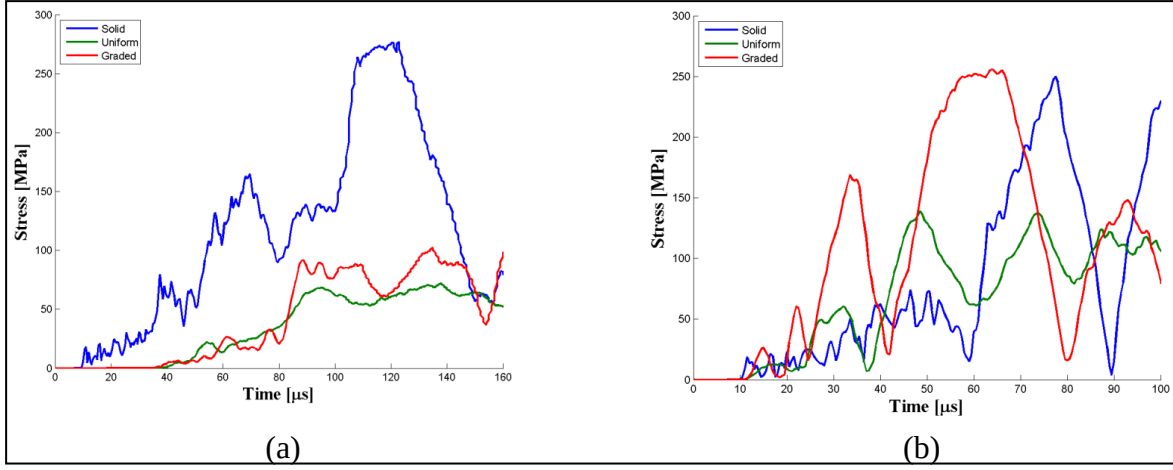


Figure 12. Out-of-plane loading solid vs. lattice configuration: (a) point 4 and (b) point 8.

From figure 12a, the incident wave arrives at Point 4 in the solid configuration by a factor of 3 faster than the graded and uniform configuration, and the peak amplitude is reduced by a factor of 1.8. Comparing the in-plane loading response in figure 10a to the out-of-plane loading response in figure 12a, one concludes that a marginal sensitivity to loading orientation exists relative to the unit cell periodicity. However, the results require additional investigation, such as unit cell variation to primary load frequency content, and material variation. As seen in figure 12b, the peak amplitude of Point 8 at 32 μs for the graded panel configuration is similar to the in-plane loading. Thus, the stress amplitude and consequent energy is directed in the vertical direction, or along the plate anisotropy.

4. Experimental Investigation

As a preliminary study prior to complete ballistic testing of the auxetic panel, the response to harmonic loading and low amplitude impulse loading is performed on an auxetic lattice panel. The following discussion highlights the experimental procedure and setup, and the consequent results from the tests.

4.1 Experimental Setup

In order to experimentally validate the wave guiding phenomenon, an auxetic lattice consisting of a re-entrant unit cell is excited both harmonically and through impulse loads. For convenience to the existing manufacturing capabilities, the lattice material consists of nominal Plexiglass, whose unit cell height is 3 mm, with overall rectangular dimensions of 210 x 200 mm (figure 13). Fiber Bragg grating sensors (FBGs) are bonded to the lattice's top surface to optically detect strain. FBGs are used in conjunction with a four-channel optical sensing

interrogator, an si920 purchased from MicronOptics, Inc. The si920 has a maximum sampling rate of 500 kS/s for a single channel, or a 120 kS/s. By pulsing a light through the fiber, an internal algorithm within the si920 converts the change in wavelength from the FBG to a calibrated strain.

Figure 13a–b shows the experimental setup of the Plexiglass lattice. Two FBGs are placed along the vertical Y-axis where the primary incident wave is expected to propagate. Two additional FBGs are located radially at 45° from the actuator, where the propagation is expected to be significantly less. In the harmonic loading testing, the lattice is excited using a piezoelectric actuator, which operates by converting voltage into mechanical strain. The piezoelectric actuator is driven by an input sine function from an Agilent 3320A wave generator. The amplitude is kept constant, and a frequency sweep from 10 to 120 kHz is performed to evaluate the structural response. The optical interrogator is triggered by the wave generator, such that the strain measurements as a function of time and frequency may be recorded.

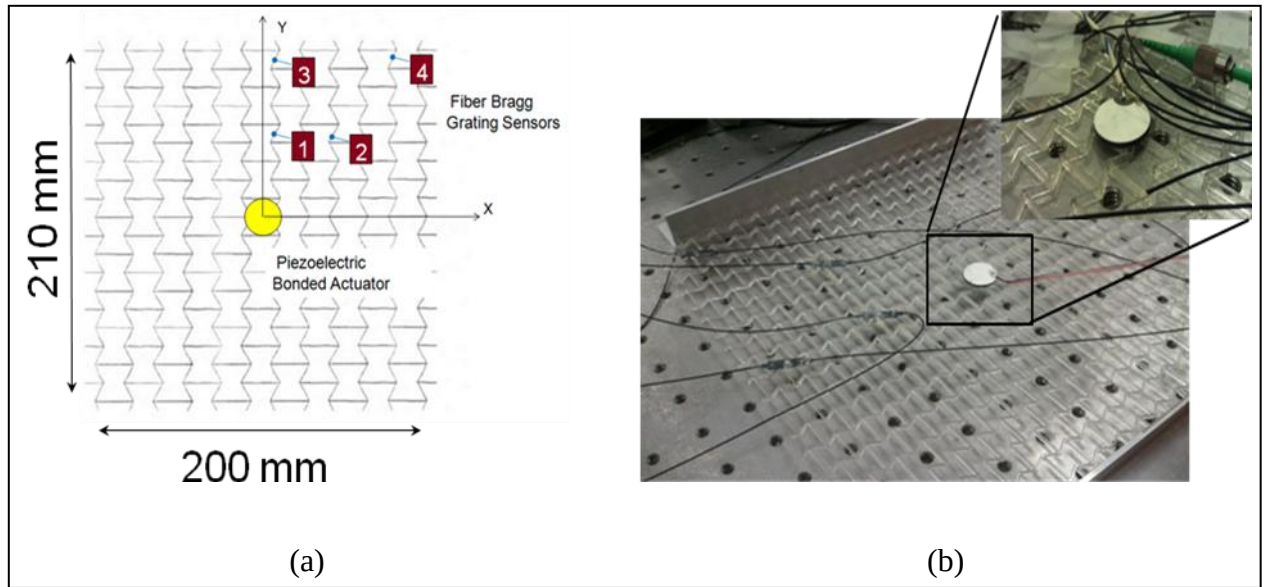


Figure 13. Auxetic panel: (a) schematic and (b) plexiglass panel with bonded piezoelectric actuator.

4.2 Experimental Results

The strain amplitudes of the auxetic lattice for different frequencies at Sensors 1 and 2 are shown in figure 14. The strain ratio from Sensor 1 to 2 varies by 3.8:1 and 17:1 for frequencies 35 and 65 kHz, respectively. The significant amplitude decrease in figure 14a–b may be attributed to the attenuation produced by the material damping of the composite and the anisotropy from the unit cell orientation.

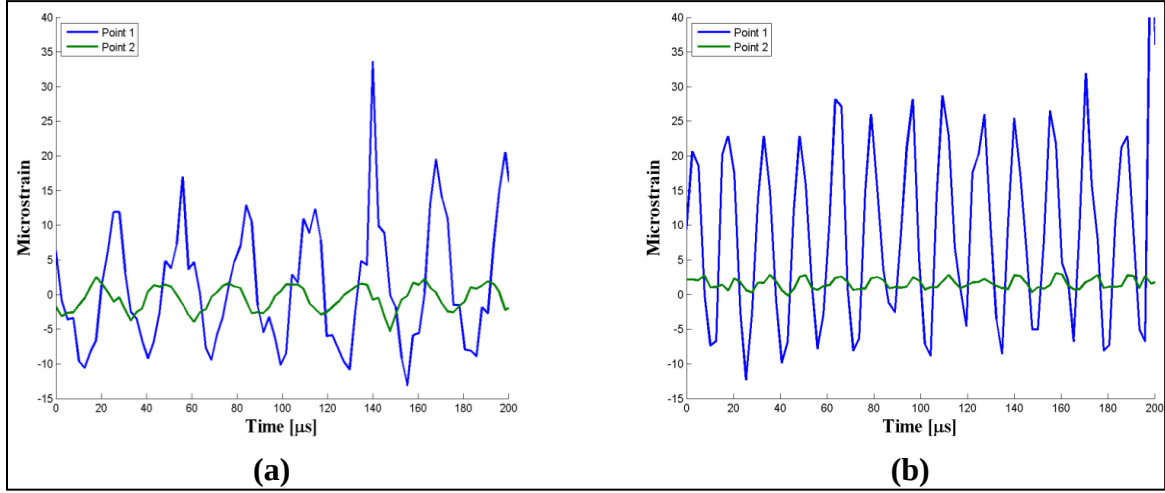


Figure 14. Auxetic panel subjected to continuous harmonic loads: excitation frequency at (a) 35 kHz and (b) 65 kHz.

5. Conclusions

Several conclusions may be derived from the numerical and experimental investigation. Numerically, the full-field results demonstrated the ability to steer energy for both in- and out-of-plane low velocity impact loading conditions. It was expected that in-plane periodicity would enable more efficient steering when subjected to in-plane impact relative to the baseline of a solid aluminum plate. However, only a marginal sensitivity to loading orientation exists relative to the unit cell periodicity, as the out-of-plane loading exhibited a calculated 10% decrease to in-plane loading. In addition, the incident arrival time of the wave is a factor of 2.9 faster in the solid plate than the auxetic lattice, and a factor of 1.9 larger in peak stress amplitude. This significant discrepancy highlights the effectiveness of the auxetic lattices to directionally orient the energy per the designed anisotropy of unit cell. Experimentally, a large amplitude differential from vertical to radial directivity may be attributed to the attenuation produced by the material damping of the composite and the anisotropy from the unit cell orientation. However, these numerical results require additional investigation, such as unit cell variation to primary load frequency content, and material variation.

Furthermore, future work consists of higher fidelity experiments that enable decoupling of the waves and to sweep higher frequency regimes, such that an accurate mapping of the wave guiding phenomenon is achieved. Instrumentation such as Digital Image Correlation (DIC) and 3-D laser Doppler vibrometry will allow for increased resolution of the stress wave. Additional testing using an impulse hammer experiment will be used to investigate low energy levels. Other considerations must include the ligament to ligament connection and related instabilities, such as

plasticity zones near the joints. A preliminary study of standing waves within individual ligaments and potential for energy cancelation mechanisms is underway. An extension of the work will consider the design, fabrication, and testing of 3-D lattice-wise periodic graded panels to explore through-thickness wave redirection. A 3-D lattice-wise system may allow for internal structural health monitoring and increase the design space for the lattice configuration as multifunctional configuration as a self-sensing, adaptive system for direct impact loads.

6. References

1. Salamone, S.; Bartoli, I.; Rhymer, J.; Lanza di Scalea, F.; Kim, H. Validation of the Piezoelectric Rosette Technique for Locating Impacts in Complex Aerospace Panels. *Proc. SPIE* **2011**, 7984, 79841E.
2. Anderson Jr., C. E.; Burkins, M. S.; Walker, J. D.; Gooch, W. A. Time-Resolved Penetration of B4C Tiles by the APM2 Bullet. *Computer Modeling in Engineering & Sciences* **2005**, 8 (2), 91–104.
3. Rimoli, J. J.; Talamini, B.; Wetzel, J. J.; Dharmasena K. P.; Radovitzky, R.; Wadley, H.N.G. Wet-sand Impulse Loading of Metallic Plates and Corrugated Core Sandwich Panels. *International Journal of Impact Engineering* **2011**, 38, 837–848.
4. Hutchinson J. W. Energy and Momentum Transfer in Air Shocks. *Journal of Applied Mechanics* **2009**, 76 (5), 051307-1–051307-7.
5. Gardner, N.; Wang, E.; Kumar, P.; Shulka, A. Blast Mitigation in a Sandwich Composite Using Graded Core and Polyurea. *Experimental Mechanics* **2011**, 52, 119–133.
6. Walker, J. Turning Bullets into Baseballs. *Technology Today* **1887**, 17–21.
7. Kataev, I. G. Electromagnetic Shock Waves. Iliffe, ISBN: 0592050017, 1966.
8. Langley, R. S. The Response of Two-dimensional Periodic Structures to Point Harmonic Loading. *J. Sound Vibration* **1996**, 197 (4), 447–469.
9. Ruzzene, M.; Scarpa, F. Directional and Band-gap Behavior of Periodic Auxetic Lattices. *Physica Status Solidi (B), Applied Research* **2005**, 242 (3), 665–680.
10. Spadoni A. Application of Chiral Cellular Materials for the Design of Innovative Components. Ph.D. Thesis, Georgia Institute of Technology, 2008.
11. Casadei, F.; Ruzzene, M.; Dozio, L.; Cunefare, K. A. Broadband Vibration Control Through Periodic Arrays of Resonant Shunts: Experimental Investigation on Plates. *Smart Materials and Structures I* **2010**, 19 (1), 1–13.
12. Li, Y.; Ramesh, K. T.; Chin, E.S.C. Dynamic Characterization of Layered and Graded Structures Under Impulsive Loading. *International Journal of Solids and Structures* **2001**, 38 (34–35), 6045–6061.
13. Johnson, G. R.; Beissel, S. R.; Gerlach, C. A.; Holmquist, T. J. *User Instructions for the 2011 Version of the EPIC Code*; Final Report; Southwest Research Institute, TX, 2011.

List of Symbols, Abbreviations, and Acronyms

3-D	three-dimensional
DIC	Digital Image Correlation
EPIC	Elastic-Plastic Impact Computations
EVE	E-Glass Vinyl-Ester
FBGs	fiber Bragg grating
FGMs	functionally graded materials
FEM	finite element method
FSP	fragment simulating projectile
GPA	Generalized Particle Algorithm
JC	Johnson-Cook's
PSE	primary structural elements
RHA	rolled homogenous armor
RL	resistive inductive
SAT	standard ACIS Text

NO. OF
COPIES ORGANIZATION

1 DEFENSE TECHNICAL
(PDF INFORMATION CTR
only) DTIC OCA
8725 JOHN J KINGMAN RD
STE 0944
FORT BELVOIR VA 22060-6218

1 PDF DIRECTOR
US ARMY RESEARCH LAB
IMAL HRA
2800 POWDER MILL RD
ADELPHI MD 20783-1197

1 PDF DIRECTOR
US ARMY RESEARCH LAB
RDRL CIO LL
2800 POWDER MILL RD
ADELPHI MD 20783-1197

ABERDEEN PROVING GROUND

6 HCS US ARMY RESEARCH LAB
ATTN RDRL VTM
J AYERS
A GHOSHAL
T CHEN
M COATNEY
N BRADLEY
D LE
APG MD 21005

2 HCS US ARMY RESEARCH LAB
ATTN RDRL WMP E
B CHAMISH
T JONES
APG MD 21005

TOTAL: 11 (3 PDF, 8 HCS)