Dynamic Axial Crushing of Multi-Layer Core Structures of Folded Chevron Patterns

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Abstract

The objective of this paper is to investigate our recently developed innovative sheet folding theory and manufacturing processes in designing impact energy absorbing structures with superior properties than existing structures such as honeycomb while achieving a volume reduction between 40 to 50%. Initial results indicate that we can mathematically generate three-dimensional patterns and use our folding technology to produce such patterns by simply folding flat sheets of materials, resulting in a significant cost savings.

The three-dimensional patterns, folded from different sheet materials, can be used as cores for laminated structures for impact energy absorptions applications, such as, in high speed airdrops of heavy items, and in improving crash worthiness of vehicle body and bumpers. The results of testing samples of the Chevron patterns (the simplest to fold from flat sheets) indicate that core structures made from this pattern will serve as absorbers of high velocity impact energy per unit volume when compared with the well-known and typically used honeycomb structures.

Keywords: Sheet material folding; Sandwich structures; Honeycomb; Lamination; Tessellation; Impact energy absorption; High speed airdrop; Plastic hinge; Kraft paper; Folding geometry

1. Introduction

Core structures are widely used in many applications ranging from temporary facilities, automotives, floor decks, bridge decks to the most advanced aircraft components. In all cases, core materials address the need for high strength and stiffness at low weight. There are several design criteria for the core structures; we briefly describe the most common ones below:

a. High Specific Strengths

For most core applications, it is necessary to maximize the compression and shear strength-to-weight ratio for structural efficiency purposes. This is important for cores primarily subject to compressive loads. In such cases, the design should also have equal shear properties both in the length and width directions. Honeycomb cores do not always have balanced properties, but the high specific properties compensate for that.

b. Damage Tolerance
Damage tolerance is the second important design criterion for core structures. The main idea of damage tolerance design is that initial defects or flaws are assumed to exist in structures before operation, and that these initial defects will grow during operation. Therefore, the design under this criterion requires that the material resist propagation of damage under both static and fatigue loading. Analytical methods using the damage tolerance criterion have been widely investigated in many areas such as aeronautical engineering (Alturi 1997, Goranson 1997, Provan, 1987, Shi and Mahadevan 2001), marine and offshore engineering (Lassen and Sorensen 2002), civil engineering (Proppe et al. 2002) and in welded joints (Mahadevan and Ni 2003). The damage tolerance is usually quantified in a probabilistic form, for example, for specific damage propagation limits the designed core should reduce the probability of the following typical failure modes:

- Facesheet to core disbond (greater bond area, provides stronger bond)
- Core crush normal to the facesheet (buckling resistance, is function of cell size, core compliance)
- Facesheet delaminations and dimpling (is function of load redistribution through core)

The method of bonding the facesheets to the core is critical. Current cores achieve this in two very efficient ways. For solid cores such as balsa and foam cores the bond is over the entire surface area, resulting in very efficient bond. Hence, lack of damage tolerances in these cores is usually due to moisture degradation, especially for balsa, and in core crushing, for foams. Honeycomb cores are bonded on a line at the intersection of the honeycomb and the facesheet. However the bond strength is formed from the bond meniscus that fairs the honeycomb vertical surface with the facesheet. This provides an efficient bond shear reaction, especially in facesheet pull off conditions (Foster-Miller 2000).

c. Non-Catastrophic Failure Modes

The third design criterion is ensuring that failure of the core structure is non-catastrophic. This means the graceful failure in compression and shear loading is required. This is usually achieved by limiting the unstable buckling mode of the core structure. In other words, the core designs should not have highly directional properties. A typical example of undesirable directional properties is the conventional hexagonally shaped honeycomb core where there is a factor of two differences in its shear strength in the length versus width direction. However, this is highly dependent on core cell geometry and core ribbon material (Foster-Miller 2000).

d. Dynamic Impact Energy Absorption

Impact energy absorption is an important criterion for the design of core structures subject to dynamic impact loads such as cushions for high velocity airdrop packages, automobile bumpers and items subject to single or multiple impact strikes. The core should be designed to absorb the total dynamic impact energy in order to minimize the destructive effect of unabsorbed energy on the items protected (cushioned) by the core structure.

This paper focuses on the design of new core structures that maximize impact energy absorption at minimum core volume. Honeycomb sandwich structures are typically used in absorbing impact loading, by dissipating the energy in plastic deformation. Such honeycomb structures have been used for buffer appliances, such as those used to absorb the impacts associated with motor vehicle impact
accidents and aircraft supply drops. The energy absorption performance of these structures under impact is strongly influenced by both the honeycomb geometrical configuration and the mechanical properties of the honeycomb material.

Characteristics of impact energy absorption via crushing have been reported for a single aluminum honeycomb panel and a honeycomb core cell, considering the dynamic effect (Foster-Miller 2000, Provan, 1987). However, the energy absorption performance of multi-layer built-up honeycomb panels, under quasi-static and impact velocity conditions, does not appear to be well established. In this study, several multi-layer panels were purposely crushed to extend the practicable design of energy absorbing buffer materials that make use of hexagonal honeycomb core panels.

In honeycomb, the impact crush performance is largely determined by core density, cell size, material properties, and the panel geometrical configuration. The dynamic axial crushing behavior of multi-layer aluminum hexagonal honeycomb sandwich structure panels, including the single-layer honeycomb panel, has been investigated experimentally. The performance of these panels used as buffer appliances was verified using the uniform cross-section type of two or three multi-layer panels (Yausi 2000) as well as using the pyramid type of two or three multi-layer panels (Aronson 1999). The pyramid type consisted of a number of square single panels of same thickness, but with different dimensions, built up in the order of decreasing area. As for all the multi-layer honeycomb panels, the height of each panel is the same.

Aluminum sandwich construction has been recognized as a prime candidate for structural design of lightweight transportation systems such as aircraft, high-speed trains and fast ships. Strength characteristics of aluminum sandwich panels with aluminum honeycomb core, have been extensively investigated, both theoretically and experimentally. A series of strength tests is carried out on aluminum honeycomb-cored sandwich panel specimen in three-point bending, axial compression and lateral crushing loads. Simplified theories are applied to analyze bending deformation, buckling/ultimate strength and crushing strength of honeycomb sandwich panels subject to the corresponding load component. The structural failure characteristics of aluminum sandwich panels are discussed and test data developed, are documented in Paik et al. (1999).

An integrated hollow E-glass/epoxy core sandwich composite construction that provides lightweight and bending stiffness has also been investigated. In comparison with traditional foam and honeycomb cores, the integrated space core has the advantage of providing a means to route wires/rods, embed electronic assemblies, and store fuel and fire-retardant foam. The low-velocity impact (LVI) response of innovative integrated sandwich core composites was investigated. However, the low-velocity impact (LVI) results indicated that these types of hollow and functionality-embedded integrated cores suffered a localized damage state limited to a system of core members in the vicinity of the impact. The peak forces attained under static compression and LVI were in accordance with Euler's column buckling equation. Stacking of the core was an effective way of improving functionality and limiting the LVI damage in the sandwich plate (Vaidya et al. 2000).

New material formed in known geometries might result in core structures with equivalent or superior characteristics than known traditional materials as discussed below.

1.1 New Light Weight Materials
Ultra-lightweight metal foams are an emerging class of new engineering materials that can be tailored to have a very attractive combination of properties. Aluminum foams produced by Fraunhofer's powder metallurgy process show significant promise as multi-functional materials for a broad range of applications. Their lightweight and very high specific stiffness offer significant potential for vehicle weight reduction and impact energy absorption.

The high energy absorption capabilities of aluminum foams can provide improved crash energy management, the ranges of materials properties that can be achieved using aluminum foams in various configurations and in combination with other structural material are reviewed. Current and potential future applications of aluminum foams in automobiles, trucks, and military vehicles for weight reduction, increased fuel efficiency, and improved mobility are also described (Claar et al. 2000).

We conclude this section by stating that the ability of a core structure of absorbing impact energy is limited by the core density, geometry, and the core material. An optimum combination of these parameters results in an optimum core structure that maximizes the energy absorption while minimizing the core volume. The objective of this paper is to introduce a recently developed core geometry and compare its performance with know core structures; namely honeycomb. The core structure is referred to as the Chevron pattern which is generated and manufacturing by a recently developed technology (Kling and Elsayed 2000a, 2000b, 2001). The developed patterns are simply folded from flat sheets of materials; hence, its manufacturing cost is minimum. We begin with a brief description of the geometry needed to generate the Chevron pattern followed by description of the folding process and technology and finally we present the experiments and comparative results with honeycomb structures.

2. Generation of Sheet Folded Structures: The Chevron Pattern

Unlike the previous approaches, a new and innovative methodology for the generation of new lightweight metal or composite structures was developed. The generated patterns have the ability to absorb significant dynamic impact energy and could have many applications in high velocity airdrop packages and the panels for energy absorption. The methodologies are based on a recently developed geometric theory developed by Kling and Elsayed (2000a, 2000b, 2001), and the innovative continuous sheet folding production machine developed by Basily et al. (2003) and Elsayed and Basily (2003). They describe folding flat sheets of material into intricate three-dimensional structures (cores) that yield an order of magnitude improvement of mechanical properties over existing structures of equivalent volume.

We utilize the recently developed sheet folding theory and technology to generate new core structures of the Chevron pattern folded from flat sheets of new or traditional materials. We intend to utilize the traditional or new material by developing sandwich structures with different geometries capable of providing improved impact energy absorption characteristics at a much reduced volume.

2.1. Sheet Folding Geometry

The sheet folding geometry describes folding 3-D configurations from any flat sheet material. For example, the patterns in Figure 1 (Kling and Elsayed 2000a, 2000b) are folded from paper,
but can be folded from aluminum, copper, steel, or other composites sheet material. It can also be laminated to provide an efficient truss work core of a high-strength lightweight rigid panel. Depending on scale and composition, the panel has applications ranging from shipping crates, stiffeners of aerospace structures, automotive chassis, auto body and vehicle floors to warehouse roofs. Moreover, with this folding technology one can design countless repetitive folding patterns with other physical and mechanical properties tailored to meet a wide variety of industrial applications.

It should be emphasized that folding of sheet material from rolled stock in possibly one of the most efficient forming processes. Other production methods such as forging, casting, forming and fabrication assembly may produce three-dimensional structures that may appear similar, but its manufacturing processes would be prohibitively expensive or very impractical. Thus, the significance of this innovative folding technology is that it will enable intricate structures to be produced at an economical production rate that makes it complementary process to most sheet materials processes.

2.2. Chevron Folding Geometry

Details of the sheet folding theory are given in references (Kling 1997, Kling and Elsayed 200a, Kling and Elsayed 2000b, Kling and Elsayed 2001, Kling et al. 2002, Basily et al. 2003, Elsayed and Basily 2003). In this paper, we limit our presentation to folding the well-known Chevron pattern from flat sheets of materials. Folded patterns have one or more elementary flat surfaces, each of which has a specific geometrical shape that forms the basic building elements of the folded pattern. Additionally, a combination or multiplication of these elementary flat surfaces of a specific geometrical shape constitutes the basic building cell of a folded pattern, as it is repeated in two dimensions, creating the three-dimensional folded shape.

In the case of Chevron folded pattern, as an example, the basic building element is a flat surface polyhedron defined by its length \( a \), width \( b \), and the included angle \( \phi \), shown in Figure 2 where...
both \( a \) and \( b \) are of arbitrary lengths with typical included angle \( \phi = 60^\circ \), however \( \phi \) could theoretically assume any value in the range of \( 0 \leq \phi \leq \pi / 2 \) (Elsayed and Basily 2003).

**Figure 2.** Basic folding element, cell, tessellated sheet and folded chevron structure respectively

The basic building cell of chevron pattern consists of four identical polyhedron \([A, B, C, \text{ and } D]\). Each of length \( a \), width \( b \) and an included angle \( \phi = 60^\circ \). The cell is arranged laying flat prior to folding as shown in Figure. 2.b. Also the repetition of the cell \( m \) times in the direction of the arrow along the \( X \) axis provides the unfolded length of the tessellated sheet, while the cell repetition \( n \) times in the direction of the arrow along the \( Y \) axis provides the unfolded width of the tessellated sheet.

Creation of three dimensional folded Chevron structures from a sheet tessellated with the basic building cell is achieved by inducing a permanent edge bending in particular directions between these four polyhedron elements and along all the edges of these four basic elements. During any folding stage, the geometrical dimensions and angles of the folded structure can be determined in terms of the three parameters of the basic building cell of the pattern \( a, b, \phi \) and the folding angle \( \theta \) with respect to \( X-Y \) plane. Where \( \theta \) varies from \( \theta = 0 \) corresponding to flat unfolded cell to \( \theta = \pi / 2 \), corresponding to fully folded block.

**3. Folding Technology**

Once the parameters of the folded Chevron pattern have been determined, it becomes important to develop some means to produce the core as specified. The authors developed an effective continuous folding machine capable of producing the desired core.
Figure 3. The continuous sheet folding machine and final sheet folding rolling sequence. The machine designed and constructed for continuous production of folded patterns is shown in Figure 3. It successfully folds patterns of different geometries from different sheet materials. This was achieved by implementing a novel technique, in which, sheet material is pre-folded through a set of sequential and circumferentially grooved rollers, followed by final set of cross folding rollers engraved with specific patterns (Patent is applied for by Rutgers University).

4. Impact Loading and Energy Absorption Characteristics

The time duration of load application distinguishes the impact loading from static loading. Impact loading occurs when \( \frac{t_l}{t_n} \leq 0.5 \), where \( t_l \) and \( t_n \) correspond to the time to peak load and the period of system natural frequency respectively. There are two general cases of impact loading, (Burr and Cheatham 1995) namely; striking impact and force impact. In addition, there are two types of stresses resulting from collisions between moving objects, namely elastic stresses and plastic stresses, with the later causing permanent deformation of the colliding bodies.

4.1 Impact of Elastic Bodies

In the case of elastic collisions, if the mass of the striking object \( m \) is large compared to that of the struck object \( m_b \), and if the striking object can be considered rigid, then the kinetic energy of the striking body will be converted to stored elastic energy in the struck body. The ratio of dynamic \( P_i \) loading to static loading \( W \) and the elastic energy stored in the struck body is then given by:

\[
\frac{P_i}{W} = \frac{\delta_i}{\delta_{st}} = v_i \sqrt{\frac{\eta}{g \delta_{st}}} \tag{1}
\]

where \( \delta_i \) and \( \delta_{st} \) are the deformation corresponding to the dynamic loading and static loading respectively, \( v_i \) is the impact velocity and \( \eta \) is defined as the correction factor for the case of axial impact , (Burr and Cheatham 1995). The kinetic energy \( E \) is then expressed as

\[
E = \eta \left( \frac{1}{2} m v_i^2 \right) \tag{2}
\]

\[
\eta = \frac{1}{1 + \frac{m_b}{3m}}
\]

For the case of a mass falling through a distance \( h \), Equations (1) and (2) can be rewritten as:

\[
\frac{P_i}{W} = \frac{\delta_i}{\delta_{st}} = 1 + \sqrt{1 + \frac{2\eta h}{\delta_{st}}} \tag{3}
\]

\[
E = mg \left( \eta h + \delta_i \right) \tag{4}
\]
This applies only to the case of resulting elastic stresses where impact forces are too small to cause permanent deformation in the folded structure during impact resulting in negligible amount of absorbed impact energy in general.

4.2. Impact of Plastically Deformed Bodies

When permanent deformation occurs during impact some parts of the folded structure will undergo plastic deformation and absorb most of the impact energy. The failure mode of these structures is mainly due to plastic hinge and a little is due to sheet plastics stretching of sheet material as a result of unfolding or buckling, depending on the following two main loading and constructional conditions.

4.2.1. Energy Absorption of Folded Sheet Impacted between Two Smooth Surfaces

The energy absorption in this case is equivalent to the total energy required for the structure to return to its flat sheet condition through unfolding. The impact energy dissipates as heat due to the plastic work consumed in unfolding the plastically bent edges of the pattern tessellations. In this case, this energy is theoretically equal to that required for folding the pattern assuming no strain hardening of the material, (Basily et al. 2003). The plastic work required to unfold the Chevron pattern of a given angle $\theta$, which is function of the bend angle $\alpha$ of the edges of the flat surface of polyhedron tessellation of length $a$, the width $b$ and the included angle $\phi$ where $0 < \theta < \pi / 2$ and $0 < \alpha < \pi / 3$, that is between the initially folded pattern ($\theta \leq \frac{\pi}{2}$ and $\alpha \leq \frac{\pi}{3}$) and the fully unfolded back to flat sheet ($\theta = \alpha = 0$) is given by:

$$W_p = \left(\frac{t_o^2 \sigma_y}{4}\right) \left\{ \left(\frac{L_o}{a}\right) \left(\frac{W_o}{b \sin \phi} - 1\right) a\alpha \left(\frac{W_o}{b \sin \phi} - 1\right) b\theta \right\}$$

where $L_o$, $W_o$ and $t_o$ are initial sheet material length, width, and thickness respectively.

4.2.2. Energy Absorption of Impacted Laminated Folded Structure

The energy absorption in the case of laminated structure is different from that given in Equation (5) This is due to the effect of the laminated sheet in imposing a failure buckling mode of the tessellated facets, rather than the plastic hinge of sheet unfolding on un-laminated cores. This mode of failure is extremely complicated to formulate analytically and requires lengthy numerical solutions. The localized sequential tessellations failure produces a festooned curve typical of that of classical buckling failure of thin cylinder under axial loading (Abramowicz 2003).

In the Chevron folded structures, the crushing buckling loads and hence the structure energy absorbing capacity, are a function of the folded geometry, number of tessellations, folded angles and the mechanical properties of sheet material. In addition, the amount of stretching in the laminate sheet material depends on the relative core/laminate stiffness ratio, structural geometry and bond strength between core and laminate sheet material. Figure 4 shows the difference between the two main loading conditions of laminated and un-laminated fold squeezed between two smooth surfaces. The impact energy is then absorbed in a localized scale in the form of multiple plastic bending of the individual facets of the folded structure due to buckling only and not in simple plastic bending as in
un-laminated folded sheet. Therefore, higher crushing forces are involved in the absorbing of the impact energies of the folded structure when compared with typical folding mode of un-laminated structure.

Figure 4. Deformation of un-laminate and laminated folded structures

The plastic bending moments and forces, and hence energy required to permanently crush these truss like elements to a given height is derived from the plastic work involved in the bending of these initially flat elements around the newly developed ridges within the element itself, due to localized buckling, to a given permanent angle. These angles, on average, correspond to what degree the initial structure was deformed under impact. This crushing mechanism is so complicated that only experimental investigations were used to determine the parameters influencing energy absorbing capacity of different structures in a comparative scale.

5. Constructions and Testing of the Chevron Folded Structures

Impact energy absorbing pads were constructed from multiple layers of laminated cores of folded Kraft paper sheet material. The folded core was initially compacted to a specific ratio, which corresponds to a given fold angle $\theta$. In the prismatic pads, a sheet of the same Kraft paper on one side laminates the core only, since consecutive lamination will build up the structure with alternative layers of cores and laminated sheet respectively. Elm paper adhesive was used in gluing the structured pads that are then cured at $200^\circ F$ for 24 hours before conducting the impact tests. In the Cylindrical configuration, the folded layers are rolled vertically in a circular shape forming a cylinder which has a diameter of 6.2” that provides a cross section area equivalent to 5.5” x 5.5” of above prismatic pads.

Impact tests were conducted using the Dynatup 950 INSTRON impact testing machine. The test pads were constructed by multiple laminations and were trimmed to 5.5” x 5.5” in cross section and to multiple heights of 3” to facilitate comparison with standard honeycomb sandwich structures of a fixed 3” height, already used in similar commercial applications. Samples of
5.5” x 5.5” and of 3, 6 9 and 12 inches in height respectively were tested at various impact speeds according to their height.

6. Test Sample Orientation of Prismatic and Cylindrical Core Structures

Impact tests were conducted on Kraft paper Chevron folded structures samples using four orientations, namely; a) flat orientation, b) side orientation c) vertical orientation and d) axial orientation for cylindrical samples, as shown in Figure 5. The orientation of folded structure is related to the direction of folded pattern and lamination with respect to the direction of the applied impact force as clearly shown in the figures by blue arrows.

Test samples are subjected to different impact speed varying from 20 of 40 ft/sec. Multi-layers of the 3” standard height of the honeycomb samples were glued to achieve heights (6”, 9” and 12”) equivalent to those of the Chevron samples. Additionally, the choice of the cylindrical configuration is intended for individual packaging applications such as of relatively large caliber
ammunitions, since the geometry, folding properties and ease of manufacture, makes it ideal for such applications.

7. Impact Energy Tests and Results

Impact testing was conducted on the Dynatup 950 INSTRON Impact Testing Machine at four settings of predetermined different speeds namely 20, 25, 30, 35 and 40 ft/sec. Using a hammer weight of 21.0 lb which provided a pre-calculated impact energy of about: 25, 130, 200, 300, 400 and 525 lb-ft corresponding to the above pre-determined impact speeds.

7.1. Test Results of Honeycomb Samples:

Typical load deflection diagram of the results of impact test conducted on a two-layered 5.5” × 5.5” cross section honeycomb samples is shown in Figure 6. The load is shown in red while the total absorbed impact energy is in blue. All samples were subjected to 30ft/sec impact velocity. For the honeycomb sample, it is shown that the maximum impact load is 1444 lbs and the maximum deflection is 4.85 inches. The absorbed impact energy is 279.52 lb-ft. with typical two humps load deflection characteristics reflecting the energy absorbed by the two layers of the honeycomb sample.

![Figure 6. Load-energy-deflection diagram of the honeycomb sample](image)

Photograph of the impacted folded Chevron cylindrical and the honeycomb samples are shown in Figure 7.
7.2. Test Results of the Chevron Samples:

Laminated folded chevron samples of similar dimensions to that of honeycomb were tested along the three orientations of the lamination, namely, flat, side and vertical loading directions using same impact speed of 30 ft/sec and drop weight of 21.5 lb.

The test results of the flat impacted sample are shown in Figure 8.a. It can be seen that the flat sample absorbs the energy gradually at a constant rate of 500 lbs. but since it could not absorb the entire impact energy at that rate, the remaining impact energy resulted in a peak load of 1450 lbs near the end of load deflection diagram. This directional type of cushioning can be used for packaging highly sensitive and fragile objects. The results of the side impacted sample show that these samples behaved similar to that of the flat samples.

Figure 8. Load-energy-deflection diagrams for flat and vertically oriented Chevron samples
The test results of the *vertical impacted sample* outperform the honeycomb samples as it absorbs the total energy at a uniform load when compared with the honeycomb sample as shown in Figures 8.b and 9. The total deflection is significantly less than the honeycomb sample, implying that energy absorbed per unit volume for the vertical sample is higher than that of the honeycomb sample. Hence, a significant reduction in packaged volume can be achieved using the vertical sample configuration. Combining these three directional configurations would provide a means of tailoring the cushioning pad to absorb a given impact energy at minimum volume for a specific object fragility.

![Graph](image)

*Figure 9.* Load-energy-deflection for both the honeycomb (two humps curve) and vertically oriented Chevron samples

### 7.3. Test Results of Impacted Cylindrical Samples:

The test results of the *axially impacted Cylindrical sample* is shown in Figure 10.a. It can be seen that the cylindrical samples also outperformed the honeycomb samples (Figure 10.b) in that, it absorbs the total energy at higher load than the honeycomb. However, it is important to note that the total deflection is significantly less than the honeycomb sample, implying that energy absorbed per unit volume for the vertical sample is higher than that of the honeycomb sample.
8. Test Results and Conclusions

The energy absorbing pads of folded Kraft sheet paper produced by the folding technology outperformed the standard honeycomb sandwich structure for high speed airdrop applications. Comparison is based on energy absorbing capacity per unit volume.

- Comparison between folded and honeycomb structures, in energy absorbing capacity per unit volume at different impact speeds, indicates that the vertically impacted folded structures exceeded that of the honeycomb particularly at higher speed where it nearly absorbed double the energy that can be absorbed by the honeycomb, Figure 11.

Figure 10. Load-energy-deflection for both the cylindrical Chevronl sample and the honeycomb (two humps curve)

Figure 11. Variation of absorbed impact energy /unit volume with impact speed of folded and honeycomb structures
• The ability of the folded structure to absorb energy in the three directions of orientation is a valuable and important factor, which is a major drawback of honeycomb structures, in that, the honeycomb structures do not have energy absorbing capacities in directions normal to the surface resulting in total collapse under slight load application in other directions. Therefore, the specifications of high speed airdrop require that the direction of dropped items cushioned by a honeycomb structure should not exceed 2.5° deviation from normal to the surface at impact. It is usually difficult to maintain such a specific angle of orientation of the dropped items in actual airdrop applications.

• For any given impact speed the folded patterns absorb impact energy gradually and in a more uniform fashion when compared with the atypical stop-go characteristics of successive collapsing of each honeycomb layer during deformation. The results show that the folded structures absorb the same impact energy at almost half the deformation. In other words, the folded Chevron structures can absorb the same impact energy at half the volume of that of the honeycomb structures.

• The above results demonstrate the great design flexibility of the folded structures as it can be designed to vary from low values of impact loads suitable for packaging of fragile product to a much higher impact loads for minimum material usage. This is due to the main characteristic of the folded Chevron pattern as fully extended (becomes a flat sheet again), fully compacted or be in any other configuration in between these to extremes. In each case, the mechanical properties and the impact energy absorption capability of the resultant structure (configuration) vary significantly.

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