

ABSTRACT

Title of Dissertation: **ENERGY ABSORBING
CELLULAR STRUCTURES FOR
CRASHWORTHINESS APPLICATIONS**

Colleen Marie Murray
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Dissertation Directed by: **Professor Norman Wereley
Department of Aerospace Engineering**

Energy absorbing materials are utilized in many applications. Aircraft, automobiles, and helmets all use energy absorbing materials to ensure the safety of the individual during an impact event. The seats in aircraft are made from a material that can minimize the force that is transferred from the impact to the occupant. In a similar manner, the material in the front of an automobile is designed to absorb the energy from an impact event and redistribute it in a manner that minimizes the amount of energy experienced by the main cabin. Helmets perform in the same way: by taking the impact and distributing the load to protect the wearer. The materials used in these applications were tailored to meet the needs of the application, particularly the density and strength of the material. Using cellular structures allow for more control of the design for energy absorbing applications, particularly when looking to increase the performance of the material.

There are three options for increasing the energy absorption in materials for crashworthiness applications: decrease the force with a constant mean crush stress, increase the mean crush

stress with a constant force, or decrease the force while increasing the mean crush stress. In a force- displacement diagram, the area under the curve is the amount of energy that a material can absorb during an impact. By decreasing that initial force, the initial peak force will begin to equilibrate with the mean crush, resulting in a higher energy absorption.

The structures that have been relied on throughout history for these applications are cellular structures. Cellular structures are described as any structure that is made of one phase composed of either air or fluid. As Lakes describes in his work, foams, honeycombs, and lattices are categorized as such; the voids allow the materials to reach physical limits beyond their previous. With the improvements of technology, it is important to re-asses these structures to determine whether they too can be manufactured and remain as effective in their original crashworthiness applications as before. Throughout this work, different methods of additive manufacturing are used to create honeycomb structures specifically for energy absorption applications. Each of these studies focuses on a different attribute that additive manufacturing can help improve in energy absorption materials.

In this dissertation, four case studies involving the out-of-plane compression of additively manufactured honeycomb will be discussed. The first chapter will center on the applications of visco-elastic thermoplastic polyurethane (TPU) as a potential material of choice for energy absorption materials. TPU is a material that has the ability to achieve significant deformation and return to its original shape within a matter of minutes. This material is of interest due to the need to re-use helmet liners and other safety mechanisms before buying a new one. This work also focuses on the impact that adding buckling initiators will have to the structure in terms of energy absorption during quasi-static conditions.

The next chapter is centered on the applications of these TPU honeycomb undergoing dy-

dynamic testing. Crashworthiness materials experience impact velocities bordering on 10- 15 m/s (22- 35 mph). These tests differ from the previous due to the velocity no longer being constant. As the impactor falls, the velocity changes, while the quasi-static tests were completed under a constant velocity. This set of dynamic tests is most representative of long term applications, however the performance of these materials change drastically as discussed.

In some applications, a visco-elastic plastic is not going to be able to absorb the energy from the impact. In these situations, a stiffer material would be necessary. To provide an alternative for these applications, acrylonitrile butadiene styrene (ABS) was studied since it is a commonly used plastic when additively manufacturing. Once again, honeycomb were manufactured and tested under out of plane, uni-axial quasi static compression. The samples were studied to determine the effects of buckling initiator location as well as the effect of the inscribed diameter. For this, samples were manufactured with an internal diameter of 10, 15, or 20 mm. The buckling initiators were located either 1/2, 3/4, or at the top of the samples to determine the design which enables the best energy absorption.

The final study recognizes that traditional honeycomb has been manufactured using metals like aluminum and steel. By moving towards an additively manufactured honeycomb, this work has been focusing on polymeric honeycomb instead. The metallic additive manufacturing methods require drastic safety precautions be taken. A safer alternative is proposed in this last study: combining stereolithography and electroplating. Here, an isotropic material can be the core of the structure, with a thin layer (about 150 μm) of metal creating the ductile layer. These samples demonstrate a ductile failure as opposed to their plastic only counterparts who experience a brittle failure. The energy absorption performance is then characterized as a function of buckling initiator height as well.

ENERGY ABSORBING CELLULAR STRUCTURES FOR
CRASHWORTHINESS APPLICATIONS

by

Colleen Marie Murray

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Advisory Committee:

Professor Norman Wereley, Chair/Advisor
Professor Hugh Bruck
Professor Abhijit Dasgupta
Professor Amr Baz
Professor Lourdes Salamanca-Riba

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Preface

The following work includes previously published work:

Chapter 3 was published in *Polymers* in August 2023 (<https://doi.org/10.3390/polym15163350>). The author of this dissertation manufactured, tested, and analyzed all samples that were used in this publication. The author also prepared the manuscript and assisted with editing.

Chapter 5 was previously published in *SAMPE Journal* in July 2024 (<https://doi.org/10.33599/SJ.v60no4.04>). The author of this dissertation planned and executed the experiments using samples manufactured by a colleague. The author also analyzed the data and prepared the manuscript.

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List of Abbreviations

α	Internal angle
A	Area
ABS	Acrylonitrile butadiene styrene
ABS-R	Acrylonitrile butadiene styrene- research
AM	Additive Manufacturing
A_{uc}	Unit cell area
Avg η_{SD}	Average crush efficiency
B	Buckling initiator dimension
BIs	Buckling initiators
C	Inscribed diameter
CAD	Computer aided desing
$\delta\epsilon$	Change in strain
δH	Change in height
$\Delta\sigma$	Change in stress (Peak stress- Mean crush stress)
$\delta\sigma$	Change in stress
DED	Direct energy deposition
D_I	Inner diameter
D_O	Outer diameter
d	Displacement across entire strain range
ϵ	Strain
ϵ_d	Densification strain
ϵ_{pk}	Peak strain
η_{EA}	Energy absorbed efficiency
$\eta_{EA,T}$	Theshold energy absorbed efficiency
η_{SD}	Crush efficiency
$\eta_{SD,T}$	Threshold crush efficiency
E_s	Bulk modulus
EA	Strain energy density
F	Force
FDM	Finite Deposition Molding
FEM	Finite element model
FFF	Fused filament fabrication
F_{pk}	Peak Force
$F(x)$	Force at a given displacement

H	Height of sample
HC	Honeycomb
K	End constraint factor constant
KE	Kinetic energy
L	Length
m	Specific mass
MTS	Materials Testing System
P_{crit}	Buckling load
PBF	Powder bed fusion
PLA	Polylactic acid
σ	Stress
σ_{pk}	Peak stress
σ_{mc}	Mean crush stress
σ_{ys}	Yield strength
$\sigma_{\eta SD}^2$	Crush efficiency variance
SEA	Specific energy absorbed
SLA	Stereolithography
t	Wall thickness
TPE	Thermoplastic elastomer
$U(\epsilon)$	Energy absorbed
V	Crush velocity
ν_s	Bulk Poisson's Ratio
x	Displacement
0BI	No buckling initiators
0.50BI	Buckling initiator 50% height
0.75BI	Buckling initiator 75% height
1BI	Buckling initiator 100% height

Chapter 1: Introduction

1.1 Literature Review

One critical consideration in engineering applications is improving structural crashworthiness. This requirement has constraints though, such as a limit on the force transmitted or an acceptable amount of deformation [1]. Applications of these constraints would be in automobiles, trains, and aircraft, where in the case of an accident, there is a threat to the passengers' life and safety [2, 3]. In train and aerospace applications, these materials would act as shock absorbers since they increase the time over which the shock is applied to the vehicle by increasing the folds of the material [4]. The kinetic energy from the impact is transformed when it deforms the energy absorber into a plastic strain energy [4].

Cellular structures are commonly selected for these energy absorption applications due to their light-weight and high stiffness. The energy absorption properties are dependent on the material along with the geometric conditions [5–7]. As Deqiang, et al. show in their study, the ratios of the cell wall thickness of the honeycomb to the edge length will be directly related to the mean out of plane dynamic plateau stress [6]. Zou et al. experienced similar results while studying bamboo tubes. As the bamboo tubes were divided into sub-regimes, there was an increase in the initial force, however there was also a significant increase in the overall specific energy absorbed, or the energy absorbed per unit weight [7]. To better understand these terms, it is

important to understand what the force-displacement curve looks like for crashworthy materials.

1.1.1 Analysis of Energy Absorption

Energy absorbing materials will experience a three stage force-displacement curve. The first stage shows an axial load increasing drastically in the elastic regime until the force reaches the initial peak force, F_{pk} , as seen in Figure 1.1 [8,9]. The second stage is the plateau or platform stage, where the force drops down to the plastic region and fluctuates in response to the progressive buckling, or folding, of the sample. In Figure 1.1, this corresponds to the second red box. This is the non-linear plastic regime where the majority of the energy absorption will occur [10]. The amount of fluctuation corresponds directly to the type of sample tested. Cellular structures, like honeycomb, lattices, and foam, experience a near constant stress, even with damage accumulation [11]. Once the sample can no longer buckle, the third stage, densification, begins. This is the region where the force rapidly increases since the sample is no longer viable [12]. This is the remainder of the force- displacement curve in Figure 1.1. From this curve, the energy absorption metrics can be determined.

There are a series of commonly accepted parameters used to characterize the energy absorption of materials during an impact collision. These parameters can be calculated from a force-displacement curve. To begin, the stress- strain curve must be calculated.

$$\sigma = \frac{F}{A} \quad (1.1)$$

Here, F is the the force being applied and A is the cross sectional area that is in contact with the

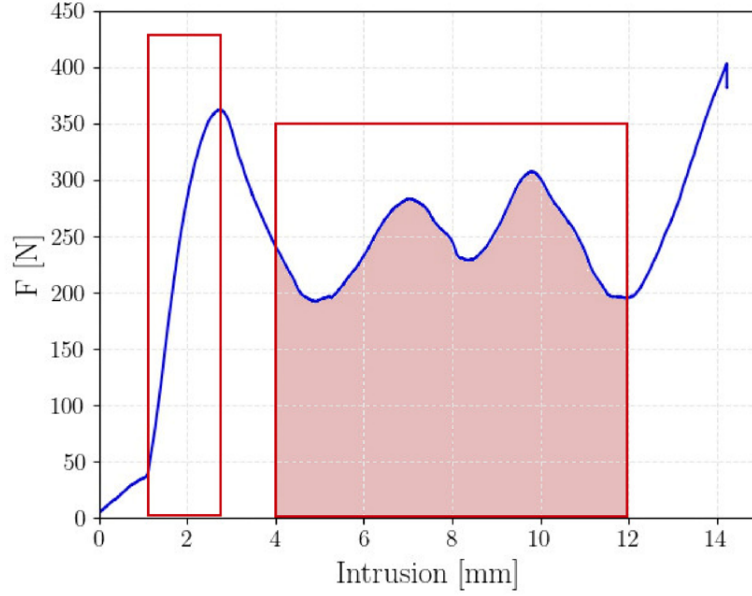


Figure 1.1: A force-displacement curve as adopted from Niutta et al. Figure 4 showing the three stages that are characteristic of crashworthy materials

platen. The strain can be determined using the following:

$$\epsilon = \frac{\delta H}{H} \quad (1.2)$$

Here, H is the height of the original sample and δH is the change in height. With these calculations, the stress- strain curve can be determined and the energy absorption parameters can be calculated.

The first crashworthiness parameter is the energy absorbed by the sample. The energy absorbed is the area under the force- displacement or stress-strain curve, which can be shown mathematically using the following [13].

$$EA = \int_0^x F(x)dx = \int_0^\epsilon \sigma(\epsilon)d\epsilon \quad (1.3)$$

Here, x is the displacement and $F(x)$ is the force at a given displacement.

Knowing the energy absorbed, the specific energy absorption (SEA) can be determined. This is a ratio between the energy absorbed prior to densification divided by the material's mass. [8, 12, 14]

$$SEA = \frac{EA}{m} = \frac{\int_0^\epsilon \sigma(\epsilon) d\epsilon}{m} \quad (1.4)$$

where m is the mass of the sample.

Throughout literature, there is disagreement as how the mean crush stress or plateau stress is calculated. Some sources find the average stress across the entire strain range, where d is the total displacement of the sample [8, 13, 15].

$$\sigma_{mc} = \frac{EA}{d} = \frac{\int_0^\epsilon \sigma(\epsilon) d\epsilon}{d} \quad (1.5)$$

This methodology is useful when the stress- strain curve does not experience a large stress variation when comparing the peak stress to the plastic regions. For some materials, however, it becomes necessary to look at just the plateau region due to the peak stress skewing the mean crush stress. Niu et al. and others show this in their definition of the mean crush stress [16–18].

$$\sigma_{mc} = \frac{EA}{\epsilon_d - \epsilon_{pk}} = \frac{\int_0^\epsilon \sigma(\epsilon) d\epsilon}{\epsilon_d - \epsilon_{pk}} \quad (1.6)$$

Here, ϵ_d is the densification strain and ϵ_{pk} is the strain at the peak stress. This will remove any influence caused by the peak stress. For example, Yin et al. introduce Equation 1.5 as the mean crush stress in their work because the stress is relatively constant throughout the test, and thus it can be averaged from the beginning of compression until complete compaction [19].

Once the general metrics have been determined, the efficiencies are used to determine the overall performance of the sample. Crush efficiency is the ratio of the energy absorption of the structure to the possible energy absorption of the material up to that strain. Mathematically it can be written as follows:

$$\eta_{SD} = \frac{EA}{\sigma_{pk}\epsilon} = \frac{\int_0^\epsilon \sigma(\epsilon)d\epsilon}{\sigma_{pk}\epsilon} \quad (1.7)$$

This is a strain dependent crush efficiency because it determines how efficient the material has been at absorbing energy up to the strain. However it can also be useful to determine how efficient the material is at absorbing energy assuming there is complete densification of the material. To do so, the strain is set to 1 [20, 21].

$$\eta_{EA} = \frac{EA}{\sigma_{pk}\epsilon|_{\epsilon=0}} = \frac{\int_0^\epsilon \sigma(\epsilon)d\epsilon}{\sigma_{pk}} \quad (1.8)$$

From this, the energy absorbed efficiency provides a quantitative value on how the sample performed.

It is important to remember that the force-displacement curve, and thus the energy absorption metrics are dependent on the geometry and material of the energy absorber that is selected.

1.1.2 Energy Absorbing Structures

The original energy absorbers that were studied were metallic tubes. Tubes, by definition, have a constant cross-section throughout the length of the shape. Some common tubes that are studied within the energy absorption field have circular, square, or hexagonal cross sections. Due to the complexity of the later shapes, energy absorption analysis began with circular tubes.

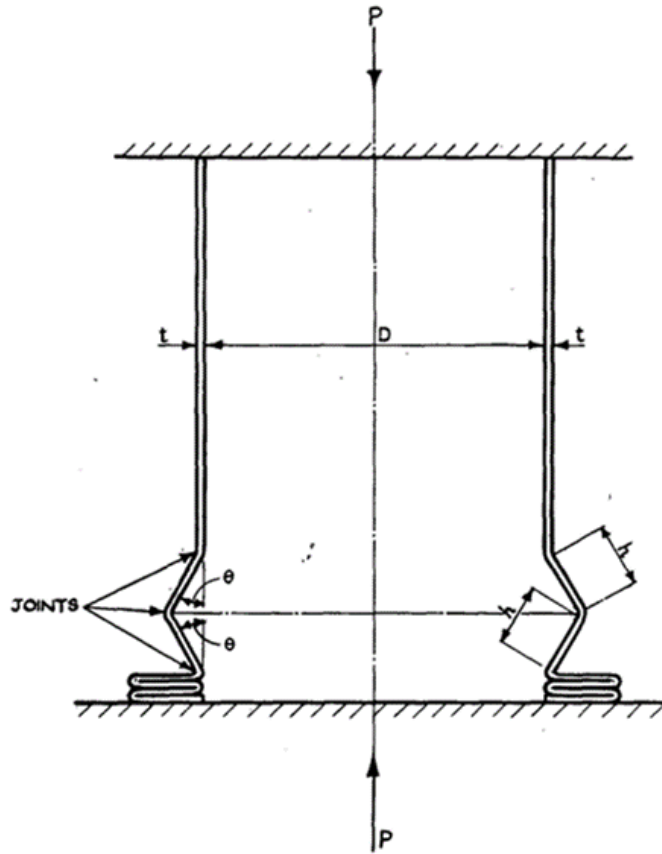


Figure 1.2: The collapse mode that Alexander assumed as adopted from Alexander et al. Figure 1

As Alexander explained, circular tubes can collapse such that they form symmetrical folds similar to bellows, or they can form transverse and longitudinal waves [22]. When these tubes collapse in the symmetric folds, they are often called a concertina (Figure 1.2). In his model, Alexander was able to derive an equation where the collapse load for a tube can be approximated once the material constant is determined experimentally for tubes that experience concertina folding [22].

Abramowicz modified Alexander's theoretical approximation of the collapse load for concertina deformations in circular tubes. The updated version included the effects of the effective crushing distance, so that it further improved the accuracy of the model for static crushing

loads [23]. He also improved the mean dynamic crushing loads by including the effects of the material strain rate sensitivity [23].

Similar theoretical models were also developed for square and rectangular cross section tubes. Wierzbicki et al. discuss how the mean crushing force is heavily dependent on the wall thickness of the tube for axially compressed rectangular tubes [24]. Abramowicz et al. continued to modify the quasi-static mean axial crushing load equations to achieve results that agree reasonably well with the experimental results [25].

More recent studies like Wang et al. have moved away from studying metallic circular tubes, but instead implementing polymers to manufacture the tubes. As Wang found, the material can greatly effect the folding pattern as well as the mean crushing loads, so the models that exist cannot be used to predict the performance of polymer samples [26]. Ozbbeck et al. discuss how glass fiber reinforced composite pipes result in a more brittle fracture as opposed to the concertina folding that is associated with metallic tubes [27]. As a result, their study is focused on implementing other methods, such as trigger mechanisms, to improve the energy absorption (Figure 1.3).

This concept of triggers were implemented in additional energy absorption samples, regardless of the bulk material. Triggers come in many different forms and shapes, however they all serve the same purpose: to decrease the peak stress and increase the mean crush stress.

The most common types of triggers are buckling initiators. Buckling initiators are purposeful stress concentrators intended to control the failure mechanism of the sample. There are many types of these including holes, wall thickness reduction, grooves, notches, beads, and corrugation [28]. As Bhutada et al. describes, removing material symmetrically on a metallic circular tube surface can modify the deformation mode so that a long tube that traditionally deforms un-

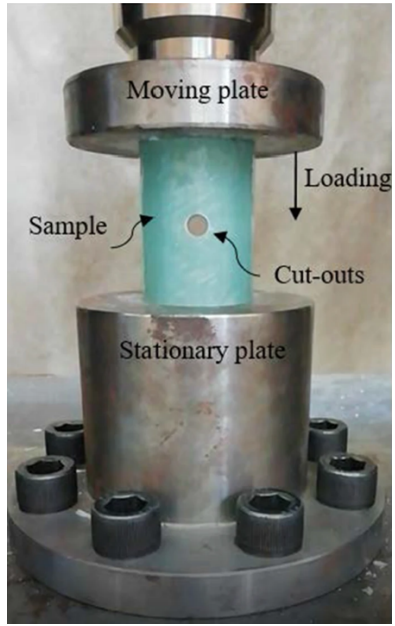


Figure 1.3: The glass fiber reinforced composite circular tubes with trigger mechanism Ozbeck et al. tested as shown in Ozbeck et al. Figure 3

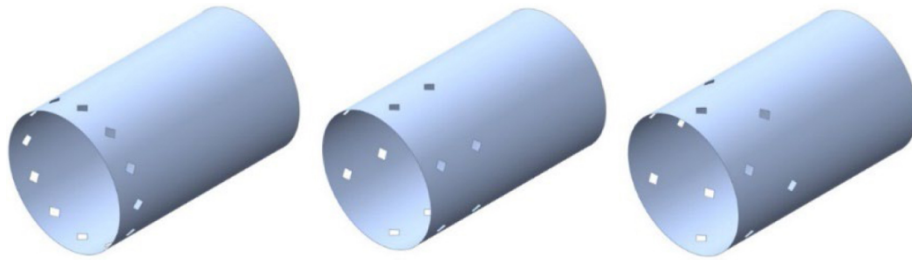


Figure 1.4: A representation of the samples with trigger mechanism that were tested as adopted from Bhutada et al. in Figure 3

der Euler buckling will experience a more stable collapse [29]. Figure 1.4 shows the 3D models of the samples that were investigated. With the numerical studies, it was determined that the location and size of the cut-outs will determine the deformation pattern of the metallic tubes [29].

Additional cross-sections have been studied to determine what the effects of buckling initiators are. Arnold et al. implemented circular buckling initiators on opposing walls in an aluminum square tube and studied the effect of the diameter of the buckling initiators on the collapse of the tube and the energy absorption [30]. In this work, Arnold et al. determined that collapse mode

and energy absorption were dependent on the presence of buckling initiators, not necessarily the geometry [30]. Cheng et al. conducted similar studies, however in their work, either a circular, elliptical, or slotted discontinuities was machined into the sample [31]. In their studies, it was determined that the dimensions and geometric shape of the discontinuity do not effect the energy absorption if the discontinuity was smaller then a critical dimension [31]. Dionisius et al. also studied the effects of circular buckling initiators, but this time in square steel tubes, while quantifying the effects that the wall thickness, diameter, and angle of the buckling initiators have on the energy absorption [28]. A function model was generated using numerical simulation methods to quantify these effects [28].

Similar to the previously reported studies, there have been trigger mechanisms implemented in composite pipes as well. Ozbeck et al. analyzed the effects of the number, location, and size of circular trigger mechanisms in a glass fiber reinforced composite pipe [27]. To improve energy absorption, the trigger mechanisms should be located closer to the impacted edge for laminates. It was also reported that as the diameter became too large, the energy absorption decreased, so the buckling initiator size must be optimised [27].

Another type of initiator that has been reported throughout literature is designing the end of the sample to match the collapsing mode shape. As Kim describes, the simplest collapsing mode is designed to match the first elastic buckling mode shape [32]. The study focuses on how the simple trigger mode compares to the complex trigger mode in aluminum square tubes, where the end of the sample is designed to take the shape of a plastic quasi-inextensible fold [32]. By implementing the the complex trigger mode, the complex mode of crushing occurs for just the first fold, and crushing for the remainder, providing an increased stability in the progressive collapse [32]. Ma et al. also provide examples of pre-folding the structure so that the collapse of

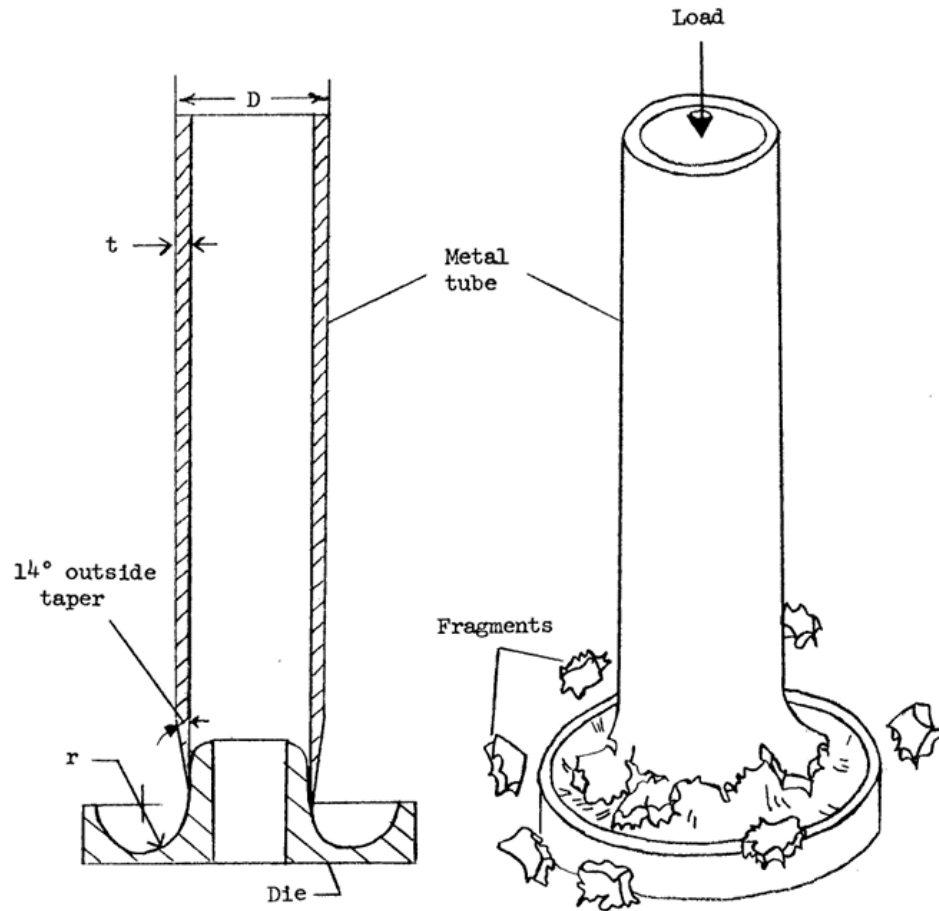


Figure 1.5: A sketch of the testing setup with no load and then with load as adopted from McGehee et al. Figure 2

the structure can be controlled and tailored to the design application [33].

If the application of the material allows for a permanent attachment, a cap or hat can be implemented to encourage a controlled failure. McGehee et al. describe this process as a tapered tube coming into contact with a die that has an edge with a radius as shown in Figure 1.5 [34]. The fragmenting that occurred when the circular aluminum tube came into contact with the die results in a stress that can fluctuate as load is being applied. The fluctuations were found to decrease when the ratio of the internal diameter of tube to the die forming radius increased [34].

Depending on the final application of the energy absorption structure, it is possible to im-

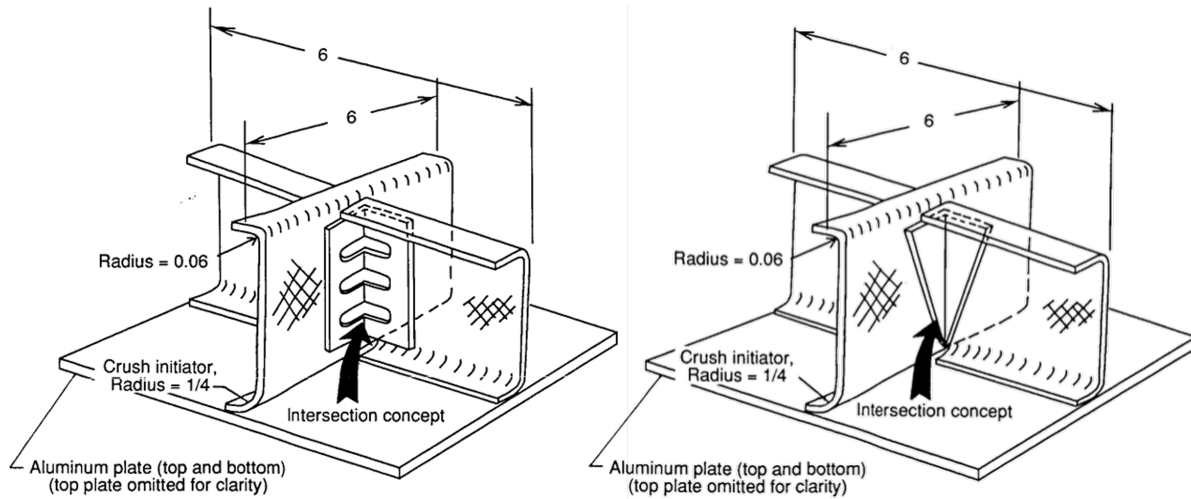


Figure 1.6: A sketch of the two intersection methods used in tests as adopted from Jones et al. Figure 2

plement a radius as an initiator between the structure and the structure applying to load. In Jones et al. the location where the longitudinal subfloor beams and the lateral bulkheads meet were analyzed to increased energy absorption [35]. For this reason, it was crucial to include the top and bottom plates since the load is distribute over these surfaces. In this study, the intersection between the longitudinal and lateral beams was open to design, so a radius was applied to the end of the beams as a crush initiator, while also varying the joint in the middle of the beam (Figure 1.6). From the study, it was determined that using a tapered design to attach the intersections improves the energy absorption parameters the most [35].

Another method that is used to help stabilize the force- displacement curve of energy absorbing materials is by implementing a foam filler. Goel studied the effect of filling both square and circular aluminum tubes with an aluminum closed cell foam for a varying number of concentric tubes [36]. From this work, it is noted that having a foam-filled structure greatly improves the energy absorption abilities of the structure and that when experiencing dynamic loading, having multiple tubes, allows for the stress wave propagation to dissipate, all while maintaining a light

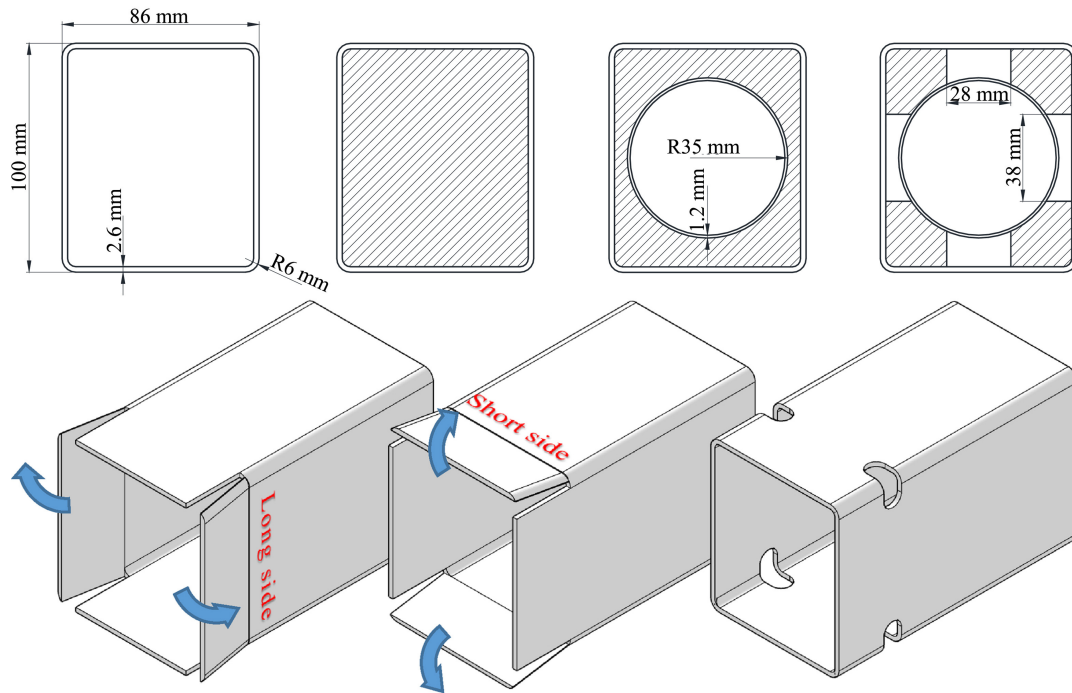


Figure 1.7: A demonstration of (top row) the different foam filling and (bottom row) the trigger mechanisms used as adopted from Wang et al. Figures 2 and 4

weight structure.

There are ways though to combine buckling initiators with foam filled boxes though. Wang et al. studied crash boxes that are used in vehicles. To do so, the study was composed of four different foam filling scenarios: no foam, completely filled, double filled, and corner filled (Figure 1.7). From each, three different trigger mechanisms were tested: folds on the long side, folds on the short side, and cut outs. Wang et al. found that using the foam in the corners was able to improve the energy absorption parameters while still balancing other objectives like maintaining a lightweight structure and increasing the load carrying abilities.

Although these energy absorption strategies have been implemented on circular and tubular structures, they can also be implemented on another familiar tubular structure: honeycomb.

1.1.3 Honeycomb

Honeycomb is an array of repeating prismatic cells that nest together to form a plane [11, 37]. Honeycomb is most often designed as a 2D lattice structure, with cells that can be hexagonal, but can also be triangular, square, or rhombic [18, 37]. Hexagonal honeycomb is based in a triangle unit cell, where each edge length is constant as it is spread 120° around the vertex. Six of these triangular unit cells are joined to create a hexagon, resulting in additional locations to continue the pattern. Due to the triangle at each vertex, there is a sharp corner where a stress concentration can occur. Nazir et al. showed that by rounding these corners, the stiffness and energy absorption increase [20].

Honeycombs can be compressed in one of two ways: in plane and out of plane. Figure 1.8 shows an example of a honeycomb plate. If this honeycomb were to be compressed in the $X_1 - X_2$ plane, this would be in plane compression [13]. As the load is applied the cell walls bend due to linear elastic deformation before collapsing [37]. The reason for collapse is dependent on the material of the honeycomb, but it could be elastic buckling, plastic yielding, creep, or brittle fracture [37]. If the sample experiences plastic yielding, there will be a region of plasticity deforming the sample, but for brittle samples, they can be identified by fracturing. Regardless of the mode of collapse, the cells will collapse until they touch each other, resulting in the structure densifying as the stiffness increases [37].

When a sample is compressed in the out of plane direction, the load would be applied in the X_3 direction. When this happens, the load is applied parallel to the cell walls, resulting in either extension or compression of the walls [37]. As a result, the modulus and collapse stress are higher than those experienced during an in plane compression. The linear elastic deformation

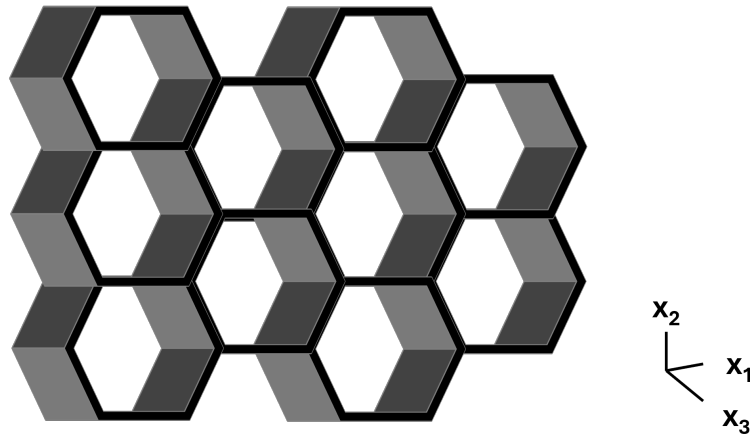


Figure 1.8: A sketch of a honeycomb plane with the orientations identified

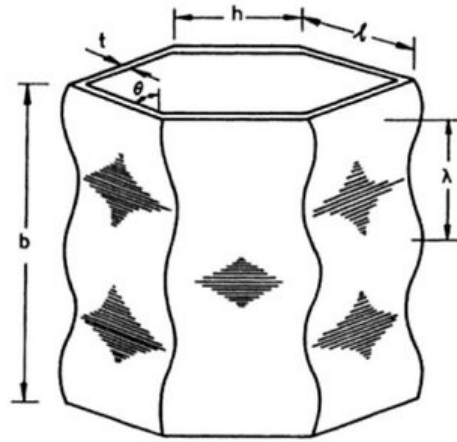


Figure 1.9: A sketch of a honeycomb under axial elastic buckling as adopted from Gibson et al. Figure 4.38

is controlled by the buckling of the cell walls as seen in Figure 1.9, so both axial and bending contribute to the plastic collapse strength [37].

Due to the complexity of these honeycomb, numerical analysis was developed to predict the performance of these structures. Beginning in 1961, McFarland produced an equation that provided the average compression force for the out of plane quasi static compression of metallic hexagonal honeycomb [38]. By 1983, Wierzbicki et al. modified McFarland's work using the principle of energy conservation. The updated results provided a solution for the static average

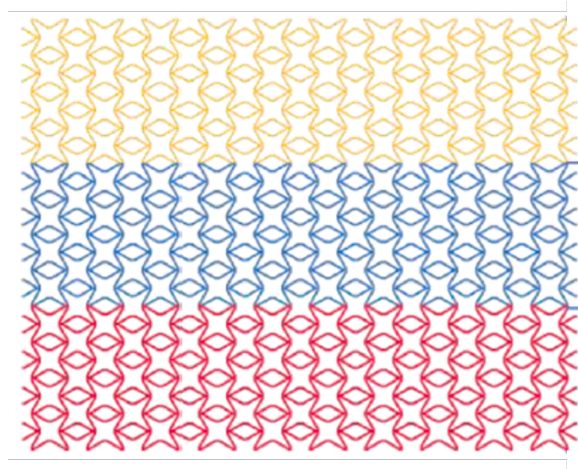


Figure 1.10: A model where each color is representative of a different density of honeycomb as adopted from Liu et al. Figure 1

compression force for an out of plane compression test of hexagonal aluminum honeycomb [39]. Gibson and Ashby used the previous work to determine the displacement of a honeycomb sample subjected to out of plane quasi static compression [37]. The methodology for deriving all moduli needed to calculate the displacement is provided in Section 4.5 in *Cellular Solids: Structure and Properties* [37].

The traditional hexagon honeycomb structure has three main reinforcement designs that will improve the energy absorption: the negative Poisson's ratio structural design, the functionally graded design, and the bio-inspired hierarchical design [40].

Anni et al. implemented the functionally graded design in a thermoplastic polyurethane (TPU) honeycomb by changing the density of different sections as the height of the honeycomb increased [41]. Liu et al. conducted a similar experiment, however each section of the sheet of honeycomb was a different thickness (Figure 1.10) [17]. These samples are also known as auxetic because they have a negative Poisson's ratio.

Liu et al. describe the process of designing a bio-inspired re-entrant honeycomb [42]. The

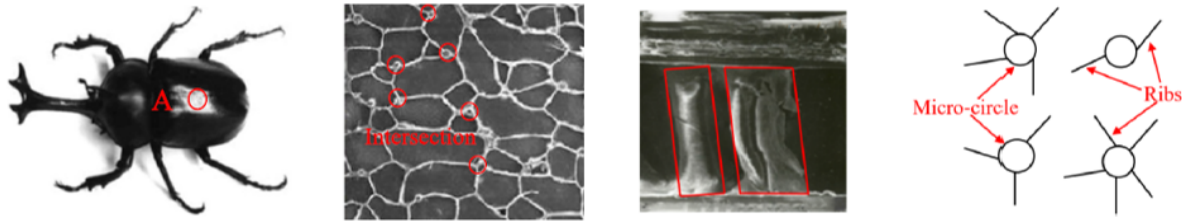


Figure 1.11: The beetle and the intersection points that inspired the micro-circle and rib design for honeycomb application as adopted from Niu et al. Figure 1

reinforcements that were added were similar to those used in plants to support the forces they encounter. Niu et al. implemented a bio-inspired hierarchical design by using a unit cell with a central micro-circle and a varying number of ribs, similar to the cellular structure of beetles [16]. The simplified microstructure shown in Figure 1.11 was implemented in a hexagon for the studies.

Similar to Niu et al., Sharma et al. were inspired by another living organism: a sea sponge. It is a cylindrical skeleton that consists of small square units cells which are composed of two open and two closed cells [21]. This same unit cell was replicated in the lab using PLA and TPU. The samples with TPU for the horizontal and vertical struts and the PLA for the diagonal struts were found to have the highest energy absorption parameters. Others insist that by using materials with different properties, the combination of strength and toughness will be similar to that of bone and nacre [43].

Another method used to improve the energy absorption properties of honeycomb is through the use of hierarchical honeycombs. A hierarchical honeycomb is created when a cell wall of the hexagon is replaced with a series of smaller hexagonal honeycomb [14]. There are examples of this micro- meso scale structural hierarchy in bone, tendon, nacre, and coconut shell [9, 44, 45].

1.1.4 Honeycomb Manufacturing

The need for faster and cheaper honeycomb manufacturing has increased with many industries looking to implement honeycomb as an energy absorber in their respective fields. The material will dictate what manufacturing methods can be used. With the increased understanding of additive manufacturing, there are many new manufacturing options that are available.

The preliminary manufacturing methods that were developed focused on manufacturing metallic honeycomb. The first method of these is the stamp forming method. In this process, a punch and die are used to transfer the desired pattern onto a metal plates [46]. The internal structure is then free to be removed. If necessary, a secondary step can be used to bend the structure if needed, prior to welding [46]. Stretch mesh folding is another option that can be used to manufacture a flat plate with the desired design. Here, a punch is used to remove the excess material [47]. At this point, the flat plate goes through a roller to flatten it and deform the honeycomb to the correct dimensions [47]. Another example of the manufacturing process is taking long, thin sheets of metal and applying an adhesive strip in the desired locations. A second thin sheet of metal is placed on top while additional adhesive is applied. The process repeats to create flattened honeycomb. The structure is expanded through the use of compressed air. The final example of metallic honeycomb manufacturing is Gypsum pressure percolation. A low-melting polymer model is manufactured and placed in a mold. A gypsum slurry is used to fill the mold before leaving the gypsum to dry [48]. Once dried, the polymer model is removed and liquid aluminum is used to fill the mold. This is placed in a vacuum to ensure the aluminum fully penetrates the mold [48]. The final mold can be rinsed with water to remove the aluminum part.

Although these methods are consistent, they cannot be used to manufacture complex honeycomb, such as a constant wall thickness honeycomb or a honeycomb with buckling initiators. These individual processes must be combined with welding or subtractive manufacturing. Welding though, can cause stress concentrations at the weld bead, therefore weakening the entire structure [18]. Another material choice is a polymeric honeycomb.

Two processes will be highlighted for manufacturing non-metallic honeycomb. The first is the laser cutting method. Depending on the material, the material is laid out and a laser probe is used to remove the excess material in the plate [49]. The consistency of this process is dependent on the accuracy of the stage that the material is placed on as well as the stiffness of the material [49]. Another similar process is water jet cutting. Here, a water jet is used to cut the honeycomb pattern into the material. Once completed, multiple pieces are stacked together and attached to the face plates so that a sandwich structure is manufactured [50]. There is still room for improvement when manufacturing large pieces of honeycomb though [18].

Additive manufacturing was developed as an alternative to subtractive manufacturing. Subtractive manufacturing begins with a large block of material and removes what is unnecessary, whereas additive manufacturing adds material only to the areas where it is needed. There are seven families in which additive manufacturing technology falls into: binder jetting, material extrusion, powder bed fusion, vat polymerization, direct energy deposition, material jetting, and sheet lamination. Of these families, only two will be reviewed in the following.

Material extrusion is the form of additive manufacturing that most individuals think of when they hear the phrase "additive manufacturing." Finite deposition modelling (FDM) is the process of melting, extruding, and depositing thermoplastic polymer to manufacture the desired geometry [51]. The raw material, or filament, is kept on a spool which is fed into the nozzle.

The filament is heated to above the glass transition temperature to allow for the ability to place the material as needed in a layer by layer process [21]. The most common polymers used in FDM are as follows: polylactic acid (PLA), polycarbonate (PC), polyethene terephthalate (PET), TPU, ABS, and Nylon 6 [52]. The main concerns with FDM is the build orientation or the placement on the part relative to the build platform [53]. As Anni et al. explain, it is necessary to determine the material properties relative to the testing orientation [41]. Additional work has been conducted to quantify the mechanical properties [13, 54].

Vat Polymerization encompasses any additive manufacturing process that uses a photosensitive liquid. For both processes that follow, the structure being manufactured is sliced into 2D layers. The first process is Stereolithography (SLA). This is a process where a photo-curable resin is placed in a transparent container to allow a laser to point cure the resin per the design [55]. SLA is commonly used because it has high precision, however there is a limit on available resins and there is an extensive post processing step. The second vat polymerization process that is commonly used is digital light processing (DLP). Here, a light is projected over the entire bath of resin so that the entire layer of the print is cured at once [56]. This process continues until all layers of the print have been cured [57]. Both of these methods create a solid-body object with no concerns regarding anisotropy.

1.2 Organization of Dissertation

The following dissertation is organized by topic area. Each chapter consists of a unique set of studies that were completed.

Chapter 2 discusses the effects of cell size and buckling initiator location in an ABS hon-

eycomb. Here, three inscribed diameters are tested under uni-axial quasi- static compression while the effect of buckling initiator is quantified. Three unique buckling initiator locations were studied: located at the top of the sample, 3/4 up the height of the sample, and at the midpoint of the sample. These samples were compared to the performance of the samples without buckling initiators.

Chapter 3 is focused on a series of studies involving a visco-elastic honeycomb. For this set of studies, thermoplastic polyurethane (TPU) was used to manufacture a honeycomb unit cell with either no buckling initiators or buckling initiators located halfway up the height of the sample. This study quantified the effects of buckling initiators and cross head velocity on the energy absorption properties. The repeatability of the testing is also quantified.

Chapter 4 continues on the previous study to further quantify the performance of the visco-elastic honeycombs when subjected to dynamic impact events. Here, the TPU samples with buckling initiators located at the top and midpoint of the sample along with samples having no buckling initiators were subjected to a series of impact velocities. These results were compared to those of the constant velocity and quasi- static tests that were conducted in the previous chapter to determine if there is a simpler test method that could predict the energy absorption of the dynamic samples.

In Chapter 5, a series of uni-axial quasi-static compression tests were conducted on both electroplated and no plated resin honeycomb. Due to the increased safety concerns and cost of additively manufacturing metallic honeycomb, a set of stereolithography samples were studied to determine if electroplating the mandrel would result in a more ductile performance. Here, a set of SLA printed honeycomb with and without buckling initiators were tested and compared to their electroplated counterparts.

Chapter 2: Effect of Cell Size on Energy Absorption Properties of Additively Manufactured Honeycomb at Low Strain Rate Events

Honeycomb materials are being used for energy absorption applications in aerospace and automotive industries due to their high strength to weight ratio. In this work, additively manufactured honeycomb with different inscribed diameters were tested in quasi-static compression on a servo-hydraulic material test system to determine how the geometry effects the energy absorption properties. Samples were manufactured with buckling initiators, or small triangle cutouts, located at various positions vertically up the height of the sample, while others had no modifications. As this study showed, the strain dependent crush efficiency and energy absorbed efficiency increase as the inscribed diameter decreases. When the inscribed diameter is 10 mm, the crush efficiency is 62%, while it is 3 times smaller when the inscribed diameter increases to 20 mm (20.29%). The energy absorbed efficiency is 45% for the 10 mm sample while it decrease to 16.70% when the diameter is 20 mm (36% decrease). Similarly, the presence of buckling initiators will increase the crush efficiency and energy absorbed efficiency of the samples when compared to their no buckling initiator counterparts, regardless of the size of the honeycomb.

2.1 Introduction

Additive manufacturing has been incorporated into industries such as automotive, construction, aerospace, medical, and others in recent years [58]. The reduction in cost and time to manufacture complex geometries, along with minimal capital investment and versatile production has resulted in more of an interest in the field [58, 59]. The most common and affordable additive manufacturing technique is finite deposition molding or FDM [60, 61]. Here, an object is manufactured by depositing material layer by layer on a build plate [58]. The concern with this method is it will result in high anisotropy and weak interlayer bonding [60, 62].

The aerospace, automotive, and defense industries have been increasingly interested in the use of additively manufactured honeycomb for sandwich panels in energy absorption applications [63, 64]. When printed in the out-of-plane direction and loaded like such, the highly anisotropic layers would allow for the honeycomb to absorb more energy. These honeycomb cores are of great interest due to the high strength-to-weight ratio, high stiffness-to-weight ratio, and high energy absorption capabilities [65]. As Habib et al. explains, when designing a honeycomb for energy absorption applications, a significant amount of time must go into selecting the correct cell geometry to keep the transmitted force below the force threshold that can cause damage [64].

Manufacturing these honeycomb cores using finite deposition molding allows for greater control of the geometries. Previously, honeycomb structures could not be modified beyond the cellular dimensions due to the manufacturing methods, however honeycomb structures can now be tailored to create stronger and more efficient structures [20]. One example of this is varying the wall thicknesses. Honeycomb used to have varying wall thicknesses due to the manufacturing method, however using FDM allows for the cores to be manufactured to final dimension and

thus have a constant wall thickness. The following study shows how the use of FDM can create an ABS honeycomb core with integrated buckling initiators. To date, literature does not document the correlation between the buckling initiator performance as the honeycomb core geometry changes.

In this study, a series of honeycomb cores were tested under out of plane quasi-static compression with buckling initiators in a variety of locations. Each of these honeycomb cores had a different inscribed diameter, increasing from 10 to 20 mm in increments of 5 mm. As the inscribed diameter increased, the crush efficiency was found to decrease, however the cores with buckling initiators always out performed their counterparts without buckling initiators.

2.2 Materials and Methods

2.2.1 Manufacturing and Testing

For this study, a series of additively manufactured honeycomb of varying inscribed diameters were tested to identify the energy absorption properties. These samples were manufactured using acrylonitrile butadiene styrene (ABS-R), which has a tensile strength and modulus of 41 and 2400 MPa respectively (Makerbot, New York, NY). The samples are composed of six hexagons surrounding a central hexagon. For the study, there were three types of samples manufactured: those with inscribed diameters of 10, 15, and 20 mm respectively. The samples kept all other geometric values constant by using a height of 30 mm and a wall thickness of 0.7 mm. Each type of sample were designed to include buckling initiators (BIs), or small diamond cutouts located at the vertices. There were four unique locations of the buckling initiators: a) no buckling initiators; b) buckling initiators located halfway up the height; c) buckling initiators located 3/4

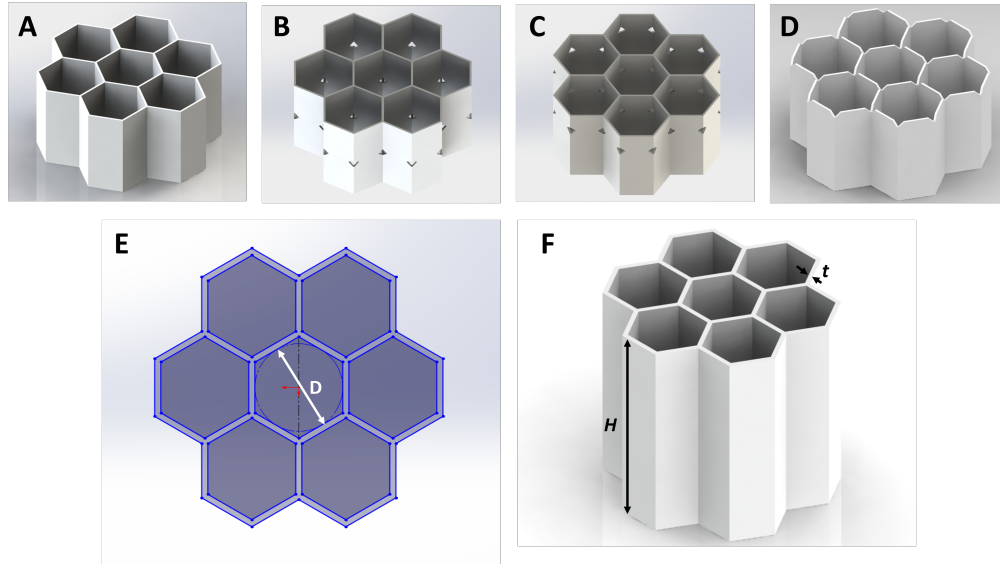


Figure 2.1: Computer aided design rendering of samples. (A) 0.00BI; (B) 0.50BI; (C) 0.75BI; (D) 1.00BI; (E) inscribed diameter varies, and (F) height and thickness of the sample are held constant.

up the height; and d) buckling initiators located at the top. These buckling initiators are 4 mm in length and 4 mm in height. This created a total of 24 different types of samples (Figure 2.1).

The samples were modeled using Solidworks and then sliced using Makerbot's CloudPrint software. The Method X was used to print the samples due to the accuracy and precision (Makerbot, New York, NY). ABS-R was selected as the filament of choice due to the well-understood material properties.

The samples were tested in uni-axial compression on a servo-hydraulic material test system in the out of plane orientation (MTS, Eden Prairie, MN). The samples were tested at $1\text{E-}3\text{ s}^{-1}$ or a cross head velocity of 0.03 mm/s. The samples were imaged using a Nikon every 10 seconds so that the failure could be documented and reviewed later.

2.2.2 Metrics

Energy absorption metrics have been identified from literature to assist in the assessment of these samples. The stress must be determined first.

$$\sigma = \frac{2F}{21L^2\sqrt{3}} \quad (2.1)$$

Here σ is the stress, F is the force, and L is the length of the side wall. Because the sample is composed of seven independent hexagons, the area was determined using:

$$A = \frac{21\sqrt{3}}{2}L^2 \quad (2.2)$$

From this, the energy absorbed can be determined.

$$U(\epsilon) = \int_0^\epsilon \sigma(\epsilon) d\epsilon \quad (2.3)$$

The strain dependent crush efficiency can be determined when the idealized energy absorption is compared to the energy absorption.

$$\eta_{SD}(\epsilon) = \frac{U(\epsilon)}{\max[\sigma(0), \sigma(\epsilon)]\epsilon} = \frac{\sigma_{mc}}{\max[\sigma(0), \sigma(\epsilon)]} \quad (2.4)$$

In this equation, σ_{mc} is the mean crush stress and it can be found using:

$$\sigma_{mc} = \frac{U(\epsilon)}{\epsilon} \quad (2.5)$$

The mean crush stress provides a representative value of the stress throughout the entire strain range of the sample. When the energy absorbed is compared to the idealized energy absorbed across the entire strain range, the energy absorbed efficiency can be determined. Mathematically, it would be the following:

$$\eta_{EA}(\epsilon) = \frac{U(\epsilon)}{\max[\sigma(0), \sigma(\epsilon)]\epsilon|_{\epsilon=1}} = \frac{U(\epsilon)}{\max[\sigma(0), \sigma(\epsilon)]} \quad (2.6)$$

2.2.3 Computational Analysis

In order to investigate the honeycomb behavior under uni-axial quasi-static compression, a finite element model (FEM) was developed to simulate the out of plane compression in ABAQUS. The dimensions, cell shape, and overall geometry of the honeycomb including buckling initiators and wall thickness were represented using the shell elements model. To explore the advantages of honeycomb structures with buckling initiators, the FEM model of the structure without buckling initiators was also simulated. The shell element thickness of both model was set to be 0.7 mm. Two plates (modeled as rigid bodies) were added to the honeycomb to represent the MTS test fixture and facilitate the load being applied. In the uni-axial compression simulation, the bottom and top plates were modeled as a general surface-to-surface contact with the honeycomb block bottom and top surfaces with a friction coefficient of 0.6. The bottom plate was fixed and a displacement of 24 mm was applied to the top plate to mimic testing. The dynamic explicit solver in ABAQUS was adopted with a simulation time period of 0.02 s and the compression displacement was ramped from 0 to 24 mm in this period.

The material properties of the ABS-R adopted in the FEM simulations are: an effective

elastic modulus of 1702 MPa, a Poisson's ratio of 0.193, and a yield stress of 71.79 MPa. For simplicity, a linear isotropic hardening plastic model after yielding was used in the simulation with a yield stress of 71.79 MPa at a plastic strain of 0 and 82 MPa at a plastic strain of 0.3. In addition, shear failure with an initiation value of 1.4 was added in the analysis.

2.3 Results

2.3.1 Preliminary Data Review

As the buckling initiator height increases, the peak stress was found to decrease as Figure 2.2A shows. This occurs regardless of the inscribed diameter. The peak stress is found to decrease as the inscribed diameter increases due to the increase in contact area over which the load is being applied (Figure 2.2A-C). The peak stress also experiences a shift from a later strain range to an earlier strain as the buckling initiator height increases.

The crush efficiency of these samples show a consistent trend. The samples experience an initial increase in crush efficiency until it plateaus before decreasing once densification initiates. Figure 2.3A-C show that the maximum crush efficiency decreases as the inscribed diameter increases. Regardless of the inscribed diameter, the samples with the buckling initiators located at the top result in the highest crush efficiency across the usable strain range. This is followed by the samples without buckling initiators for the samples with an inscribed diameter of 15- and 20-mm. When the inscribed diameter is smaller, having buckling initiators are found to increase the crush efficiency across the usable strain range.

The energy absorbed efficiency describes the ability of the sample to absorb the energy, thus protecting the occupant. Regardless of the inscribed diameter, the maximum energy absorbed

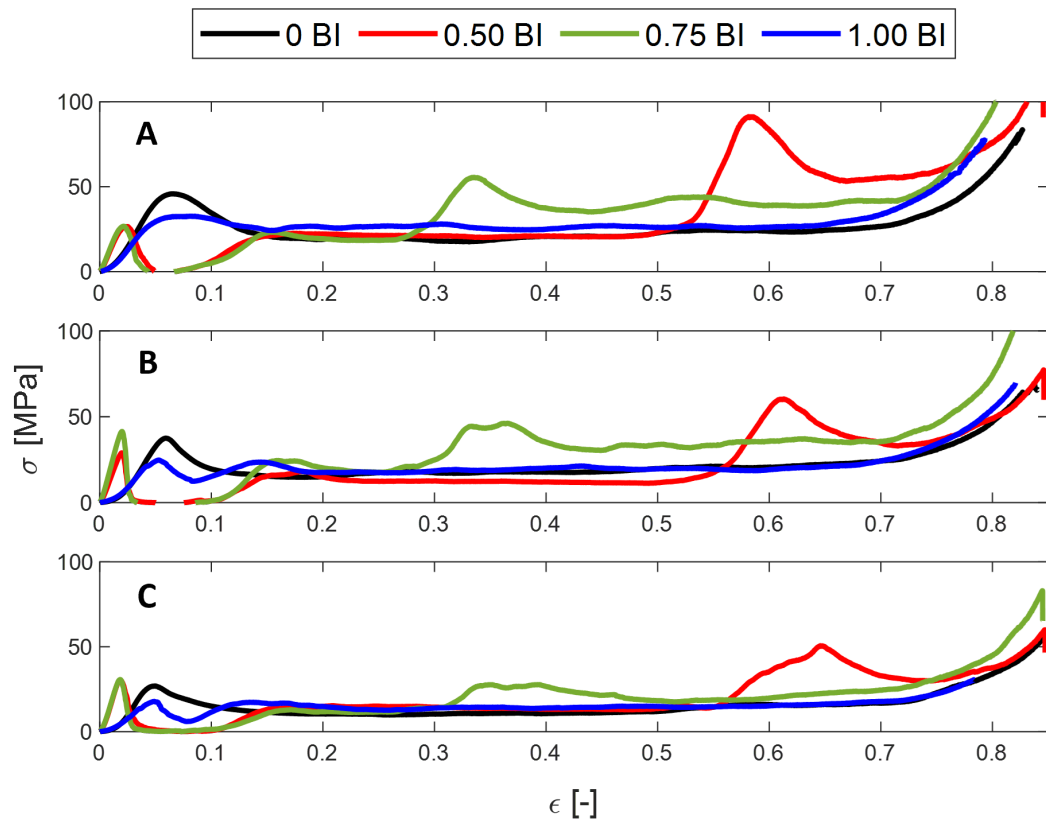


Figure 2.2: The stress- strain behavior of the samples under quasi-static conditions. A) 10-, B) 15-, and C) 20-mm inscribed diameters.

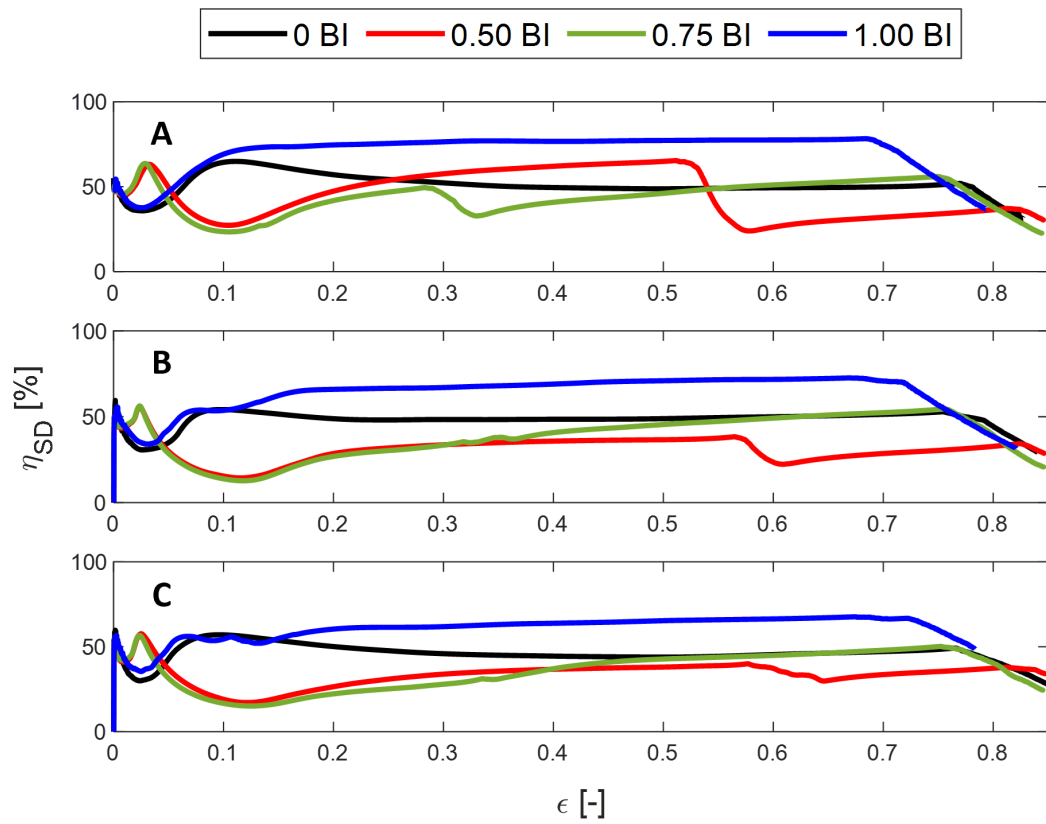


Figure 2.3: The strain dependent crush efficiency of the samples under quasi-static conditions. A) 10-, B) 15-, and C) 20-mm inscribed diameters.

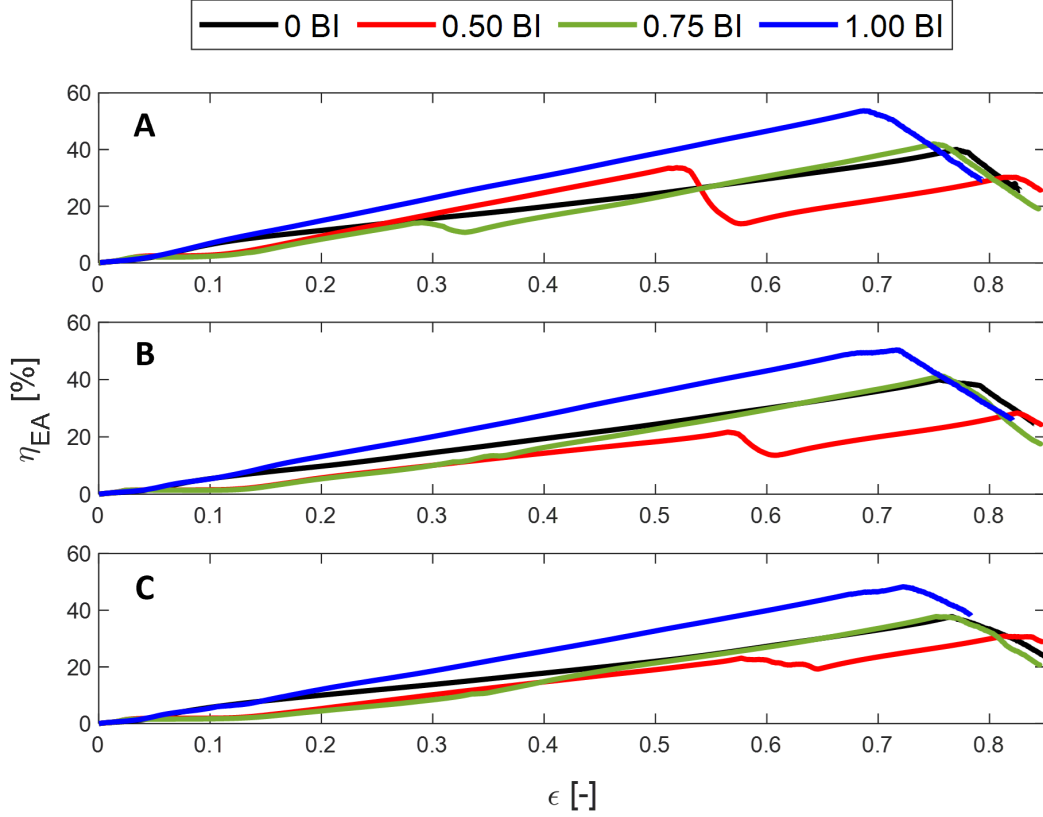


Figure 2.4: The energy absorbed efficiency of the samples under quasi-static conditions. A) 10-, B) 15-, and C) 20-mm inscribed diameters.

efficiency is achieved by the samples with buckling initiators located at the top, followed by 0.00BI, 0.75BI, and 0.50BI respectively (Figure 2.4). The samples also densify in the same order, so the 1.00BI sample has the shortest usable strain range, about 70% strain, compared to 0.50BI, which is usable up to 85% strain.

The metrics for these quasi-static tests are summarized in Figure 2.5. The peak stress is found to decrease as the height of the buckling initiator increases with the exception of the sample without buckling initiators. The peak stress decreases from over 90 MPa to less than 40 MPa by moving the buckling initiator from the midpoint to the top of the sample (Figure 2.5A). Also, increasing the inscribed diameter of the sample results in a decrease of the peak stress. For the samples with the buckling initiator at the midpoint, the peak stress decreases from about 90 to 50

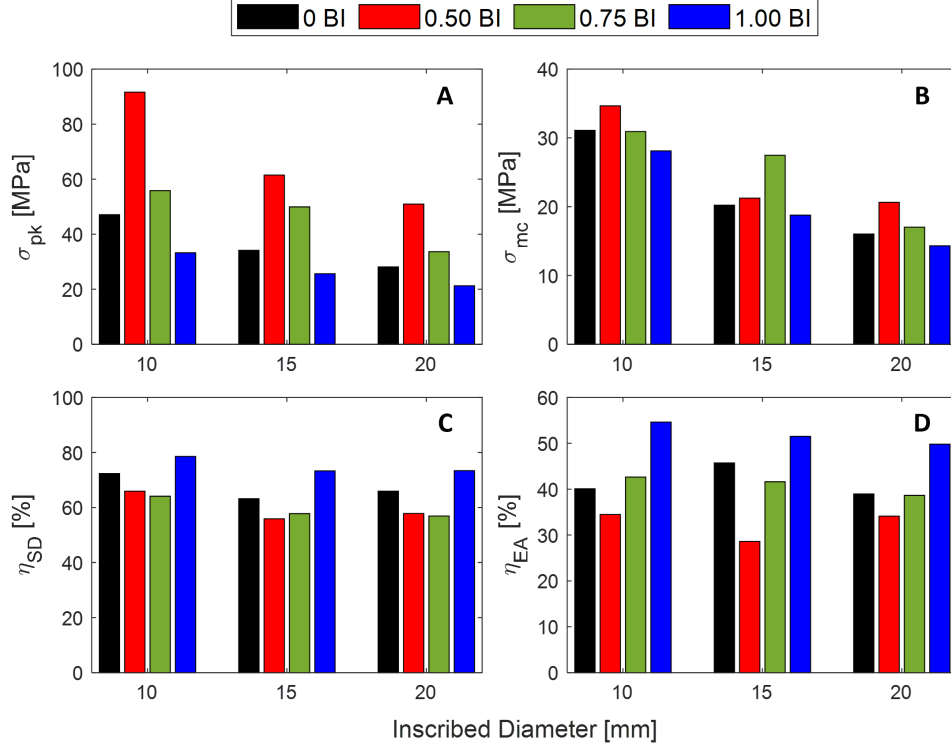


Figure 2.5: The metrics for the tested samples: A) peak stress, B) mean crush stress, C) maximum strain dependent crush efficiency, and D) maximum energy absorbed efficiency.

MPa by increasing the inscribed diameter from 10 mm to 20 mm.

The mean crush stress is a metric that reports the average stress value over the full strain range. According to this metric, the 0.50BI sample has the highest average stress for both the 10- and 20-mm inscribed diameter samples (Figure 2.5B). The lowest reported mean crush stress for all samples is the 1.00BI samples.

The maximum strain dependent crush efficiency is highest for the 1.00BI samples for all tested diameters by 5-10%. This is followed by the samples without buckling initiators. Regardless of the situation, it will be more beneficial to use no buckling initiators before implementing buckling initiators 50 or 75% of the way up the sample.

The maximum energy absorbed efficiency is dominated by the 1.00BI samples regardless of the sample's diameter. These 1.00BI samples absorbed are almost 10% more efficient than the

Table 2.1: The average properties for the samples with varying BI location and inscribed diameters.

D [mm]	BI [-]	σ_{pk} [MPa]	σ_{mc} [MPa]	$\Delta\sigma$ [MPa]	η_{SD} [%]	η_{EA} [%]
10	0.00	47.09	31.09	16.00	72.37	40.10
	0.50	91.62	34.66	56.96	65.96	34.49
	0.75	55.83	30.92	24.92	64.11	42.65
	1.00	33.26	28.11	5.15	78.57	54.64
15	0.00	34.11	20.21	13.90	63.20	45.72
	0.50	61.48	21.25	40.24	55.92	28.60
	0.75	49.92	27.47	22.45	57.77	41.62
	1.00	25.63	18.77	6.86	73.31	51.53
20	0.00	28.10	16.02	12.08	65.92	38.97
	0.50	50.94	20.63	29.32	57.83	34.31
	0.75	33.64	17.02	16.62	56.90	38.64
	1.00	21.24	14.31	6.93	73.40	49.82

next most efficient samples (Figure 2.5D). The quantitative vales are provided in Table 2.1.

2.3.2 Validation of Results

2.3.2.1 Computational Analysis

A computational analysis was completed on the 0.00BI and 1.00BI samples to determine whether the experimental results could be predicted. These two classes of samples were selected due to their promising outcomes with regards to the metrics.

The computational analysis shows agreement with the experimental results for the 0.00BI stiffness results. The initial increase in slope matches well, reaching a peak stress of similar values at the same strain (Figures 2.6B and C). The mean crush stress is over-predicted by the computational analysis by approximately 5 MPa in the three inscribed diameters. This will likely result in an over-prediction of the crush efficiency.

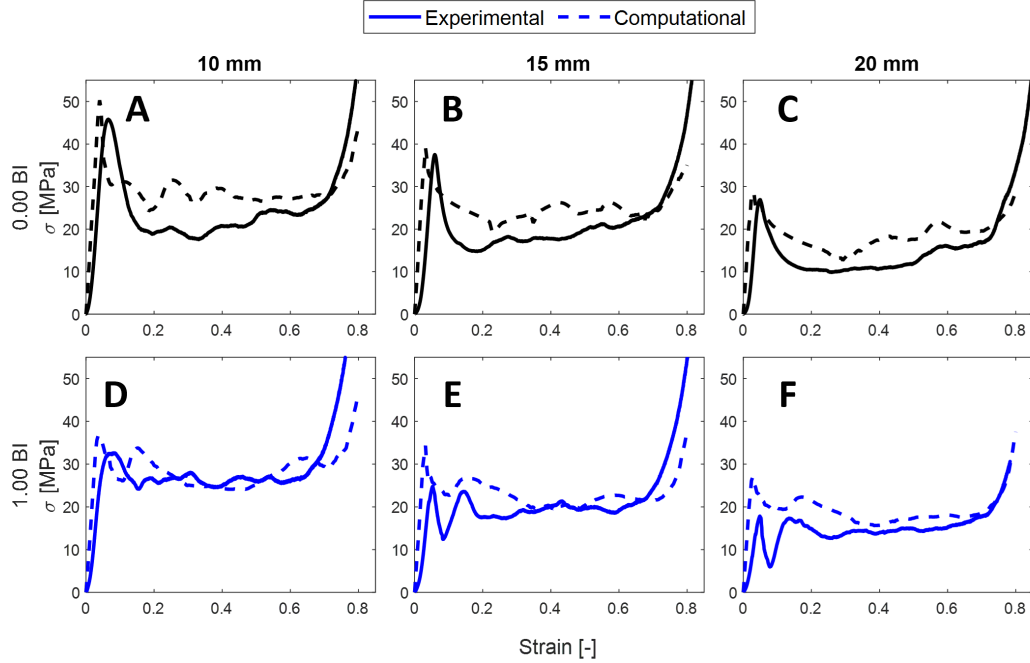


Figure 2.6: A computational analysis of 0.00BI and 1.00BI samples. A) 10 mm with 0BI; B) 15 mm with 0BI; C) 20 mm with 0BI; D) 10 mm with 1BI; E) 15 mm with 1BI; and F) 20 mm with 1BI.

Reviewing Figures 2.6 D, E, and F shows the computational analysis over predicts the stress in the 0 - 20% strain range. Although the strain at the peak stress is correct, the increase in stiffness results in a higher peak stress value. Each of the metrics were computed for the computational and experimental sets of data (Figure 2.7).

The computational analysis shows strong agreement between the metrics for the experimental and computational samples. Figure 2.7A shows the crush efficiency decreases as the inscribed diameter increases. Similarly, it shows the maximum crush efficiency decreases when there are buckling initiators located at the top of the sample as compared to having no buckling initiators. Similarly, the maximum reported energy absorbed efficiency is found to decrease as the inscribed diameter increases (Figure 2.7B). Likewise, the maximum energy absorbed efficiency value decreases with the presence of buckling initiators.

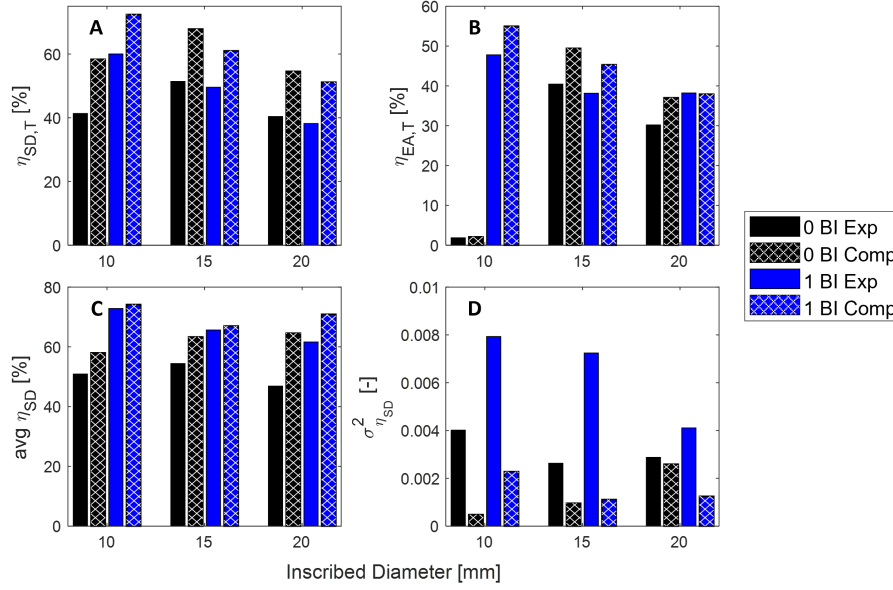


Figure 2.7: The computational analysis metrics for the samples. A) The threshold strain dependent crush efficiency, B) the threshold energy absorbed efficiency as calculated using a threshold of 40 MPa. C) The average and D) variance in crush efficiency from 2- 75% strain.

The average crush efficiency across the strain range of 2 to 75% strain shows a different set of trends. The samples with buckling initiators have a higher average crush efficiency than those without buckling initiators (Figure 2.7C). The samples maintain a relatively consistent crush efficiency across the range of inscribed diameters studied. The variance in this crush efficiency is found to be significantly larger in the samples with buckling initiators, however the computational analysis does not capture this response. Figure 2.7D shows the disagreement between the computational analysis and the experimental study.

With the exception of the variance in the crush efficiency, the computational analysis provides the ability to predict the performance of the samples. The behavior of the computational analysis will allow for the ability to design future samples without extensive testing. The table below includes the values for each metric that was analyzed in this study, as determined by the computational model and the experiments (Table 2.2). The difference between these values are

reported to provide additional insight into the precision of the model.

Table 2.2: The computational and experimental metrics for all three inscribed diameters.

Diameter [mm]			σ_{pk} [MPa]	σ_{mc} [MPa]	$\eta_{SD,T}$ [%]	$\eta_{EA,T}$ [%]	avg η_{SD} %	$\sigma_{\eta_{SD}}^2$ [-]
10	0.0BI	Measured	8.00	5.28	41.35	1.86	50.90	0.0040
		Computed	50.30	30.99	58.34	2.10	57.99	0.0005
		% Change	528.8	998.3	41.08	12.90	13.93	87.5
	0.5BI	Measured	5.93	5.01	60.01	47.79	72.84	0.0079
		Computed	36.73	28.96	72.39	54.96	74.17	0.0022
		% Change	519.4	478.0	20.63	15.00	1.83	72.15
	15	Measured	4.66	2.84	51.40	40.44	54.40	0.0026
		Computed	39.13	27.13	67.82	49.41	63.32	0.0010
		% Change	739.7	855.3	31.95	22.18	16.40	61.59
20	0.0BI	Measured	3.38	3.10	49.57	38.15	65.62	0.0072
		Computed	34.32	24.40	60.99	45.30	66.98	0.0011
		% Change	915.4	687.1	23.04	18.43	2.07	84.72
	0.5BI	Measured	2.92	1.77	40.37	30.20	46.87	0.0029
		Computed	28.74	21.82	54.55	37.00	64.58	0.0026
		% Change	884.2	1132	35.13	22.52	37.78	10.34
	0.0BI	Measured	2.27	1.72	38.21	30.64	61.61	0.0041
		Computed	27.08	20.46	51.16	37.92	70.88	0.0012
		% Change	1092	1089	33.89	23.76	15.05	70.73

2.3.2.2 Mathematical Analysis

The analytical analysis for honeycomb materials have existed for well over 50 years. The original buckling load within a single panel of a honeycomb was derived by Timoshenko and Gere in 1961 [66]. In their work, Timoshenko et al. determined that the buckling load is

$$P_{crit} = \frac{KE_s}{(1 - \nu_s^2)} \frac{t^3}{l} \quad (2.7)$$

where K is a constant for the end constraint factor, E_s is the modulus of the material, v_s is the Poisson's Ratio, and the remaining variables correspond to geometric dimensions of the honeycomb. The honeycomb in this study have a singular wall thickness, t , so the elastic buckling stress must be re-derived slightly, since Roark's equation (originally derived from Timoshenko et. al) assumes walls of varying thicknesses [67].

For this study, the elastic buckling stress was derived knowing that all six walls have a singular thickness, t , and thus will maintain the same load after they reach a collapse load of P_{crit} [67]. The elastic buckling load is the sum of the individual loads that each walls carries, so the elastic collapse stress or peak stress is:

$$\sigma_3 = \frac{6P_{crit}}{2\cos\alpha(1 + \sin\alpha)l^2} = \frac{3KE_s}{(1 - v_s^2)\cos\alpha(1 + \sin\alpha)} \frac{t^3}{l^3} \quad (2.8)$$

This equation requires knowing the material properties of the honeycomb. From data sheets, the modulus was determined to be 2400 MPa with a yield stress of 41 MPa and a Poisson's ratio of 0.25 [Ultimaker]. To determine the predicted value, it is important to identify the end constraint factor. When the ends are rigidly clamped, literature has shown that $K = 6.2$, however this is not always the case [66,67]. A conservative estimate is $K = 3.29$ because each wall is simply supported along the edges. These two values will provide an upper and lower bound, respectively, for the elastic collapse stress of the tested honeycomb [67]. To analyze the behavior of these honeycomb, the end constraint factor chosen for this analysis was $K = 5.73$ because it is preferential to a clamped setup, but is not rigidly clamped [66].

As Figure 2.8A shows, the experimental peak stresses fall within the upper and lower bounds that was derived using the modified Roark analysis. Each of these points is an average

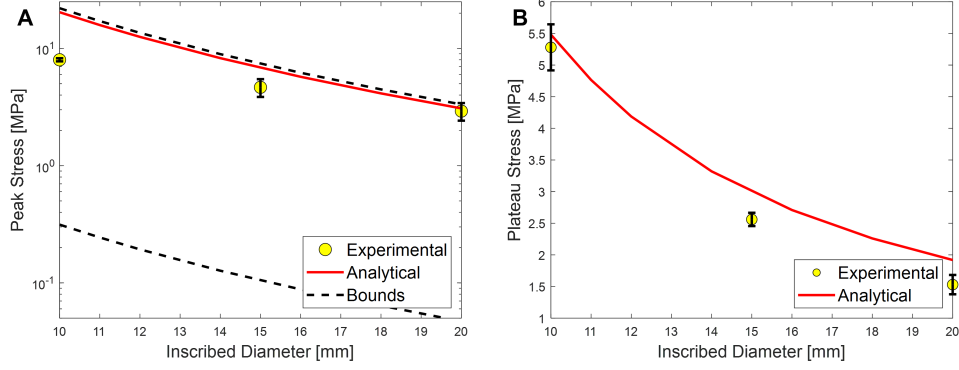


Figure 2.8: Analytical analysis of the experimental results for (a) peak stress and (b) plateau stress.

Table 2.3: The results of the analytical models in comparison with the experimental results.

	Diameter [mm]	Upper Bound [MPa]	Analytical [MPa]	Experimental [MPa]	Lower Bound [MPa]
σ_{pk}	10	22.05	20.38	8.00	0.31
	15	6.84	7.41	4.66	0.13
	20	3.33	1.92	2.92	0.05
σ_{pl}	10	-	5.48	5.28	-
	15	-	2.99	2.56	-
	20	-	1.92	1.53	-

peak stress for the given inscribed diameter, with the error bar denoting the standard deviation of the measurements. The analytical analysis is an appropriate fit for this data, confirming the experimental tests (Table 2.3).

Wierzbicki derived another relationship to describe the behavior of honeycomb. This one determines the plastic buckling stress of honeycomb using the geometric and material properties [39]. Ashby and Gibson provide an overview of the derivation for regular hexagons with a uniform wall thickness [37]. This plastic buckling stress or mean crush stress is defined as

$$\sigma_3 = 5.6\sigma_{ys}\left(\frac{t}{l}\right)^{5/3} \quad (2.9)$$

This is the region during which the buckling occurs.

Figure 2.8B shows the analytical equation is a good predictor of the mean crush stress of the experimental samples for the ABS-R honeycomb, once again confirming the experimental results.

2.3.3 Design for Application

Due to the application of these materials, the materials must not exceed a threshold stress value. If they do, the energy would not be absorbed and therefore the occupant would be damaged. For this study, the representative threshold stress selected was 40 MPa. Figure 2.9 shows the threshold stress marked on the stress-strain curves. Any of the samples that exceed this threshold stress are considered in-effective for this application. Reviewing Figure 2.9A, 0.00BI, 0.50BI, and 0.75BI are unable to meet the threshold requirement. Similarly, 0.75BI and 0.50BI are unable to meet the threshold requirement for the 15 mm diameter samples and the 0.50BI sample is unable to meet the requirement for the 20 mm diameter samples.

The strain dependent crush efficiency shows the performance of these samples taking into account the restricted threshold stress of 40 MPa. In Figure 2.10, the 1.00BI sample reaches a crush efficiency of 65% by 10% strain and maintains it over the full strain range. Similarly, at 15 mm, the 0.00BI and 1.00BI samples reach a consistent crush efficiency of 45% by 25% strain and hold that value until densification is achieved.

The energy absorbed efficiency is also plotted in Figure 2.11. For all samples, it is shown to be constantly increasing. As the inscribed diameter increases, the maximum energy absorbed efficiency is found to decrease. None of the samples are found to densify in the given strain range

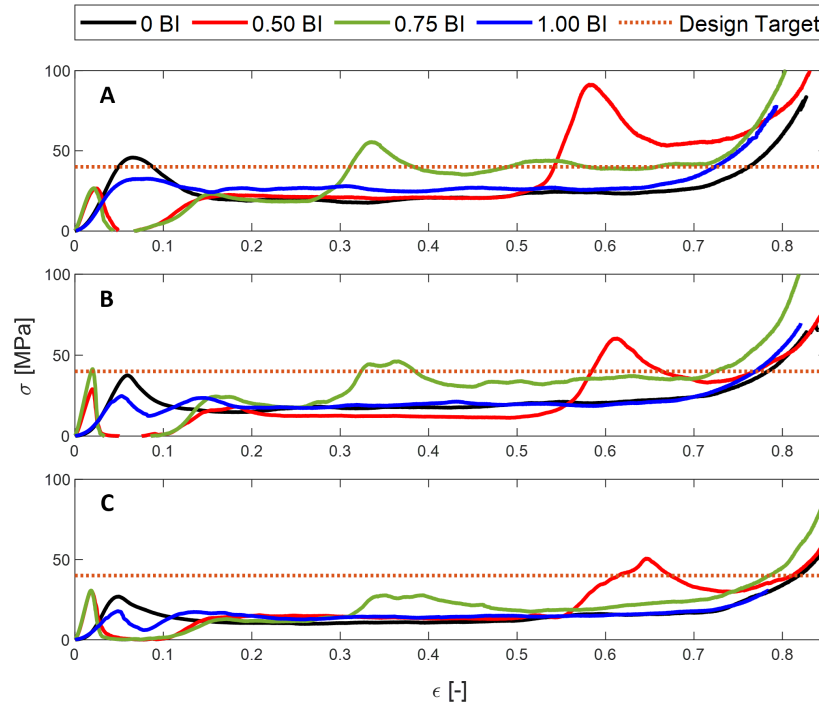


Figure 2.9: Analyzing the samples for a given design application using a representative threshold stress value of 40 MPa where (A) is 10 mm, (B) is 15 mm, and (C) is 20 mm inscribed diameter.

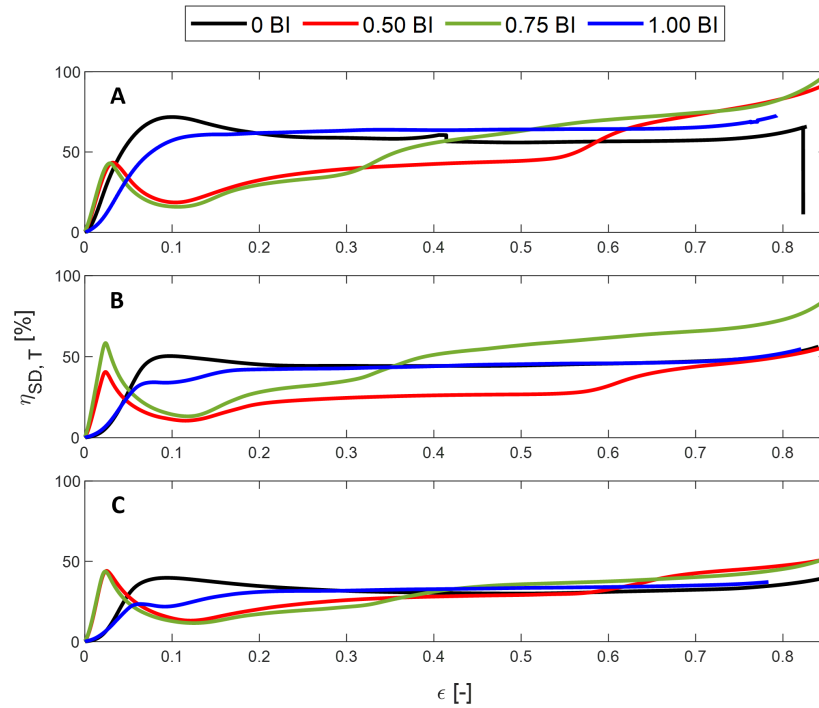


Figure 2.10: The strain dependent crush efficiency of the quasi-static samples after the threshold has been applied for an inscribed diameter of A) 10-, B) 15-, and C) 20-mm.

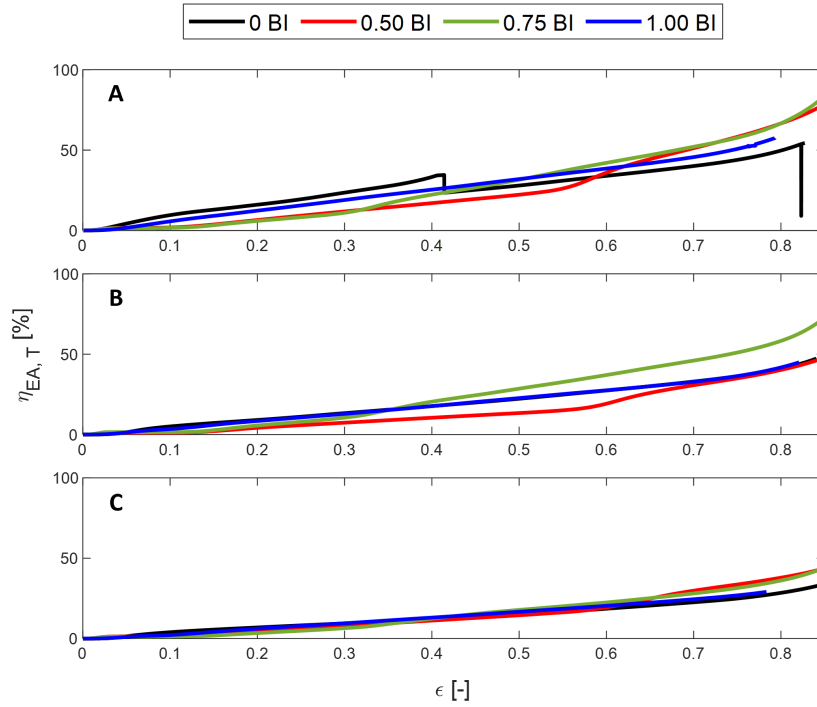


Figure 2.11: The energy absorbed efficiency of the samples tested quasi-static conditions after the threshold has been applied. A) 10-, B) 15-, and C) 20-mm inscribed diameters.

either, indicating the occupant would be injured before the sample fully densifies.

The performance metrics are reported in Figure 2.12. Any sample that did not meet the threshold requirement was denoted with an 'x' of the respective color. Although the maximum reported crush efficiency was the lowest for the samples with 1.00BI at all diameters, the average crush efficiency was highest for these samples.

The energy absorbed efficiency and variance of crush efficiency further confirm why these 1.00BI samples are a good candidate for this end application.

2.4 Discussion

As discussed throughout this Chapter, the geometry of the honeycomb cell will effect the energy absorption properties. To demonstrate the effects of the metrics selected, a series of radar

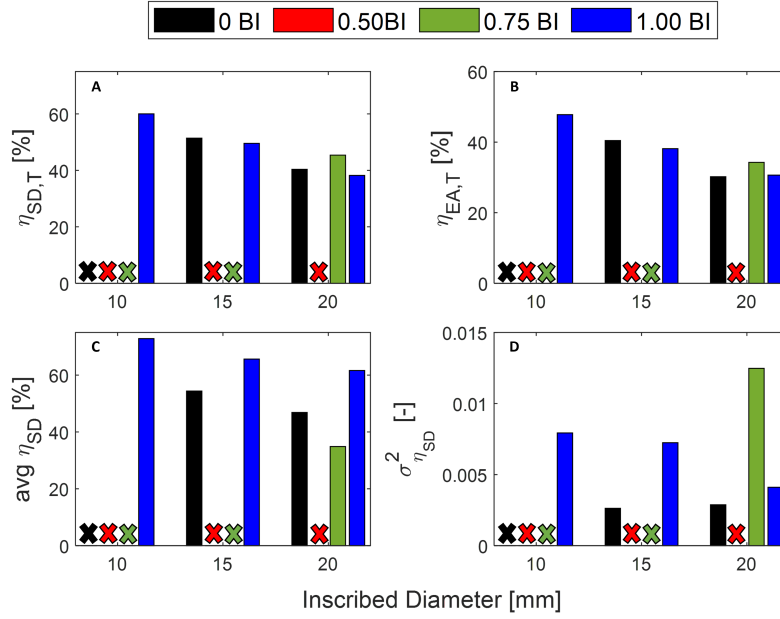


Figure 2.12: The design metrics as calculated using the threshold stress for (A) the threshold crush efficiency, (B) the threshold energy absorbed efficiency, (C) the average crush efficiency and (D) the variance in crush efficiency from 2- 75% strain. Any samples that had not met the threshold requirement are denoted with an 'X'.

plots are presented in Figure 2.13 to assist in the decision making process. Each spoke portrays a different crashworthiness metric of interest. Beginning with the topmost spoke, the change in stress is shown using a range shown in Table 2.4. The change in stress is the difference between the peak stress and the plateau stress. This spoke has been inverted such that the smallest value (3 MPa) is on the exterior, indicating best performance. The less deviation between the peak and plateau stress, the more area under the curve and thus an increase in crashworthiness. The next spoke portrays the maximum strain dependent crush efficiency recorded for the thresholded data. The spoke is designed to have the maximum crush efficiency on the exterior and the minimum crush efficiency shown on the interior. The third spoke analyzes a similar characteristic called the threshold energy absorbed efficiency. Once again, it shows the maximum efficiency on the exterior of the radar and the minimum efficiency on the interior of the radar. The final two spokes

Table 2.4: The minimum and maximum range over which each individual spoke is plotted.

	$\Delta\sigma$ [MPa]	$\eta_{SD,T}$ [%]	$\eta_{EA,T}$ [%]	Avg η_{SD} [%]	$\sigma^2_{\eta_{SD}}$ [-]
Minimum	3	35	30	30	2
Maximum	18	65	50	75	15

return to analyzing the initial data without thresholding it. The first shows the average crush efficiency recorded between 2 and 75% strain. This is representative of the efficiency across the full impact event. Similarly, on the final spoke, the variance of the crush efficiency is provided. This is intended to provide additional information regarding the relative error seen with this sample.

Figure 2.13 shows all three geometries as radar plots. Each plot consists of the five metrics that have been studied throughout this work. The values most suited for energy absorption applications are listed furthest from the center of the radar plot. Each of these three plots show the 1.00BI sample encompasses the entire 0.00BI and 0.75BI samples when applicable. This is indicative of the 1.00BI sample outperforming in all metrics, regardless of the geometry of the cell. When looking at the individual radar plots, it is evident that the 1.00BI sample with the smallest inscribed diameter (Figure 2.13A) is the best or second best choice in all metrics except the peak crush stress. For this reason, the 10 mm inscribed diameter honeycomb with buckling initiators will perform the best in crashworthiness applications.

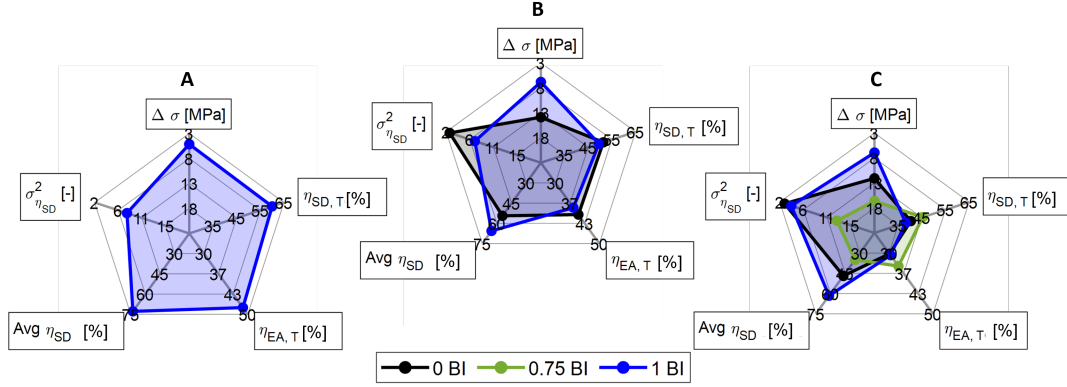


Figure 2.13: A radar plot of the samples that meet the threshold requirement for the design application.

2.5 Conclusions

During the course of this study, honeycomb with three different inscribed diameters were manufactured using ABS-R to study the influence of buckling initiators on changing geometries. The following conclusions can be drawn from this work.

1. The peak stress and mean crush stress will decrease with the increasing inscribed diameter, regardless of the presence of the presence of buckling initiators. Similarly, the crush and energy absorbed efficiency will decrease as the inscribed diameter increases. For all metrics, except the peak stress, the presence of buckling initiators will increase the performance compared to their counterparts. As mentioned, the peak stress will decrease with the presence of buckling initiators.
2. The performance of these samples have been validated through the use of a finite element model in ABAQUS. The same trends are apparent: as the inscribed diameter increases, the peak and mean crush stress and energy absorbed and crush efficiencies will decreases regardless of the presence of buckling initiators.

3. The analytical analysis validated the performance of the samples as well. The re-derived version of Roark's equation allows for the peak stress to be accurately predicted. The peak and mean crush stress decrease with increasing inscribed diameters.

Chapter 3: Visco-Elastic Honeycomb for Low-Strain Rate Energy Absorption

Energy-absorbing materials have extensive applications in aerospace and automotive applications. Research has shown buckling initiators, or triggers, in energy-absorbing tubular structures increase the energy absorbed by encouraging the side panels to fold when loaded out of plane in compression conditions. Additively manufactured TPU honeycombs were designed in this study to include these buckling initiators, which introduced a slight decrease in initial weight, as well as initial stress concentrations, while improving crashworthiness characteristics. The samples with buckling initiators located 50% up the height (0.5BI) showed an increase in crush efficiency when directly compared to their no buckling initiator (0.0BI) counterparts. The 0.5BI samples maintained an increased crush efficiency regardless of the strain rate used. The samples with 0.5BI were able to better equilibrate the peak stress with the plateau stress. These honeycomb samples were found to maintain their crush efficiency, even after multiple rounds of compression testing. The quasi-static 0.0BI samples experienced a 23.4% decrease in the peak stress after multiple rounds of compression testing, while the 0.5BI samples saw approximately a 23.0% decrease. The 0.5BI samples averaged a decrease in crush efficiency of 0.5%, while the 0.0BI samples saw a decrease in crush efficiency of 5%. As the strain rate increased, the crush efficiency for the 0.5BI samples showed an increase in performance, with a smaller degradation in crush efficiency over multiple uses. Visco-elastic honeycomb with buckling initiators

has a higher energy absorption than samples with no buckling initiators when exposed to multiple impact cycles.

This research was published in *Polymers* [68].

3.1 Introduction

Crashworthiness and energy-absorbing materials are of great interest to both automotive and aerospace industries due to the need for occupant protection. Work to date has shown that foam and honeycomb materials have a promising future in regard to energy absorption [69, 70]. Using a controlled failure mechanism in a honeycomb will allow for a further increase in the energy absorption of the material.

Buckling initiators, sometimes referred to as trigger mechanisms, have been a commonly studied mechanism through which to introduce the controlled failure of a material structure. Two methods are typically used to introduce controlled failures [71]. For the purpose of this paper, they will be differentiated by the names buckling initiators and trigger mechanisms. Buckling initiators are voids introduced into the structure via a subtractive manufacturing method [72, 73]. These initiators are purposeful stress concentrations intended to fail first, thus encouraging the structure to begin folding [74, 75]. Traditionally, the part is completed before a drill is used to remove a portion of the material along the vertices. This method can be difficult to use due to the lack of control when implementing the buckling initiators. If the buckling initiator is implemented too high on the wall of the structure, there is the potential for the structure stiffness to decrease, causing the energy absorption to decrease [72]. Similarly, machining may introduce residual stresses into the part, potentially reducing the repeatability of the buckling performance.

On the other hand, an external trigger mechanism can also lead to controlled failures. These trigger mechanisms tend to be a plate placed at either the top or bottom of a tube [76–78]. These plates have a rectangular protuberance, so that when a compressive load is applied, the walls of the tube will experience a localized stress regime until failure occurs [79–81]. These plates, or trigger mechanisms, are easier to implement in a laboratory setting; however, they can be more difficult to implement in a large-scale setting. External trigger mechanisms also add weight to the structure; and so they are less desirable in vehicle applications.

Buckling initiators and trigger mechanisms have been extensively studied in tubular samples. There is extensive literature available regarding the behavior of tubes having different forms of defects. The most common cross-sections are circular and square tubes [82–84]. This concept has been studied in metals in the literature as far back as the 1960s, but the focus has been primarily on aluminum and its alloys [22, 85–88].

Researchers saw the potential of combining lightweight aluminum with the high-strength, low-density design of the honeycomb [89–92]. Aluminum honeycomb is typically manufactured by gluing strips of aluminum together and inflating them to obtain the final structure [37, 93, 94]. The location of these strips of glue will increase the honeycomb wall thickness at those interfaces, causing the honeycomb to fail due to those interfaces as opposed to failing in buckling [95]. The thickness of the honeycomb walls will not be consistent using this manufacturing method. The varying wall thickness increases computational complexity, so consistent wall thickness has been assumed for simplicity [96, 97]. Honeycomb can be designed to have various core shapes, including rectangular, triangular, and hexagonal [98–104]. Although aluminum is a common honeycomb material, honeycomb has been manufactured out of many materials, including—but not limited to—steel, fiber glass, paper, acrylonitrile butadiene styrene (ABS), polylactic acid

(PLA), and thermoplastic elastomer (TPE) [105–110].

Additively manufactured honeycombs like ABS, PLA, and TPU provide numerous benefits. The need for glue strips, unlike aluminum honeycomb, is eliminated. When oriented properly on the print bed, the fused filament fabrication (FFF) process will maintain the strength of the material, as many additive manufacturing studies have shown [111, 112]. Additive manufacturing enables the precise fabrication of honeycomb geometry, especially with respect to a constant wall thickness. BIs can be introduced in any location and in any shape during printing so that residual stress from subtractive machining can be eliminated. Even with all of these benefits, additively manufactured honeycomb structures have not been extensively studied due to their brittle nature [59, 113, 114]. ABS and PLA exhibit brittle failure and high stiffness where it might be desirable to have buckling failure and low stiffness with the potential for shape recovery, which would suggest the use of a softer, visco-elastic material. Moreover, if a flexible, lighter weight visco-elastic material is identified, a honeycomb could be manufactured that could include buckling initiators and still be crashworthy [115].

Extensive research on honeycomb materials has been reported in the literature, including research on metallic honeycombs (ductile materials) and polymer material-based honeycombs (brittle materials). The original contributions of this current work are focused on: (1) the use of low shore hardness visco-elastic polymers with a goal of creating a low-pressure honeycomb that is suitable for occupant protection, (2) the introduction of buckling initiators (diamond-shaped holes) that are integrated into the structure to encourage the folding of the honeycomb faces and to improve the crush efficiency of the honeycomb structure, (3) to exploit the deformation recovery that may be possible when using buckling initiators of this type so that protection against multiple impacts can be provided (albeit with reduced effectiveness), and (4) to exploit additive

manufacturing to fabricate these visco-elastic honeycomb structures with these buckling initiator features.

To achieve these goals, this study focuses on the influence of buckling initiators in a thermoplastic polyurethane (TPU) honeycomb structure (or a visco-elastic honeycomb structure). The buckling initiators are expected to increase the crush efficiency due to the controlled buckling of the honeycomb faces (sides). Using an additive manufacturing process should minimize stress concentrations prior to testing, while ensuring that all walls are of the same thickness. Additive manufacturing enables the precise fabrication of cell size, as well as the location, shape, and size of the buckling initiators. The low shore hardness TPU should allow for the honeycomb to maximize the energy absorbed at low stroking loads as well. We will compare the energy absorption characteristics of visco-elastic honeycomb structures with buckling initiators located on the vertices (0.5BI samples) to those without buckling initiators (0.0BI samples) in order to assess their relative merits as crashworthy structures.

3.2 Materials and Methods

3.2.1 Manufacturing

Honeycomb materials are commonly provided in sheets and have a repeating pattern. As explained in [37], the unit cell of a honeycomb structure may be represented as a vertex with its three adjoining walls (Figure 3.1A). Because of this lack of additional vertices, the interaction between cell BIs could not be easily observed in the experiment. As a result, preliminary tests were conducted on the samples that were square in shape; however, there were multiple free-standing walls (Figure 3.1B). When these honeycomb were tested, the walls collapsed in unrepeatable

manners that were not representative of the honeycomb. These walls also blocked the view of the buckling initiators.

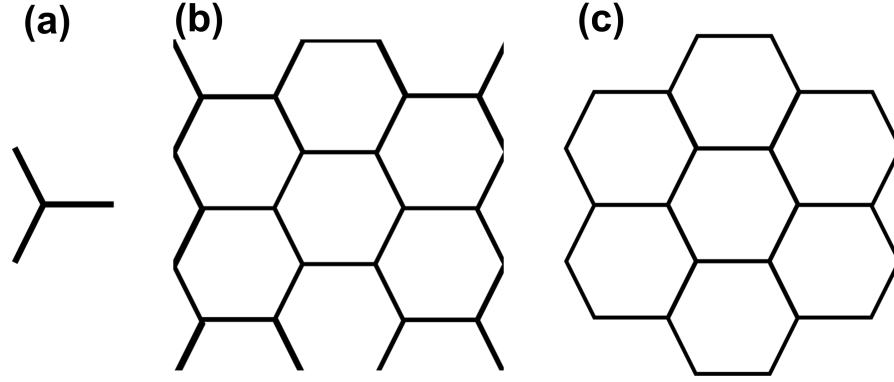


Figure 3.1: The unit cell of the tested honeycomb. **(A)** Accepted representative volume element according to Gibson; **(B)** originally tested sheet of honeycomb; and **(C)** Walls with a free edge obstructed the view of the honeycomb walls during crush, so that all such free edges were eliminated in the unit cell shown here, which was used in this study.

Because the goal of this study was to analyze the effects that BIs have on visco-elastic honeycomb, it was imperative that the BIs were visible. To maintain the representative performance of a full sheet of honeycomb and ensure that the BIs were visible, a representative volume element of six hexagonal cells surrounding a central hexagonal cell was selected (Figure 3.1C).

Samples were manufactured using the Pro Series Flex TPU filament (MatterHackers, Lake Forest, CA, USA, 2018). The TPU had a Shore hardness of 98A. Samples were manufactured using a Diabase H-Series 3D Printer (Diabase Engineering, Longmont, CO, USA). This fused deposition modeling printer was selected for its proprietary extruders, which are compatible with flexible filaments with a Shore hardness ranging from 83D down to 60A. All samples had an overall height of 30 mm, with individual cells having a wall thickness of 0.85 mm, and an inscribed circle diameter of 30 mm (Figure 3.2). The samples with buckling initiators (0.5BI) had the BI half way up the wall at all vertices. The diamond shape was defined by a point-to-point interior dimension of 4 mm in each direction (Figure 3.2C). Honeycomb samples without buck-

ling initiators (0.0BI) were also manufactured, for the purpose of comparison with the samples that had 0.5BIs, to assess how BIs affect performance.

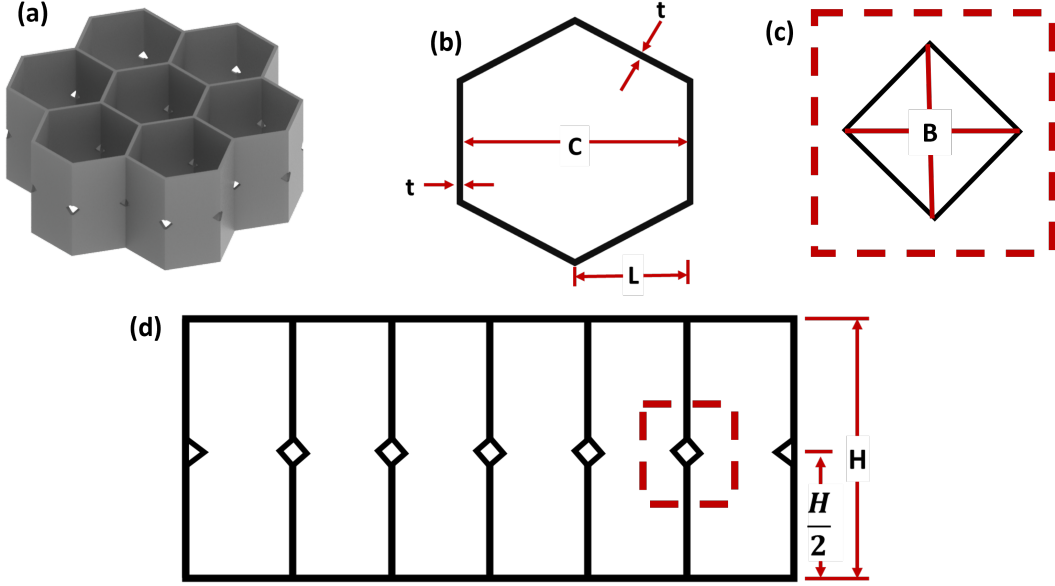


Figure 3.2: The dimensions used to manufacture the honeycomb. (A) The buckling initiators are voids on the vertices in the isometric view of the representative volume element. (B) The thickness and cell dimensions are shown in the top view. (C) Diamond-shaped buckling initiator. (D) The remaining dimensions in the side view. The honeycomb was designed so that $t = 0.85$ mm, $C = 30$ mm, $L = 18.3$ mm, and $H = 30$ mm. In addition, the honeycomb had diamond-shaped buckling initiators, where $B = 4$ mm.

3.2.2 Testing

All testing was conducted using an MTS-810 servo-hydraulic load frame (MTS, Eden Prairie, MN, USA). Three strain rates were studied to assess the effect of the strain rate on the buckling initiators. One group was tested under quasi-static compression conditions with a crush velocity, V , of 3×10^{-5} m/s or a strain rate of 0.001 s^{-1} . The second group was tested at a velocity of 0.25 m/s (or a strain rate of 8.33 s^{-1}), and the final group was tested at 0.5 m/s (or a strain rate of 16.67 s^{-1}). Each group consisted of 0.0BI and 0.5BI samples that were compressed to 90% strain.

During testing, a camera recorded the loading and unloading of the honeycombs. For the quasi-static samples, a camera captured an image every 10 s, while the higher strain rates used a high-speed video camera (Redlake MotionProX3 Plus, San Diego, CA, USA) to record the behavior of the sample under compression loading. For all tests, the rebounding behavior was captured using a video camera as the sample was unloaded.

Each sample was compressed a total of three times with a 24 h waiting period between each crush experiment. The crush and strain recovery behavior of the honeycomb was studied using this data.

3.2.3 Performance Metrics

The analysis of these samples involves additional terminology. The stress was calculated by using the following:

$$\sigma = \frac{F}{A_{uc}} \quad (3.1)$$

where F is the force and the area is calculated using the following:

$$A_{uc} = \frac{21\sqrt{3}}{2} L^2 \quad (3.2)$$

Therefore, the stress is

$$\sigma = \frac{F}{A_{uc}} = \frac{2F}{21\sqrt{3}L^2} \quad (3.3)$$

where L is the side length as shown in Figure 3.2D. At this point, the stress–strain curves can be computed from the test data for the sample analysis. As Figure 3.3 shows, there are two distinct behaviors for the samples with and without BIs. The methods for this will be described in order

to characterize these curves.

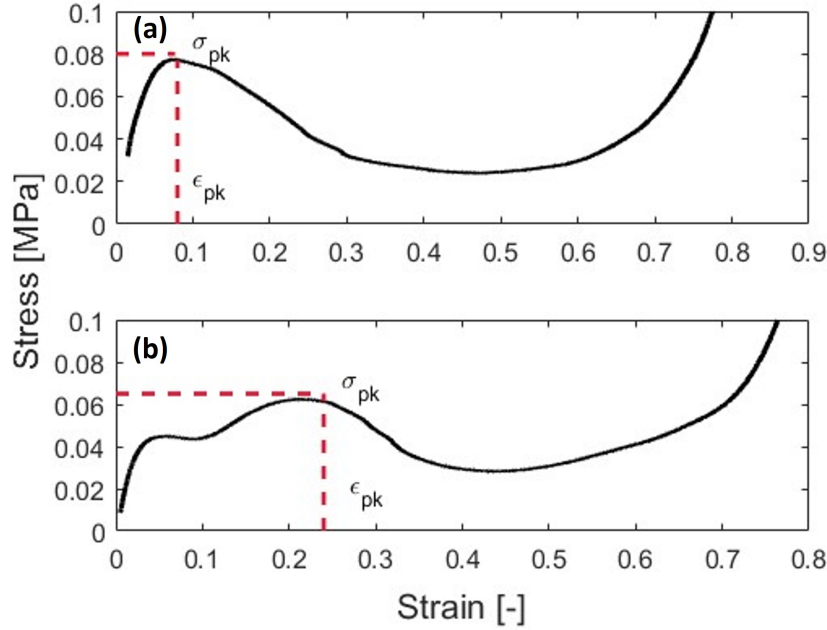


Figure 3.3: Honeycomb stress–strain curves of the out of plane honeycomb compression. **(a)** Representative curve for the samples with no buckling initiators. **(b)** The representative curve of the samples with a single symmetric buckling initiator. For each curve, the peak stress, σ_{pk} , and its corresponding strain value, ϵ_{pk} , are identified.

To quantify strain energy density, the integral of the curve must be calculated:

$$EA = \int_0^{\epsilon} \sigma(\epsilon) d\epsilon \quad (3.4)$$

The units of this calculation are J/m^3 . The strain energy density allows for additional metrics to be determined, showing the overall behavior of the materials. The first is the strain-dependent crush efficiency (SDCE), η_{SD} . The SDCE shows how crush efficient the material is at a given strain. It takes the strain energy density and divides it by a localized ideal strain energy density.

$$\eta_{SD} = \frac{EA}{\max[\sigma(0), \sigma(\epsilon)]\epsilon} = \frac{\sigma_{mc}}{\max[\sigma(0), \sigma(\epsilon)]} \quad (3.5)$$

where σ_{mc} is the mean crush stress. This value provides an average stress over the strain range with units of MPa. It is determined using the following:

$$\sigma_{mc} = \frac{EA}{\epsilon} \quad (3.6)$$

If the efficiency is studied over the entire strain range, or $\epsilon = 1$, then the energy absorbed efficiency can be calculated as shown in the following equation:

$$\eta_{EA} = \frac{EA}{\max[\sigma(0), \sigma(\epsilon)]\epsilon} = \frac{\int_0^\epsilon \sigma(\epsilon) d\epsilon}{\max[\sigma(0), \sigma(\epsilon)]} \quad (3.7)$$

This value will constantly increase until densification is achieved, at which point it will decline.

To complete this analysis, additional values must be identified. The first is the peak stress, which will be dependent on the stress calculation. The peak can be identified using the following:

$$\sigma_{pk} = \frac{d\sigma}{d\epsilon} = 0 \quad (3.8)$$

There are nominally three phases that are classically exhibited by an energy absorption material under crush. The first phase is the collapse. During this phase, the sample will deform but will present elastic deformation [116, 117]. The second phase is a stress plateau, which is indicative of elastic buckling. During this phase, the sample absorbs energy transferred to the sample via cell wall collapse. This phase is called progressive collapse since the sample begins to fold. Densification occurs when voids in the honeycomb collapse and relative density and apparent stiffness greatly increase, so that the material is no longer usable as an energy absorbing material. Graphically, the stress will increase exponentially during this phase. The samples with

and without BIs present these characteristics as shown in Figure 3.3.

3.3 Results

3.3.1 Buckling Features

During crushing, samples without buckling initiators experience a repeatable folding pattern. Figure 3.4 shows the process of crushing the 0.0.0BI and 0.5BI. As the load is introduced to the sample, the honeycomb begins to form waves along its walls. As compression continues, the peaks of these waves become the hinge point for the folding to initiate. These samples showed a first buckling mode that is similar to the aluminum samples that Wilbert et al. recorded in their study [118]. The folds are symmetric around the middle of the wall until collapse occurs. During the collapse, some walls are pushed out, while others are pulled into the middle of the honeycomb, as depicted in Figure 3.4. This failure has been termed non-axisymmetric buckling [119].

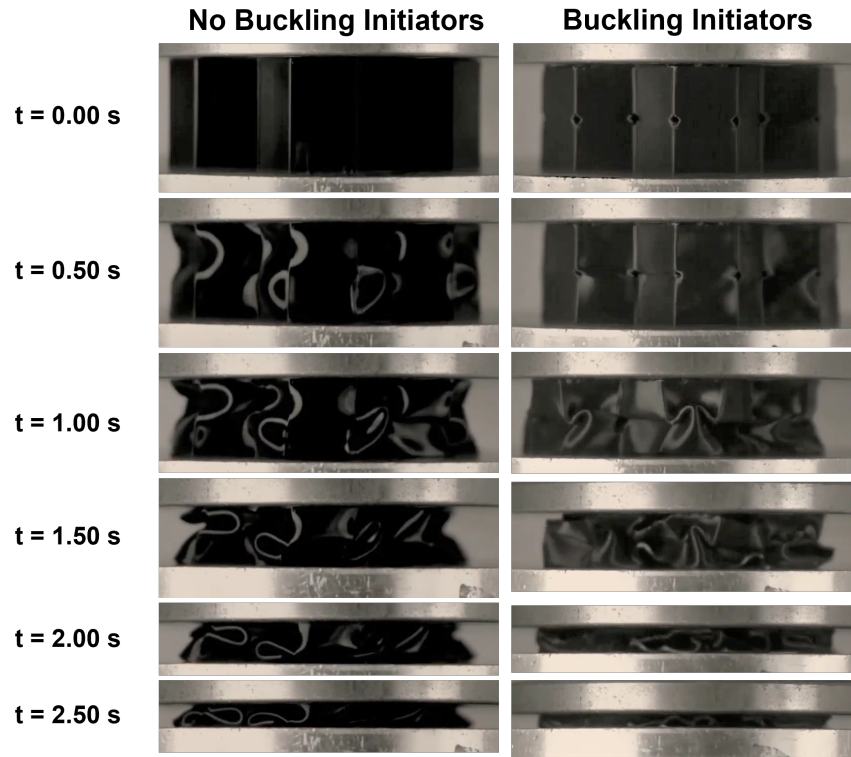


Figure 3.4: The process of crushing the honeycomb results with **(left)** no buckling initiators and **(right)** buckling initiators. This was recorded at a time interval of 0.50 s to analyze the folding mechanisms.

The samples with BIs undergo two sub-phases during crushing in progressive collapse. The first phase is characterized by the BI closing, while the second phase is the formation of the hinge points. The BI controls the location of folding because it induces a stress concentration on the sample. As shown in the images taken at 0.50 s, the vertical corners of the initiator are pushed down so they come into contact, which pushes the horizontal corners further away, thus closing the BI. Once the BI is closed, the sample will attempt to collapse in a similar wave-type pattern. Because of the smaller wall height, this form of compression appears differently from the compression in the 0.0.0BI case, as shown in Figure 3.4. The collapse will instead form a series of organized folds due to the consistent locations of BIs, and this is called axisymmetric folding.

In a similar manner, the behavior of the samples was recorded as the load was removed. A constant crosshead velocity (≈ 2 mm/s) was used to unload the samples. The samples without buckling initiators showed the complex buckling modes as the platens moved apart. As the separation started, the folds opened wider, allowing for the walls to straighten more. Once the platens were entirely open, the sample was able to support itself, even with visible deformation on the walls, as shown in Figure 3.5.

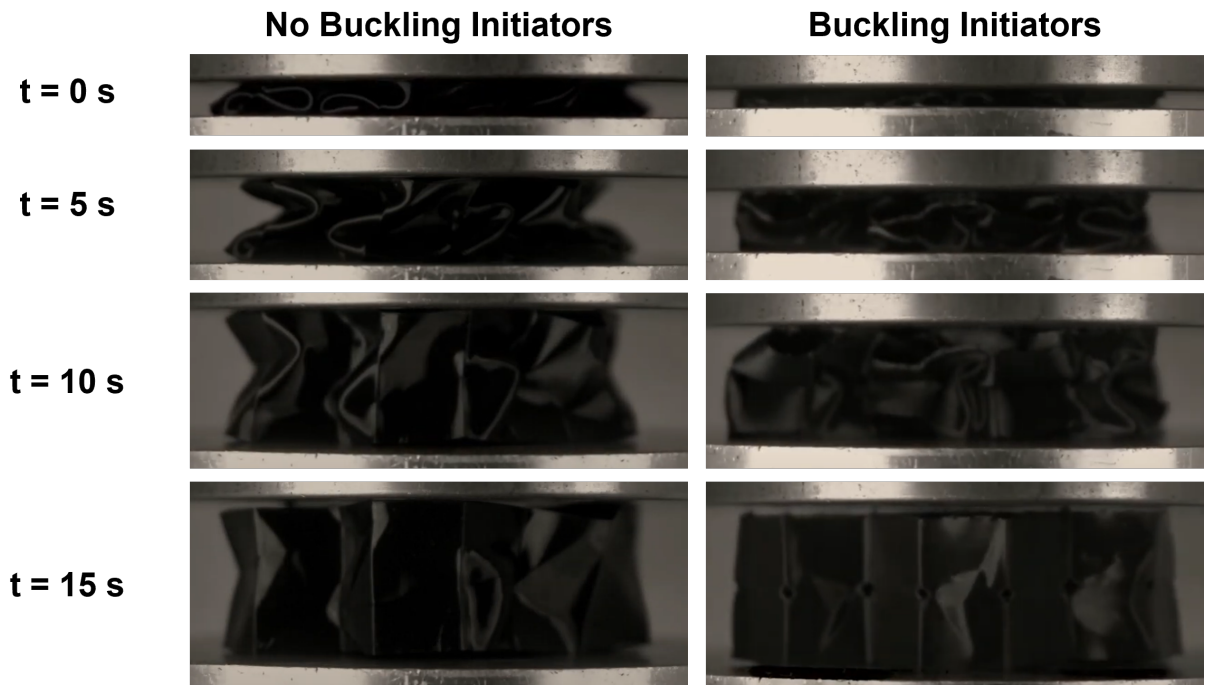


Figure 3.5: A 0.0BI and 0.5BI sample rebounding after an initial uni-axial compression test.

When the load was removed from the samples with buckling initiators, the samples recovered from their strain by opening the hinges. The process of opening these folds required a significant amount of time. The buckling initiators opened last, allowing the samples to achieve over 90% of its original height. These samples took longer to rebound to their initial shape as shown in Figure 3.5, but were still able to withstand additional rounds of testing.

Post analysis of the samples allows for the further behaviors to be recognized. After resting

for 24 h after the 3rd cycle of compression, the samples exhibit unique folding patterns that were specific to their sample type. The 0.0.0BI samples showed a distinct diamond pattern that formed on each cell wall, and these were characteristic of shear buckling. This process occurs when the stresses build up on the top and bottom of the cell until it becomes too large, forcing the wall to either protrude or recess into the cell. Figure 3.6 shows how a small rectangle on each of the walls will be undeformed due to the shear buckling mechanism, regardless of the number of times the sample is tested.

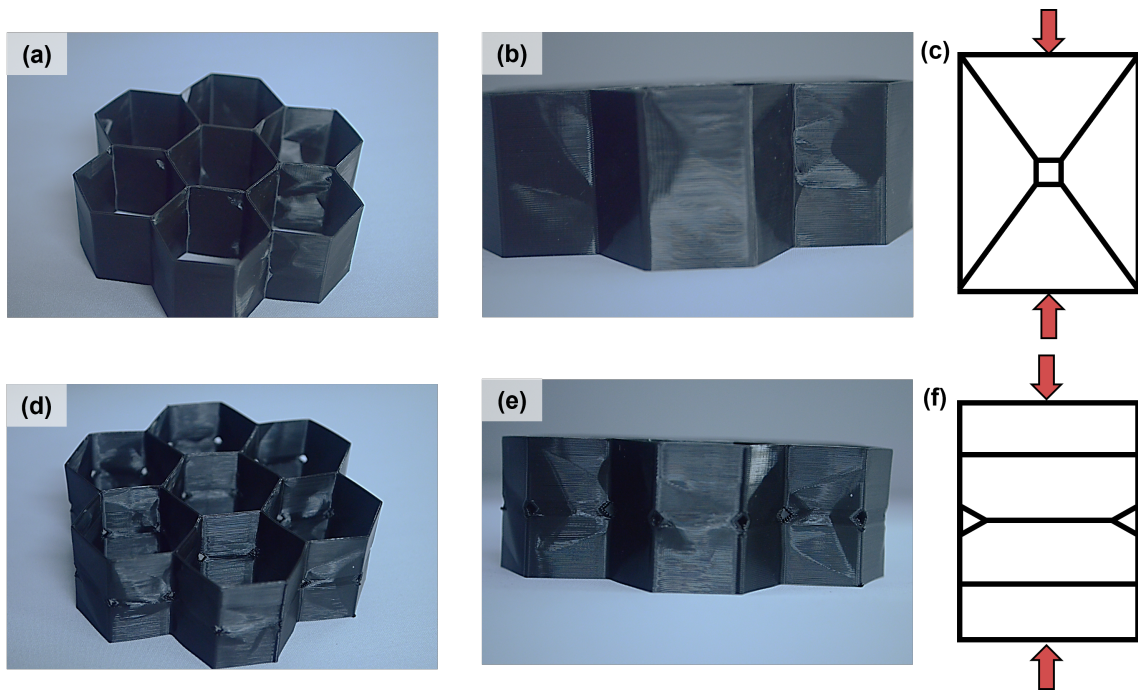


Figure 3.6: The failure mechanism is dependent on the presence of buckling initiators in the honeycomb. **(A)** The isometric view shows the shear buckling panels forming after 3 cycles of testing. **(B)** A front view of the triangular buckling panel. **(C)** Model of the shear buckling. **(D)** Isometric view shows folding failure after 3 cycles of testing. **(E)** The front view shows that the folding failure aligns with the neighboring cells. **(F)** Model of the folding failure.

For the 0.5BIs, a linear pattern became obvious after multiple rounds of testing. There were a series of horizontal pleats that formed on each face, and these corresponded to the collapse of the buckling initiators. With further observation, there were two other rows of pleats that

were located halfway above the midpoint pleat and halfway below the midpoint pleat, as seen in Figure 3.6. These were the locations of the hinge points of the samples. The samples with buckling initiators favored a folding-based buckling failure due to the shortened wall height and the increased stress concentrations.

3.3.2 Quasi-Static Testing

Under quasi-static strain rates, performance of the 0.0.0BI and 0.5BI honeycomb were distinctly different. Looking at Figure 3.7, the samples with 0.0.0BI show a larger peak stress than the samples with 0.5BI. The 0.0.0BI sample has a peak stress of approximately 0.08 MPa, while the 0.5BI sample reaches approximately 0.064 MPa. The 0.5BI sample has three distinct regions where the stress increases. The first, where the sample experiences a 0 to 5% strain, corresponds to the initial loading of the sample. The second region of increase concludes at the peak stress. This region is dominated by the buckling initiators closing and generally lasts from approximately a 10 to 25% strain. The final region of increase corresponds to the densification of the sample. At this point, the sample has been compressed and is no longer useful.

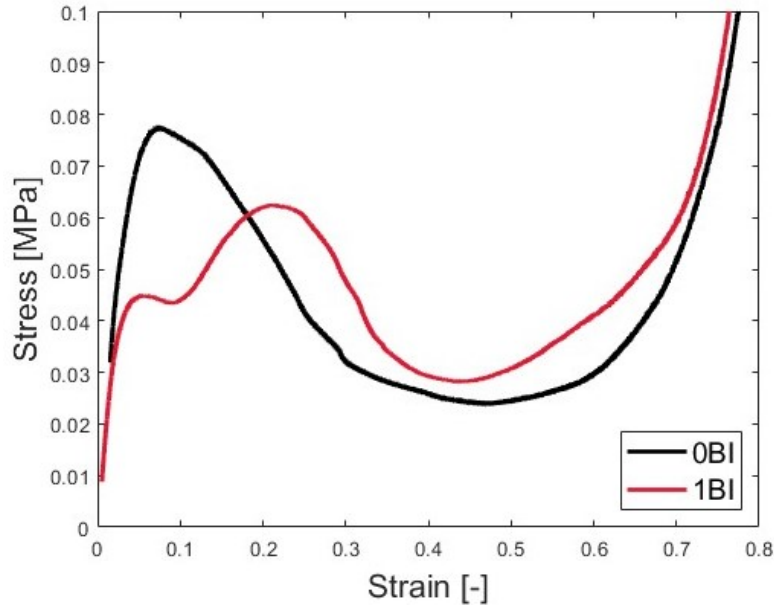


Figure 3.7: The stress-strain behavior of 0.0BI and 0.5BI samples.

The metrics from the stress–strain curve show significant differences between the two samples. The 0.0BI sample reached its peak stress at a corresponding strain of 0.07, while the samples with buckling initiators reached their peak stress at a strain of 0.21. The mean crush stress values also showed this deviation. The 0.0BI had a mean crush stress of 0.07 MPa, while the 0.5BI samples had a mean crush stress of 0.05 MPa. These peak stresses and strains can be identified graphically as well (Figure 3.7).

Using Equation 3.5, the strain-dependent crush efficiency shows the crush efficiency as a function of strain. As Figure 3.8 shows, the 0.0BI sample reached a maximum crush efficiency of 82% at a nominal strain of 0.15. After this point, the crush efficiency continued to decrease for the remaining usable strain range. This was a direct result of the high peak stress. When strain increased above the strain when the peak stress occurred, the stress continued to reduce dramatically below the peak stress (i.e. the target stroking stress), resulting in decreasing crush efficiency.

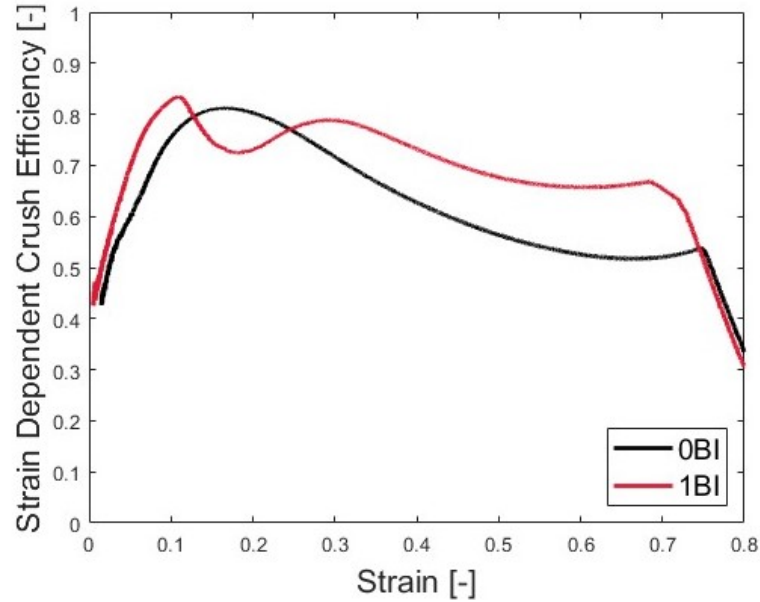


Figure 3.8: The strain dependent crush efficiency at quasi-static strain rates.

The samples with 0.5BI showed a different behavior, with the crush efficiency decreasing over the strain range of 0.1 to 0.3. The decrease corresponded to the second increase in the stress–strain curve. The sample showed a stepped behavior in its stress–strain curve, so the crush efficiency decreased during this time after reaching its maximum value of about 84% crush efficiency. The 0.5BI sample also showed a decrease in its crush efficiency from 0.3 strain onward. Once again, this corresponded with the plastic collapse region and then the densification region. Once the densification strain was reached, a monotonically decreasing linear behavior dominated the crush efficiency. At this point, the load was increasing, but the walls had collapsed, so that the sample could no longer transfer energy, so that crush efficiency was lost.

The second efficiency used to characterize the performance of the honeycomb was the energy-absorbed efficiency. The energy-absorbed efficiency monotonically increased until the peak stress was reached, at which point the EAE experienced a slight change in slope. As Figure 3.9 shows, the peak EAE occurred when the densification strain was reached for the 0.0BI sam-

Table 3.1: The average properties for the quasi-static strain rate samples.

BI	σ_{pk} [MPa]	σ_{mc} [MPa]	$\Delta\sigma$ [MPa]	η_{SD} [%]	η_{EA} [%]	$\epsilon _{\eta_{EA}}$ [-]
0.0	0.08	0.07	0.014	82.07	41.24	0.749
0.5	0.06	0.05	0.013	84.08	48.70	0.711

ples. The maximum EAE for 0.0BI was 41% at a corresponding strain of 0.748. When reviewing the stress–strain curve for this quasi-static sample, the peak stress of 0.08 MPa was achieved for a second time at a threshold strain of 0.749. As validated by the knee in the EAE curve, the threshold strain was the same as the densification strain. These metrics are reported in Table 3.1.

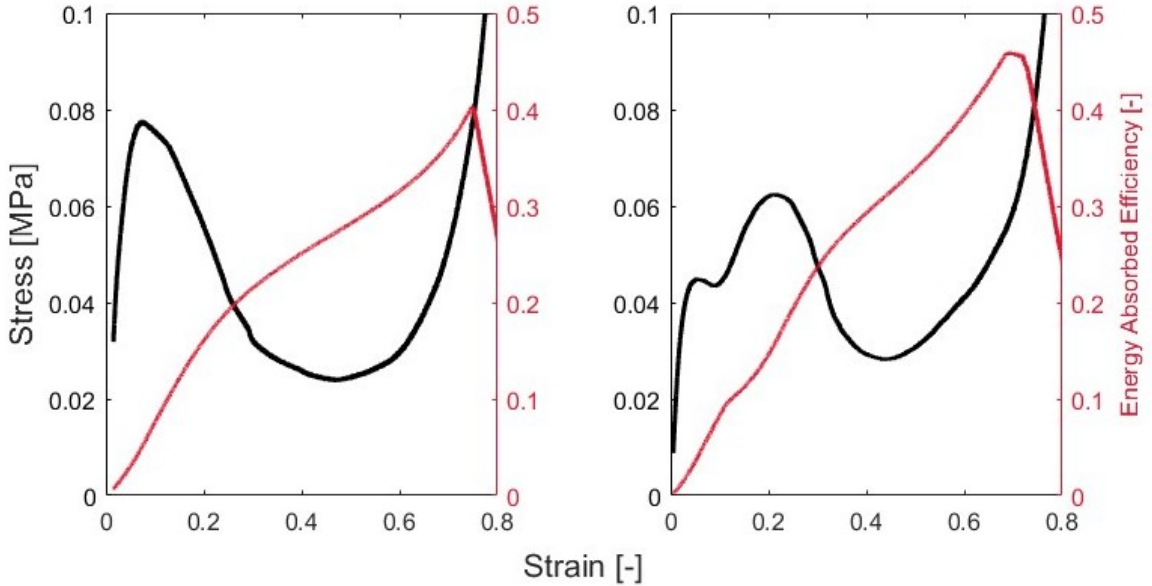


Figure 3.9: The stress–strain curves are plotted on the left axis with the energy-absorbed efficiency plotted on the right. The left-hand side shows the 0.0BI sample, and the graph on the right shows the 0.5BI sample. The peak energy-absorbed efficiency strain corresponded with the threshold strain.

For the 0.5BI samples, the same trend in EAE was identified. The EAE monotonically increased until the threshold strain of 0.729 was reached (Figure 3.9). At this strain, the peak stress of 0.064 MPa was reached for a second time. The maximum EAE for 0.5BI was 48% at a

0.729 strain, thus validating that the threshold strain was the same as the densification strain. For the quasi-static strain rates, the samples with 0.5BI outperformed the 0.0BI samples in terms of crush efficiency and energy absorption.

3.3.3 Low Strain-Rate Testing

Samples were also tested at two strain rates of 8.33 s^{-1} and 16.67 s^{-1} , which are representative of low-velocity impacts (0.25 and 0.50 m/s respectively).

The stress–strain curve for the 0.0BI samples tested at elevated strain rates showed similar characteristics to the quasi-static samples. The peak stress was shown to increase as the strain rate increased. The peak stress for the 0.0BI samples at 8.33 s^{-1} was 0.182 MPa, while the 16.67 s^{-1} peak stress was 0.189 MPa. This increasing peak stress can be seen in Figure 3.10A. The mean crush stress also increased with the strain rates. The mean crush stress for the 8.33 s^{-1} samples was 0.17 MPa, while the 16.67 s^{-1} stress was 0.18 MPa. Overall, the curves were shifted versions of the quasi-static samples. The stress–strain curves for the 0.5BI samples at low strain rates appeared to be shifted versions of the quasi-static samples as well. The peak stress increased from 0.159 MPa at a strain rate of 8.33 s^{-1} to 0.199 MPa at a strain rate of 16.67 s^{-1} . This behavior also occurred with the mean crush stress. The mean crush stress for the 0.5BI samples tested at a strain rate of 8.33 s^{-1} was 0.13 MPa, and this increased to 0.16 MPa when the strain rate was increased to 16.67 s^{-1} (Figure 3.10B).

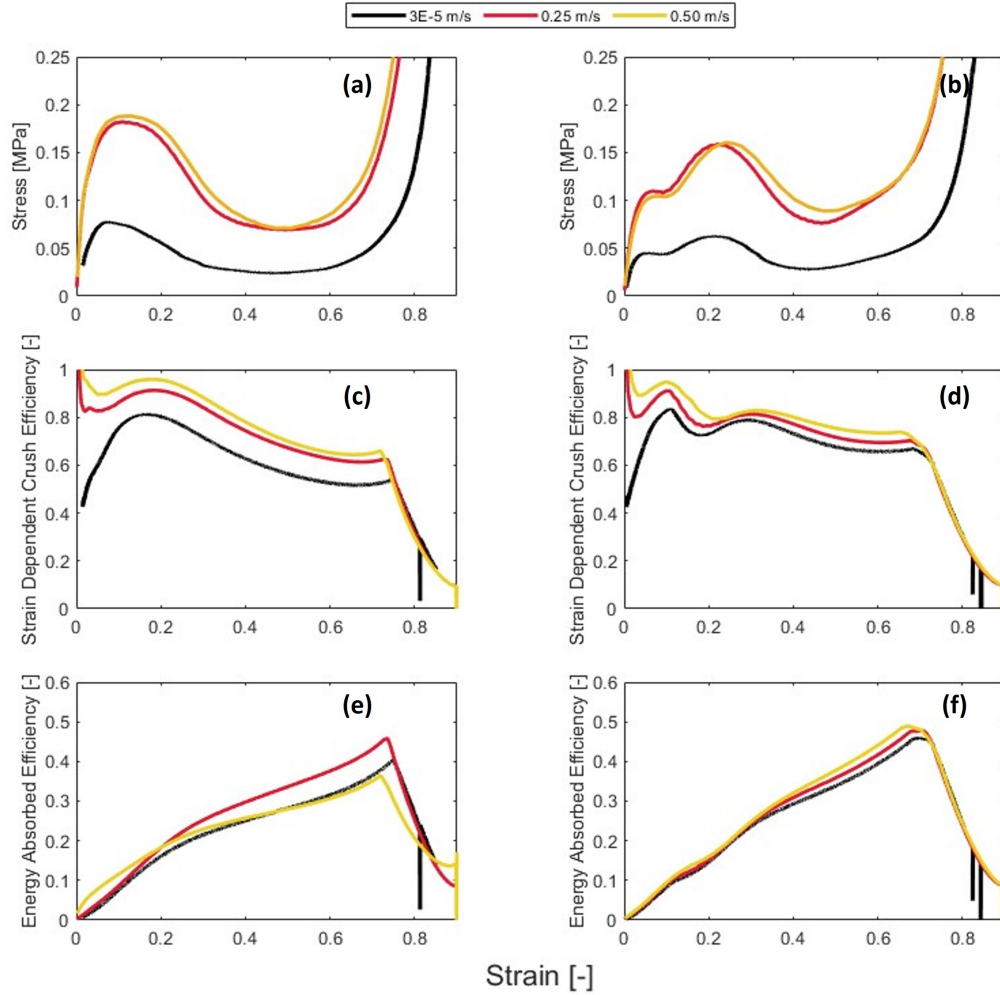


Figure 3.10: The behavior of visco-elastic honeycomb tested under three different strain rates. Left column shows 0.0BI and right column shows 0.5BI. (A) and (B) show stress-strain curves, (C) and (D) show crush efficiency, and (E) and (F) show energy absorbed efficiency.

The crush efficiency shows that the 0.5BI samples outperformed the 0.0BI samples. When reviewing the crush efficiency data, there are two trends. The first is that the presence of buckling initiators does not degrade the crush efficiency as crush velocity increase. The 0.0BI samples averaged 91.34% and 96.02% at velocities of 0.25 m/s and 0.50 m/s, respectively. The 0.5BI samples averaged 91.46% and 93.86% at 0.25 m/s and 0.50 m/s, respectively. The samples crushed at a velocity of 0.25 m/s saw the crush efficiency maintained with the presence of buckling ini-

Table 3.2: The average properties for the quasi-static strain rate samples.

V [m/s]	BI [-]	σ_{pk} [MPa]	σ_{mc} [MPa]	$\Delta\sigma$ [MPa]	η_{SD} [%]	η_{EA} [%]	$\epsilon _{\eta_{EA}}$ [-]
0.25	0.0	0.18	0.167	0.016	91.34	45.97	0.733
0.25	0.5	0.16	0.130	0.030	91.46	49.73	0.702
0.50	0.0	0.19	0.181	0.008	96.01	47.49	0.720
0.50	0.5	0.20	0.161	0.038	93.86	51.72	0.706

tiators, while the 0.50 m/s samples saw a slight decrease (Table 3.2). The second trend is that the crush efficiency increases as the strain rate increases. Together, these trends indicate that the 0.5BI sample was able to maintain its crush efficiency as strain rate was increased.

The energy absorption efficiency increased with an increase in the crush velocity. The 0.0BI samples had an average energy absorption efficiency of 46% at 0.25 m/s, which increased to 47% at 0.50 m/s. At higher velocities, the samples with buckling initiators outperformed their counterparts. The 0.5BI sample had an energy absorption efficiency of 49% at a strain rate of 0.25 m/s compared to an efficiency of 51% at a strain rate of 0.50 m/s.

3.3.4 Repeated Testing

As part of this study, the re-usability of the honeycomb was characterized. There were two purposes for these tests: to determine whether the samples could recover elastically after testing; and to quantify the effects on the energy absorption and crush efficiency of the samples.

The visco-elastic honeycomb was able to successfully rebound back to at least 98% of its original height with minimal defects. In reviewing Figure 3.6, both types of the samples successfully rebounded. The samples showed different folding patterns due to the presence or lack of buckling initiators, as discussed in Section 3.2.1.

The re-usability was also analyzed by reviewing the performance metrics. As Figure 3.11 shows, the stress–strain curve shifted down with repeated testing. This makes sense because the sample had been pre-stressed. The honeycomb would be unable to support that much stress. The peak stress decreased from 0.081 MPa to 0.064 MPa for the 0.0BI samples that were tested in quasi-static conditions. When tested at an elevated strain rate of 16.67 s^{-1} , the peak stress also decreased: from 0.189 MPa to 0.149 MPa. The samples with 0.5BI showed the same decreases in their peak stresses. In quasi-static conditions, the peak stress dropped by 0.013 MPa. Similarly, the 16.67 s^{-1} samples saw a decrease in the peak stress of 0.068 MPa (Table 3.3). Regardless of the strain rate, there was a decrease in the peak stress over continued testing cycles.

Table 3.3: The decrease in the metrics when comparing the following tests to the first test.

V m/s	BI [-]	Test [-]	σ_{pk} [MPa]	σ_{mc} [MPa]	$\Delta\sigma$ [MPa]	η_{SD} [%]	η_{EA} [%]	$\epsilon _{\eta_{EA}}$ [-]
0.25	0.0	2	0.157	0.140	0.017	89.18	41.14	0.748
0.25	0.0	3	0.148	0.132	0.015	89.62	41.08	0.751
0.25	0.5	2	0.130	0.107	0.023	90.17	48.20	0.708
0.25	0.5	3	0.117	0.097	0.020	90.76	46.58	0.708
0.50	0.0	2	0.158	0.150	0.008	95.14	43.88	0.735
0.50	0.0	3	0.149	0.141	0.008	94.53	42.50	0.735
0.50	0.5	2	0.143	0.119	0.024	94.42	48.51	0.699
0.50	0.5	3	0.131	0.110	0.021	93.22	48.41	0.706

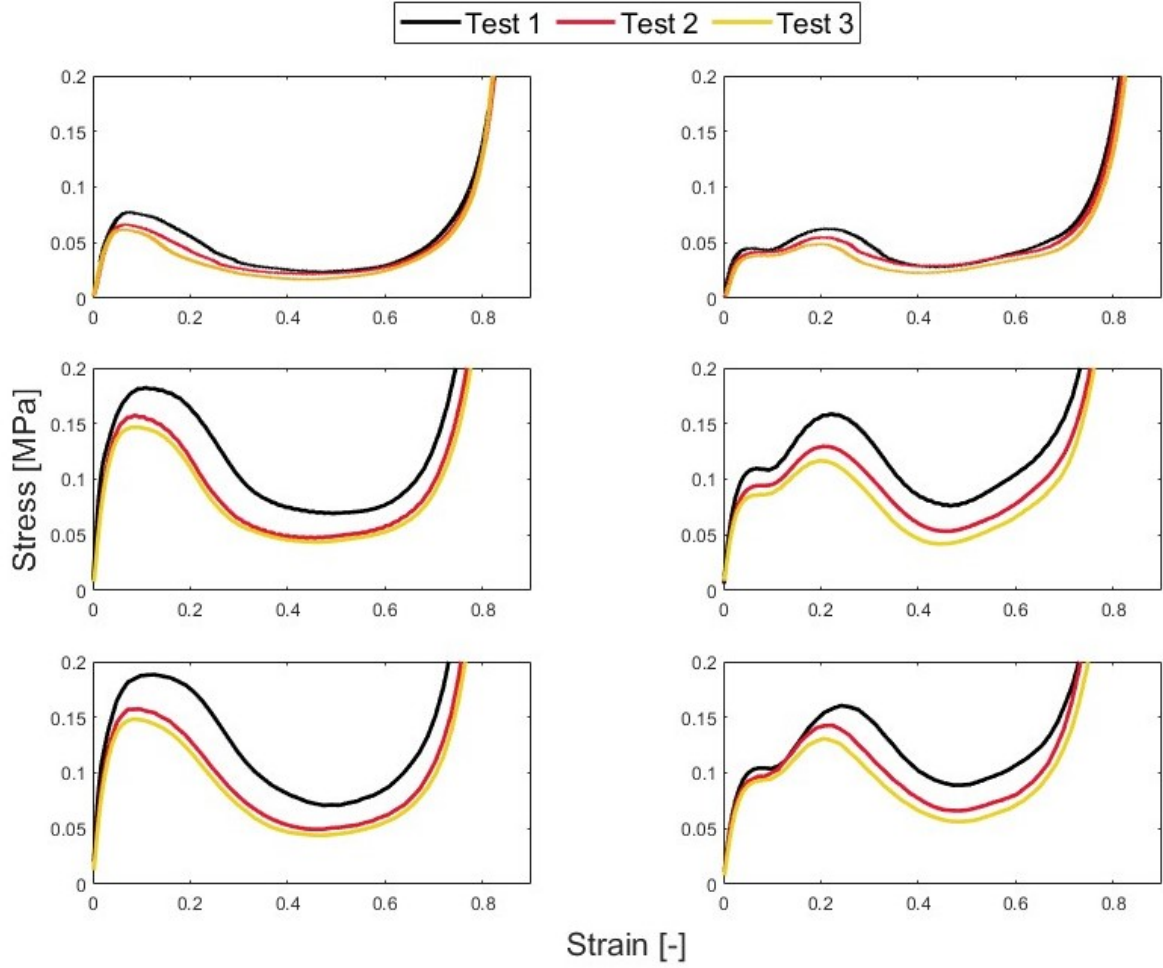


Figure 3.11: The stress–strain curves during three different tests. The left column is for 0.0BI and the right column is for 0.5BI. The top row is for the quasi-static conditions, the middle is for 0.25 m/s, and the bottom is for 0.50 m/s.

Although the crush efficiency showed the same trend, it was less drastic of a decrease. The samples with 0.0BI that were tested at quasi-static strain rates showed that their crush efficiency decreased by 0.43% from the first test to the third. The 0.5BI samples showed a 4.16% decrease. Implementing the buckling initiators yielded a similar decrease in the crush efficiency with repeated testing. The samples that were tested at 0.25 m/s showed a 1.9% and 0.70% decrease for the 0.0BI and 0.5BI samples, respectively. Similarly, the samples tested at 0.50 m/s showed a 1.49% and 0.64% decrease. As the crush velocity increased, the buckling initiator samples

showed a smaller decrease in their crush efficiency after multiple tests.

As anticipated, there was some degradation in the honeycombs, but these showed an ability to rebound and were able to be used for additional tests. The presence of buckling initiators minimized the degree of damage in the honeycomb structure.

3.4 Analysis

A finite element analysis was conducted in ABAQUS to simulate the crush efficiency of the honeycomb at a strain rate of 3×10^{-5} (or quasi-static conditions). The simulation was intended to better understand the influence of the buckling initiators on the honeycomb. The model selected was the imperfect perturbation factor, which was chosen so that the buckling modes could be properly captured. The elastic material was modeled using a Young's modulus of 40 MPa and a density of 1053 kg/m³.

The samples with 0.5BI were modeled using a standard surface-to-surface contact with a friction factor of 0.9 at the bottom interface and 0.6 at the upper interface. These values were selected because the FEA models aligned closest to the experimental behavior of the honeycomb. The linear buckling mode shape perturbation scale factors were 0.085 for modes 1 to 8. To model the wall thickness at the buckling initiator, a smaller wall thickness was used. The honeycomb had a modeled walled thickness of 0.85 mm except for in the buckling initiator region. At this location, the wall thickness was identified as 0.65 mm. To model the behavior of the honeycomb, at least one degree of freedom was required. The friction factor was identified to be this degree of freedom. The other factors in the study were set and the friction factors were tuned until an optimal stress–strain curve was achieved.

The performance of the 0.5BI quasi-static honeycomb showed a good agreement between the model and the experimental results, as shown in Figure 3.12. The model shows a crush efficiency of 85% compared to the experimental results of 84%.

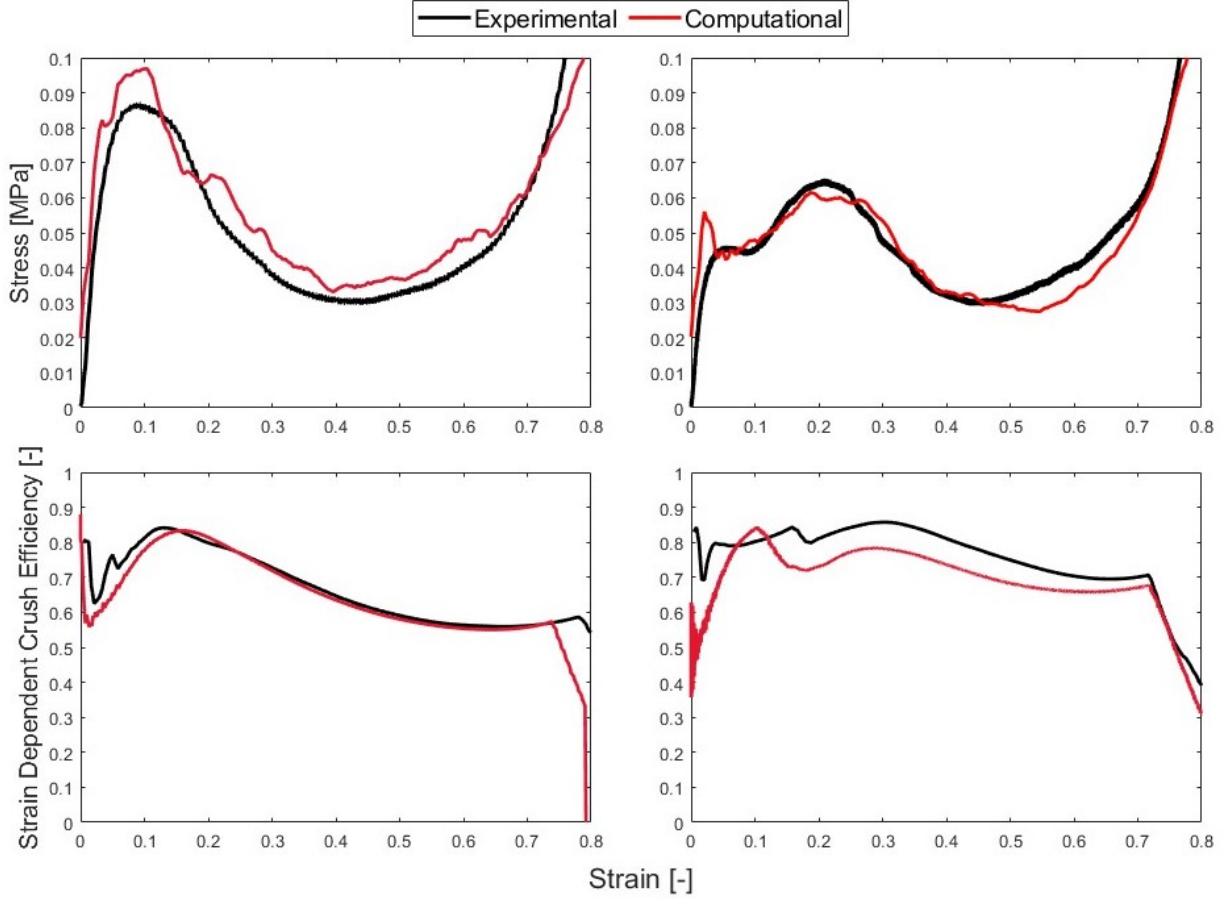


Figure 3.12: The computational and experimental stress–strain curves for the samples tested at a quasi-static strain rate in the top row and the strain-dependent crush efficiency in the bottom row. The left column shows the 0.0BI samples and the right column shows the 0.5BI samples.

Using similar conditions, the quasi-static 0.0BI can be modeled. For the 0.0BI sample, the simulation used a standard surface-to-surface contact with a friction factor of 0.01 early in the experiment and near the end, and this value was used due to the honeycomb losing contact with the platens. As the sample densified, the friction factor used was 0.9 at the bottom interface and 0.6 at the upper interface. This was due to the honeycomb maintaining direct contact with

the platens during that time. Because there were no buckling initiators, the wall thickness was 0.85 mm. The samples with 0.0BI required two sets of friction factors to match the experimental curves. It was observed in the experiment videos that the top and bottom edges of the honeycomb samples initially had partial contact with the platens, but that this contact off the edges improved greatly as loading increased.

The model for the 0.0BI samples slightly overpredicted the crush efficiency. The model showed a projected crush efficiency of 84%, while the experimental results showed a crush efficiency of 82%. The behavior of the stress–strain curve followed the experimental performance of the honeycomb, as shown in Figure 3.12. The behavior computational model was a near perfect prediction of the 0.0BI strain-dependent crush efficiency; however, it under predicted the 0.5BI performance over the full strain range. In the low-strain range (less than 0.1 strain), there was a difference between the computational and experimental results regardless of the sample analyzed, as Figure 3.12 shows. The honeycomb did not see this low of a strain, so it can be ignored. As the strain increased, the 0.0BI samples showed good agreement between the experimental and computational model; however, the 0.5BI model under predicted the crush efficiency across the full strain range.

When reviewing all metrics, the computational analysis was able to represent the performance of the experimental data at quasi-static strain rates. A full summary of the performance of the computational data is provided in Table 3.4. The peak stress and crush efficiency were accurately represented with the computational model, which validates the experimental work conducted.

Table 3.4: The properties of the experimental and computational quasi-static samples

BI	σ_{pk} [MPa]			η_{SD} [%]			σ_{mc} [MPa]		
	Exp	Comp	% Diff	Exp	Comp	% Diff	Exp	Comp	% Diff
0.0	0.086	0.096	10.4	82.07	84.13	2.48	0.07	0.08	13.3
0.5	0.065	0.061	6.15	84.08	85.73	1.94	0.06	0.05	18.1

3.5 Discussion

Throughout this study, five metrics were used to compare the performance of the samples with and without buckling initiators in a variety of strain rates. To assist in understanding which type of samples were most effective, a radar plot was used. Around the exterior of the plot are the metrics, as Figure 3.13 shows. The axis for each metric was oriented so that the axis increases or decreases depending on which denotes the best performance. If one sample encompasses another, it denotes the best solution (as defined by the metrics).

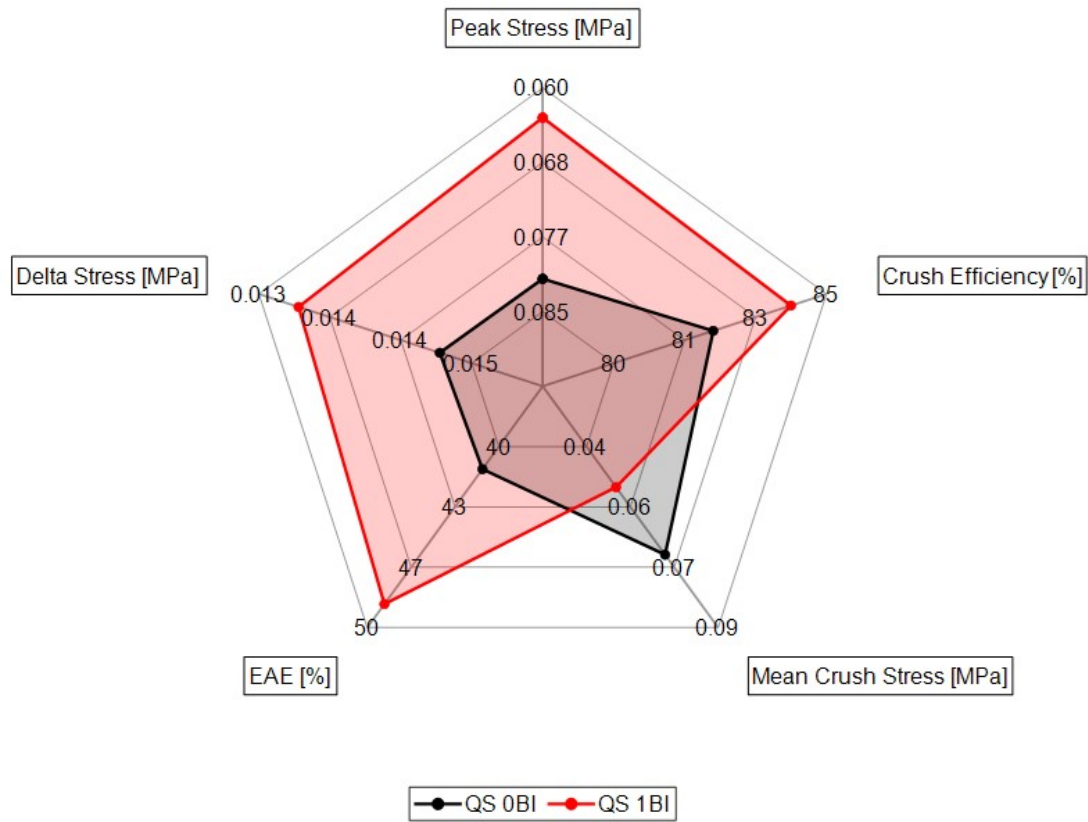


Figure 3.13: The radar plot shows the performance of the quasi-static conditions with the 0.0BI and 0.5BI samples in regard to these particular metrics.

When reviewing the quasi-static results, the 0.5BI samples encompassed the 0.0BI sample, indicating the 0.5BI samples have the best geometry given these metrics. The 0.5BI samples showed a lower peak stress and higher change in stress value, indicating a higher crush efficiency. All three of these metrics were dominated by the 0.5BI samples, along with the energy absorbed efficiency. These samples were also more efficient at transferring crush energy.

3.6 Conclusions

Visco-elastic TPU honeycomb manufactured with 0.5BI have been shown to outperform their 0.0BI counterparts with regard to the metrics set forth by this study. The following conclu-

sions can be drawn from this work.

1. Visco-elastic honeycomb with buckling initiators experiences axisymmetric failure as opposed to their counterparts that are without buckling initiators. Folding initiates at the buckling initiator and continues until the sample has been folded in a controlled manner. The samples without buckling initiators experience shear buckling, which results in non-axisymmetric folding patterns.
2. Visco-elastic honeycomb is able to rebound to over 95% of its initial height after testing three different periods. The honeycomb experiences some permanent deformation, but following 24 h, it is able to be reused.
3. Visco-elastic honeycomb with buckling initiators that are located midway up the sample are more crashworthy in quasi-static applications. The buckling initiators assist in lowering the peak stress, thus increasing the strain-dependent crush efficiency. Similarly, the energy-absorbed efficiency is shown to increase with the presence of buckling initiators.
4. Visco-elastic honeycomb with buckling initiators increases the energy-absorbed efficiency and decreases the peak stress when implemented in low-strain rate settings. The crush efficiency is preserved as the strain increases when buckling initiators are implemented.
5. After repeated testing at low-strain rates, the visco-elastic honeycomb with buckling initiators experiences less degradation in its crush performance. Thus, these visco-elastic honeycomb structures were observed to provide deformation recovery when using this type of buckling initiator. Protection against multiple impacts can be provided, albeit with reduced effectiveness.

6. Numerical analysis validated the experimental results for samples with and without buckling initiators in quasi-static conditions.

In the future, the behavior of these samples should be characterized at high-strain rates. The low-strain rate environment has been characterized; however, most impact and energy absorption events for humans begin at 6.7 m/s. Quantifying the behavior of these energy absorbers at higher velocities will further define the performance over a higher range of safety applications.

Chapter 4: Dynamic Crush of Visco-Elastic Honeycomb for Crashworthiness Applications

Visco-elastic polymers are being explored as an energy absorption material in crashworthiness applications due to their high strain range and reversibility. Additively manufactured thermoplastic polyurethane (TPU) was used to print honeycomb without buckling initiators as well as having buckling initiators located at the midpoint (0.50BI) and top (1.0BI) of the sample to study the energy absorbing characteristics of these materials during a dynamic impact of 1-4 m/s in 0.5 m/s increments. In this study, an improvement in stroking load was found in most velocities with a maximum increase of 102% with the 1BI samples. Samples were also studied in a quasi-static condition (0.03 mm/s) as well as constant velocity (0.25 and 0.50 m/s) to determine if either of these tests could be used to predict the performance of a dynamic impact test. The quasi-static testing is a reasonable upper bound measure of dynamic energy absorption for these TPU honeycomb.

4.1 Introduction

Honeycomb is a frequent choice in energy absorption applications due to its high strength to weight ratio [10, 120–123]. With the increased need for speed, there has been a rise in the research in energy absorption materials for automotive applications. As Huang introduces in

Section 1.2, after conducting impact tests on twenty-two vehicles, the air bag should deploy at 12 mph or 5.36 m/s [124].

Dynamic impact tests have been conducted before, however only with a limited types of materials. Nemat-Nasser et al. describes the performance of aluminum foam when it undergoes high- rate pressure loading situations as well as high impact velocities [125]. Ozdemir et al. takes an additive manufacturing approach to manufacturing different lattice structures to test under both quasi-static and dynamic loading [126]. In their work, a titanium alloy was used to fabricate the lattices that were used as a sacrificial protective system during a dynamic impact [126]. Dorival et al. studies the energy absorption of the foam composites manufactured using a variety of sewing techniques per Airbus standards [127]. As indicated by these three studies and many others, metals and metallic foams have been characterized in dynamic impact testing, however polymeric samples have not been studied [1, 3, 23, 25].

In the literature, there has been extensive work conducted on polymeric honeycomb, however it has been conducted at quasi-static conditions. Mansour et al. describe the effects of reinforcing acrylonitrile butadiene styrene (ABS) with carbon nanotubes and carbon fibers [58]. A finite element analysis simulation was also developed to model the experimental results in order to derive constitutive laws [58]. Menegozzo et al also studied ABS, however they improved the energy absorption properties by modifying the unit cell [65]. The diagonal walls, along with traditional vertical walls, provide additional load paths, increasing the energy absorption abilities of these structures [65]. Ozen et al. studied re-entrant and honeycomb structures used as cores in carbon fiber reinforced composite face sheets [63]. Through this work, the energy absorption was characterized using three different impact velocities: 2.2, 3.2, and 4.2 m/s [63]. Although this is dynamic characterization of the samples, it is full scale implementation of the core material, and

of a brittle material: ABS. Studies have been conducted on visco-elastic materials like thermoplastic polyurethane (TPU) and thermoplastic elastomers (TPE), however, these were conducted under quasi-static conditions [115].

In this study, additively manufactured TPU samples are tested in quasi-static, constant speed, and dynamic impact tests to identify the effects of buckling initiators on the energy absorption. From these tests, it will be ideal to find a type of testing that can help predict the energy absorption efficiency of these materials.

4.2 Motivation

The dynamic analysis of a drop test can be done in a few different methodologies, however it is important to understand the assumption that are included in each scenario. The governing equation of motion for a drop test is:

$$m\ddot{x} + F_{crush} = mg \quad (4.1)$$

If the crush force is linearly elastic, then $F_{crush} = kx$. Here, k , represents linear stiffness. In a drop test, the initial conditions are $x(0) = 0$ and $\dot{x}(0) = -\Delta v$, because the displacement is defined as zero when the impactor strikes the sample, and the initial velocity is known. The assumed displacement is the sum of the homogeneous and particular solutions:

$$x = A\cos(\omega_n t) + B\sin(\omega_n t) + \frac{mg}{k} \quad (4.2)$$

The constants are determined using the initial conditions. Resolving initial displacement,

$$x(0) = 0 = A + \frac{mg}{k} \quad (4.3)$$

so that $A = \frac{-mg}{k}$. Similarly, resolving initial velocity,

$$\dot{x}(0) = -\Delta v = B\omega_n \quad (4.4)$$

With these constants, the position and velocity equations can be determined for a linear elastic material.

$$x(t) = \frac{mg}{k}(1 - \cos(\omega_n t)) - \frac{\Delta v}{\omega_n} \sin(\omega_n t) \quad (4.5)$$

$$\dot{x}(t) = \frac{mg\omega_n}{k} \sin(\omega_n t) - \Delta v \cos(\omega_n t) \quad (4.6)$$

This dynamic analysis of the drop test assumes that the stiffness is linearly elastic. However, from quasi-static testing, the crush force was identified as, at least, a nonlinear function of displacement, so that

$$F_{crush} = F_{crush}(x) \quad (4.7)$$

In addition, the constant velocity testing suggests that this relationship also depends on the crush velocity. As the cross head velocity increases, there was a direct effect on the performance of the visco-elastic material, so that

$$F_{crush} = F_{crush}(x, \dot{x}) \quad (4.8)$$

Implementing this nonlinear, strain dependent crush force into our governing equation, we find:

$$m\ddot{x} = F_{crush}(x(t), \dot{x}(t)) + mg \quad (4.9)$$

It is challenging to empirically determine the precise nature and values of $F_{crush}(x(t), \dot{x}(t))$ over the entire range of crush displacements and velocities. For example, if it is desired to perform dynamic crush tests at speeds of 5 m/s, then it is reasonable to expect that constant velocity crush tests should be conducted at incremental speeds up to 5 m/s in order to determine F_{crush} . However, this is beyond the capabilities of our testing machines. Therefore, an alternative approach is needed.

In a drop test, acceleration, $\ddot{x}$, can be measured, and the effect of F_{crush} is embedded in the measured response. Thus, if we measure acceleration of the impactor, then we can resort to numerical integration to determine the velocity and position of the impactor, because the measured acceleration includes the influence of the crush force. Thus, this is the method that will be undertaken here.

4.3 Materials and Methods

4.3.1 Sample Manufacturing

The unit cell for a honeycomb (HC) was expanded upon to ensure the tests that were being conducted would be successful. The unit cell of HC is three walls spaced 120° around a central point. This structure would not be stable enough to test and does not provide enough surface area to implement buckling initiators (BIs). For this reason, a section of honeycomb was selected to

be studied, however the BIs were not visible and the unsupported walls collapsed prematurely. As a result, a primary hexagon with 6 surrounding hexagons was selected as the unit cell for this study (Figure 4.1).

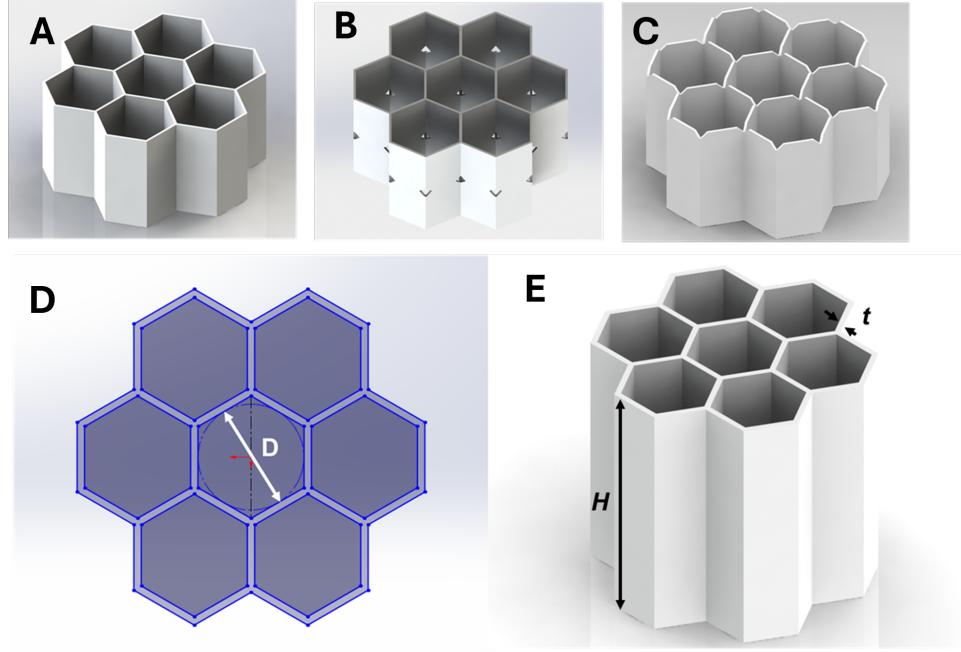


Figure 4.1: Samples that were used for testing. (A) is 0BI; (B) is 0.5BI; and (C) is 1BI. (D) shows the inscribed diameter, where $D = 25$ mm, while (E) shows the height, H , of the samples is 30 mm and the wall thickness, t , is 1.4 mm.

Samples were designed in a computer aided design (CAD) software, so that they could be printed using the Pro Series Flex TPU filament (MatterHackers, Lake Forest, CA, USA, 2018). The TPU had a Shore hardness of 98A. Samples were manufactured using a Creality Ender 3-S1 (Shenzhen Creality 3D Technology Company Ltd, Longhua District, Shenzhen, China). Due to the simplicity of the prints, this single nozzle printer was able to complete the prints without using support material.

All samples had an overall height of 30 mm, with individual cell walls having a wall thickness of 1.4 mm, and an inscribed circle diameter of 30 mm (Figure 4.1D and E). The samples

had BIs at one of two locations at all vertices: midway up the height (0.5BI) or at the top (1.0BI) as seen in Figure 4.1B and C respectively. A third group was manufactured without BIs (Figure 4.1A). The diamond shaped- BIs are defined by a point-to-point interior dimension of 4 mm in each direction.

4.3.2 Testing

This study is comprised of three different types of testing as follows: quasi-static (V_{QS}) testing, constant velocity (V_0) testing, and dynamic velocity (ΔV) testing.

The V_{QS} testing was conducted on the MTS-810 servo-hydraulic load frame (MTS, Eden Prairie, MN, USA). The 0BI and 0.5BI samples were tested in triplicate at $3E-5$ m/s to quantify their performance. During this time, a camera captured an image every 10 seconds so that the deformation mechanics could be analyzed later.

The V_0 testing was conducted in a very similar manner. The 0 and 0.5BI samples were tested on the MTS-810 servo-hydraulic load frame (MTS, Eden Prairie, MN, USA) at 0.25 and 0.5 m/s. Each of these conditions was done in triplicate to quantify the overall performance. Due to the higher speeds, a high-speed video camera (Redlake MotionProX3 Plus, San Diego, CA, USA) was used to record to deformation of the samples.

The final set of tests that were conducted were the ΔV impact tests. Here, 0, 0.5, and 1BI samples were tested in a free fall guided impact on a monorail impact machine (Cadex, Quebec, Canada) with a customized impactor. A flat end impactor was designed to ensure the area in contact with the sample was constant. These three types of samples were tested at 7 speeds: 1-4 m/s at 0.5 m/s intervals. Each of these tests were conducted three times to create an average

acceleration vs. time curve that could be analyzed. During testing, the impacts were recorded on a high-speed video camera for later analysis.

4.3.3 Data Analysis Methods

Due to the three different types of tests that were conducted, there was some processing that need to be done to the ΔV samples so that the force displacement data can be obtained. The following steps were conducted on just the dynamic impact test results.

To reach the displacement, the acceleration must be integrated twice. The first integration will result in the velocity.

$$V = \int_0^t a \delta t \quad (4.10)$$

When solving this equation, the initial condition was the velocity that was put into the impact machine. At this point, the velocity-time curves can be plotted, however the velocity must now be integrated to reach the displacement.

$$d = \int_0^t V \delta t \quad (4.11)$$

In a similar manner as before, an initial condition is required. This time though, the initial condition is 0 since the sample has not begun to crush at $t = 0$.

At this point, the acceleration, velocity, displacement, and time have been determined, however the force is required in order to calculate the metrics. To determine the force that was absorbed, the mass that impacted the sample must be know.

$$F = ma \quad (4.12)$$

At this time, all conducted tests have the force-displacement information, so the metrics can be determined.

The following methods for analysis are applicable for all three types of testing that were conducted. To begin, the area of contact for the sample must be determined.

$$A = 30lt \quad (4.13)$$

where l is the length of the wall and t is the wall thickness. From this, the stress can be determined

$$\sigma = \frac{F}{A} = \frac{F}{30lt} \quad (4.14)$$

where F is the force.

The energy density can then be calculated using the integral of the curve.

$$EA = \int_0^\epsilon \sigma(\epsilon) d\epsilon \quad (4.15)$$

The units of this calculation are J/m^3 . As Figure 4.2 shows, the green area under the curve is what was just determined. The strain energy density allows for additional metrics to be determined, showing the overall behavior of the materials. The first is the strain-dependent crush efficiency (SDCE), η_{SD} . The η_{SD} shows how much of the total crush the material was able to achieve at a given strain. It takes the strain energy density and divides it by a localized ideal strain energy density, which is denoted in Figure 4.2 by the yellow rectangle.

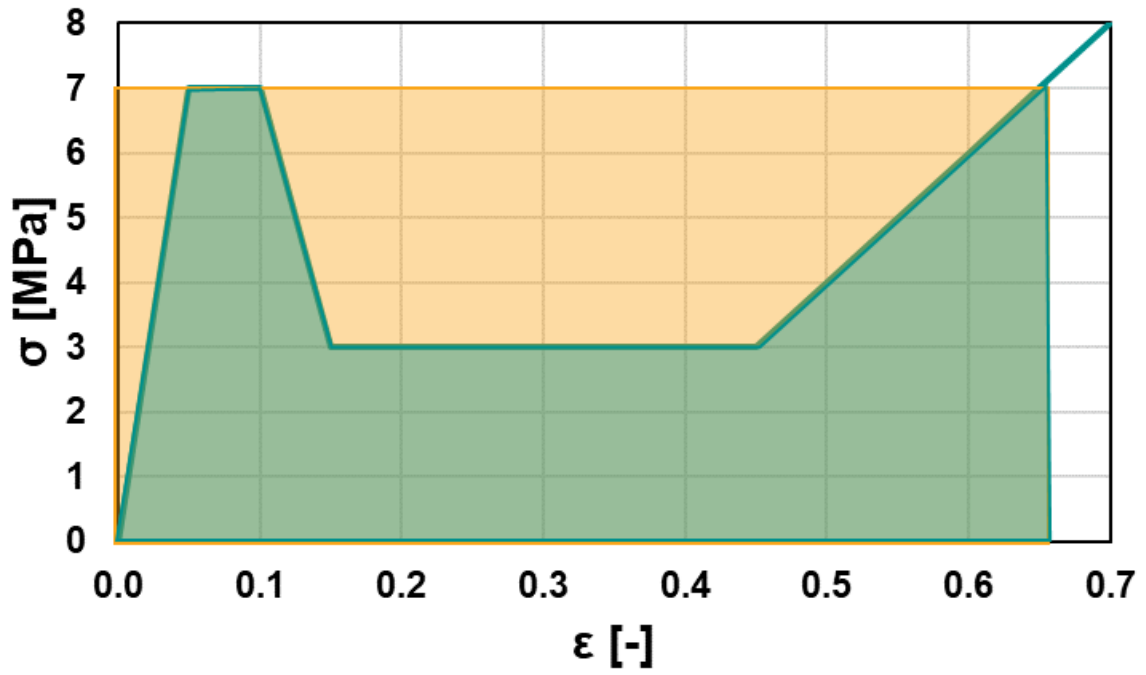


Figure 4.2: Representative stress strain curve with idealized area shown in yellow.

$$\eta_{SD} = \frac{EA}{\max[\sigma(0), \sigma(\epsilon)]\epsilon} = \frac{\sigma_{mc}}{\max[\sigma(0), \sigma(\epsilon)]} \quad (4.16)$$

where σ_{mc} is the mean crush stress. This value provides an average stress over the given strain range. It is determined using the following:

$$\sigma_{mc} = \frac{EA}{\epsilon} \quad (4.17)$$

If the efficiency is studied over the entire strain range, when $\epsilon = 1$, then the energy absorbed efficiency can be calculated as shown in the following equation:

$$\eta_{EA} = \frac{EA}{\max[\sigma(0), \sigma(\epsilon)]\epsilon} = \frac{\int_0^\epsilon \sigma(\epsilon) d\epsilon}{\max[\sigma(0), \sigma(\epsilon)]} \quad (4.18)$$

This value will constantly increase until densification is achieved, at which point it will decrease. The assumption of a material reaching 100% strain is highly unlikely due to the risk of compromising the occupant or items that are being protected.

To complete this analysis, additional values must be identified. The first is the peak stress, which is the maximum of the initial sharp increase of the stress-strain curve within the elastic curve. It can be determined using the following.

$$\sigma_{pk} = \frac{d\sigma}{d\epsilon} = 0 \quad (4.19)$$

The strain at this given point is referred to as the peak strain. The calculation is as follows.

$$\epsilon_{pk} = \epsilon|_{\sigma_{pk}} \quad (4.20)$$

4.4 Results

4.4.1 Quasi-Static and Constant Velocity Behavior

The quasi-static (V_{QS}) and constant velocity (V_0) samples were tested on the MTS as described in Section 4.3.2. This machine ensures the cross-head is moving at a constant velocity, regardless of how far along the test is.

The V_{QS} samples are intended to show how these visco-elastic HC would perform under nearly static loading conditions. As Figure 4.3 shows, the V_{QS} samples reach a peak load of 0.08 MPa for 0BI and 0.06 MPa for 0.5BI. The 0BI curve shows the characteristic energy absorption profile with the three unique stages, however there is a change in the 0.5BI stress- strain profile.

The stress increases, however it plateaus around 10% strain before increasing a second time to the peak stress. It is important to note that the initial plateau region nearly aligns with the mean crush stress over the entire strain range until densification.

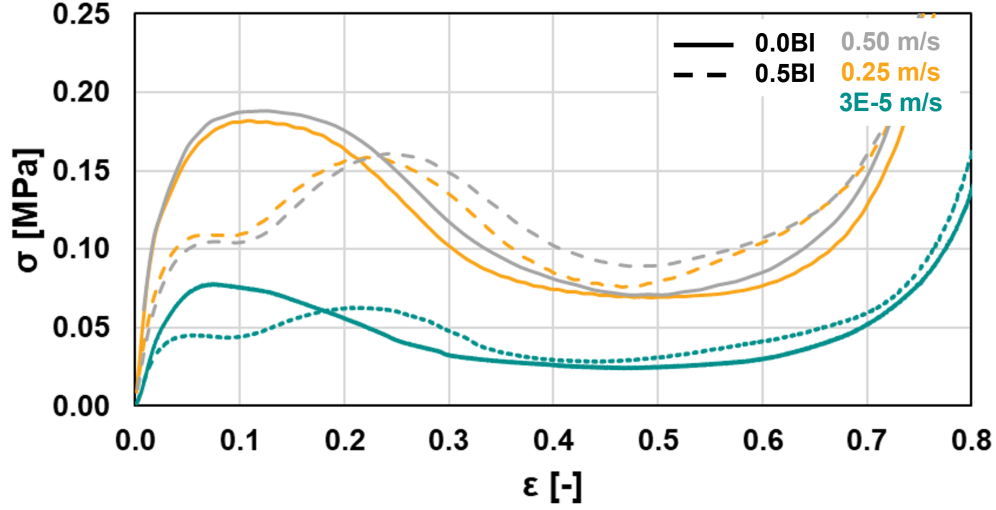


Figure 4.3: The stress-strain curves for the quasi-static and constant velocity samples with 0BI and 0.5BIs

The constant velocity tests were examined at two different velocities: 0.25 m/s and 0.50 m/s. Looking at the 0BI samples for V_0 in Figure 4.3, they follow the same trend as the V_{QS} with 0BI samples. These also have a substantial peak stress followed by a decrease in stress prior to the densification of the sample. Reviewing the metrics in Table 4.1 from these two types of samples confirms they are nearly identical with the crush efficiency varying by only 0.25%.

Reviewing the V_0 with 0.5BIs show a similar trend to the V_{QS} samples with 0.5BIs. The magnitude of the stress has increased, however the initial plateau region prior to the peak stress is evident in these V_0 tests. Here, Table 4.1 shows that the presence of buckling initiators in these visco-elastic honeycomb will maintain, if not increase the energy absorption capabilities of these shapes, regardless of impact speed, so far.

Table 4.1: Performance metrics for the quasi-static and constant velocity tests

	V [m/s]	σ_{pk} [MPa]	σ_{mc} [MPa]	η_{SD} [%]	η_{EA} [%]
0.0BI	3E-5	0.08	0.07	82.04	41.24
	0.25	0.18	0.17	87.30	45.97
	0.50	0.19	0.18	87.55	47.49
0.5BI	3E-5	0.06	0.05	84.81	48.70
	0.25	0.16	0.13	83.00	49.73
	0.50	0.16	0.16	82.22	51.72

4.4.2 Dynamic Impact Behavior

Dynamic impact tests (ΔV) vary significantly from the constantly velocity tests because the velocity changes as a function of time in impact tests. Figure 4.4 shows how each type of test starts at the determined, however the velocity decreases due to the sample decelerating the impactor until it reaches a resting position. Because the impactor is moving downwards, the Figure is displayed with a negative velocity.

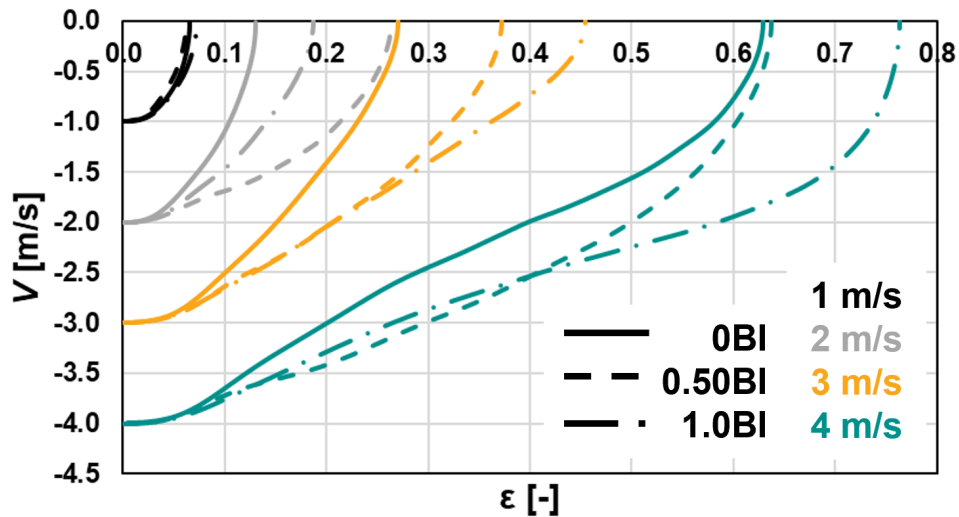


Figure 4.4: The velocity- strain curves show how the presence of buckling initiators effect the strain range of the test

With this changing velocity in mind, the stress- strain curves can be determined. Figure

4.5 shows the stress- strain curves for each of the three types of BIs that were tested. For the 0BI samples, there is a notable peak stress with minimal or no stroke. The stroke is amount of displacement that is able to achieved with the sample. As Figure 4.5A shows, between 1 and 3 m/s, the samples do not even reach 30% strain. That leaves most of the material still available to absorb energy, therefore this would be considered an inefficient energy absorber.

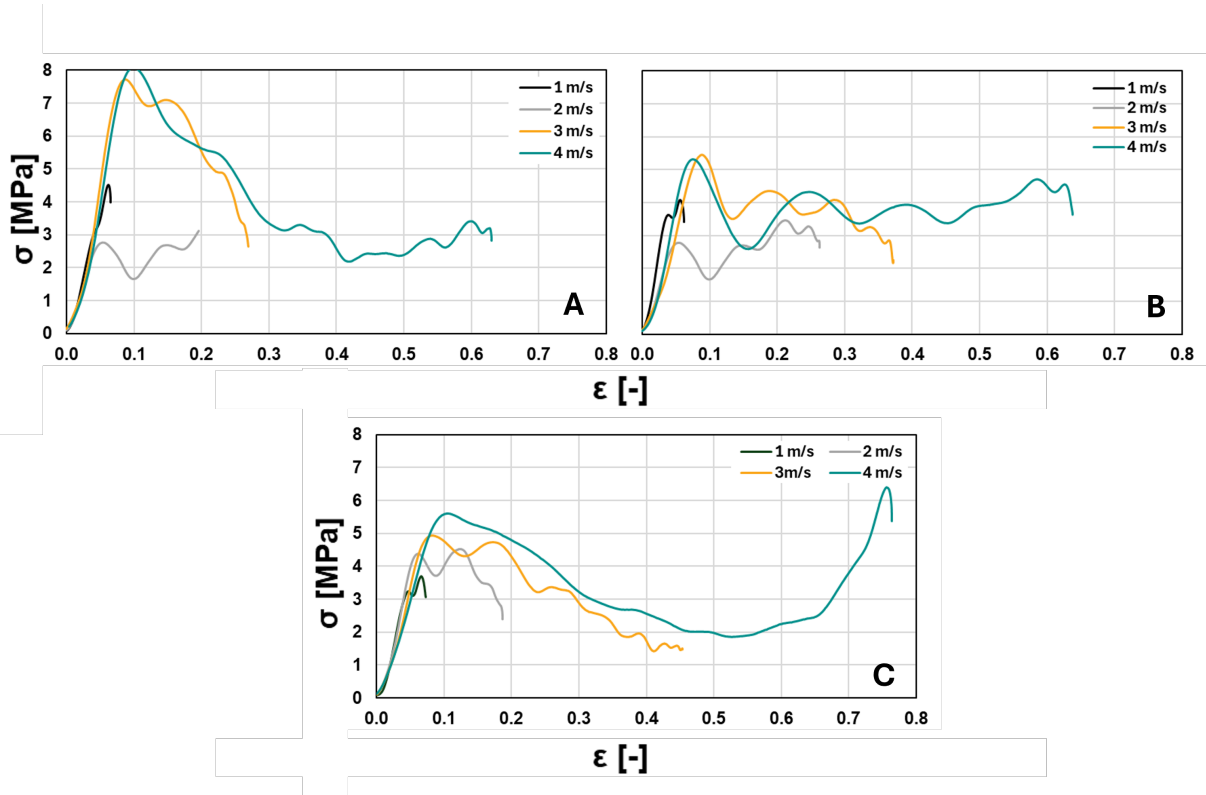


Figure 4.5: The stress- strain curves for the dynamic impact tests. (A) 0BI; (B) 0.5BI; and (C) 1.0BI

Continuing into the 0.5BI samples, there is improvement to the stroke. Most of the samples have a peak stress and a stroke following. Unlike before, it becomes noticeable that the 4 m/s is able to stabilize the stroke around 3.5 MPa. This results in an increase in energy absorbed, which will increase the crush efficiency and the energy absorbed efficiency. It must still be highlighted, that in Figure 4.5B, none of the samples achieve densification.

The samples with the buckling initiators located at the top, 1.0BI, show some improved characteristics. The peak stress has decreased from what was experienced with the 0BI samples, however it is still higher than the 0.5BI samples. As the samples continue to be compressed, the stress decreases, with the exception of the 4 m/s samples. The 4 m/s samples experience full densification. The mean crush stress for these samples are significantly lower than those with 0.5BI. Regardless of the speed, the 1.0BI samples show a decrease in energy absorption properties when compared to the 0.5BI samples.

As highlighted with all ΔV , the stroke varies drastically. As Figure 4.6 shows, the displacement of these samples is always increasing, but the displacement is dependent on the initial velocity of the impactor. The graph is a function of time so to emphasize that the end of each test, or when the velocity reached 0, was at a different time and the sample was also displaced a different amount as explained further. Regardless, any samples with BIs outperform their 0BI counterpart.

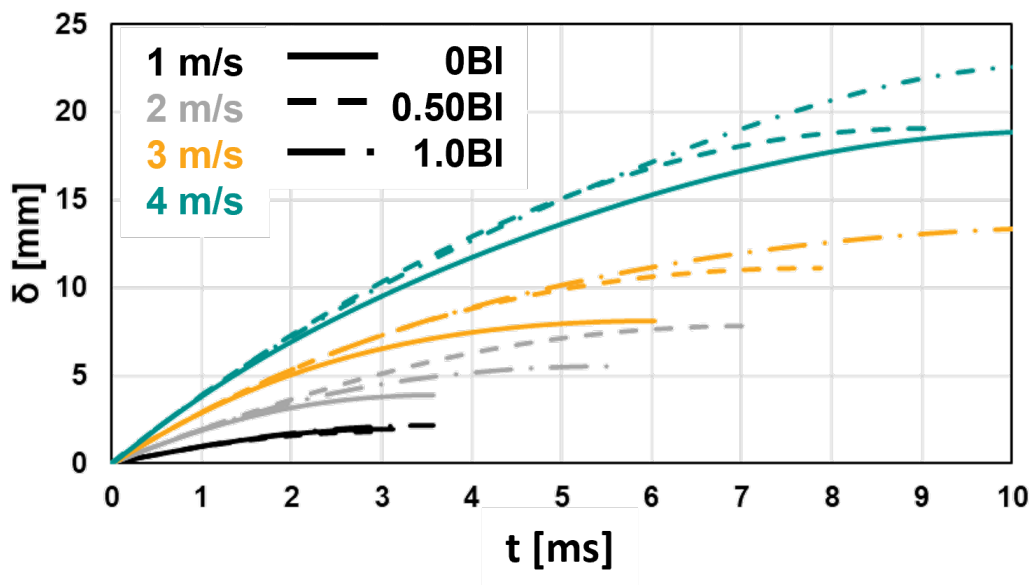


Figure 4.6: The displacement of the samples directly corresponds to the velocity of the test

The dynamic impact tests require that a kinetic energy from the impactor be transferred into a potential energy from the sample. All energy, with the exception of some frictional losses must directly be transferred from the impactor to the sample. To calculate this, the following kinetic energy equation can be used.

$$KE = 1/2mv^2 \quad (4.21)$$

The kinetic energy can be used to predict the displacement of the sample by re-arranging the potential energy equation as follows:

$$PE = mg\delta \quad (4.22)$$

$$\delta = \frac{PE}{mg} \quad (4.23)$$

From this, a maximum displacement can be determined. Any loss in displacement is a result of friction in the monorail system.

4.5 Discussion

4.5.1 Strain Dependent Crush Efficiency

From the stress-strain curve, the strain- dependent crush efficiency can be determined. The strain- dependent crush efficiency determines how effective the sample was at absorbing all possible energy up to the given strain. This metric allows different types of samples to be compared to each other.

The strain-dependent crush efficiency curves tell an interesting story about the samples that

were analyzed. Figure 4.7 shows how samples tested at 1 m/s, regardless of buckling initiators, do not reach anywhere near the peak η_{SD} of the other speeds. All three types of this sample have reached a maximum of 60% crush efficiency with a maximum stroke of less than 10% strain. The maximum η_{SD} is achieved by the 3 and 4 m/s samples with 1.0BI, but looking at the maximum η_{SD} can be misleading.

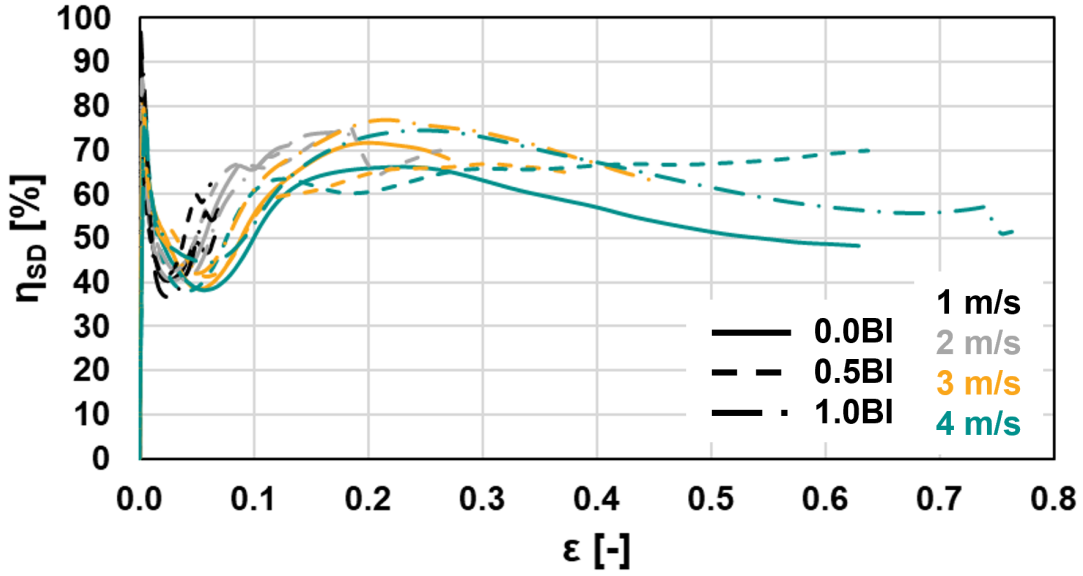


Figure 4.7: The strain dependent crush efficiency of the dynamic samples across the entire stroke

Under an impact, the best performing energy absorption material will maintain a consistent η_{SD} across the stroke. This allows for the material to be useful for as long as possible. Looking at the 4 m/s 0.5BI, the profile reaches an initial peak of approximately 65% efficiency, however after a slight dip, it continues to increase between 65 and 70% efficient across its entire strain range. Reviewing the maximum η_{SD} sample (3 m/s with 1.0BI), the samples reach that peak and then continuously decline from that 77% value until the stroke ends at about 62% strain. This results in the material being unable to absorb as much energy as before.

4.5.2 Energy Absorbed Efficiency

The energy absorbed efficiency is the other metric that is used to compare different types of samples to each other. Here though, the curves continue to increase until densification has been achieved. At that point, there will be a decrease in the energy absorbed efficiency. This is portrayed as a function of strain, so that the strain at the onset of densification can be identified.

To understand the performance of the three different studies, the maximum energy absorbed efficiency is shown on a plot as a function of the velocity. Figure 4.8 shows the distinct regions of the studies that were conducted. Starting from left to right, the quasi-static testing is shown as about 0 m/s. Moving towards the right, the energy absorption efficiency increases for the constant velocity tests conducted at 0.25 and 0.50 m/s. Once the dynamic impact tests begin around 1 m/s, there is a significant decrease in energy absorption efficiency. The efficiency is shown to go from 50% down to 5% for the 0.5BI samples that increase from 0.5 to 1.0 m/s. This is a direct result of the type of test that is being conducted.

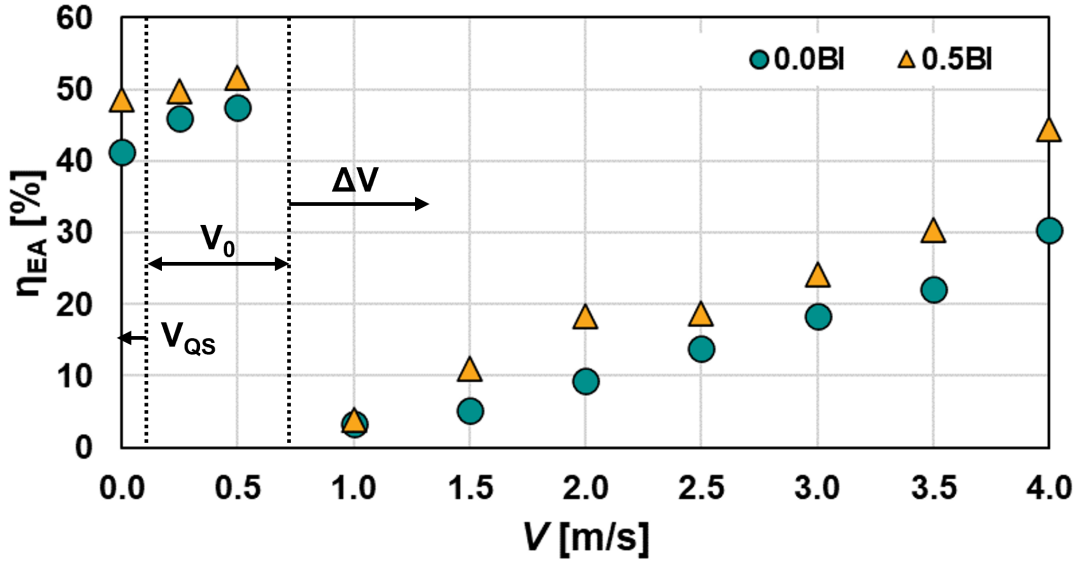


Figure 4.8: The data falls into three groups based on the studies that were conducted. The first is the quasi-static samples (V_{QS}), which is an example of the second group: constant velocity, V_0 . The final group is the dynamic impact (ΔV)

When comparing the energy absorption efficiency of all samples that were tested, there is a significant decrease between the constant velocity samples and dynamic impact samples. This is due to the velocity changing throughout the dynamic test, while it is maintained throughout the constant velocity test as the name implies. The decrease in velocity over the stroke directly contributes to the decrease in the energy absorption efficiency.

The energy absorption efficiency for all 0BI samples, regardless of study, are shown in Figure 4.9. From this chart, there are three distinct groups, once again, divided by the type of test. All samples experience the same η_{EA} for the first 5% strain. After this point, the V_0 has a longer linear region, before changing slope around 30% strain. This is indicative of having passed through the linear elastic region and beginning to experience the plastic region. These V_0 samples reach their maximum energy absorbed efficiency between 70 and 75%. This directly corresponds to the densification of the samples.

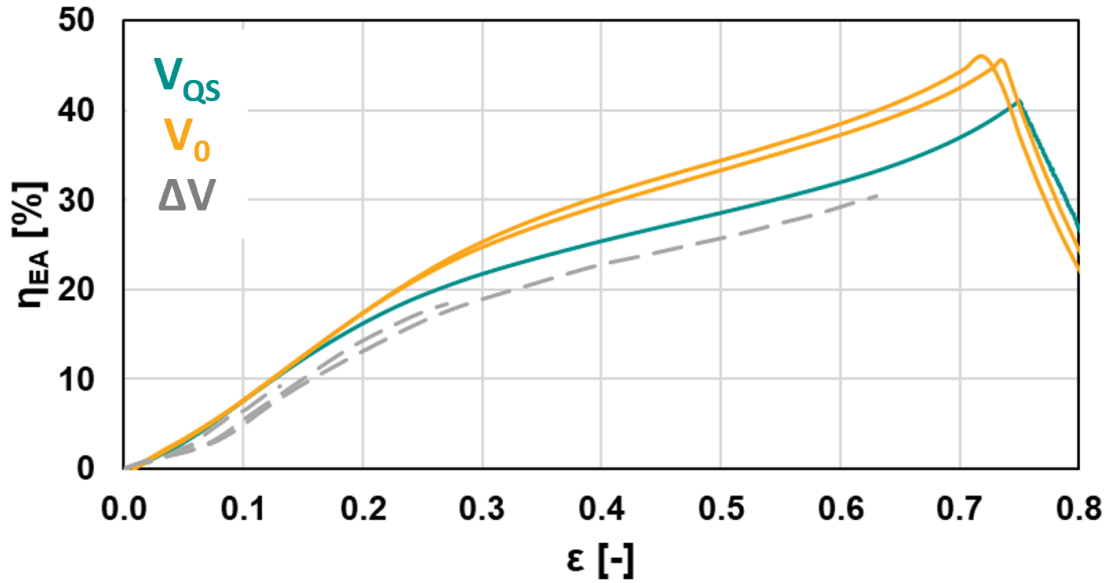


Figure 4.9: The energy absorption efficiency for visco- elastic honeycomb during three different types of testing: quasi-static (green), constant velocity (yellow), and dynamic impact (grey)

The quasi-static samples follow the constant velocity samples. These have two distinct slopes once again before reaching densification. Overall though, the energy absorbed efficiency is less than the constant velocity tests throughout the stroke. The dynamic tests provide a unique set of tests, where they tend to overlay each other even though they were conducted at different initial velocities. The general trend of the η_{EA} for the ΔV samples is the same as the other tests. Here though, Figure 4.9 shows that the samples did not densify. They do not reach the corner of the energy absorbed- strain curve.

Regardless of the initial velocity used in a dynamic impact test, the quasi-static test provides a reasonable upper bound for these visco-elastic TPU honeycomb without buckling initiators. The energy absorption efficiency values from the dynamic impact testing will be lower than the constant velocity tests because the impactor decelerates, thus decreasing the velocity.

Due to the difficulty of running dynamic impact tests, it is useful to have a representative

test. When trying to increase the stroke of the sample so that it reaches the target of 65- 70% strain, the initial velocity must also be increased, however if it is increased too high, the energy could be transferred into the ground, making it unsafe. For this reason, all tests are conducted at the lowest speed and slowly increase.

The energy absorption efficiency must be determined for the samples with 0.5BIs as well. For the samples with 0.5BIs, all energy absorption efficiency curves overlap with minimal error. The constant velocity curves appear to be slightly more efficient than the quasi-static tests, however the dynamic tests follow the trend line as well (Figure 4.10).

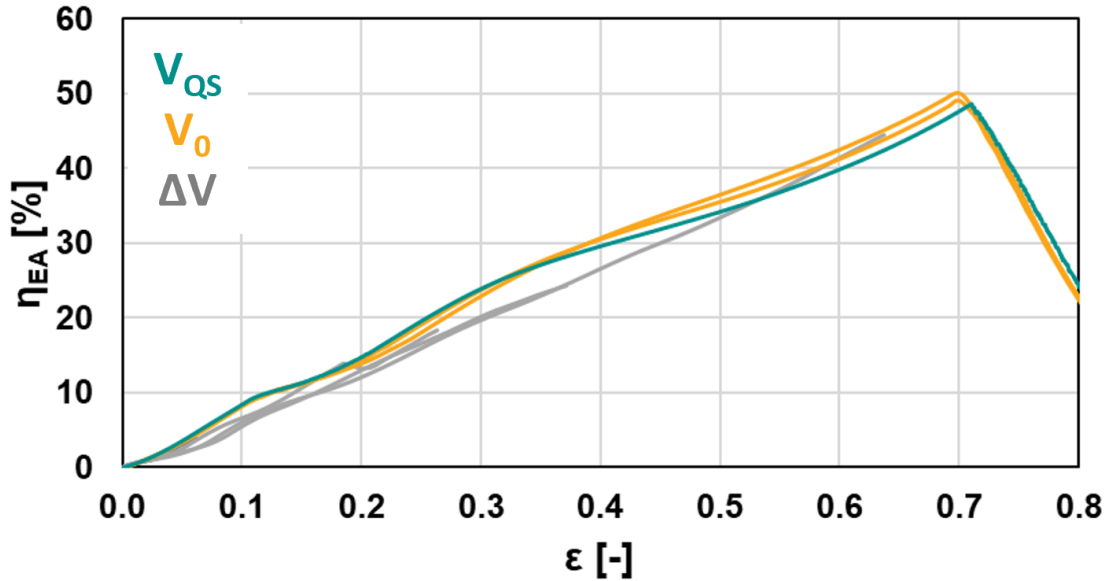


Figure 4.10: The energy absorbed efficiency for visco-elastic TPU samples with a buckling initiator located midway up the height.

The buckling initiators in these samples minimize the strain- dependent effects, so these quasi-static and constant speed tests at low speeds align. As a result, either of the tests can be used to predict the behavior of the dynamic tests as they reach higher strains. Once again, this will be useful in projecting the behavior of the energy absorbed efficiency. It will not provide the densification point, however the efficiency can be predict with reasonable accuracy.

From this, is it sufficient to model the crush forces as a non-linear function of the displacement ($F_{crush}^{QS} = F(x(t))$) or does the non-linear function need to also include the strain rate ($F_{crush} = k(x(t), \dot{x}(t))$)? Moving forward, the error between the theory and experiment must be better understood for completeness.

4.6 Conclusions

During this work, a series of series of tests were conducted on visco-elastic TPU honeycomb to determine a method to predict the dynamic crush properties. Each sample, 0.0BI and 0.50BI, were tested under quasi-static, constant velocity, and dynamic impact conditions. The key findings are as follows:

1. Thermoplastic polyurethane (TPU) honeycomb see an increase in the energy absorbed efficiency when buckling initiators are present in constant velocity tests.
2. Dynamic impact tests with the buckling initiators located midway up the height of the sample result in the crush efficiency with the least variance across the stroke. Similarly, this sample experiences a near linear energy absorbed efficiency behavior as well.
3. The energy absorbed efficiency curves can be calculated for a dynamic impact test where crush is measured just below the onset of densification.
4. Dynamic impact tests report lower energy absorbed efficiency values than the constant velocity tests because the impactor decelerates. As this is happening, the velocity is also decreasing, thus less kinetic energy is available for transfer.
5. Quasi-static testing is a reasonable upper bound measure of dynamic energy absorption for

these TPU honeycomb regardless of the presence of buckling initiators.

Chapter 5: Electroplating Additively Manufactured Honeycomb Structures to Increase Energy Absorption Under Quasi-Static Crush

Honeycomb (HC) has been used in energy absorption applications due to its high stiffness and low density. Metallic HC are used for energy absorption applications, however, these metallic structures can be challenging to manufacture if complex geometric features designed to improve energy absorption are used, which motivates the use of additive manufacturing (AM). Metal AM methods include powder bed fusion (PBF) and direct energy deposition (DED). In addition to capital equipment cost, these processes possess challenges that include a required inert environment, powder handling, final part porosity, residual stresses, and nonuniform surface finish. These concerns can be alleviated through the use of polymer AM, however, polymeric parts exhibit brittle failure and have a lower stiffness than metallic HC structures. In this study, a low-cost 3D polymer printing method, stereolithography (SLA), is combined with a conventional electroplating process to fabricate a metal-plastic composite HC structure with energy absorption capability much greater than of a plastic HC structures of the same nominal volume. SLA parts have a smooth surface, so that the surface finish is at least as uniform after electroplating as the SLA part. The energy absorption characteristics of the electroplated HC is studied to determine how these energy absorbing materials can be manufactured at reduced cost. Our study confirms that the metal-plastic composite HC increases both the crush strain range and the mean

crush stress of these samples, resulting in metal-plastic composite HC structures with substantially increased energy absorption. This study also examines how buckling initiators (BIs), or diamond shaped holes located at 50, 75, and 100% of the height of the hexagonal cell vertices, can influence energy absorption performance. This study shows that it is feasible to fabricate electroplated HCs, using an SLA preform, to achieve a substantial increase in energy absorption over using SLA alone.

This research was published in *SAMPE Journal* and presented at 2024 CAMX San Diego. [\[128\]](#).

5.1 Introduction

Energy absorption to mitigate impact or crash loads is typically achieved in compression by crushing foam [\[129\]](#) or honeycomb [\[123\]](#) materials. Honeycomb (HC) has been used for energy absorbing applications because it has a high stiffness and low density [\[121–123\]](#), and are amenable to additive manufacturing. HC is most commonly manufactured using steel or aluminum, and has been typically manufactured using processes such as adhesive bonding, resistance welding, diffusion bonding, brazing, thermal fusing, or expansion and corrugation, but these methods have their own challenges [\[10\]](#). Advances in additive manufacturing (AM) have provided a means to manufacturing metallic HC; these new methods eliminate many constraints of conventional manufacturing, while saving time and money when making customized parts or when implementing specialized geometric features for energy absorption [\[10, 120, 121\]](#).

Some commonly used metallic additive manufacturing methods include powder bed fusion (PBF) and direct energy deposition (DED) [\[130, 131\]](#). PBF will scan a powder bed at a pre-

determined velocity, while a laser selectively melts the metallic powder. The elevated temperature from the laser can introduce residual stresses into the final part. Additional stresses can also result from the thermal expansion and shrinkage [131]. DED, on the other hand, will place a melt pool onto the part using a 3-axis machine [130, 132, 133]. This technique results in poor surface finish and low build accuracy, along with uneven temperature gradients [134, 135]. Both PBF and DED must be conducted in an inert environment to reduce oxidation of the raw materials and require that a large number of processing parameters be optimized, while ensuring adequate ventilation of metal powder feedstock materials.

In this study, plastic HC samples fabricated via SLA (unplated HC samples) are compared to electroplated HC samples (plated HC samples). Both the unplated and plated HC samples have nominally the same volume of material. The plastic HC preform used for the plated samples has thinner walls than the unplated samples, and the metallic coating restores the wall thickness so that it is the same as that of the unplated samples. Quasi-static crush tests are used to measure the energy absorption of both the unplated and plated HC samples. Our hypothesis is that the plated samples will exhibit a sufficient increase in stiffness and strength to exhibit greatly improved energy absorption due to the combination of a larger stroking load during crush as well as a wider strain range over which crush takes place. Finally, the addition of buckling initiators in these unplated and plated HC structures is assessed.

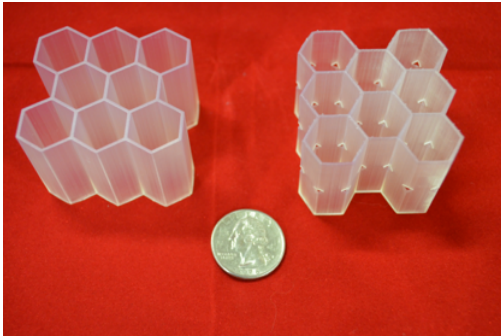
5.2 Methods and Materials

5.2.1 Sample Fabrication

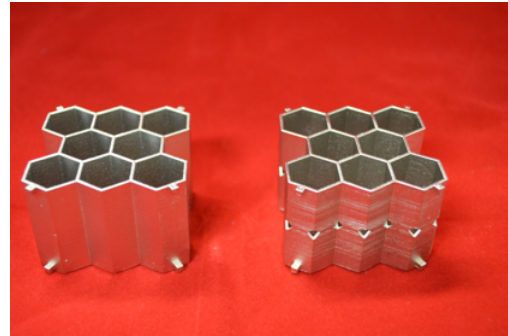
HC samples were designed using computer aided design (CAD) software to the final dimensions. HC samples had three rows of hexagons, each having an inscribed diameter of 15 mm. The top and bottom rows had 3 hexagons each, while the middle row had two. All samples had a height of 30.0 mm and a wall thickness of 1 mm. The samples with BIs had a diamond-shaped cut-out located at every vertex in one of three vertical locations on the samples: 50, 75, or 100% of the sample height (Figure 5.1). All BIs had vertices with point-to-point dimensions of 4 mm.

The samples that were not being electroplated (i.e. unplated samples) were printed using stereolithography (SLA) on a Form 3 (Formlabs) 3D printer using the Clear Resin (Formlabs) (Figure 5.1a). These unplated samples have a constant wall thickness of 1 mm (Figure 5.1c). The samples to be electroplated, or plated samples (Figure 5.1b), were required to have the same volume as the unplated samples. For the plated samples, the wall thickness of the plastic HC was reduced by the thickness of the metal plating on either side of the wall. The desired plating thickness was 150 μm , on each surface, so that the wall thickness was reduced by 300 μm . This HC part served as the mandrel for the electroplating process. A plating thickness of 150 μm was selected to allow for 50 μm hard Ni, 50 μm soft Ni, 50 μm Cu, 700 μm of Clear Resin followed by 50 μm of Cu, 50 μm of soft Ni and 50 μm of hard Ni (Figure 5.1d). The volume difference between the as-built SLA HC samples and the SLA preform is the nominal volume of metal added during the electroplating process. This volume can be used to estimate the expected weight gain from the electroplating process and thus the anticipated volume fraction of metal.

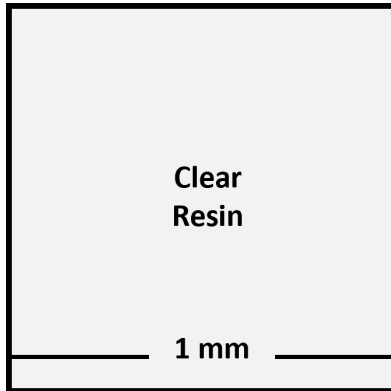
Once the HC samples were removed from the print platform, the samples were triple rinsed in a 91% isopropyl alcohol cleaning bath. They were left to dry overnight at room temperature before curing in an oven for at least 60 minutes. A UV light was used to cure any residual resin. Once cleaned, HC samples were placed onto a rack to be etched by spraying a fine abrasive onto all surfaces. This enables the autocatalytic nickel to deposit a nickel phosphorus conductive layer onto the samples. At this point, the samples were placed into the copper, ductile nickel, and hard nickel tanks to complete the electroplating process.



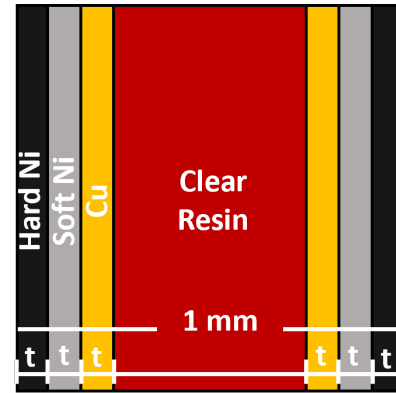
(a) Unplated samples without and with buckling initiators (BIs) located at the midpoint (0.50BI)



(b) Plated samples without and with BIs located at the midpoint (0.50BI)



(c) Wall cross section for unplated samples



(d) Wall cross section for plated samples, where $t = 50 \mu\text{m}$

Figure 5.1: The constant volume additively manufactured HC samples: (A, C) plastic HC via SLA; (B, D) plastic HC preform via SLA electroplated with CU, soft Ni, and hard Ni.

5.2.2 Testing Samples

The samples were tested using quasi-static compression conditions on a servo-hydraulic load frame (810 MTS, Eden Prairie, MN). The tests were conducted at a strain rate of 0.001 s^{-1} up to 85% strain so that the full strain range up to densification can be captured. During testing, a Nikon D5100 camera (Nikon Inc., Melville, NY, USA) was used to record sample deformation. An image was taken every 10 seconds, so that failure modes could be observed and analyzed.

5.2.3 Energy Absorption Metrics

The HC samples are being studied for energy absorption applications, so that a number of key mechanical characteristics, or metrics, must be defined and quantified. The HC samples are composed of seven hexagons with overlapping walls, so the contact area was calculated noting that there are 35 individual walls in the sample:

$$A = 35Lt \quad (5.1)$$

where t is the wall thickness, and L is the length of a side of the hexagon. The stress is given by:

$$\sigma = \frac{F}{A} = \frac{F}{35Lt} \quad (5.2)$$

where σ is the stress, and F is the force. The energy absorbed can be found by calculating the area under the stress vs. strain curve:

$$U(\epsilon) = \int_0^\epsilon \sigma(\epsilon) d\epsilon \quad (5.3)$$

The strain dependent crush efficiency can be determined using the energy absorbed:

$$\eta_{SD}(\epsilon) = \frac{U(\epsilon)}{\max[\sigma(0), \sigma(\epsilon)]\epsilon} = \frac{\sigma_{mc}}{\max[\sigma(0), \sigma(\epsilon)]} \quad (5.4)$$

Here, $\max[\sigma(0), \sigma(\epsilon)]$ is the maximum stress over the strain range from zero strain to the current strain level. The mean crush stress, σ_{mc} , is the mean stress over the strain range and can be determined via:

$$\sigma_{mc} = \frac{U(\epsilon)}{\epsilon} \quad (5.5)$$

The material's efficiency of absorbing energy is similar to the strain dependent crush efficiency, however, it describes how the sample absorbs energy across the full strain range of the material. This is done by setting the normalizing strain in the denominator, $\epsilon_{max} = 100\%$ strain.

$$\eta_{EA}(\epsilon) = \frac{U(\epsilon)}{\max[\sigma(0), \sigma(\epsilon)]\epsilon_{max}} \Big|_{\epsilon_{max}=1} = \frac{U(\epsilon)}{\max[\sigma(0), \sigma(\epsilon)]} \quad (5.6)$$

5.3 Results

5.3.1 Effects of Plating

First, let us examine the effects of electroplating in these samples. Two sets of samples were fabricated: one set unplated (all plastic) and one set plated (metal-plastic composite). The samples were crushed using an MTS system with a strain rate of 0.001 s^{-1} . Figure 2 depicts the stress vs. strain for the average of three unplated and three plated HC samples.

The unplated HC samples exhibit brittle failure at about 10% strain on average. The samples experience their linear elastic region before immediately decreasing due to brittle fracture.

The average peak stress seen from these samples is 55 MPa. As a result, these unplated HC samples experience a very short strain range. This brittle unplated HC is an unlikely choice for energy absorption applications due to the low strain range, which minimizes the opportunities for the HC to fold and thus absorb energy. On the other hand, the plated HC samples demonstrate far better energy absorption characteristics. There is a linear elastic region where the initial stress is being loaded, prior to the progressive collapse region that occurs between 10 and 60% strain, at which point densification initiates (Figure 5.2). The plated HC samples are able to withstand a significantly wider strain range (about a seven times greater strain range) at slightly higher loads. The plated HC samples are shown to hold peak load closer to 70 MPa. Plating the samples results in over a 25% increase in the peak stress and 600% increase in strain.

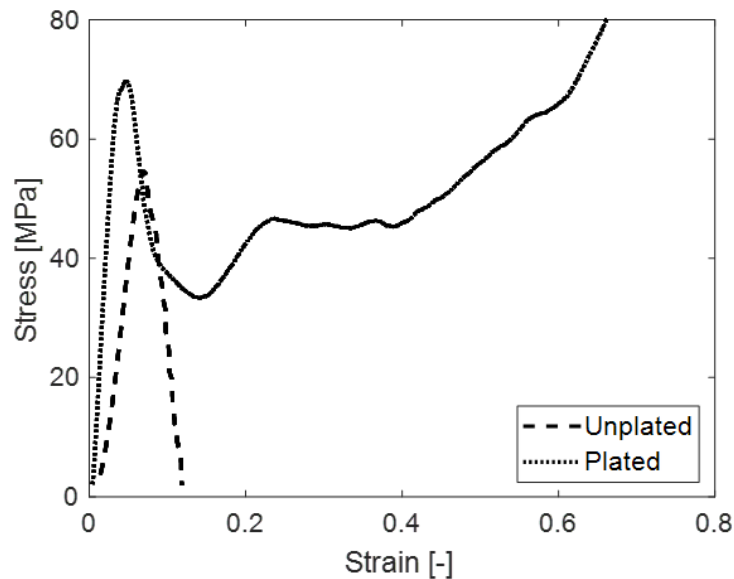


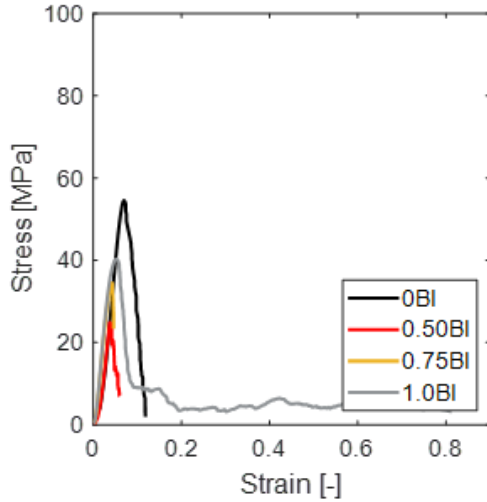
Figure 5.2: Stress vs. strain diagram for unplated and plated HC samples with no BIs

5.3.2 Effects of Buckling Initiators

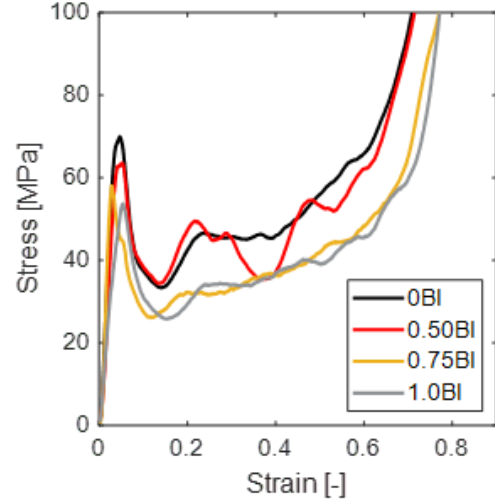
As discussed in the previous section, the plated HC samples indicated the potential to be used in energy absorbing structures. A study was conducted to observe the effects of BIs in the performance of both unplated and plated HC samples. BIs, sometimes called stress concentrators, are introduced to the honeycomb structure to encourage folding in a predictable way. In this study, BIs were placed in three locations: 50, 75, and 100% the height of the HC sample, denoted as 0.50BI, 0.75BI and 1.0 BI samples, respectively, in order to assess BI location on energy absorption. HC samples with no BIs, denoted as 0BI samples, were also fabricated for comparison.

Figure 5.3 shows the performance of the unplated and plated HC samples with BIs. The unplated HC samples exhibit a peak stress of $\sigma_{pk} = 56$ MPa, and exhibit brittle failure, and can no longer carry any significant stress for strain levels above 10-20% (Figure 5.3a). This low strain range over which compressive stress can be supported greatly reduces their energy absorption capacity. The 0BI plated HC samples exhibit a peak stress of $\sigma_{pk} = 70$ MPa and a mean crush stress of $\sigma_{mc} = 55$ MPa, while the 0.50BI samples average a peak stress of $\sigma_{pk} = 63$ MPa and a mean crush stress of $\sigma_{mc} = 60$ MPa (Figure 5.3b). To help determine the energy absorption of these materials, the change in stress is calculated using $\Delta\sigma = \sigma_{pk} - \sigma_{mc}$. This quantifies the difference between the maximum reported value in the linear elastic range and the average stress across the entire strain range. Here, a lower value is better, since it would indicate the peak stress is equilibrated with the mean crush stress, so that the crush efficiency would increase.

As the buckling initiator continues to move vertically up the wall of the plated HC samples, the overall energy absorption capabilities remains relatively unchanged. The 0.75BI samples



(a) Unplated HC samples



(b) Plated HC samples

Figure 5.3: Stress vs. strain for the unplated and plated samples with no buckling initiators (0BI), and with BIs at 50, 75, and 100% of the sample height (0.50BI, 0.75BI, and 1.0BI, respectively)

exhibits a noted decrease in the peak stress, down to $\sigma_{pk} = 58$ MPa, however the mean crush stress also decreases at the same time, to $\sigma_{mc} = 52$ MPa. This results in a change in stress of about 6 MPa, which is less than the 0.50 sample. A similar trend occurs with the 1.0BI samples, where the peak stress is about $\sigma_{pk} = 53$ MPa, but the mean crush continued to decrease to $\sigma_{mc} = 50$ MPa. This results in approximately a 3 MPa difference, which is similar to that which was reported from the 0.50BI samples. These key stress values are listed in Table 5.1 for each group of samples.

It should be noted that the weight of the 0BI and 0.50BI samples averaged 42 g whereas the 0.75BI and 1.0BI samples averaged 35 g, so that the former two group of samples were nominally 20% heavier than the latter two groups, so that the volume of metal coating was not consistent between the two groups of plated samples (Table 5.1). However, these results do support the feasibility of electroplating the SLA preform to increase energy absorption capacity because stress is supported over a much wider strain range of crush.

Table 5.1: Performance metrics of samples

Plating	BI	W [g]	σ_{pk} [MPa]	σ_{mc} [MPa]	η_{SD} [%]	η_{EA} [%]	SEA [MJ/kg]
Unplated	0.0	13.11	54.54	29.51	54.11	5.88	246.7
	0.50	12.64	24.86	11.77	47.36	2.77	56.48
	0.75	13.32	34.53	18.84	54.56	2.50	71.37
	1.0	13.01	40.32	25.80	63.97	14.05	441.4
Plated	0.0	43.38	70.02	56.24	68.97	43.07	853.7
	0.50	40.72	63.55	60.18	71.61	44.21	873.7
	0.75	34.94	58.07	52.11	65.62	43.74	1277
	1.0	35.10	53.74	49.81	67.80	44.66	1192

To better understand what occurs as the samples are crushed, images were taken of the quasi-static crush tests as a function of strain. The top rows of Figure 5.4 depict a representative crush of a 0BI plated HC sample. The 0BI plated HC sample initiated crush nearest to the bottom platen and slowly collapsed upward as the compressive strain increased. This resulted in a consistent folding, regardless of which individual hexagon is being observed. The bottom rows of Figure 5.4 depict a representative crush of a 0.50BI plated HC sample. The peak stress decreases because, at 10% strain, about half of the hexagonal cells are collapsing at the BI locations, while the other half are collapsing at the upper platen. This continues as the strain increases. By 40% strain, the left-side tubes are collapsing or folding top to BI, however the right-side tubes are collapsing or folding in closer proximity to the BI location. This collapse process is not uniform and so reduced the mean crush stress during the test.

From the stress vs. strain data, the strain dependent crush efficiency was determined. Figure 5.5 shows the crush efficiency as a function of strain for the unplated HC samples (Figure 5.5A) and plated HC samples (Figure 5.5B). The crush efficiency data exhibit a rapid increase as the stress climbs to its peak stress value between 5 and 10% strain, and maximum crush efficiency

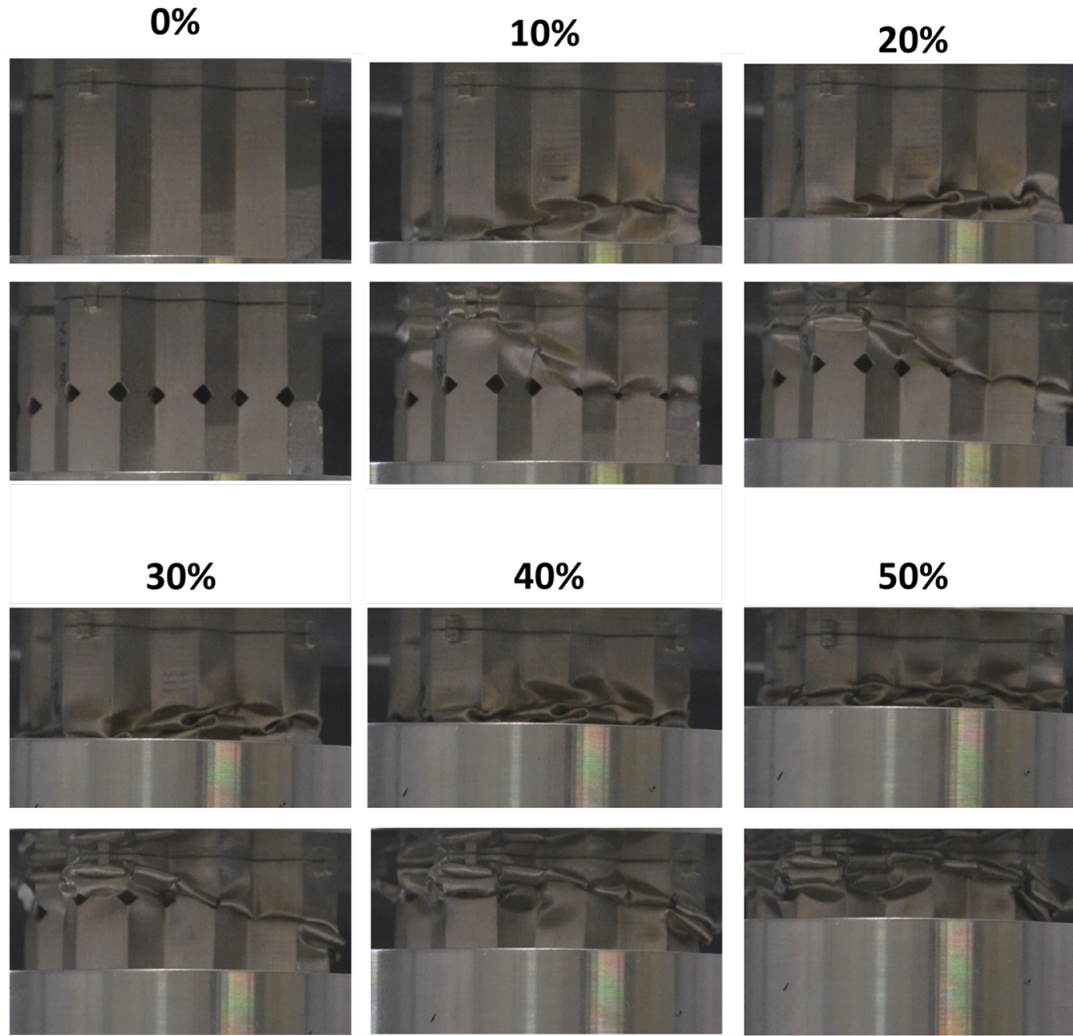
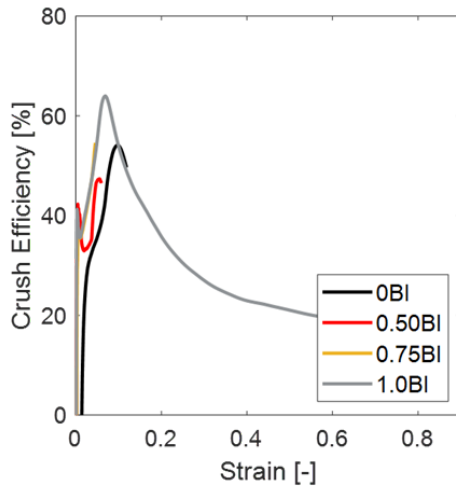


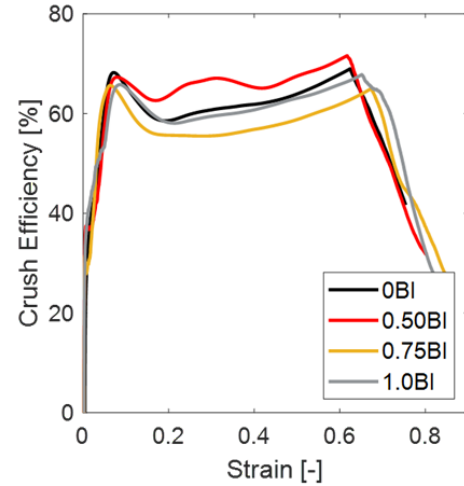
Figure 5.4: Progression of crush as a function of strain: (Top Rows) Plated HC sample without BIs; (Bottom Rows) Plated HC sample with BI at 50% sample height (0.50BI)

is reached. At this point, the crush efficiency decreases until the stress reaches the plateau stress, which is maintained until densification begins. Densification is the strain at which most of the crush deflection has occurred, or when the peak stress is reached for the second time during testing, and above this strain level the crush efficiency will rapidly decay.

Figure ??A, shows the crush efficiency for the unplated HC samples. For the 0BI and 0.50BI samples, the unplated HC samples exhibited primarily brittle failure, and failed at 10% strain and 8% strain, respectively. In contrast, the sample with BIs at the top of the HC was able



(a) Unplated HC samples



(b) Plated HC samples

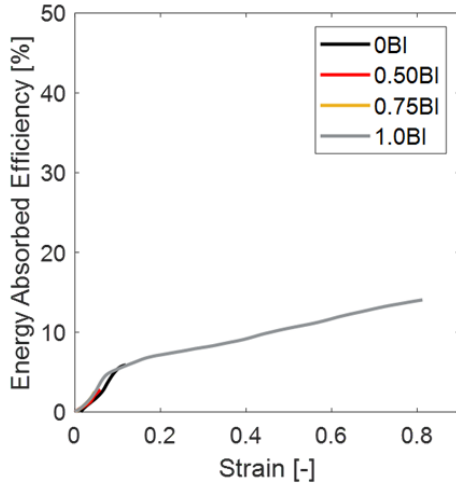
Figure 5.5: Crush efficiency vs. strain for the unplated and plated samples without buckling initiators (0BI), and with BIs at 50, 75, and 100% of the sample height (0.50BI, 0.75BI, and 1.0BI, respectively)

to be crushed to a relatively high strain range, so that the crush efficiency is measurable up to 80% strain. However, because the mean crush stress is very low relative to its peak stress, this results in low crush efficiency.

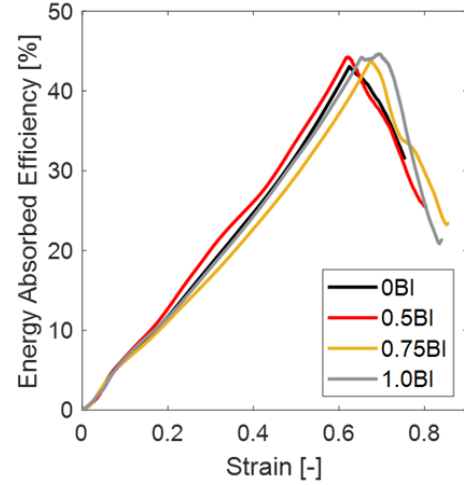
The crush efficiency of the plated HC samples is indicative of energy absorbing materials (Figure 5.6B). The initial increase in stress occurred between 0 and 8% strain. At this point, the stress in all four samples settled down to their respective plateau stresses, as the folding process got underway during crush. Once the peak crush efficiency was achieved, there is a slight decrease in crush efficiency, about 10%, as the samples continued folding, until samples reached their densification strain at nominally 65% strain. Above this strain level, there was a rapid decline in crush efficiency from 65% to 10% over the remaining 20% of measured strain range. Peak values of crush efficiency are listed in Table 5.1 for both unplated and plated samples.

The energy absorbed efficiency assesses how well a material is able to absorb the energy across its full strain range. As previously discussed, the unplated HC samples exhibit a low

strain range of only 10%, with the exception of the 1.0BI sample (Figure 5.6A). None of the unplated HC samples exceeds an energy absorbed efficiency of greater than 15% over its tested strain range. The plated HC samples could be tested to a higher strain level of nominally 80-85% strain, so that more energy can be absorbed by these samples. The densification of these plated HC samples occurred between 65 and 70% strain. The energy absorbed efficiency vs. strain is very similar for all four plated HC sample types (Figure 5.6B). All four samples exhibited a peak energy absorbed efficiency of about 44%. Peak values of energy absorbed efficiency are listed in Table 5.1 for both unplated and plated samples.



(a) Unplated HC samples



(b) Plated HC samples

Figure 5.6: Energy absorbed efficiency vs. strain for the unplated and plated samples without buckling initiators (0BI), and with BIs at 50, 75, and 100% of the sample height (0.50BI, 0.75BI, and 1.0BI, respectively)

5.3.3 Performance Summary

In order to assess which material should be used in a particular crashworthiness application, a number of metrics must be considered because trade-offs exist between the various metrics. Requirements of the specific application will determine the priority of these metrics.

In this study, four metrics were introduced: peak stress, mean crush stress, crush efficiency, and energy absorbed efficiency (Figure 5.7). Here, we examine the trade-offs between these metrics in assessing the energy absorption performance of each HC configuration. Note that these results are also summarized in Table 5.1.

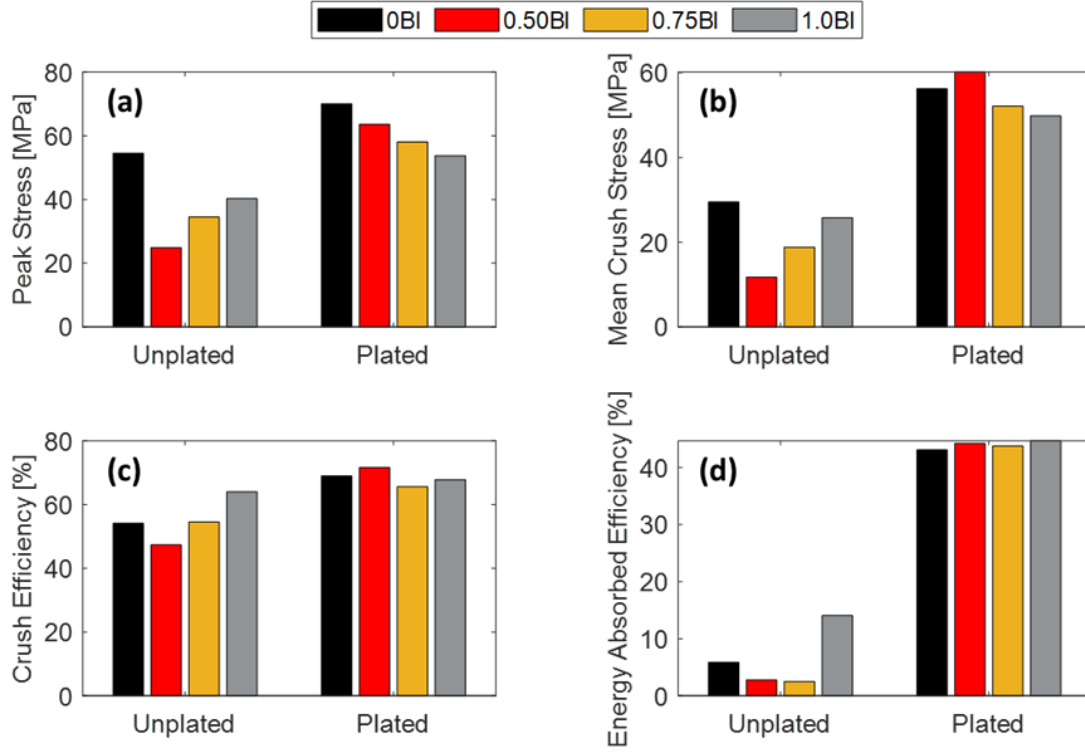


Figure 5.7: The performance metrics computed in this study for the unplated and plated HC samples without BIs (0BI) and with BIs at 50, 75, and 100% of the sample height (0.5BI, 0.75BI and 1.0BI, respectively). Here, peak values of crush efficiency and energy absorbed efficiency are used.

The first metric of interest is the peak stress, σ_{pk} . Unplated HC samples presented a general increase in the peak stress as the BIs moved up the sample from $\sigma_{pk} = 25$ MPa (0.5BI) to $\sigma_{pk} = 40$ MPa (1.0BI), but the samples with BIs had a reduced peak stress compared to the sample without BIs. In contrast, the plated HC samples exhibited a marked decrease in the peak stress as the BIs moved up the sample, from $\sigma_{pk} = 63$ MPa to $\sigma_{pk} = 53$ MPa (Figure 5.7A). In addition, the samples with BIs also had a lower peak stress when compared to the samples without BIs.

The second metric is the mean crush stress. The plated samples exhibit a much greater mean crush stress over a much wider strain range than their unplated counterparts (Figure 5.7B).

The peak crush efficiency of each sample was determined for its own peak stress and the full strain range per the sample. As shown in Figure 5.7C, the plated HC samples exhibited a substantial increase in crush efficiency. The same can be said for the energy absorbed efficiency (Figure 5.7C). Plating the samples increases the energy absorbed efficiency, however, the increase between the unplated and plated HC samples is much more substantial (Figure 5.7D).

Finally, it is important to assess how the addition of metal to the SLA honeycomb structure impacted the energy absorption performance. The specific energy absorption is used to make this assessment. For the unplated samples, the energy absorption was calculated up to the measured strain range until the sample exhibited nearly complete brittle failure. For the plated samples, the energy absorption was calculated up to the strain where the measured stress reached 100 MPa. The plated HC samples had a five-fold increase in specific energy absorption over the unplated samples (Table 5.1).

5.3.4 Comparison of Metrics for Plated Samples

To better visualize these results, a radar plot (Figure 5.8) of the plated samples is provided using the performance metrics as the individual spokes. This plot places the metrics along the exterior of the graph, so that the optimal sample will envelope suboptimal samples. Starting at the topmost spoke, the peak stress, σ_{pk} , is provided ranges from a high value of $\sigma_{pk} = 75$ MPa at the interior to a value of $\sigma_{pk} = 52$ MPa at the exterior, which implies that a lower peak stress is more optimal. Moving clockwise around Figure 5.8, the peak strain dependent crush efficiency,

η_{SD} , is next with efficiency values ranging from $\eta_{SD} = 64\%$ up to 72% being shown. Next, mean crush stress, σ_{mc} , is shown, which ranges from $\sigma_{cm} = 48$ MPa to 62 MPa, implying that a greater mean crush stress is desirable. Next, the peak energy absorbed efficiency, η_{EA} , which ranges from $\eta_{EA} = 43\%$ to 45% . The difference between the peak stress and the mean crush stress, or $\sigma_{pk} - \sigma_{mc}$, is the last spoke: a value of 15 MPa used at the origin of the spoke, and the exterior point has a value of 2 MPa, which implies that a smaller value is optimal.

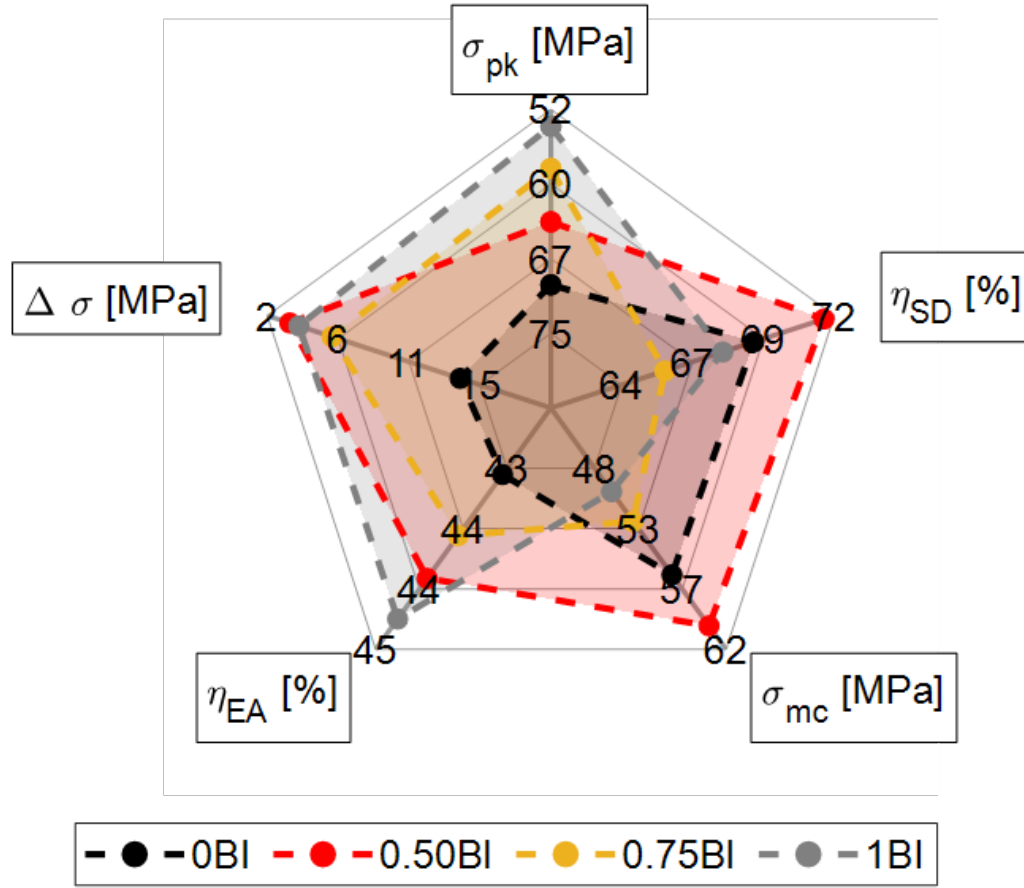


Figure 5.8: Performance metrics for plated samples displayed on a radar plot.

As Figure 5.8 shows, having BIs in the plated HC samples provides better energy absorption characteristics. Here, the 0BI sample is enveloped in all metrics with the exception of the mean crush stress. Mean crush stress only metric where it performs as one of the best two

choices. For the presented metrics, the optimal appears to be the 0.50BI plated HC sample. The only metric where the 0.5BI plated HC samples is lacking is the peak stress, however, the mean crush stress is nearly the same as the peak stress for this sample, so that this sample is the best performing from an energy absorption perspective and using this value system. Because the peak stress is only slightly greater than the mean crush stress, both the energy absorbed efficiency and the crush efficiency are nearly optimal.

5.4 Conclusions

Plastic honeycomb (HC) samples manufactured using SLA both with and without an electroplated coating were tested under quasi-static compression to determine their energy absorption characteristics. These samples also included buckling initiators (BIs) to determine the benefit of BIs in these applications. The following conclusions were found in the course of this study:

1. The unplated plastic HC samples experienced brittle failure under quasi-static compression loading. Unplated plastic HC samples without BIs exhibited brittle failure at low strain levels. However, as BIs were introduced to these plastic HC samples, the BIs created localized stress concentrations, which encouraged folding. The folding allowed for the samples to endure slightly higher strain ranges and thus absorb more energy than the unplated samples without BIs. However, even with the addition of BIs, all unplated samples exhibited brittle failure at low strain levels (nominally less than 20% strain). Therefore, these unplated HC samples are not well suited as an energy absorbing structures due to the low strain range over which stress can be supported.
2. The metal-plastic composite HC samples exhibited a remarkable improvement in energy

absorption behavior. First, the plated HC samples exhibited a linear elastic region followed by a progressive collapse region (in the nominal strain range from 10-60% strain), at which point densification begins. The plated HC samples were able to withstand a significantly wider strain range (about a seven times greater strain range) at higher mean crush stress. Plating the samples results in over a 25% increase in the maximum stress and a 600% increase in compressive strain over which stress could be sustained.

3. The plated HC samples exhibited folding under compression testing, and had stress vs. strain profiles that demonstrated substantially improved energy absorption over the plastic HC samples. BIs were also introduced in order to assess their effectiveness in improving energy absorption and crush efficiency. Performance gains were demonstrated with the introduction of BIs, and it was shown that plated HC samples with BIs at the sample half-height performed best among the plated HC samples when considering peak stress, mean crush stress, the increment between these two stresses, and the crush and energy absorbed efficiency.
4. On average, the plated HC samples exhibited a five-fold increase in specific energy absorption over the unplated HC samples.

Chapter 6: Conclusions

6.1 Conclusions

Honeycomb has been a commercial structure used in energy absorption applications for aerospace and automotive application. Throughout this work, different methods for improving energy absorption of three unique materials have been studied. Each study brings new findings to the scientific community, while finding new significant conclusions. Below, the conclusions from each study, the unique contribution to the scientific community, and the proposed path forward are presented.

Chapter 2 begins with the analysis of ABS honeycomb being compressed in the out of plane orientation using uni-axial quasi-static conditions to quantify the energy absorption properties. 24 unique samples were manufactured using FDM. The first set of samples had an inscribed diameter of 10 mm and buckling initiators located at $1/2$, $3/4$, and $4/4$ of the height of the honeycomb. A control sample was manufactured so that it had no buckling initiators. A similar set of samples were manufactured with an increasing inscribed diameter of 15 and 20 mm. Each type of sample was tested in triplicate so that an average could be found. The experimental results were validated through the use of analytical and computational analysis. The following conclusions can be drawn from this work.

1. The peak stress and mean crush stress will decrease with the increasing inscribed diameter, regardless of the presence of buckling initiators. Similarly, the crush and energy absorbed efficiency will decrease as the inscribed diameter increases. For all metrics, except the peak stress, the presence of buckling initiators will increase the performance compared to their counterparts. As mentioned, the peak stress will decrease with the presence of buckling initiators, which is most beneficial for energy absorption performance.
2. The performance of these samples have been validated through the use of a finite element model in ABAQUS. Similar are apparent: as the inscribed diameter increases, the peak stress, energy absorbed and crush efficiencies will decrease regardless of the presence of buckling initiators.
3. The analytical analysis validated the performance of the samples as well. The re-derived version of Roark's equation allows for the peak stress to be accurately predicted. The peak and mean crush stress decrease with increasing inscribed diameters.

Chapter 3 focused on the effect of buckling initiators on visco-elastic honeycomb samples. A series of samples were manufactured using thermoplastic polyurethane (TPU) in an FDM printer. Here, the inscribed diameter remained constant, while the samples had buckling initiators located halfway up the height or no buckling initiators. The testing conditions were either quasi-static or a constant velocity of 0.25 or 0.50 m/s. Each sample was tested at the assigned velocity and then allowed to rest for 24 hours. After that point, they were compressed a second time before resting and testing a third time. From these results, the average of the samples could be determined to 1) identify the effects of buckling initiators; 2) quantify the effects of cross

head velocity; and 3) determine the effects of repeated impacts. The metrics were verified by implementing a numerical analysis. From this work, the following conclusions were made:

1. Visco-elastic honeycomb with buckling initiators experiences axisymmetric failure as opposed to their counterparts that are without buckling initiators. Folding initiates at the buckling initiator and continues until the sample has been folded in a controlled manner. The samples without buckling initiators experience shear buckling, which results in non-axisymmetric folding patterns.
2. Visco-elastic honeycomb is able to rebound to over 95% of its initial height after testing three different periods. The honeycomb experiences some permanent deformation, but following 24 h, it is able to be reused.
3. Visco-elastic honeycomb with buckling initiators that are located midway up the sample are more crashworthy in quasi-static applications. The buckling initiators assist in lowering the peak stress, thus increasing the strain-dependent crush efficiency. Similarly, the energy-absorbed efficiency is shown to increase with the presence of buckling initiators.
4. Visco-elastic honeycomb with buckling initiators increases the energy-absorbed efficiency and decreases the peak stress when implemented in low-strain rate settings. The crush efficiency is preserved as the strain increases when buckling initiators are implemented.
5. After repeated testing at low-strain rates, the visco-elastic honeycomb with buckling initiators experiences less degradation in its crush performance. Thus, these visco-elastic honeycomb structures were observed to provide deformation recovery when using this type of buckling initiator. Protection against multiple impacts can be provided, albeit with reduced

effectiveness.

6. Numerical analysis validated the experimental results for samples with and without buckling initiators in quasi-static conditions.

Chapter 4 continued to focus on visco-elastic honeycomb using a free fall guided impact on a monorail impact machine. Here though, the samples had buckling initiators located at the midpoint of the sample or the top of the sample and compared the results to those samples without buckling initiators. In these tests, the samples were tested using an initial velocity of 1- 4 m/s in 0.5 m/s intervals. The samples were tested in triplicate to quantify the energy absorption properties. These results were compared to the results for the quasi-static and constant velocity tests discussed in Chapter 3. The key findings are as follows:

1. Thermoplastic polyurethane (TPU) honeycomb see an increase in the energy absorbed efficiency when buckling initiators are present in constant velocity tests.
2. Dynamic impact tests with the buckling initiators located midway up the height of the sample result in the crush efficiency with the least variance across the stroke. Similarly, this sample experiences a near linear energy absorbed efficiency behavior as well.
3. The energy absorbed efficiency curves can be calculated for a dynamic impact test where crush is measured just below the onset of densification.
4. Dynamic impact tests report lower energy absorbed efficiency values than the constant velocity tests because the impactor decelerates. As this is happening, the velocity is also decreasing, thus less kinetic energy is available for transfer.

5. Quasi-static testing is a reasonable upper bound measure of dynamic energy absorption for these TPU honeycomb regardless of the presence of buckling initiators.

In Chapter 5, a series of brittle resin honeycomb samples were manufactured using stereolithography. These samples had either no buckling initiators or buckling initiators located at the midpoint of the sample. Half of the samples were coated using an electroplated process to deposit a 150 μm layer of metal composed of nickel and copper. All samples were tested in triplicate using uni-axial quasi-static compression in the out of plane orientation. The following conclusions were found in the course of this study:

1. The unplated plastic HC samples experienced brittle failure under quasi-static compression loading. Unplated plastic HC samples without BIs exhibited brittle failure at low strain levels. However, as BIs were introduced to these plastic HC samples, the BIs created localized stress concentrations, which encouraged folding. The folding allowed for the samples to endure slightly higher strain ranges and thus absorb more energy than the unplated samples without BIs. However, even with the addition of BIs, all unplated samples exhibited brittle failure at low strain levels (nominally less than 20% strain). Therefore, these unplated HC samples are not well suited as an energy absorbing structures due to the low strain range over which stress can be supported.
2. The metal-plastic composite HC samples exhibited a remarkable improvement in energy absorption behavior. First, the plated HC samples exhibited a linear elastic region followed by a progressive collapse region (in the nominal strain range from 10-60% strain), at which point densification begins. The plated HC samples were able to withstand a significantly wider strain range (about a seven times greater strain range) at higher mean crush stress.

Plating the samples results in over a 25% increase in the maximum stress and a 600% increase in compressive strain over which stress could be sustained.

3. The plated HC samples exhibited folding under compression testing, and had stress vs. strain profiles that demonstrated substantially improved energy absorption over the plastic HC samples. BIs were also introduced in order to assess their effectiveness in improving energy absorption and crush efficiency. Performance gains were demonstrated with the introduction of BIs, and it was shown that plated HC samples with BIs at the sample half-height performed best among the plated HC samples when considering peak stress, mean crush stress, the increment between these two stresses, and the crush and energy absorbed efficiency.
4. On average, the plated HC samples exhibited a five-fold increase in specific energy absorption over the unplated HC samples.

6.2 Original Contributions

Prior to this work, literature had shown how the energy absorption is effected when an ABS honeycomb is subjected to out of plane compression as the inscribed diameter is varied. Other studies also quantified the effects of buckling initiators on the energy absorption of ABS honeycomb, however these two factors have not been done concurrently. This study advanced the state of the art by quantifying how the energy absorption is effected by the buckling initiator location and inscribed diameter. Buckling initiators located at the top of the sample help stabilize the stress- strain curve so that $\Delta\sigma (\sigma_{pk} - \sigma_{mc})$ is the smallest. This is constant regardless of the inscribed diameter, resulting in a near constant crush efficiency across the strain range. Prior to

this, the energy absorbed was assumed to be a function of the inscribed diameter.

In a similar manner, the energy absorption of visco-elastic honeycomb was quantified as a function of cellular geometry (inscribed diameter, wall thickness, etc). In a similar manner, the energy absorption performance of metallic honeycomb and tubular structures have been quantified. The deeper understanding of the folding mechanisms within 0.0 and 0.5 BI visco-elastic honeycomb samples under 3E-5, 0.25, and 0.50 m/s out of plane compression was able to advance the state of the art. This study quantified the energy absorption abilities of multiple impacts to the sample, by impacting each three times, with 24 hours rest for each speed and buckling initiator location. The long-term effects of these visco-elastic honeycombs with buckling initiators were not previously quantified

Electroplating is a manufacturing process that has been studied extensively in literature, however it has not been implemented in an energy absorption structure. In this work, electroplating is used to improve the energy absorption performance of a brittle plastic resin, such that it exhibits properties similar to those of metals. This novel manufacturing process has shown success as a lightweight and crashworthy option for honeycomb samples.

6.3 Future Work

Although this work has contributed to expanding the current state of knowledge within cellular materials for energy absorption, there is still substantial work to be done. As literature has shown, quasi-static conditions for both metallic and polymeric honeycombs are well understood. On the other hand, substantial work needs to continue with dynamic impact testing.

Dynamic impact testing has not been studied in depth for a large class of materials. To

the author's knowledge, Chapter 4 is the first documentation of visco-elastic honeycomb studied in dynamic impact testing. Furthermore, this section also described the behavior of the energy absorption as a function of the strain.

The energy absorption and crush efficiencies should be determined for the electroplated honeycomb during dynamic impact testing. With the impact testing, there is the potential the quasi-static tests are representative of the dynamic tests. It will be vital to test the samples with buckling initiators in all four potential locations, 0BI, 0.5BI, 0.75BI, and 1.0BI. These samples should experience folding, similar to what was seen in the quasi-static testing.

In a parallel vein, the metrics are applicable to all cellular structures. There are two other types of cellular structures that were initiated: foams and lattices. Closed cell foams are another option for an energy absorber that can be tailored to the desired load profile. Similarly, lattices have a high strength to weight ratio, making them an appealing option for energy absorption. Testing an electroplated lattice during a dynamic impact test will quantify the overall performance of these materials.

One concern with using the electroplated samples is that the external faces receive a thicker coating than the internal surfaces. Considering an extruded hexagon, the external six faces receive a thicker coating than the internal faces due to the placement of the electrodes. To fully understand the dynamics of the electroplating process, it is important to quantify the thickness of the plating on the samples. The plating directly effects the strength, so it is crucial to ensure a consistent plating thickness.

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