Beam Deletion in Square Honeycombs for Improved Energy Absorption Under Quasi-Static In-Plane Compression

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Abstract

When selecting cellular materials for energy absorption applications, there have traditionally been two choices: a periodic structure such as a honeycomb, or a stochastic one, as seen in foams. Both choices involve a global definition governing the allocation of the members of the structure, be they beams or surfaces. With Additive Manufacturing, the exploration of more complex structures enables the creation of aperiodicity through the local modification of periodic structures. This paper explores one application of this approach by deleting beams in square honeycombs, with the aim of avoiding localization of failure that generates significant undulations in the stress plateau under in-plane quasi-static compression. These perturbed structures show improved energy absorption behavior by generating higher Specific Energy Absorption for a given transmitted stress and relative density than their periodic counterparts. This work thus argues for further exploration of localized aperiodicity as an approach to finely tune energy absorption performance.

Keywords: Additive Manufacturing, beam deletion, cellular materials, densification strain, maximum transmitted stress, perturbation, energy absorption.

Introduction

Nature has an intriguing way of leveraging cellular materials in its many forms, many of which have served as inspiration for engineering design [1]. Structures like bone and insect nests integrate a solid and an empty phase to generate multifunctionality, which have been explored in different fields. One such field is art, in which notions of symmetry, negative space, and periodicity have been studied in the context of form and design [2]. In this field, not only is the distribution of the solid area emphasized, but also how it blends and interacts with the empty region, also known as negative space. In engineering, this interaction of solid and negative phases has a myriad of applications, one of which is energy absorption. Some examples in nature where negative space is optimized is in the peel of the pummelo. Pummelo is a fruit that can grow on trees at a height of 25 feet above ground [3]. When the fruit has ripened, it falls but is not damaged by the impact. A closer examination of the peel of this fruit shows a graded and stochastic cellular pattern, which has been related to its impact damping properties [4]. This phenomenon can be observed in animal organs as well, such as in a Toucan beak or a Woodpecker skull [5], [6]. Both structures have an aperiodic open-cell structure similar to that seen in spongy bone [7]. All of these structures have been associated with enhanced energy absorption.

Historically, honeycombs and foams have been the primary cellular materials that have found use in energy absorption applications [8]. With the advent of Additive Manufacturing (AM) technologies, research into energy-absorbing cellular materials is exploring different design concepts to enhance their properties. There are several different metrics that characterize an energy-absorbing cellular material [9][10]. From a designer's perspective, an energy absorber is a material that should be able to stay beneath a particular stress threshold and maintain it until material densification, while maximizing the energy absorbed in the process [11]. An ideal energy absorber should thus satisfy three main characteristics:

1. Constant crushing stress
2. High densification strain
3. High Specific Energy Absorption (SEA) per unit mass for a given Maximum Transmitted Stress (MTS)

Different cellular design strategies have been explored to approach ideal behavior. For example, the use of a pre-crushed Aluminum honeycomb can substantially decrease the MTS while maximizing SEA due to a more stable plateau stress [12]. The use of metallic and polymer foams has also been explored since stochastic materials are associated with good energy absorption properties in the context of uncertainty in loading direction, similar to spongy bone found in nature. Other examples of design innovation for energy absorption can be found in studies with hollow twin hemispheres [13], which allowed for higher densification strains with low compression modulus. Other designs include the use of lattices that can spread impact loading over time and reduce the first maximum stress [14], and micro-lattices that enable tunability with high energy absorption and longer densification with a tradeoff of poor constant crushing behavior [15], [16].

This study builds on prior work [17] where the idea of breaking symmetry was explored in square grid honeycombs. Symmetry has been explored in the field of mathematics, nature, and art, and is described by mathematicians to be a measure of "invariance to any of various transformations such as rotation, reflection or scaling" [18], [19]. In the prior study, aperiodic honeycombs were designed arbitrarily, as shown in Figure 1, to study what effect they have on large deformation behavior under in-plane compression. For the purpose of the current study the main idea was to design aperiodicity in a more deterministic manner by deleting beams in a 2D square grid honeycomb following a triangular waveform approach and examine how it can influence the mechanical properties. The following sections discuss the approach, the results and conclusions associated with the current study, while also drawing comparisons to prior work.

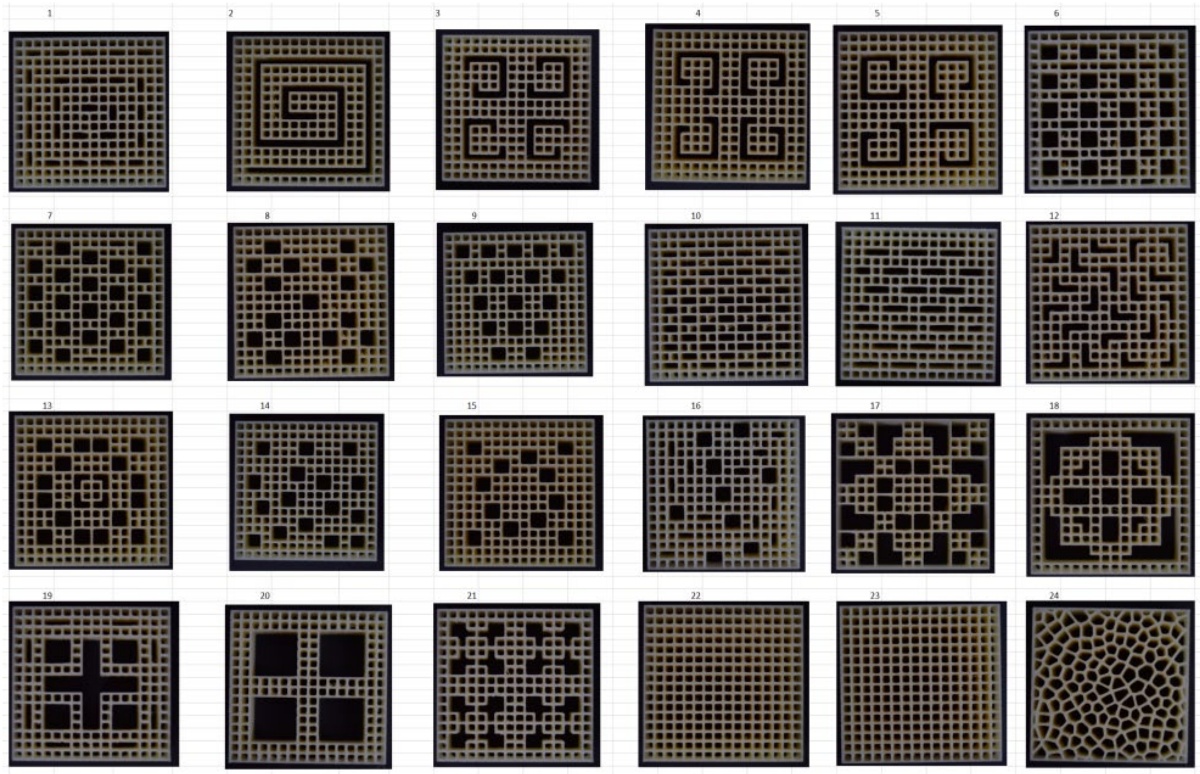


Figure 1. Design strategies using beam deletion, reproduced from prior work [17]

Design Approach

I. Beam Deletion Approach

A classification of aperiodic architected cellular materials was previously proposed, wherein three main types of aperiodicity were identified: gradation, perturbation, and hybridization [20]. Hybridization was shown to have two main characteristics: a feature and a method. For this study, the beam member was selected as the feature and the method used to achieve hybridization was deletion. By following this approach, a square honeycomb's appearance would start to change and generate a hybrid cellular structure, an example of which is shown in Figure 2.

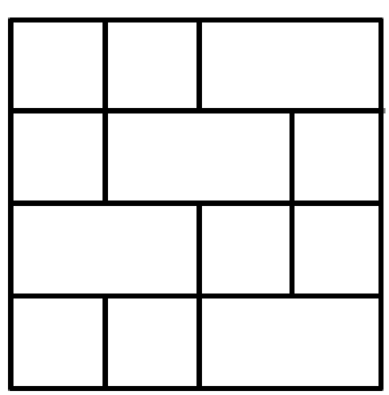


Figure 2. Beam deletion technique for generating aperiodicity, reproduced from [20]

Prior work developed two key insights. The first of these emerged after comparing the compression stress-strain response of baseline regular square honeycomb against a form with an embedded spiral with 73 deleted beams, as shown in Figure 3. Beam deletion has the effect of reducing relative density, which tends to be associated with higher densification strain. However, the connected spiral nature of the structure also resulted in lower First Peak Stress (FPS) and a lower MTS, with a reduced undulation in the plateau region. These are all promising directions towards an ideal energy absorber.

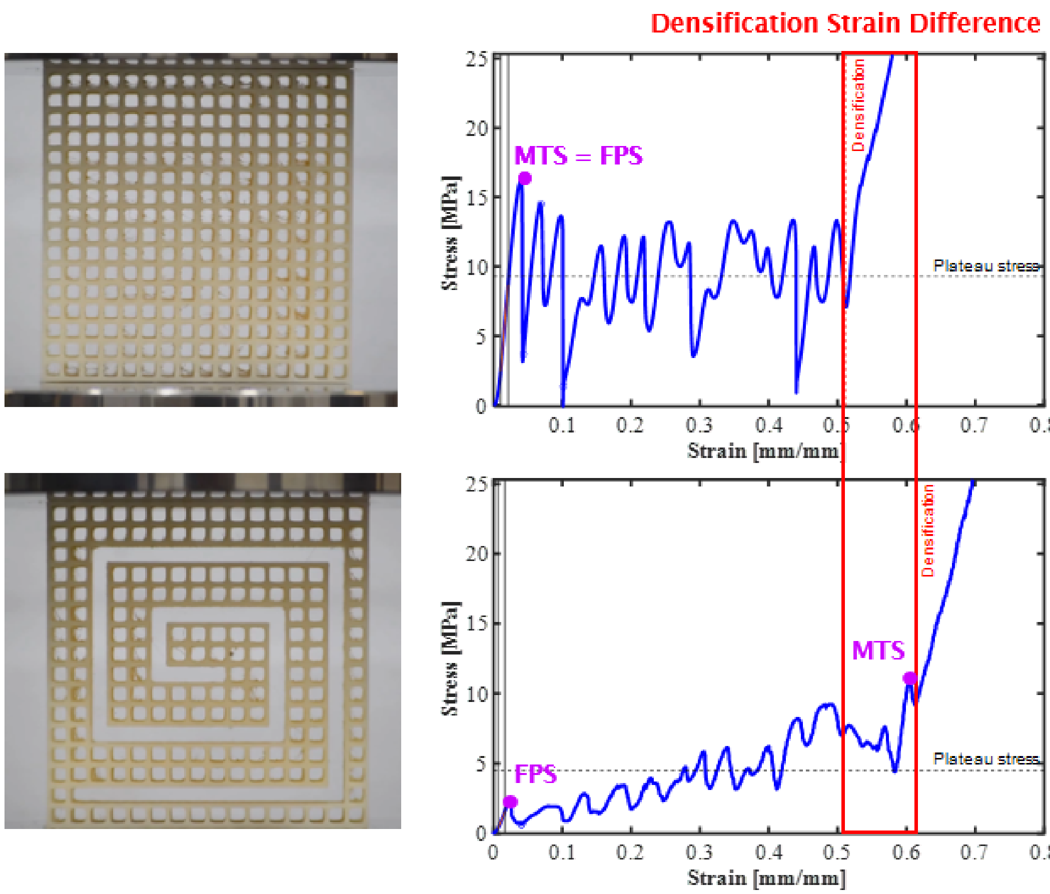
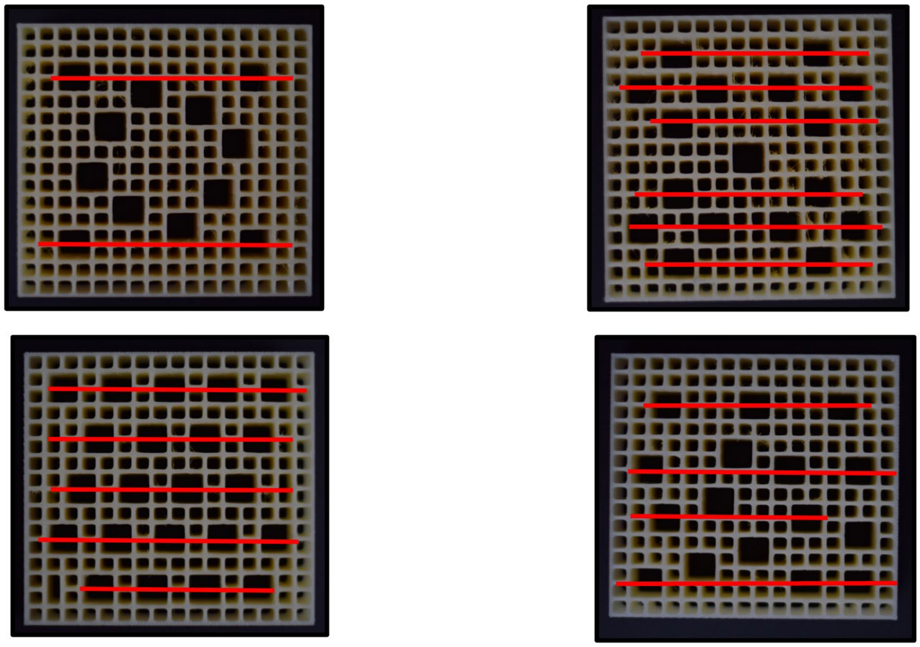


Figure 3. Spiral channel dropping peak stress and prolonging densification, adapted from [17]

The second important insight and one that inspired the current work, is demonstrated in Figure 4. The red lines connect centers of cells with deleted beams. The deletion of beams in a particular row was found to initiate early failure and therefore a lower FPS, but having too many empty cells in a row resulted in lower energy absorption because the stress levels remained low. The structure with the highest SEA at the lowest MTS was found to be the one in the top left corner of Figure 4, with only two rows connecting empty cells. The best performing structure with regard to maximizing SEA for a given MTS, is reproduced in Figure 5, in comparison to the baseline. Failure bands were observed in both specimens, but the second specimen with staggered empty cells, had bands that formed at an angle instead of the horizontal row by row collapse of the baseline square grid, with each collapse corresponding to a load drop. Thus, a hypothesis was formulated that staggering beam deletion, in such a manner as to avoid collinear empty cells, is likely to improve energy absorption. This is the hypothesis that the current work examines.



Casanova et al. (2018)

Figure 4. The hypothesis of the load transfer mechanism, reproduced from [17]

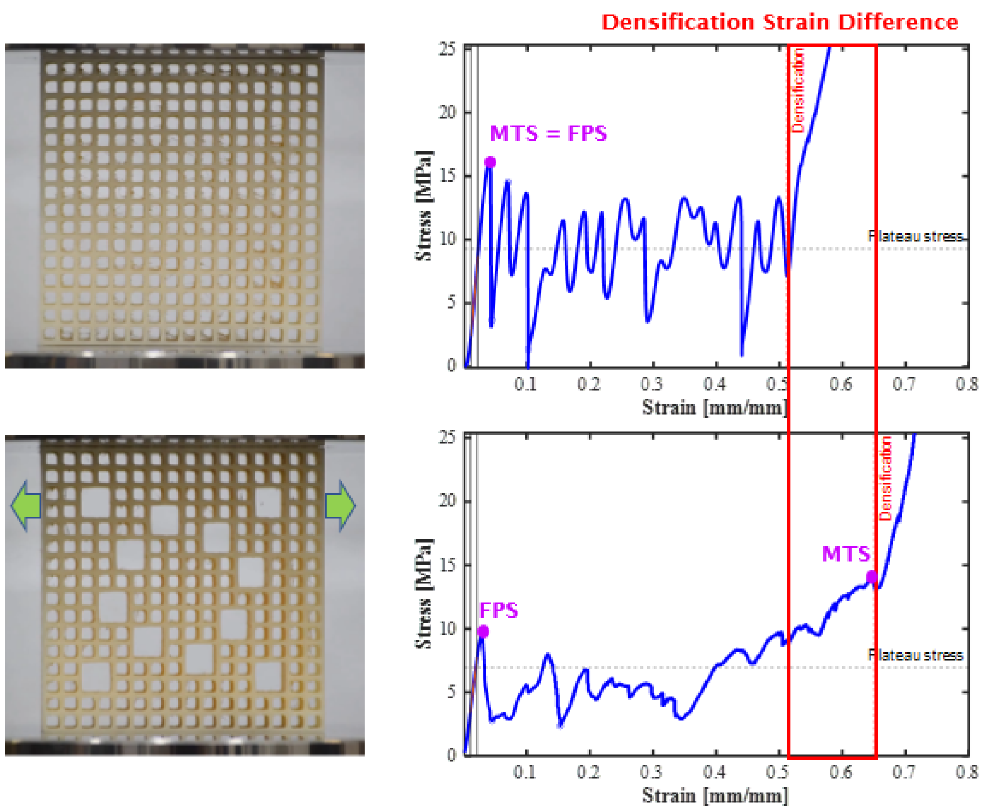


Figure 5. Asymmetric member deletion suggests promising behavior, reproduced from [17]

II. Triangular Wave Rationale

Following the observations made from the previous study, a design strategy was developed to enhance the energy absorption properties of the square honeycomb by exploiting the observation of staggered negative space and avoiding collinear deletion of beams. To minimize edge effects, two columns of square cells were not modified in any specimen on either side of the specimen, as shown in Figure 6. Since prior results showed deleting four beams at a time showed promising results, this was the strategy employed here as well. Finally, vertical (V) and horizontal (U) spacing between the centers of empty cells was defined as shown in Figure 6, for the purpose of placing the negative spaces in a systematic way. U and V thus enable the formation of triangular wave-like pattern, which it was hypothesized would guide the failure band formation without having large reductions in stress during the compression event, and a more stable plateau.

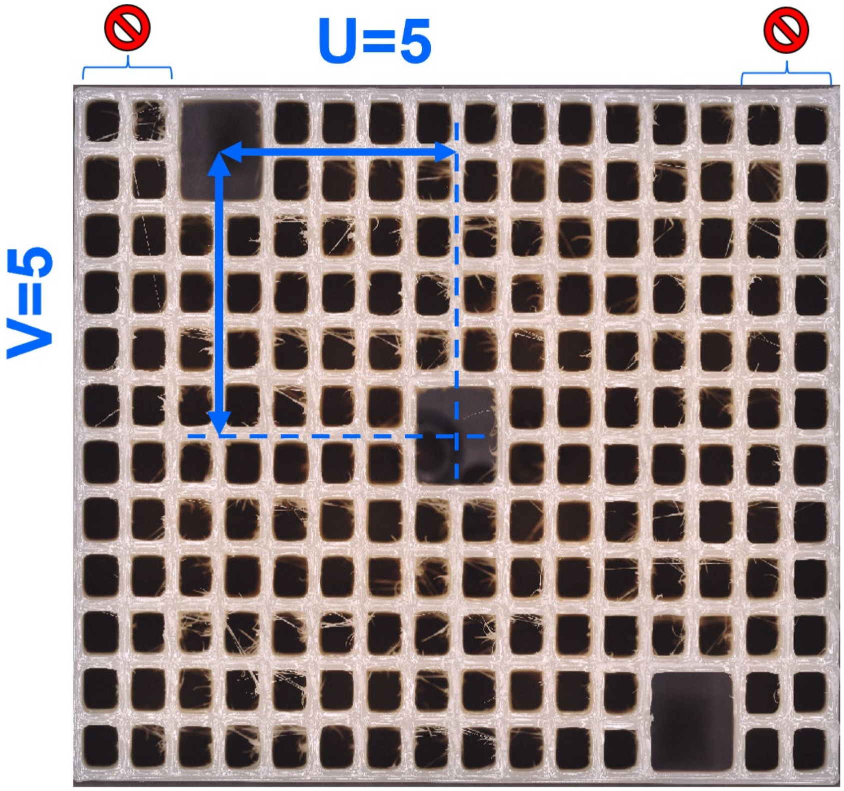


Figure 6. Triangular wave beam deletion design

Figure 7 shows all the triangular wave designs developed for this study, with their respective U and V values. A total of 16 triangular wave designs and 2 baselines were designed. It can be observed that the triangular wave is more apparent in some specimens than others because of the spacing values and bounding box size. The bounding box sizes are different in some cases which was done to ensure completeness of the design and avoid empty cells of varying sizes. This discrepancy was addressed in the data analysis, by the use of stress and strain normalization based on the specimen width and depth (to compute area for stress calculation) and specimen height (for strain). In all cases, at least 12 cells were defined in all directions, to minimize size effects, per ISO 13314.

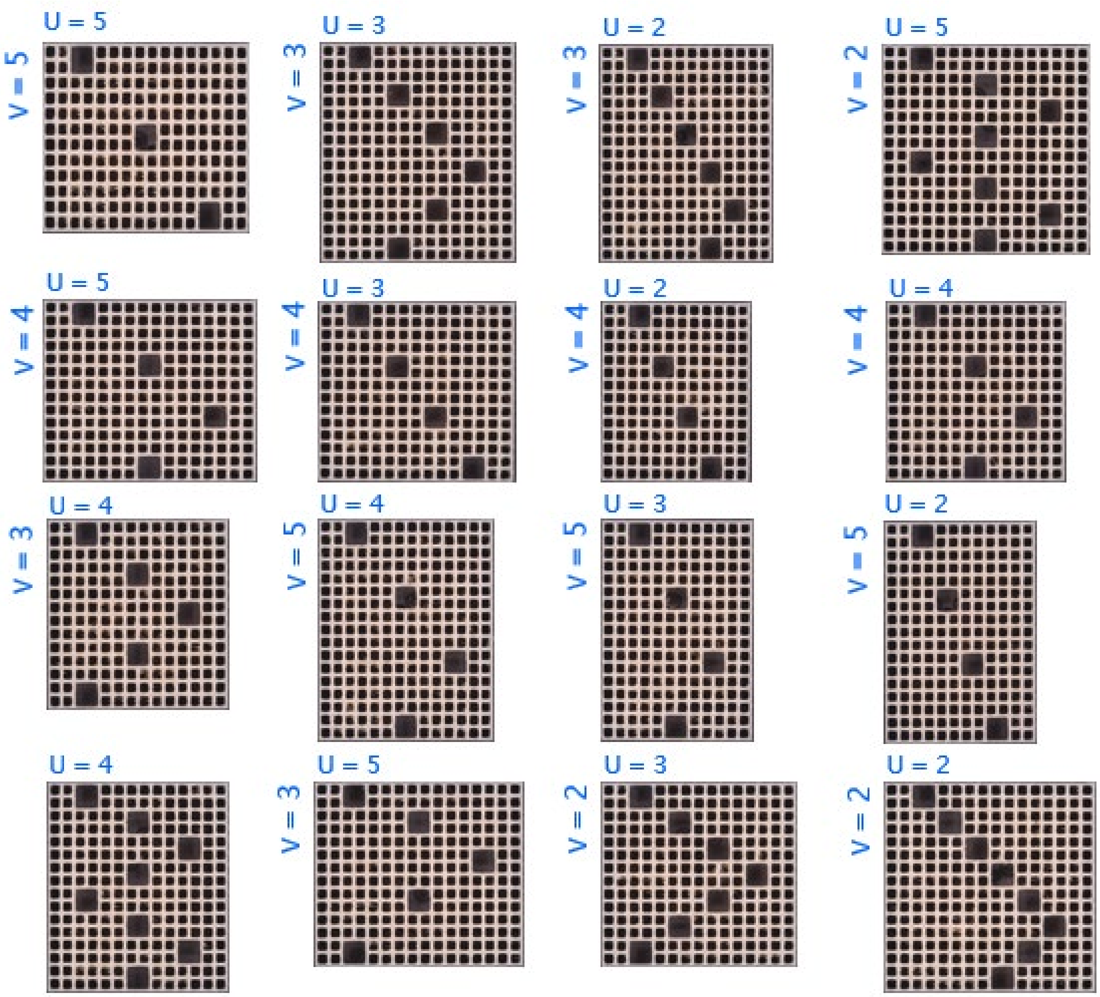


Figure 7. Triangular wave designs used in this work, with different U and V spacing

Methods

The methodology followed in this study is summarized in Figure 8 and involved the following steps: (i) CAD designs were created with deleted beams and exported to a Stratasys Fortus^{TM} 450mc printer which manufactured the specimens using fused deposition modeling (FDM) process with ABS (Acrylonitrile Butadiene Styrene); (ii) This was followed by mechanical testing on an Instron 8801 using a compression setup and an effective strain rate of 10^{-3} s^{-1}; and (iii) analysis of the data was then performed to extract metrics of interest. The following sections detail these steps.

I. Design & Manufacturing

A total of 16 designs and 2 baselines were designed as shown in Figure 7 using the aforementioned triangular wave design approach. CAD designs were generated using SolidWorks^{TM} software and then imported to a Stratasys Fortus^{TM} 450mc 3D printer. ABS was the selected material, and the single contour printing parameters were used. The specimens were designed with a constant 1-inch thickness so as to have enough stability against buckling during in-plane compression.

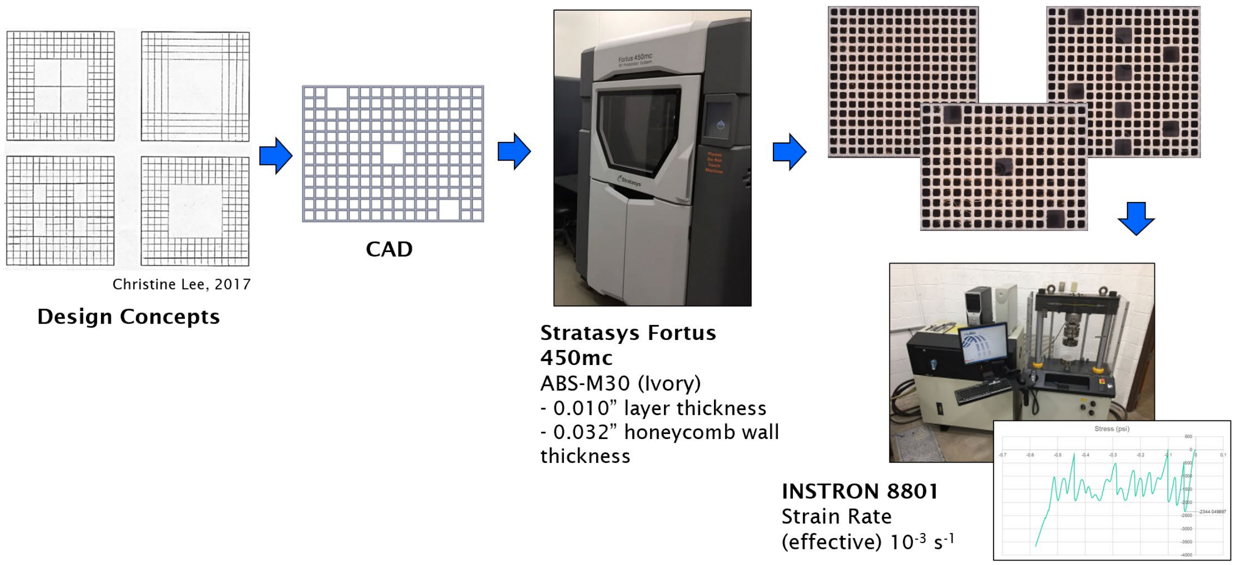


Figure 8. Three main steps used in the study: design and manufacturing, mechanical testing, and computation of energy absorption metrics.

II. Mechanical Testing

The honeycombs were tested under quasistatic compression with an effective strain rate of $10^{-3}s^{-1}$ on an Instron 8801 machine with a 50kN load cell, following ISO 13314. Tests were conducted till densification with a load-based test stop criteria. This test results in force/displacement data that can be used to compute energy absorption metrics for analysis. Since the specimens had slightly different sizes, this force/displacement data was converted to stress/strain, in order to, be able to normalize and compare properties among them.

III. Computation of Energy Absorption Metrics

Once the stress/strain data is obtained, it was plotted to obtain graphs similar to that shown in Figure 9. MATLAB was then used to obtain the following two metrics:

a) First Peak Stress and Maximum Transmitted Stress

The Maximum Transmitted Stress (MTS) is the highest stress reached prior to densification, indicated in Figure 9 with the green marker, and is typically normalized by the material yield stress. MTS may or may not be the first peak (FPS), indicated with the red marker, and is of greater interest from a designer’s perspective.

b) Specific Energy Absorption (SEA)

This is defined as the area under the curve from the origin to strain densification (ε_D) and then normalized by the specimen density (ρ). It is shown as the shaded blue region in Figure 9 and estimated as:

$$SEA = \frac{\int_0^{\varepsilon_D} \sigma d\varepsilon}{\rho} \tag{1}$$

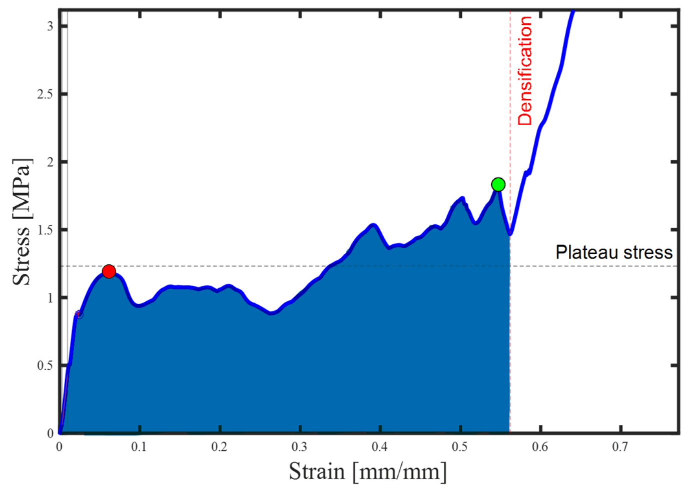


Figure 9. Mechanical properties of interest for energy absorption

Results

I. Comparisons between prior and current work

A commonly used approach to identify promising cellular material candidates for energy absorption is to plot SEA vs FPS, with the preferred options having high SEA at low FPS values. The data from the prior study from 2018 [17] was combined with the results from this study and are shown together in Figure 10. Baseline square and spiral specimens were tested in the current study to ensure no significant deviation in print quality or testing conditions and are shown encircled at the extremes of the data collected. The majority of the results, including all results from the prior study, fell on a line connecting these extremes, but crucially from this study, it was found that most of the triangular wave designs were remarkably clustered together at a higher level of SEA relative to expectation for the FPS associated with them. This suggests that the triangular wave design approach is a favorable allocation of negative space for improving energy absorber design.

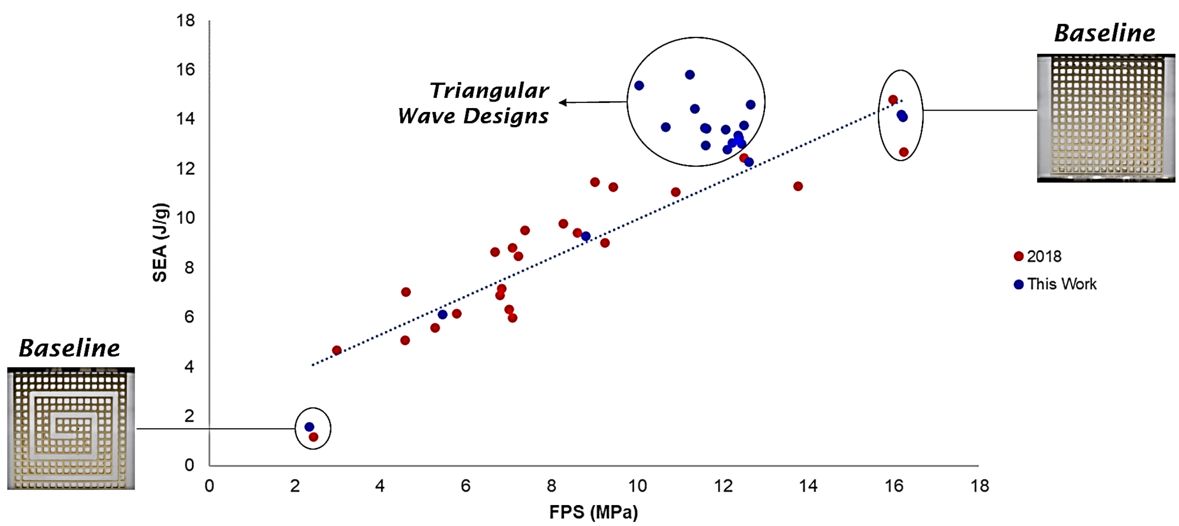
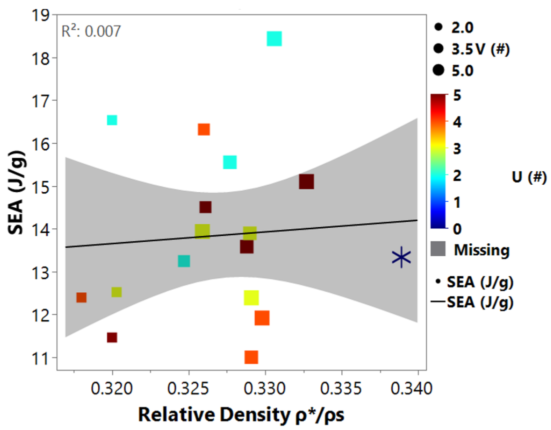


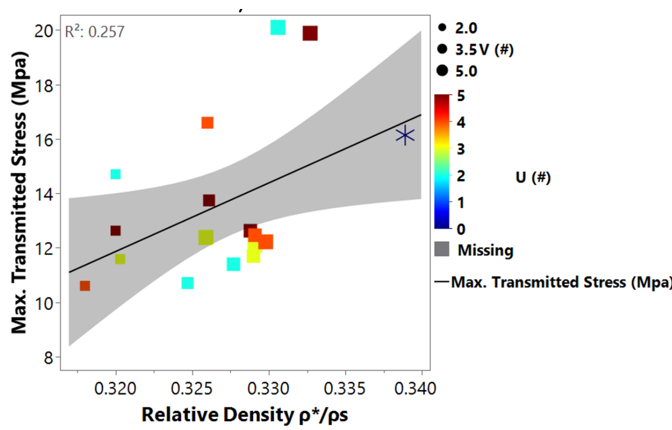
Figure 10. SEA vs FPS comparison between this work and prior [17]

II. SEA and MTS

An examination of the SEA and MTS values for the specimens in the current work, relative to their U and V values is shown in Figures 11a and 11b, respectively. The asterisk marker represents the baseline periodic square grid honeycomb. Several designs have higher SEA and lower MTS than the baseline, but in particular, a few points have higher SEA than the trend, and are worthy of further examination.



(a)



(b)

Figure 11. a) SEA vs relative density, and (b) MTS vs relative density for the triangular wave designs studied in this work, the asterisk (*) represents the periodic square baseline

In Figure 12, a more meaningful, designer's plot which shows SEA vs MTS, allows the identification of high performing structures with high SEA for a given MTS (top left corner). When observing Figures 11 and 12 together, it is remarkable how values of horizontal spacing U=2 (represented by the light blue markers), tends to have the best performance across different V values.

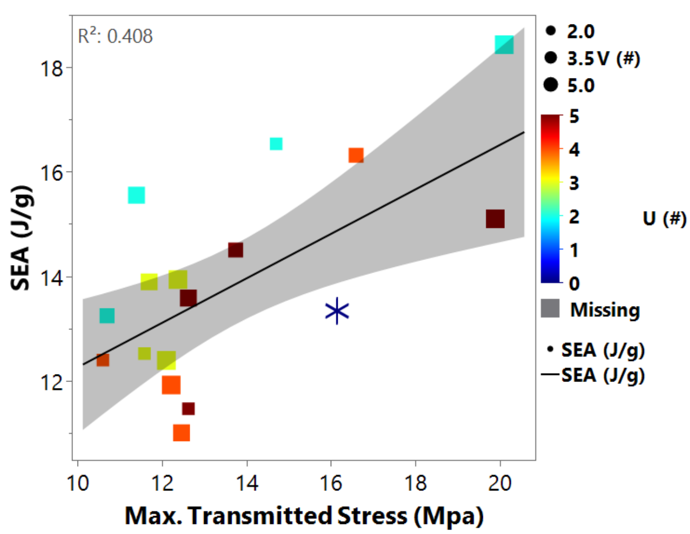


Figure 12. SEA vs MTS for the triangular wave designs studied in this work, the asterisk (*) represents the periodic square baseline

To try and understand why the U=2 specimens had higher SEA values, it is useful to study the nature of their compression response relative to the baseline, as shown in Figure 13. From the stress/strain plots it can be seen how undulation is reduced and densification strain is extended, while conserving a lower FPS and MTS, with the net effect of improved SEA.

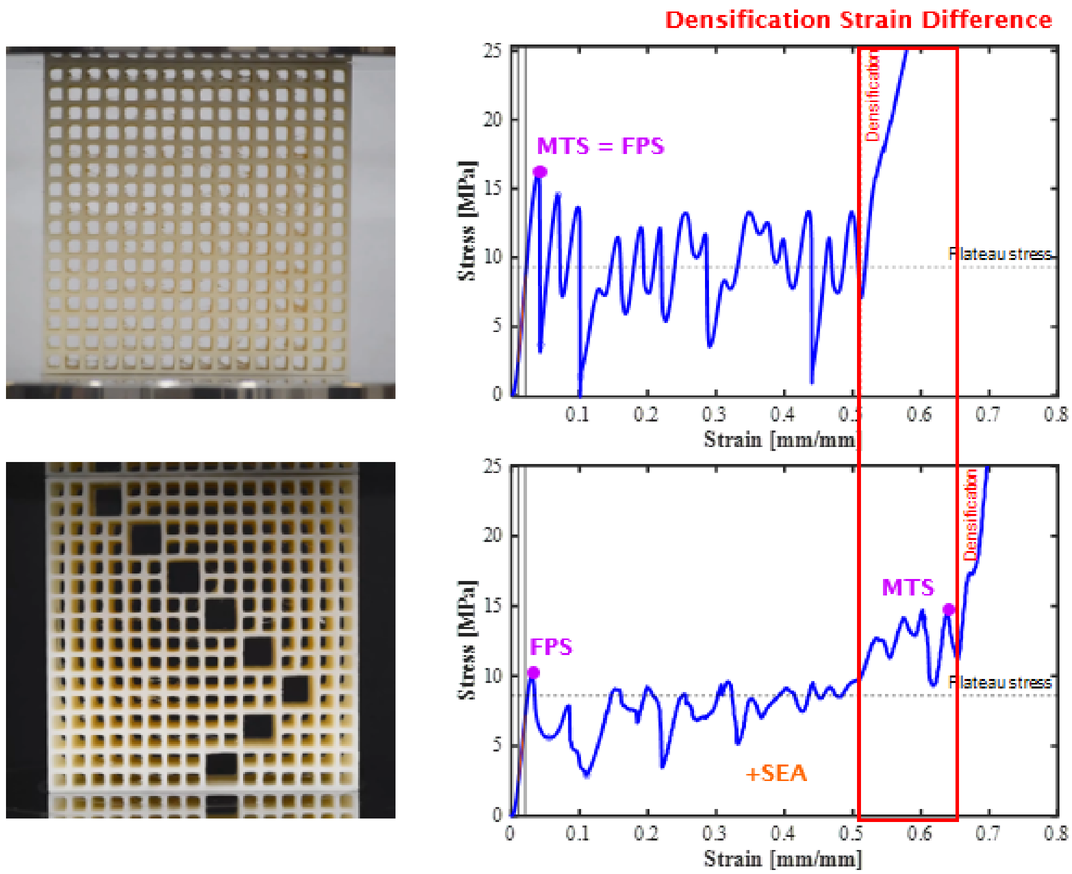


Figure 13. U2V2 specimen compression response compared to the periodic square baseline

III. Significance of Statistical Correlations

The prior discussion demonstrated that the introduction of triangular wave approach to negative space improves SEA by greatly reducing the FPS and MTS, pushing out densification strain, and reducing undulations. To assess whether the U and V factors do indeed correlate to observations, a bivariate fit was done and p-value assessed for the significance of the fit, for SEA and SEA/MTS in Figures 14 and 15, respectively. The latter ratio was chosen to condense the designer's perspective into a single metric, where higher values of SEA/MTS are desirable. A caveat with this analysis is that it is conducted with one variable (U or V) at a time only. Given this limitation, any significance is particularly remarkable – and it was found to be significant (p-value less than 0.05 in only one instance, viz. for SEA/MTS versus U, in Figure 15. This adds more weight to the prior observation that the horizontal spacing between empty cells is a more important variable than the vertical spacing, in improving energy absorber performance, for the triangular wave design approach proposed here.

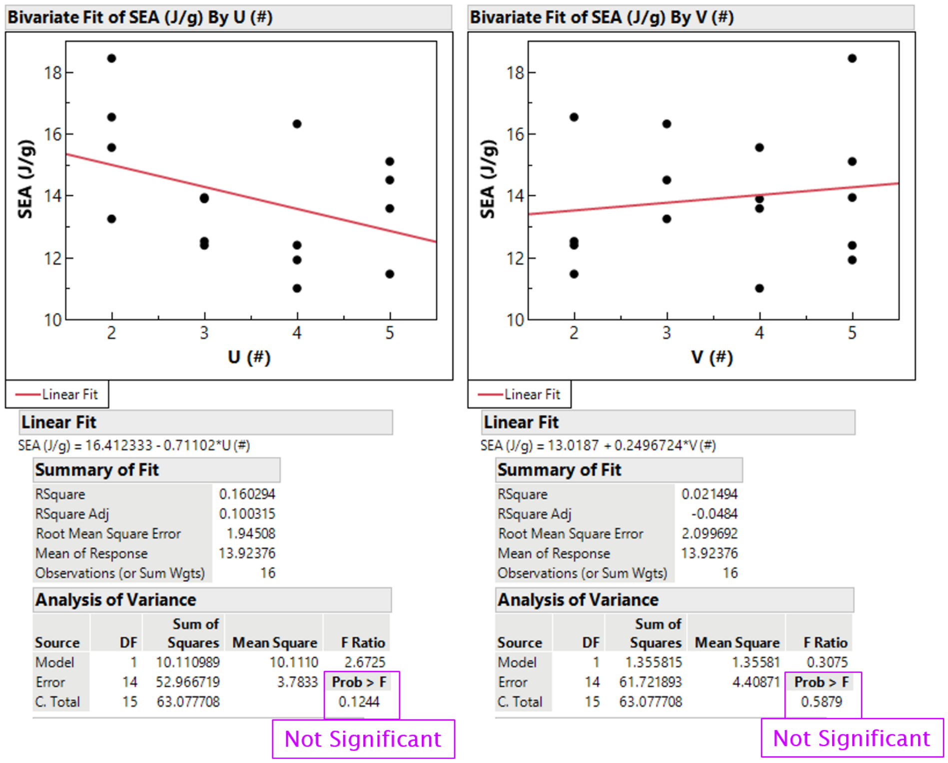


Figure 14. Bivariate analysis for SEA as a function of U and V separately

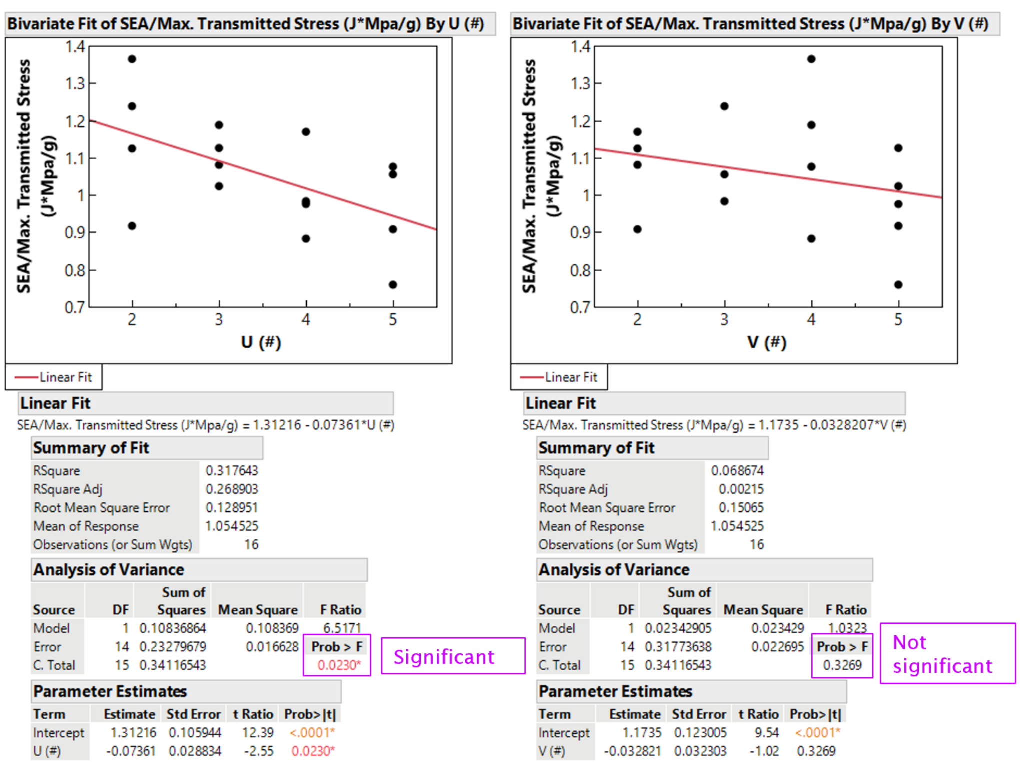


Figure 15. Bivariate analysis for SEA/MTS as a function of U and V separately

Conclusions

The current work proposed a new triangular wave design derived from beam deletion to create negative space that resulted in a cluster of designs in which the majority showed improved energy absorption performance more than baseline regular square honeycombs, and prior work with arbitrarily distributed negative space. This was determined by a study of the effect of these beam deletion designs on Specific Energy Absorption, stresses (MTS and FPS) and densification strain. The triangular wave approach of beam deletion influences the failure band trajectory which directly impacts the overall plateau stress undulation, densification, and in some cases, reduces the MTS, and FPS, and increases the SEA/MTS. With regards to the latter parameter, statistical analysis suggests the key design parameter that influences SEA/MTS is the horizontal spacing between beam deleted empty cells. More work is needed to further explore the role of deleting cellular members in influencing mechanical behavior, as one of many strategies to explore aperiodicity in these fascinating materials.

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