



Doğadan İlhamlı Bal Peteği Tasarımlarının Sıkıştırma Davranışının Sayısal Olarak İncelenmesi

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Öz

Bu çalışma, doğadan ilham alınmış bal peteği yapıların sıkıştırma davranışını ve enerji absorpsiyon performansını sayısal olarak incelemektedir. Düzenli altıgen bir bal peteği için doğrulanmış bir LS-DYNA sonlu elemanlar modeli oluşturulmuş ve deneysel sonuçlarla karşılaştırılmış, kuvvet-şekil değiştirme tepkisi ve deformasyon modları açısından iyi bir uyum elde edilmiştir. Ardından, örümcek, salyangoz, dalgalı, bambu, pomelo kabuğu, çim sapı ve hiyerarşik olmak üzere yedi farklı doğadan ilhamlı konfigürasyon yarı-statik sıkıştırma altında modellenmiştir. Sonuçlar, bu tasarımların deformasyon yolları ve enerji absorpsiyon kapasitesi üzerinde düzenli altıgen yapıya kıyasla önemli bir etkiye sahip olduğunu göstermektedir. Pomelo kabuğu, çim sapı ve hiyerarşik bal petekleri, çok hücreli ve hiyerarşik yük aktarım mekanizmaları sayesinde densifikasyonu geciktirerek uzun bir plateau bölgesi oluşturmalarıyla en yüksek özgül enerji absorpsiyon değerlerini (sırasıyla 7.88, 7.50 ve 7.39 J/g) göstermiş ve referans altıgen yapıya kıyasla %47'ye varan oranda performans artışı sağlamıştır. Örümcek ve bambu tasarımları orta seviyede özgül enerji absorpsiyonu ile dengeli bir performans sergilerken, dalgalı ve salyangoz geometrileri daha düşük tepe kuvvetleriyle daha düzgün plateau davranışı göstermiştir. Genel olarak, bulgular doğadan ilhamlı geometrik özelliklerin hafif yapılarda çarpışma dayanımını artırmak için etkili bir şekilde kullanılabileceğini ortaya koymakta; ulaştırma, paketleme ve enerji depolama sistemleri gibi gelecekteki uygulamalara değerli katkılar sunmakta ve yeni nesil hafif yapı tasarımlarına yön verecek bilgiler sağlamaktadır.

Anahtar kelimeler: Doğadan ilhamlı yapılar, Bal peteği çekirdekler, Çarpışma dayanımı, LS-DYNA, Sayısal analiz

*Yazılan yazar



Numerical Investigation of Compression Behavior of Bio-Inspired Honeycomb Designs

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Abstract

This study numerically investigates the compressive behavior and energy absorption performance of bio-inspired honeycomb structures. A validated LS-DYNA finite element framework was first established for a regular hexagonal honeycomb and correlated with experimental results, showing good agreement in terms of force-strain response and deformation modes. Subsequently, seven bio-inspired configurations-spider, snail, wavy, bamboo, pomelo peel, grass stem, and hierarchical-were modeled under quasi-static compression. The results revealed that bio-inspired designs significantly influence deformation pathways and energy absorption capacity compared to the regular hexagon. Among the proposed designs, the pomelo peel, grass stem, and hierarchical honeycombs exhibited the highest specific energy absorption (7.88, 7.50, and 7.39 J/g, respectively), representing an improvement of up to 47% compared to the reference structure. This improvement is attributed to their multi-cell and hierarchical load-transfer mechanisms that delayed densification and ensured a prolonged plateau region. While spider and bamboo designs provided balanced performance with moderate specific energy absorption, the wavy and snail geometries demonstrated smoother plateau behavior with lower peak forces. Overall, the findings highlight that bio-inspired geometrical features can be effectively employed to enhance the crashworthiness of lightweight structures, offering valuable insights for future applications in transportation, packaging, and energy storage systems, and guiding the development of next-generation lightweight structural designs.

Keywords: Bio-inspired structures, Honeycomb cores, Crashworthiness, LS-DYNA, Numerical analysis

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1. Introduction

Honeycomb structures are widely employed in various engineering fields such as aerospace, automotive, packaging, and energy storage systems due to their high strength-to-weight ratio, and superior energy absorption capability [1,2]. These structures play a critical role in safety-oriented designs by guiding deformation and dissipating energy, particularly under impact and crash loading conditions.

In recent years, bio-inspired designs have attracted significant attention as an approach to enhance the performance of conventional hexagonal cells. Natural configurations such as spider webs [3-5], snail shells [6-8], woodpecker beaks [9,10], bamboo stems [11,12], pomelo peels [13-15], and grass stems [15-17] have inspired engineering designs owing to their exceptional strength, progressive energy absorption, and damage-delay mechanisms. Specifically, the spider web architecture is characterized by its radial and spiral arrangement, which effectively distributes point loads and limits the propagation of local damage, thereby increasing overall structural integrity [3-5]. The snail shell structure, with its spiral geometry, promotes progressive failure mechanisms and stable stress distribution, allowing for gradual energy dissipation rather than catastrophic collapse [6-8]. Similarly, hierarchical and multi-cell designs (like pomelo and grass stem) mimic natural cellular solids by introducing smaller sub-structures that delay densification and enhance the moment of inertia against buckling [13-17]. Through such biomimetic strategies, it has become possible to optimize the mechanical response of honeycomb structures and achieve superior energy absorption performance compared to traditional hexagonal designs.

Although there have been studies on various bio-inspired honeycomb geometries, comparative investigations of these structures under identical conditions remain limited. In many cases, research has focused on analyzing a single design in detail, while comprehensive comparisons involving both the regular hexagon and multiple bio-inspired configurations have been largely overlooked. Furthermore, the prevalence of purely numerical studies without sufficient experimental validation raises concerns regarding the reliability of such models.

The primary objective of this study is to conduct a systematic and comparative investigation into the compressive behavior of seven distinct bio-inspired honeycomb designs (spider, snail, wavy, bamboo, pomelo peel, grass stem, and hierarchical) relative to a conventional hexagonal structure. While previous studies often focus on individual designs, this research aims to address the lack of comprehensive comparative data by evaluating these geometries under identical loading and boundary conditions. To ensure numerical reliability, the finite element framework is first rigorously validated against experimental results for the regular hexagon. Specifically, the study seeks to: (i) elucidate the influence of specific bio-inspired geometric features on deformation modes and failure mechanisms; (ii) quantify the energy absorption capabilities and specific energy absorption (SEA) metrics of each design; and (iii) evaluate the trade-off between structural mass increase and energy dissipation efficiency. By doing so, this work intends to provide a selection guideline for next-generation lightweight, high-strength, and impact-resistant engineering structures.

2. Compression Test Setup and Validation of the Regular Hexagonal Honeycomb

Before examining the compressive behavior of bio-inspired honeycombs, a finite element model was established and validated against experimental test results [18]. For this purpose, post-compression images, force-strain curves and absorbed energy values were considered. The developed LS-DYNA model is presented in Figure 1. To ensure reproducibility, the specific boundary conditions—including the fixed support at the base and the applied loading velocity ($V=10$ m/s) at the top—are explicitly illustrated in this figure.

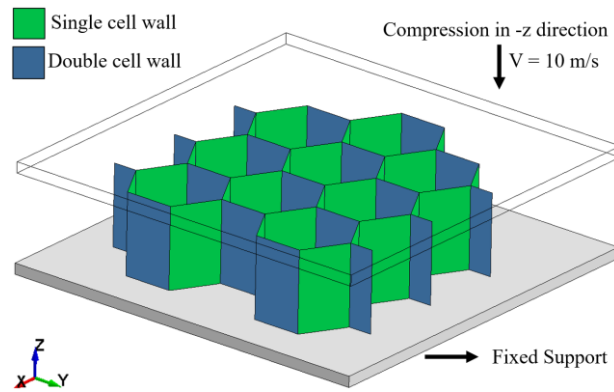


Figure 1. LS-DYNA model for the compression test

The bottom gray plate was fixed to hold the honeycomb in place, while the transparent plate at the top compressed the honeycomb in the negative z-direction. Accordingly, all six degrees of freedom of the bottom plate were constrained, whereas the top plate was restricted in five degrees of freedom and allowed to move only along the z-axis at a constant velocity of 10 m/s to simulate quasi-static loading. The honeycomb itself was left completely free.

Each unit cell of the honeycomb has an edge length of 9 mm and a height of 15 mm. During manufacturing, aluminum 3003-H18 sheets with a thickness of 0.75 mm were pressed into half-hexagonal molds and then bonded along the half-hexagonal edges. Thus, the unbonded walls remained 0.75 mm thick, while the bonded sections reached approximately twice that thickness (1.5 mm). In the numerical model, single-wall regions (0.75 mm) were represented in green and double-wall regions (1.5 mm) in blue. Since the walls were modeled as separate parts, the nodes at the interfaces were duplicated. The complete model consisted of nine full cells and four half cells.

An Automatic Surface-to-Surface contact [19] was defined between the honeycomb and the two plates. Additionally, to prevent overlapping of folded walls during compression, an Automatic Single Surface contact [20] was applied. Both static and dynamic friction coefficients were set to 0.2 [21]. To realistically capture the folding of honeycomb walls during compression, square shell elements with an edge length of 0.75 mm were employed instead of solid elements. To suppress potential element instabilities, the hourglass control option was activated. The honeycomb material, aluminum 3003-H18, was modeled using the MAT_018 Power Law Plasticity constitutive model, and its material parameters (shown in Table 1) were defined as follows:

Table 1. Mechanical properties of AA3003-H18 [18] used in the model

Definition	Symbol	Value	Unit
Mass density	ρ	2.7e-006	(kg/mm ³)
Young's modulus	E	68.95	(GPa)
Poisson's ratio	ν	0.33	-
Strength coefficient	K	0.22	(GPa)
Hardening exponent	n	0.2353	-
Initial yield stress	σ_y	0.12	(GPa)
Plastic failure strain for element deletion	ϵ_p	0.3223	-

Note: All material parameters, including the plastic failure strain (ϵ_p), were adopted from Reference [18] to ensure consistency with the experimental validation.

Figure 2 presents the comparison between the experimental image and the LS-DYNA simulation.

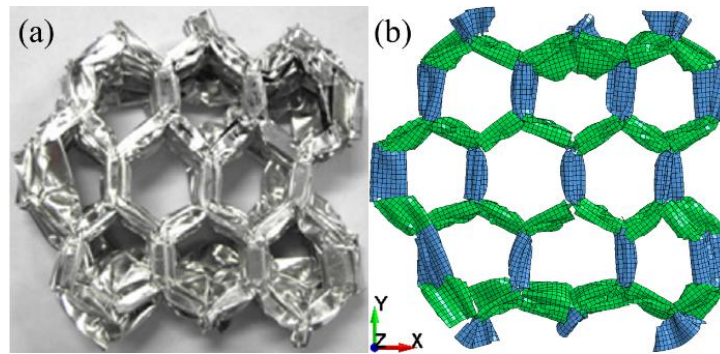


Figure 2. Comparison of the final compression images between the experimental test [18] and the LS-DYNA model

Experimental observations showed that the cell walls exhibited local buckling under compressive loading, with these deformations particularly concentrated at the cell junctions. Similarly, numerical analyses revealed that the cell walls folded at specific locations, and the collapse mode deviated from ideal symmetry. Incorporating the distinct responses of single- and double-walled cell edges into the model allowed for a more accurate representation of the structural behavior. The overall collapse mechanism was found to be consistent with the experimental results, indicating that the numerical model reliably captured the physical response. This agreement is further supported in Figure 3, where the force–strain curves obtained from the LS-DYNA simulations are compared with the experimental results.

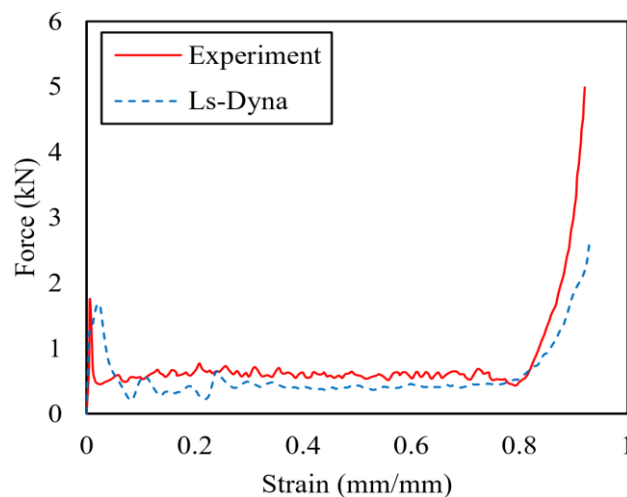


Figure 3. Comparison of experimental [18] and numerical force–strain curves

As shown in Figure 3, a distinct peak load was observed at the onset of compression in both the experimental results and the numerical simulations. This peak was measured as 1754 N in the experiments and 1676 N in the LS-DYNA simulation, corresponding to a difference of 4.40%. Following the peak, the cell walls began to fold, and a stable response of approximately 500 N was maintained up to a strain level of about 0.8. In this plateau region, the experimental and numerical curves exhibited a nearly parallel trend. The total absorbed energy was calculated as 10.45 J experimentally and 8.02 J numerically, corresponding to a deviation of 23.25%. Beyond a strain level of 0.8, the folding process of the walls was completed, and the overlapping folded elements compressed each other, leading to a stiffening effect. At this stage as well, the overall trends of the two curves remained consistent.

The comparison between experimental images and the deformation modes predicted by the numerical model, along with the similarity of the force–strain curves, demonstrates that the developed model reliably represents the compressive response of honeycomb structures. This agreement validates the accuracy of the adopted material parameters, finite element mesh, and contact definitions. Therefore, the findings of the validation study confirm that the model can be effectively applied to analyze different bio-inspired honeycomb designs.

3. Modeling and Compression Behavior Analysis of Bio-Inspired Honeycomb Structures

Along with the regular hexagonal honeycomb, seven additional bio-inspired models were analyzed under compression. The unit cells of the investigated honeycombs are shown in Figure 4.

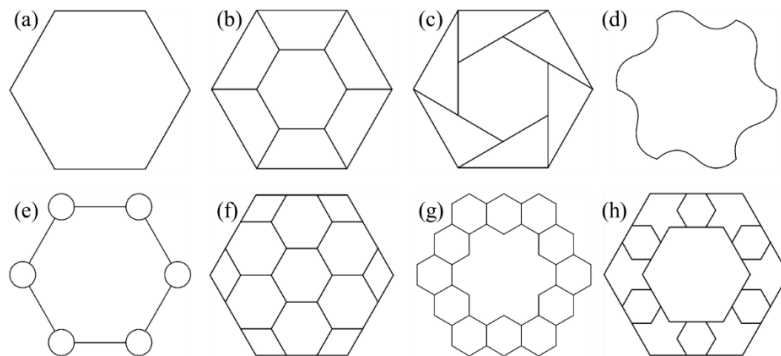


Figure 4. (a) Regular hexagon, (b) spider, (c) snail, (d) wavy, (e) bamboo, (f) pomelo peel, (g) grass stem, and (h) hierarchical unit honeycombs

The honeycomb models were designed as follows: For the spider model, a smaller hexagon with an edge length of 4.5 mm was placed at the center of a regular hexagon with an edge length of 9 mm, and the vertices of both hexagons were connected. Conversely, in the snail model, 30–60–90 triangles were added to each edge, thereby forming a smaller hexagon with an edge length of 5.19 mm, rotated by 30° at the center. The wavy model features sinusoidal curves with an amplitude of 1.5 mm, consisting of one crest and one trough, added to each edge of the hexagon. In the bamboo model, circular arcs with a radius of 1.5 mm were added to each corner of the hexagon. In the pomelo peel model, a hexagon with an edge length of 3 mm was placed at the center, and six additional hexagons of the same size were positioned between this central hexagon and the outer hexagon. In the grass stem model, three small hexagons with an edge length of 2.59 mm were vertically attached to each edge of the larger hexagon. Finally, in the hierarchical model, a central hexagon with an edge length of 6 mm was surrounded by six smaller hexagons, each with an edge length of 1.5 mm, positioned between the central and outer hexagons. The honeycomb structures generated from these unit cells and used in the compression tests are presented in Figure 5.

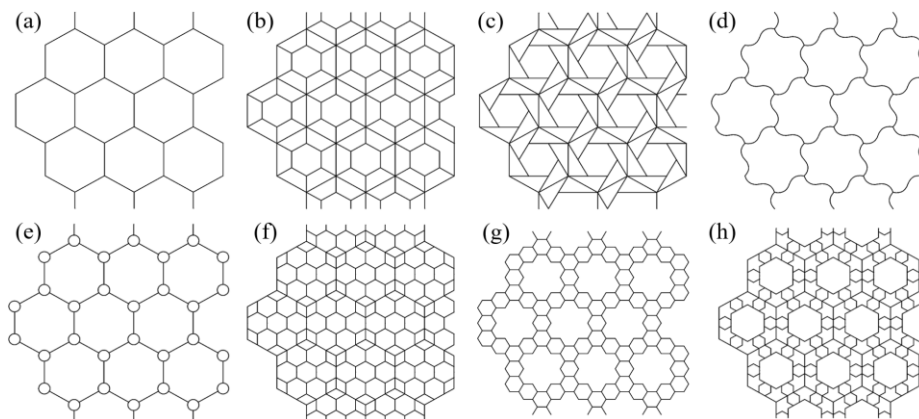


Figure 5. (a) Regular hexagon, (b) spider, (c) snail, (d) wavy, (e) bamboo, (f) pomelo peel, (g) grass stem, and (h) hierarchical honeycombs

To ensure the accuracy of the physical data, the mass of each honeycomb configuration was determined using a dual-verification approach. First, the theoretical mass was calculated analytically based on the CAD geometry: the total wall volume was derived from the cumulative cross-sectional length of the cell walls, the wall thickness ($t=0.75$ mm), and the height ($h=15$ mm), and then multiplied by the density of AA3003-H18. Secondly, these values were cross-checked against the total mass reported by the LS-DYNA pre-processor

(based on element volume and density). Both methods yielded identical results, confirming that the additional mass introduced by the internal features of the bio-inspired designs (e.g., in Spider and Pomelo peel models) was accurately represented.

These figures illustrate the honeycomb structures designed to investigate the influence of different geometric features on mechanical behavior. The regular hexagon represents the simplest configuration and serves as the reference structure, whereas the spider model offers increased stiffness and load-bearing capacity due to additional connections at the center. The snail model, with its rotated inner hexagon and inclined edges, provides a potential for gradual energy dissipation during deformation. The sinusoidal edges of the wavy model enhance local buckling and folding modes, thereby improving energy absorption. The bamboo model incorporates circular elements at the corners, which reduce stress concentrations and enhance impact resistance. The pomelo peel and grass stem models, characterized by multi-layered and multi-cellular arrangements, distribute loads more evenly and achieve higher specific energy absorption. Finally, the hierarchical model, with its multi-scale cell organization, optimizes both stiffness and energy absorption capacity. The progressive deformation modes of the different honeycomb configurations under compression are shown in Figure 6.

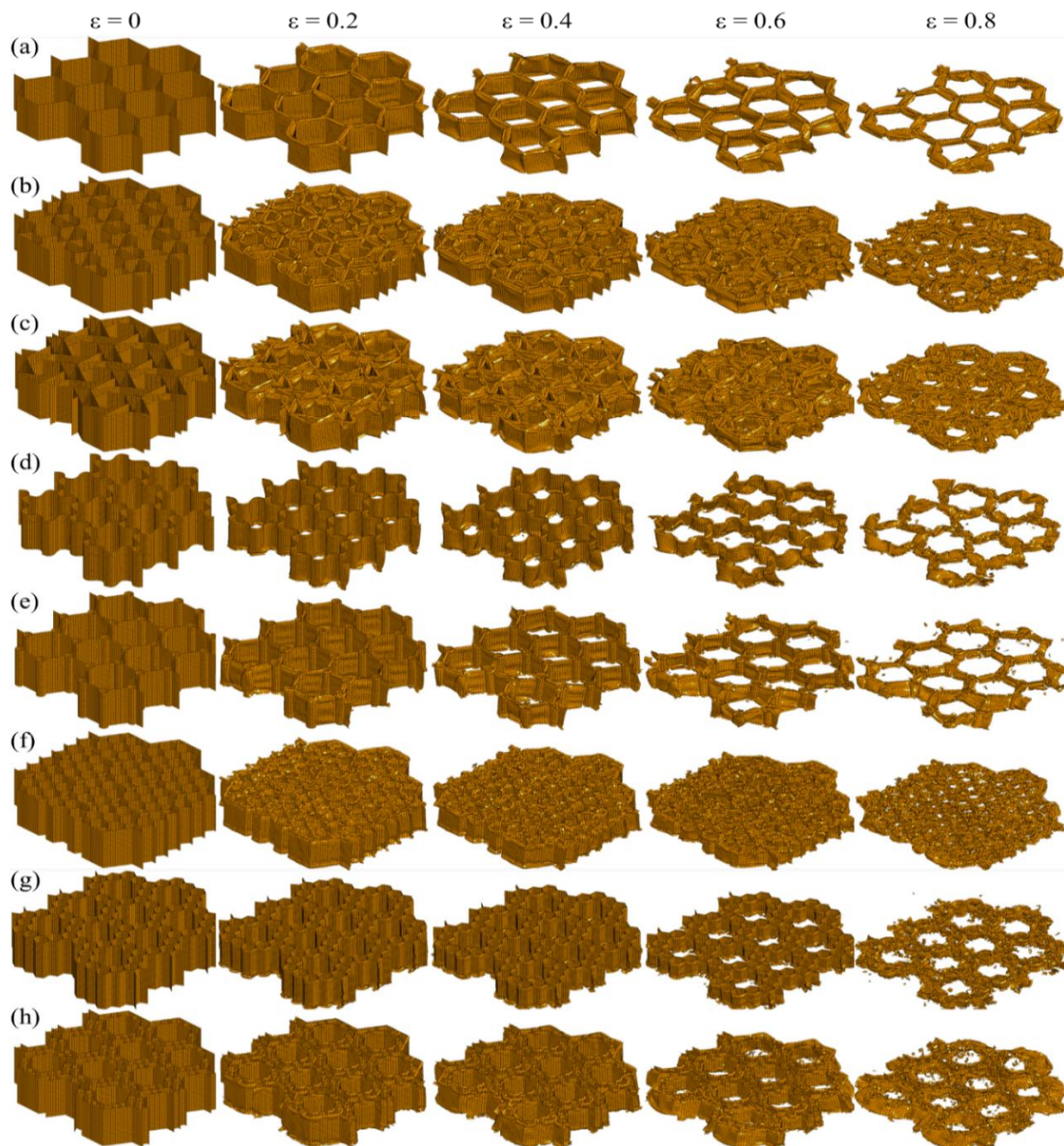


Figure 6. Progressive deformation modes of different honeycomb structures at axial strain levels of 0, 0.2, 0.4, 0.6, and 0.8

This figure illustrates the progressive deformation behavior of eight different honeycomb configurations under increasing axial loading. At low strain levels ($\epsilon = 0-0.2$), all models exhibited elastic and initial buckling stages, whereas at intermediate levels ($\epsilon = 0.4-0.6$), geometry-specific folding modes became more pronounced. The regular hexagon collapsed with predictable folding bands, while the spider and hierarchical models displayed more integrated and rigid collapse behavior due to their additional connections. In the snail and wavy models, inclined edges and sinusoidal walls promoted gradual, low-fluctuation deformation modes, thereby enhancing energy absorption. The bamboo model, with its rounded corners, limited local stress concentrations, whereas the pomelo peel and grass stem models distributed loads more uniformly through their multi-cellular structures, maintaining stability even at higher strains. At large strain levels ($\epsilon = 0.8$), all structures reached a pronounced densification region; however, the multi-cellular and hierarchical designs dissipated energy more progressively and retained their load-bearing capacity even in the final stages of collapse.

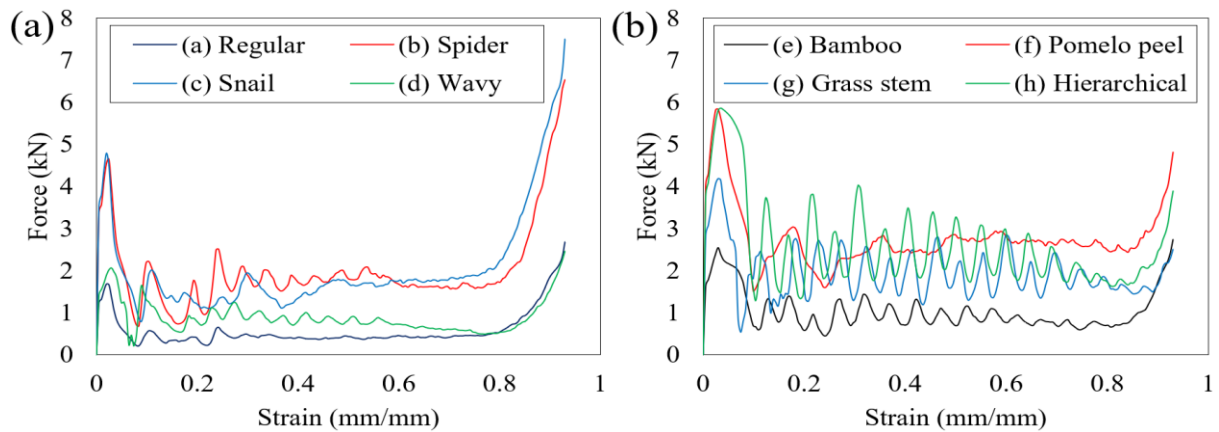


Figure 7. Force–strain curves of different honeycomb configurations under axial compression: (a) Regular, Spider, Snail, and Wavy models; (b) Bamboo, Pomelo peel, Grass stem, and Hierarchical models

In both panels, the force–strain curves (Figure 7) exhibit a similar overall trend: an initial transition and peak within $\epsilon \approx 0-0.1$, a plateau region between $\epsilon \approx 0.2-0.7$ characterized by geometry-specific oscillatory patterns, and a steep rise beyond $\epsilon \approx 0.75-0.85$ corresponding to densification. Comparing the Regular, Spider, Snail, and Wavy models, the plateau force level generally follows the order Spider \approx Snail $>$ Wavy $>$ Regular. While the Spider and Snail structures provided higher load-carrying capacity, the Wavy and particularly the Regular model displayed lower levels but a smoother energy absorption response. In terms of plateau stability, the Regular model showed the lowest oscillation with a fairly uniform curve, the Snail and Wavy exhibited moderate fluctuations, and the Spider displayed pronounced variations due to multiple folding bands. Densification occurred later in the Spider and Snail models, whereas it started earlier in the Wavy and Regular configurations, indicating a force-limiting behavior for the Regular design.

In the right panel, which compares the Bamboo, Pomelo peel, Grass stem, and Hierarchical models, the plateau level and length generally follow the sequence Pomelo peel \approx Bamboo \approx Grass stem \approx Hierarchical. The Bamboo model, owing to its rounded corners, produced a relatively smooth plateau with reduced oscillations. The Grass stem and Hierarchical models, however, exhibited distinct saw-tooth oscillations due to the sequential folding of smaller cells. The Pomelo peel model demonstrated a ring-by-ring folding mechanism, generating a moderately oscillatory yet extended plateau. The Hierarchical and Grass stem designs, with their multi-scale cell organization, exhibited shorter but higher plateaus. Densification occurred earlier in the Bamboo model, while it was delayed in the others, confirming that multi-cellular and hierarchical structures can sustain energy absorption effectively up to higher strain levels. The corresponding mass, absorbed energy, and specific energy absorption values of these structures, calculated up to a strain level of $\epsilon = 0.8$, are presented in Table 2.

Table 2. Mass, energy absorption, and specific energy absorption values of the honeycomb models

Model	Mass (g)	EA (J)	sEA (J/g)
Regular hexagon	1.5	8.02	5.35
Spider	4.04	27.95	6.92
Snail	4.41	28.69	6.51
Wavy	1.86	12.31	6.62
Bamboo	2.13	14.46	6.79
Pomelo peel	4.88	38.46	7.88
Grass stem	3.63	27.22	7.50
Hierarchical	4.87	35.99	7.39

When the eight configurations are compared, the highest specific energy absorption (sEA) is achieved by the Pomelo peel model (7.88 J/g), followed by the Grass stem (7.50 J/g) and Hierarchical (7.39 J/g) designs. The common feature of these three structures is their multi-cellular or hierarchical load paths, which delay densification and provide an extended energy dissipation plateau. The Spider (6.92 J/g) and Bamboo (6.79 J/g) models offer balanced alternatives with medium-to-high sEA, while the Wavy (6.62 J/g) and Snail (6.51 J/g) models exhibit slightly lower sEA values but provide smoother plateau responses with reduced peak forces. As expected, the Regular model (5.35 J/g) represents the reference level.

In terms of absolute energy absorption (EA), the Pomelo peel (38.46 J) and Hierarchical (35.99 J) models stand out, although their higher mass and structural complexity become evident. The Wavy model, on the other hand, is notable as a mass-efficient option, with a relatively low weight (1.86 g) while still maintaining reasonable energy absorption. In this context, Figure 8 presents a comparative evaluation of mass variation against specific energy absorption improvement. This allows for a proportional assessment of energy dissipation efficiency with respect to added mass and visually highlights the performance-to-weight balance across the different designs.

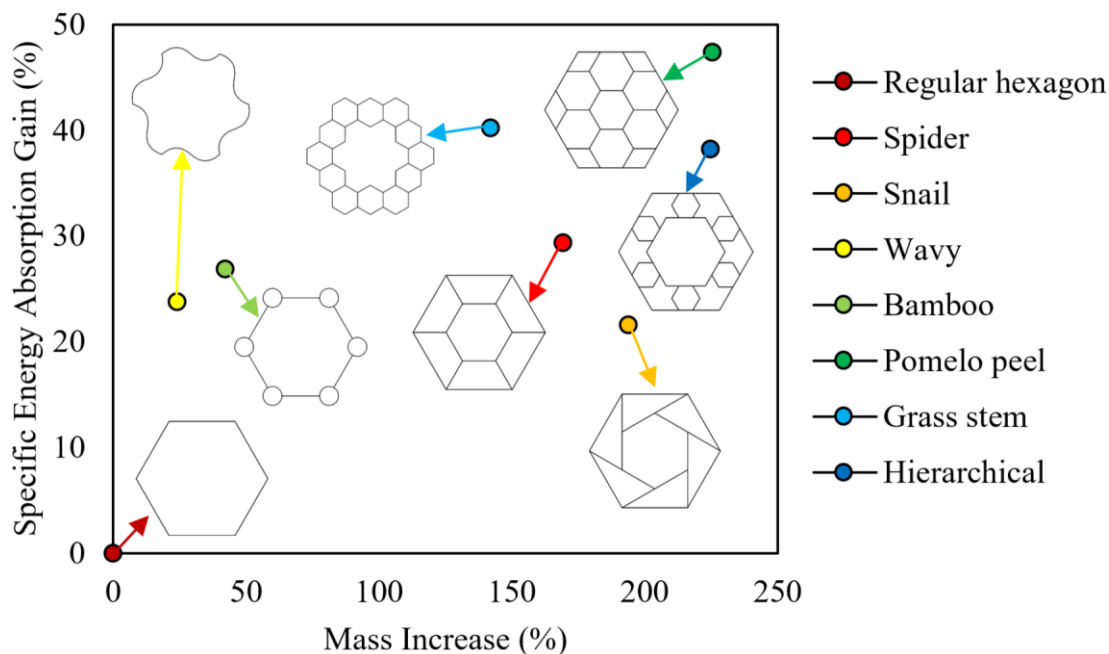


Figure 8. Comparative assessment of mass increase versus specific energy absorption gain in honeycomb configurations

Figure 8 enables a combined assessment of the proportional mass increase and the corresponding gain in specific energy absorption (sEA) relative to the regular hexagonal structure. The visualization clearly shows that while some bio-inspired designs achieve significant improvements in sEA despite added mass, others

provide more limited benefits. In particular, the multi-cellular and hierarchical structures are located in the upper-right region, representing a “high-mass/high-gain” trend, whereas the wavy and snail models, with their relatively low mass increase, fall into the “light-to-moderate gain” group. This distribution indicates that the performance-to-weight balance among different designs should be evaluated not only by absolute energy values but also by proportional efficiency metrics.

4. Discussion

The results of this study highlight the significant potential of bio-inspired geometries in enhancing the crashworthiness of honeycomb structures. While the primary findings were presented in the previous section, several critical aspects regarding the numerical methodology and comparative performance warrant further discussion.

First, regarding the validation study, a discrepancy of approximately 23% was observed between the experimental (10.45 J) and numerical (8.02 J) absorbed energy values, despite the close agreement in peak force. This deviation is mainly attributed to the element deletion technique employed in the finite element framework. In the numerical model, elements are removed from the calculation domain once they exceed the plastic failure strain (ϵ_p) to simulate material failure. Consequently, these deleted elements no longer contribute to the load-bearing capacity. In contrast, during the physical compression test, the fractured cell walls do not disappear; they remain within the structure, folding onto each other and creating a stiff debris pile. This phenomenon is particularly significant in the final stages of compression (densification), where the accumulated material in the experiment generates additional resistance forces that the numerical model—due to element deletion—cannot fully capture. Therefore, the numerical results present a slightly conservative prediction of the total energy absorption.

Secondly, the specific energy absorption (SEA) values obtained in this study are consistent with, and in some cases superior to, similar structures reported in the literature. For instance, the Pomelo peel model achieved an SEA of 7.88 J/g. When compared to similar hierarchical honeycombs studied by Zhang et al. [13] and Fang et al. [16], the proposed design demonstrates a competitive performance-to-weight ratio. While traditional hexagonal structures are typically limited by early densification, the multi-cellular arrangement in the Pomelo and Grass stem models successfully extended the plateau region, resulting in a significant improvement in energy dissipation efficiency.

Finally, regarding the numerical strategy, specific choices were made to ensure both robustness and computational efficiency. Since the explicit solver is deterministic, a single simulation was performed for each configuration, with the validity of the buckling modes confirmed against experimental data for the reference structure. Additionally, a loading velocity of 10 m/s was employed. This value was chosen in alignment with previous studies on bio-inspired structures [7], which have demonstrated that such velocities yield reliable quasi-static results for explicit solvers. In the present study, the ratio of kinetic energy to internal energy remained negligible throughout the deformation process, further confirming that dynamic inertial effects were minimized. Thus, the observed deformation modes and force responses can be considered representative of quasi-static behavior.

5. Conclusions

In this study, the compressive behavior of eight honeycomb structures, including a regular hexagonal reference and seven bio-inspired configurations, was systematically analyzed through validated finite element simulations. The developed LS-DYNA model showed good agreement with experimental results in terms of deformation modes, peak load, and energy absorption trends, confirming the reliability of the adopted modeling strategy.

The comparative analyses revealed that geometry plays a critical role in determining both the deformation mechanism and the energy absorption capacity of honeycomb structures. While the regular hexagon provided the baseline response, the bio-inspired designs introduced distinctive folding modes and plateau

characteristics. Specifically, the pomelo peel, grass stem, and hierarchical models exhibited superior specific energy absorption, primarily due to their multi-cell and hierarchical load-transfer mechanisms that delayed densification. The spider and bamboo structures exhibited balanced performance with moderate energy absorption, whereas the snail and wavy designs demonstrated smoother plateau behavior and lower peak stresses, which could be advantageous in applications requiring controlled load transfer.

It was also observed that energy absorption efficiency is strongly influenced by the trade-off between structural mass and geometrical complexity. Although multi-cell designs achieved higher energy dissipation, they also introduced additional weight. Therefore, an optimal design should be selected by considering both absolute energy absorption and design efficiency, taking into account the performance-to-weight ratio in accordance with application requirements.

Overall, this research demonstrates that bio-inspired geometrical modifications can significantly improve the crashworthiness of honeycomb structures. The findings provide practical insights for engineers and designers seeking to optimize lightweight structures where energy absorption, stability, and efficiency are critical. Future studies may extend this work by exploring dynamic loading conditions, hybrid material systems, or large-scale structural integration to further evaluate the potential of bio-inspired honeycomb concepts.

6. Author Contribution Declaration

The author solely contributed to the conception and design of the study, literature review, numerical modeling, analysis and interpretation of the results, preparation of figures and tables, and writing and revision of the manuscript.

7. Ethics Committee Approval and Conflict of Interest Declaration

This study does not involve human participants, animals, or any data requiring ethics committee approval. Therefore, ethics committee permission was not required. The author declares that there is no conflict of interest regarding the publication of this article.

8. Ethical Statement Regarding the Use of Artificial Intelligence

No artificial intelligence-based tools or applications were used in the preparation of this study. The entire content of the study was produced by the author in accordance with scientific research methods and academic ethical principles.

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