Journal of Electronic Research and Application, 2026, Volume 10, Issue 7
http://ojs.bbwpublisher.com/index.php/JERA
Online ISSN: 2208-3510
Print ISSN: 2208-3502

Design and Impact Resistance Analysis of Express Cushioning Materials Based on Biomimetic Gradient Structure

Zixuan Xia*

Nanyang Model High School, 200032 Nanyang, China

Corresponding author: Zixuan Xia, 376128053@qq.com

Abstract: With the rapid development of the logistics industry, the contradiction between green packaging and cargo safety has become increasingly prominent. Inspired by the lightweight, high-strength, and graded energy-absorbing microstructure of pomelo peel, this study proposes a novel biomimetic gradient porous cushioning structure. Using the ANSYS Explicit Dynamics module under a constant velocity crushing condition of 4.4 m/s, the impact resistance of three topologies, namely uniform circular holes (U-C), gradient circular holes (G-C), and gradient square holes (G-S), is compared. The simulation results indicate that, compared with the conventional uniform structure, the biomimetic gradient design successfully induces a controllable deformation mode characterized by layer-by-layer collapse, effectively reducing the initial impact peak. Among the three structures, G-C exhibits the best overall performance. Its peak contact reaction force is reduced by 16.2% compared with that of the uniform structure, and it avoids the mechanical instability due to stress concentration that occurs in the square-hole structure. Cross-checking the three simulation reports further indicates that the foam masses of the three models are all about 8.76g with only negligible differences. Therefore, the advantage of G-C should be interpreted as better overall cushioning performance under nearly equal-mass conditions, rather than as a direct proof of significantly reduced mass or the highest specific energy absorption. The study demonstrates that the biomimetic gradient circular hole structure has clear potential for impact protection, structural stability, and engineering feasibility in express packaging design.

Keywords: Biomimetic design; Gradient structure; Impact resistance; Finite element analysis; Lightweight

Online publication: Aug 11, 2026

1. Introduction

With the rapid development of China's e-commerce and express logistics, the consumption of packaging materials has become enormous. Foam plastics such as EPS and EPE, which are used for cushioning and protection, are difficult to degrade naturally after serving their short-term protective function, causing severe white pollution and pressure on solid waste disposal. At the same time, packaging materials have faced two conflicting demands: they need to be lightweight to reduce transportation costs, yet they also require a high energy-absorption capacity to protect the contents. Traditional homogeneous foam often fails to satisfy both requirements [1].

Nature inspires addressing this problem. The pomelo peel, with a gradient pore structure that is dense on the outside and loose on the inside, can dissipate impact energy through layer-by-layer and stable crushing deformation when the fruit falls, thereby protecting the pulp [2]. The skeleton is a gradient structure of dense cortical bone and loose cancellous bone, which maintains sufficient support strength while minimizing weight [3]. These biological prototypes demonstrate that gradient porous structures have significant potential in terms of lightness, high strength, and cushioning energy absorption.

In recent years, research on biological prototypes such as pomelo peel and macadamia nut shell has advanced (see **Figure 1**). Scholars have proposed a "low-high-low" porosity gradient model and, using techniques such as 3D printing, have shown that gradient designs enhance specific energy absorption, deformation stability, and impact resistance [2,4–6]. However, the additive manufacturing processes used in most existing studies are too costly and too slow for the express packaging industry, where cost is critical, and volumes are huge [2,4,7]. On the one hand, previous work has delved deeply into the biological porous structure. For example, the pomelo peel exhibits a typical gradient pattern along the thickness direction: low porosity in the endocarp, high porosity of the mesocarp, and low porosity of the exocarp [2]. Meanwhile, the multilayered shell of the macadamia nut shows excellent compressive resistance under lateral impact [6]. On the other hand, biomimetic designs have been extended to hierarchical honeycomb structures, partial stiffness enhancement, negative Poisson's ratio structures, and TPMS structures [8–11]. Under high strain rates, these designs exhibit stable energy absorption [12]. The porous structures have also demonstrated their value in automotive crash safety and multi-impact protection [13,14]. Meanwhile, research into design optimization methods for structural crashworthiness is advancing [15]. Moreover, modern combinations of multifunctional ultralight porous materials now integrate structural support, energy absorption, and acoustic properties [16]. In conjunction with the wide application of biomimetic honeycomb structures in various engineering fields, both achievements can provide useful information about cushioning materials [17].

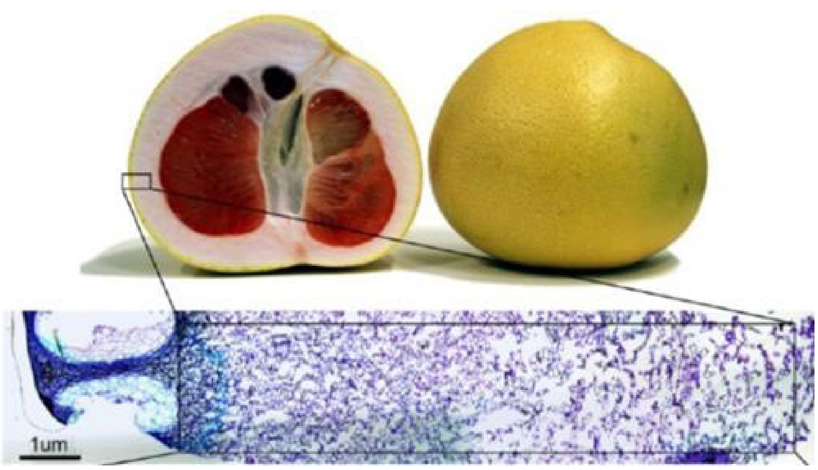

Figure 1. Cushioning energy absorption structure of pomelo peel.

Currently, several approaches are used to assess the properties of cushioning and energy-absorbing porous materials; namely, static and dynamic compression tests, drop impact hammer test, energy-absorbing efficiency and cushioning coefficient approaches, as well as numerical simulations [1,6,18–20]. All these works prove the superiority of biomimetic gradient porous materials from a theoretical point of view. However, a lack of systematic design recommendations remains an obstacle for the development of affordable, industrially produced express packages.

Therefore, in this study, whether the performance advantages of the bioinspired gradient porous structure can be integrated into express cushioning material design without affecting their manufacturability and feasibility of mass production is explored. In this study, polyurethane foam is selected as the matrix material, and numerical comparisons among the three kinds of structures of uniform circle pores, gradient circle pores, and gradient square pores are performed. Specifically, the influence of gradient porosity and geometric shape on peak impact force, maximum compression displacement, total energy dissipation, specific energy dissipation, and deformation stability will be analyzed. Finally, through comprehensive analysis, structural guidelines for actual engineering applications will be put forward. This study intends to strike a balance among cushioning properties, lightness, stability, and manufacturability in cushioning materials, which provides the structure design basis for green logistics packaging products. On the other hand, the research results also provide theoretical references for further development work in the following aspects, such as material selection, parameter optimization, and low-cost mass production.

2. Principles of finite element simulation

The Finite Element Method (FEM) is one of the most significant numerical methods used in investigating the mechanical properties of cushioning materials. Continua with complex shapes can be broken down into finite elements, and the response of the structure will then be accomplished using global assembly and solving schemes. In designing cushioning structures, the FEM analysis can predict displacement, stress, reactive forces, and energy absorption during impact events. Thus, FEM analysis is an efficient way to bridge between biomimicry and engineering design. In experimental design, FEM analysis offers several advantages, including cost savings and design selection.

In practical research, finite element analysis proceeds through a set of sequential steps that cover discretization, element analysis, global assembly, application of load and constraint, solution, and post-processing. Explicit dynamic algorithms are especially well suited to tackling the transient impact problems explored in this work. With stable performance in handling nonlinear processes linked to high velocity, large deformation, and complex contact, these algorithms can capture the full mechanical response of polyurethane foam under compression. The material's behavioral changes across the elastic, plateau and densification stages can all be clearly reflected in the simulation outputs. Once the entire solving process finishes, researchers can extract core performance metrics from the results. These metrics include peak impact force, total energy absorption, specific energy absorption, and deformation patterns for further analysis and comparison.

Built for this research, the simulation framework integrates structural design and modeling, material model and solver selection, boundary and load condition setting, and result evaluation. In the modeling phase, aperture and gradient distributions are tuned while the overall structural dimensions remain unchanged. Key parameters are finalized before the formal solution run, including impactor velocity, contact properties, and fixed bottom constraints. Post-processing work centers on extracting total deformation and reaction force data, which enables performance comparison across different topological configurations. The suitability of the selected material model and solver remains a core consideration throughout the entire workflow. Physical plausibility and numerical reliability are both verified through energy evolution checks and mesh sensitivity analysis.

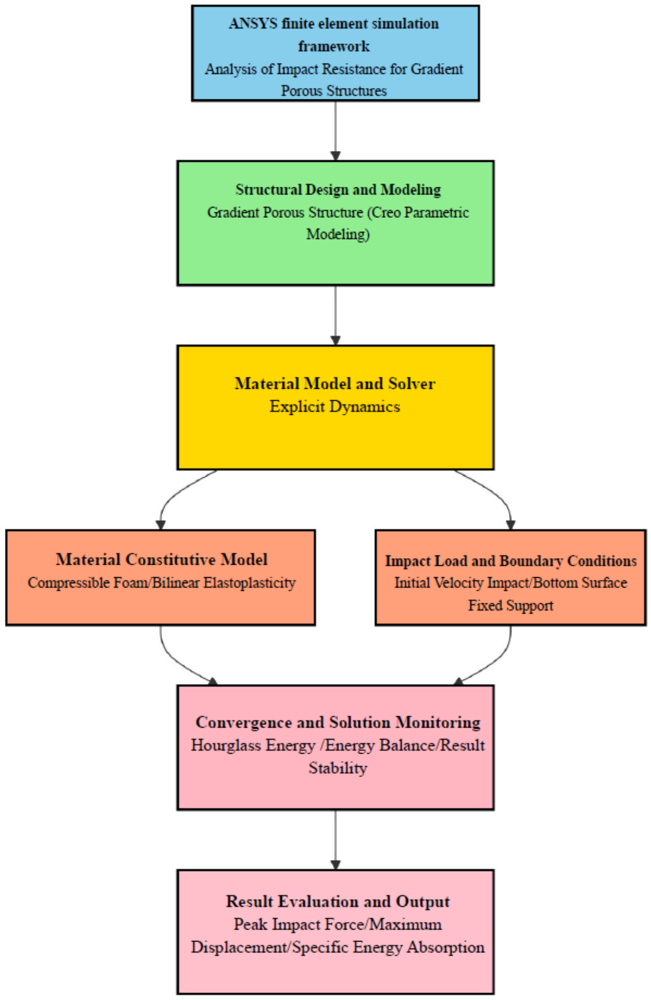

Figure 2. Finite element simulation framework.

3. Modeling and simulation schemes

Polyurethane (PU) foam is selected as the core cushioning matrix in this work. With inherent low density, high compressibility, and strong impact energy dissipation capacity, the material can be manufactured at low cost via processes including mold foaming, layer-pouring, and interlayer bonding. Such manufacturing flexibility supports its mass production and scalable adoption in express packaging. In the numerical simulation, a multilinear stress-strain relationship is applied to characterize full mechanical responses across the elastic, plateau crush, and densification stages. Considering that the emphasis of this study is on the performance comparison of various design configurations, a multilinear stress-strain curve of PU foam under compression has been assumed. This model can later be modified using information from the material data sheet and compression tests to improve the consistency between the simulation results and the actual response.

The research object is a porous plate (see **Figure 3** to **5**). To consider the processing feasibility and modeling repeatability, the porous structure adopts a regular hole array and layers along the thickness direction to form a gradient. At the same time, a uniform structure and a gradient structure are set up to compare the two typical hole shapes of circular holes and square holes. Above the plate, a 30 mm × 30 mm × 20 mm rigid impact block is set to cover multiple hole units, reducing the randomness of the falling point and the interference of the boundary effect. All models maintain a consistent outer contour to enhance the feasibility of transforming the simulation conclusion to the actual express cushioning material design.

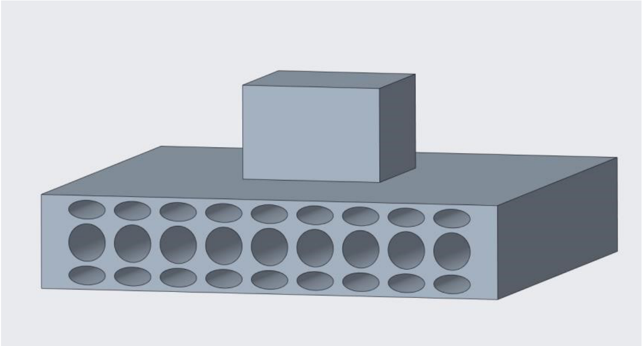

Figure 3. Gradient circular/elliptical holes.

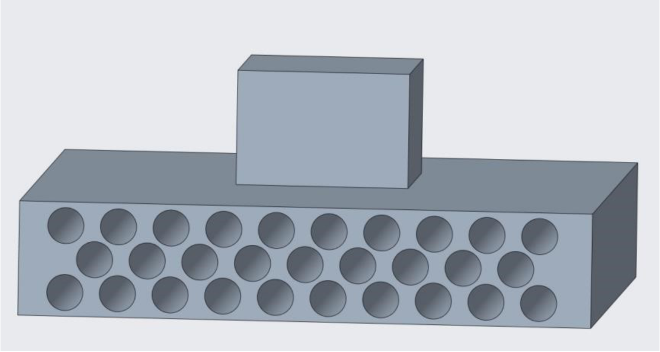

Figure 4. Uniform circular holes.

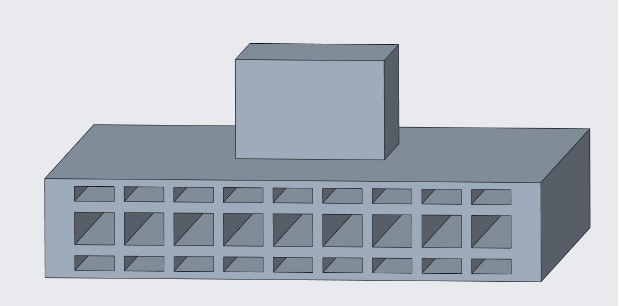

Figure 5. Gradient square holes.

To systematically examine the influence of gradient distribution on pore configuration, a controlled-variable approach is adopted, with two sets of single-factor comparative experiments designed. The first set keeps hole shape, hole position, and total mass roughly consistent, and introduces structural variation solely through differences in pore distribution patterns. Comparisons are drawn between uniform circular holes (U-C) and three-layer gradient circular holes (G-C) under these constraints to identify mechanical differences between gradient and uniform structural designs. As for the second set, the three-layer gradient pattern remains unchanged, with gradient circular holes (G-C) and gradient square holes (G-S) selected for comparative analysis. This experimental setup supports exploration of how hole geometry and stress concentration affect structural stability, and effectively weakens interference from multi-factor coupling on final research conclusions.

PTC Creo Parametric is adopted for the construction of all parametric 3D geometric models, as the platform supports efficient generation of multiple model variants by defining parameters such as hole diameters in the upper, middle, and lower layers and interlayer spacing. After being imported into Ansys, the models undergo transient impact solution via the Explicit Dynamics module. The bottom surface of each porous plate is fully constrained, and an initial velocity of 4.4 m/s is applied to the impact block. The preset analysis time course covers the entire contact establishment process and the main stage of crushing energy dissipation. To guarantee comparability across structural comparisons, a unified meshing strategy is implemented for all models, with local mesh refinement deployed around hole edges and layer interfaces. Frictionless contact is uniformly specified between the impact block and the foam, and mesh sensitivity analysis on a representative model validates the rationality of these settings. During the post-processing phase, key performance indicators are extracted for further quantitative analysis, including peak impact force, maximum compression displacement, energy absorption, specific energy absorption, and crushing force efficiency. The uniformity and stability of the crushing process are then evaluated using displacement contours and deformation animations.

4. Result analysis

4.1. Simulation conditions and evaluation system

This chapter compares three models—uniform circular hole structure (U-C), gradient circular hole structure (G-C), and gradient square hole structure (G-S) —from three perspectives: microscopic deformation mode, macroscopic mechanical curves, and energy absorption efficiency.

To systematically evaluate the mechanical response characteristics of the biomimetic gradient structure under dynamic impact, this study develops a constant velocity crushing numerical model based on the ANSYS Explicit Dynamics module. The crushing rate is set at 4.4 m/s to characterize medium- to high-speed impact conditions; the compression termination time is 4.5 m/s, corresponding to a theoretical displacement of the impact block of approximately 19.8 mm, which covers the contact establishment and the main crushing energy dissipation stage. The bottom of the model is fixed to simulate ground support, while the top impact block is given a Y-direction velocity of −4.4 m/s to model the impact.

To fully characterize the structural response, monitors such as total deformation, reaction force, and energy probes are set up in the post-processing module of each model. Among them, total deformation characterizes the macroscopic crushing mode of the structure, reaction force is used to extract the contact interface load and evaluate the impact strength, and internal energy is used to quantify the energy absorption of the structure. The relevant results are statistically analyzed through the Ansys simulation report.

4.2. Structural deformation mode analysis

The structural deformation mode directly determines the stability of the energy absorption process. The three structures, as revealed by total deformation contours derived from Workbench post-processing, present distinctly different failure mechanisms. (**Figure 6–9**)

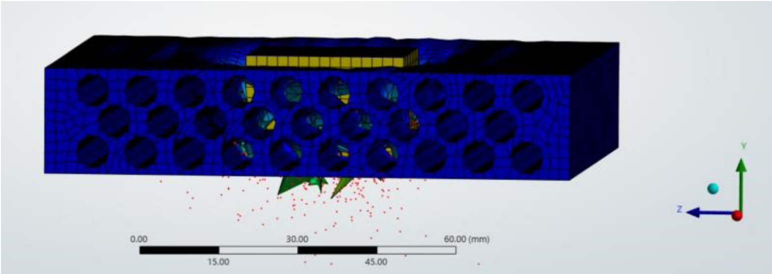

Figure 6. Deformation diagram of uniform circular hole structure (U-C).

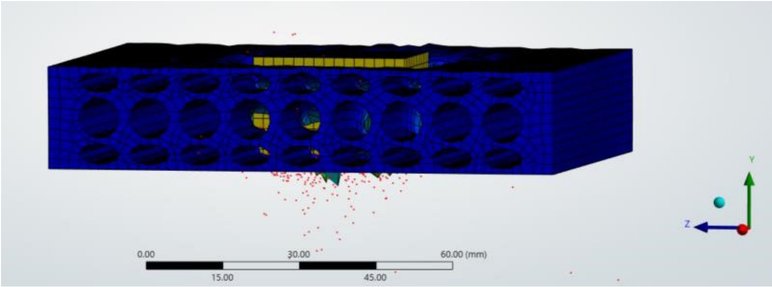

Figure 7. Gradient circular hole structure (G-C) deformation diagram.

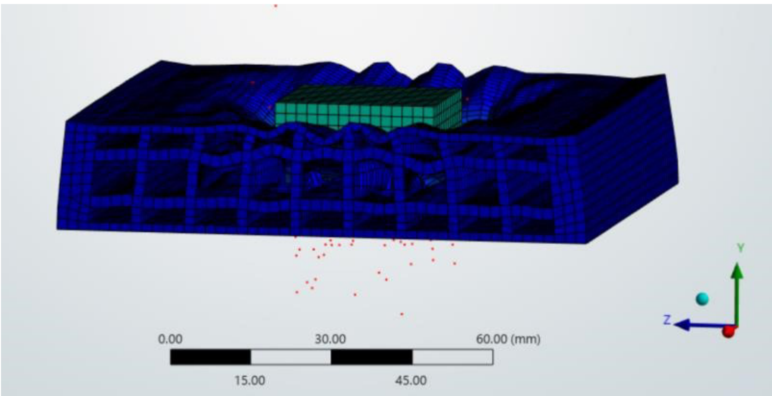

Figure 8. Gradient square hole structure (G-S) deformation.

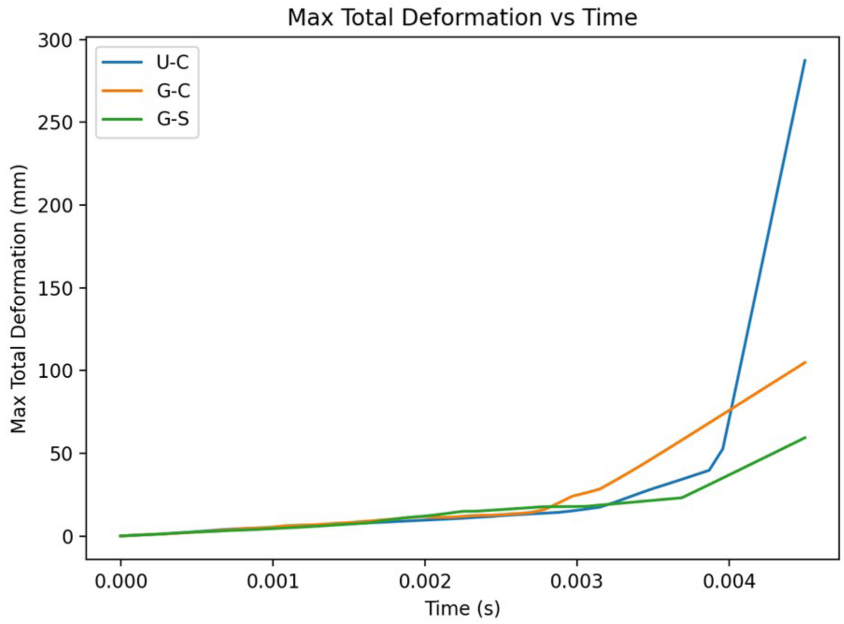

Figure 9. Time-history curves of maximum total deformation for the three structures.

In the comparison between the gradient structure and the uniform structure, the uniform circular pore structure (U-C) is more prone to random overall buckling or shear bands in weak areas at the initial stage of compression due to the uniform stiffness of the whole sample. This causes the stress to penetrate the sample and transfer to the substrate surface. Such deformation is non-hierarchical because the deformation movement of the pores can be easily exhausted, causing early local compaction. In contrast, the gradient circular pore structure (G-C) shows a mechanism of gradual collapse layer by layer. In the early stage of impact, the upper layer with high porosity first deforms and collapses; as the pressure increases, the middle and lower layers with higher density gradually bear the load and collapse in turn.

In the comparison of the hole geometric effects, although the gradient square hole structure (G-S) also adopts gradient design, there is pronounced stress concentration during its deformation process, mainly concentrated at the corners of the square holes. The vertical support ribs are also more prone to instantaneous buckling, resulting in large fluctuations in load-bearing capacity and indicating instability. In contrast, the gradient circular-hole structure (G-C) gradually evolves into an ellipse during compression, and the stress distribution along the hole wall is relatively uniform without significant concentration areas. Therefore, it can maintain good integrity under large deformation conditions, and the energy absorption process is also more stable.

4.3. Contact reaction force and impact protection performance

In express delivery logistics, the primary function of cushioning materials is to reduce the maximum impact force on the goods. This study extracts the Reaction Force at the contact interface between the impact block and the foam and uses it as a characterization parameter of the equivalent impact load on the goods during a drop.

According to the simulation results (**Table 1**), the peak reaction force (Fmax) varies significantly among the three structures: 1487.30 N for U-C and 1246.50 N for G-C—a reduction of 16.2%. For G-S, the value drops further to 980.71 N, a reduction of 34.1%. A higher peak reaction force indicates that the U-C structure generates a stiffer reaction at the moment of impact, which is detrimental to the protection of fragile goods. In contrast, G-C and G-S form a low reaction buffer through a low stiffness design at the top, effectively weakening the initial impact. The G-S has the lowest peak, mainly because the square hole structure is more prone to local instability and its overall stiffness is relatively lower. See **Figure 10**.

Table 1. Comparison of key impact resistance indicators for three structures

Model	Fmax (N)	Fmean (N)	CFE (%)	Dmax (mm)	EA(J)
U-C (uniform circular hole)	1487.30	356.32	23.96	287.260	1.4577
G-C (Gradient circular hole)	1246.50	285.43	22.90	104.750	1.2322
G-S (Gradient Square Hole	980.71	314.56	32.07	59.343	1.0946

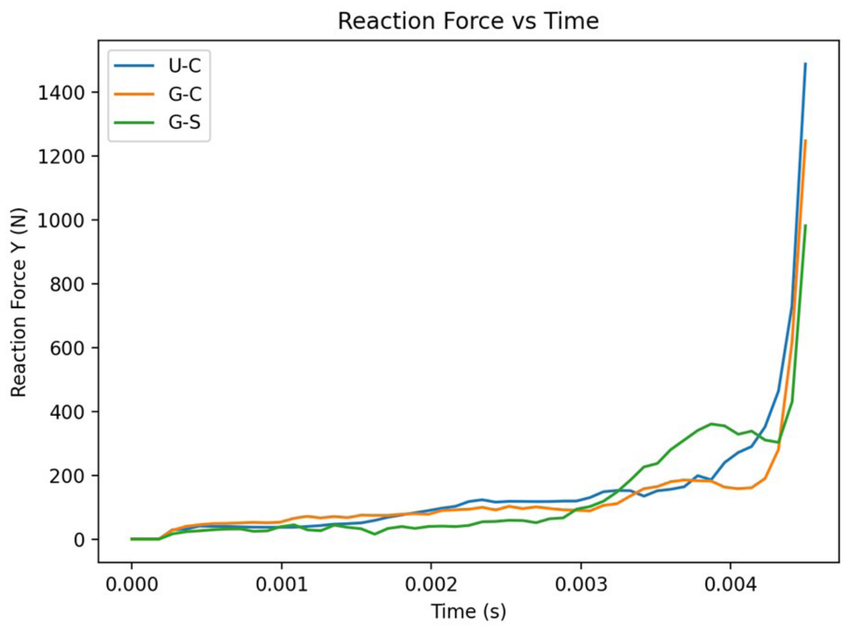

Figure 10. Time-history curves of reaction force for the three structures.

To further evaluate the stability of the cushioning process, this study introduces the crushing force efficiency (CFE, average force/peak force) indicator. The CFE of G-S is 32.07%, which appears to be the best. However, as shown in **Figure 4**, its force–displacement curve exhibits pronounced jagged fluctuations, indicating that the square-hole supporting units are prone to sudden instability during compression, which may in turn cause secondary vibration. The CFE of the G-C is 22.90%, slightly lower than that of the G-S, but its mechanical response curve is smoother with no abrupt changes, demonstrating better cushioning stability. The CFE of the U-C is about 23.96%, but its overall protection performance remains weak due to the high peak reaction force.

4.4. Energy absorption and lightweighting analysis

Another key performance indicator of the cushioning material is energy absorption capacity. In this study, the internal energy is extracted using an energy probe, as shown in **Table 1**.

The simulation results show that within the same compression duration (4.5 m/s), the U-C structure absorbs the highest internal energy 1.4577 J, but its maximum total deformation reaches 287.26 mm. It should be noted that this value is the result of cumulative mesh distortion, mainly reflecting the degree of local element failure rather than the actual physical deformation. In contrast, the absorbed internal energy of the G-C structure is 1.2322 J, and the maximum deformation is 104.75 mm; the G-S structure is 1.0946 J and 59.34 mm, respectively. Therefore, although U-C achieves relatively high total energy absorption, it does so at the expense of a higher peak force and more severe local damage. This is the classic high-stiffness behavior in impact energy absorption. In contrast, G-C and G-S engage in the loading through a gradient hierarchy, achieving energy dissipation while reducing the initial impact peak, which is more in line with the design requirements of express packaging that prioritize peak reduction while taking energy absorption into account.

The review of mass and specific energy absorption (SEA) indicates that the foam masses of the three models are 8.7618 g, 8.7571 g, and 8.7626 g, respectively, with a difference of less than 0.1%. Therefore, this group of results is more suitable for configuration comparison under nearly equal mass conditions and should not be interpreted as performance comparison under significant weight reduction conditions. In terms of EA/m, the SEA values for U-C, G-C and G-S are 166.37, 140.71 and 124.92 J/kg, respectively. Therefore, the advantage of G-C is that, under nearly equal mass conditions, the gradient circular hole design can effectively reduce the peak reaction force and improve the stability of the high-pressure breakdown process, thereby achieving better overall cushioning performance; the potential for lightweighting remains to be verified by adjusting porosity, introducing physical controls, or further parametric optimization.

4.5. Comprehensive evaluation and selection recommendations

By evaluating the three structures in terms of safety, stability, and manufacturability, the following conclusions can be drawn. The U-C hole structure is not the ideal choice due to several drawbacks. It generates the largest maximum reaction force at 1487 N, which will easily transmit a considerable load onto the protected goods in case of collision, thus increasing the likelihood of cargo damage. The deformation capacity of the U-C is relatively low, preventing full use of the shock-absorbing properties of the material. Despite generating the smallest maximum reaction force at 980 N among the considered types of holes, the G-S exhibits high stress concentrations and instability during crushing, resulting in a significant degree of irregularity and uncontrollability. In addition, the corners of the squares tend to tear off easily. This can be detrimental to the structural resistance. G-C, however, proves to be a good compromise between control over peak reaction and mechanical stability. Its total energy absorbed may be inferior to that of the U-C for this type of approximately equal mass models; nonetheless, its peak reaction is 16.2% lower than that of the U-C.

To conclude, in almost identical mass cases, the biomimetically designed gradient hole circular (G-C) structure provides a proper balance of low peak impact forces, consistent deformation behavior, and ease of manufacturing. Thus, it is considered better compared to others for express cushioning purposes.

5. Conclusions

In this paper, numerical simulations have been performed to analyze the effect of pore distribution and geometry on the mechanical behavior of cushioning materials. The key outcomes have been outlined hereafter.

(1) The results from the numerical simulation demonstrate that structures characterized by homogeneous distribution of pores tend to undergo global buckling, accompanied by fast stress transmission. The

bionic gradient structure realizes the layer-by-layer collapse mode of the soft layer yielding first and the hard layer yielding later through the spatial gradient of stiffness, thus prolonging the energy absorption process and improving the impact release effect.

(2) With regard to the reaction force, its magnitude can be decreased thanks to the introduction of gradient distribution. The G-C structure is characterized by a peak reaction force value of 1246.50 N; thus, the reduction in comparison with the U-C structure equals 16.2%. Therefore, the probability of damaging delicate cargo during transportation is greatly reduced.

(3) The hole shape is one of the factors that greatly affects the cushioning response of the material. Although the gradient square hole structure ensures the minimum peak reaction force (980.71 N), it causes high stress concentration at corners and leads to the instability of supporting layers and obvious fluctuation of mechanical response. In contrast, the stress distribution of the gradient circular hole structure is more uniform, the crushing process is more stable, and the engineering applicability is stronger.

(4) From the review of the mass and energy data, we can see that the mass of the foam for all three models is about 8.76 g, with slight differences between them. Thus, conclusions that much less mass of G-C or maximum specific energy absorption cannot be drawn. A more reasonable expression is that under the condition of approximately equal mass, G-C has both lower peak reaction force, a more stable crushing response, and better energy absorption performance, and the comprehensive cushioning performance is the best.

In summary, the biomimetic gradient circular hole structure can better balance safety, stability, and engineering manufacturability under nearly equal-mass conditions, demonstrating its potential as a cushioning packaging structure for express delivery.

Disclosure statement

The authors declare no conflict of interest.

References

[1] Zhang W, 2007, Review of Evaluation Methods for Cushioning Performance of Energy Absorbing Materials. Packaging Engineering, 28(5): 1–5.

[2] Yang B, 2022, Construction, Performance and Applications of Pomelo Peel-Inspired Gradient Porous Materials, thesis, Wuhan University.

[3] Gibson L, Ashby M, 1997, Cellular Solids: Structure and Properties (2nd ed.). Cambridge: Cambridge University Press.

[4] Wang M, 2023, Study on Impact Behaviors of Hierarchical Graded Cellular Materials and Sandwich Structures, thesis, Southeast University.

[5] Lin X, 2023, Shock Resistance and Energy Absorption Performance of Tube Reinforced Hyperelastic Gradient Porous Structure, thesis, Harbin Engineering University.

[6] Zhou J, et al., 2025, Study on Impact Resistance of Biomimetic Structures with Different Pore Shapes and Densities Under Lateral Impact. Mechanical and Electrical Engineering, 42(5): 945–954.

[7] Li J, 2021, Research on Impact Resistance and Interface Performance of Composite Structure Based on 3D Printing Method, thesis, Dalian University of Technology.

[8] Zhang S, 2022, Design of Novel Cellular Structures with Impact Resistance Properties, thesis, Harbin Engineering University.
[9] Yan J, Li X, Song X, et al., 2025, Deformation Modes and Energy-Absorbing Properties of Porous Structures of Local Stiffness-Reinforced Composites. Journal of Composite Materials: 1–16.
[10] Lian J, 2022, Research on Impact Resistance Behavior of Honeycomb Porous Structures, thesis, Harbin Engineering University.
[11] Li X, Song W, Chen J, 2019, Numerical Simulation of Mechanical Properties of 3D Printing TPMS Cellular Materials. Journal of Taiyuan University of Technology, 50(3): 386–393.
[12] Zhang W, 2023, Research Progress on Energy Absorption Properties and Vibration of Periodic Lightweight Porous Structures. Journal of Vibration and Shock, 42(4): 1–19.
[13] Peng Y, Xin Y, 2009, The Application of Cellular Materials in Automobile Crash-Safety. Journal of Mechanical Strength, 31(2): 325–329.
[14] Zhang J, et al., 2005, Preparation of Elastic Porous Composite Material and Its Energy-Absorption Characteristics. Packaging Engineering, 26(5): 13–15.
[15] Baroutaji A, Sankar A, Gilani N, et al., 2017, On Design Optimization for Structural Crashworthiness and Its State of the Art. International Journal of Crashworthiness, 22(5): 455–477.
[16] Lu T, 2009, Multifunctional Ultralight Porous Materials with Simultaneous Load-Bearing, Energy Absorbing and Sound Absorbing Capabilities. Science China: Technical Sciences, 39(9): 1477–1491.
[17] Zhang Q, Yang X, Li P, et al., 2015, Bioinspired Engineering of Honeycomb Structure–Using Nature to Inspire Human Innovation. Progress in Materials Science, 74: 332–400.
[18] Liu Q, 2016, Numerical Study on Dynamic Compression of Porous Materials, thesis, Beijing Institute of Technology.
[19] Wang D, 2006, Characterization Method of Buffering Energy Absorption Characteristics of Porous Materials. Packaging Engineering, 27(1): 37–39.
[20] Zhang H, He B, 2011, Finite Element Analysis. Beijing: Machinery Industry Press.

Publisher's note

Bio-Byword Scientific Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.