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Research on the Design of Paper-based Seamless Packaging Structures Based on Origami

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Abstract. This paper addresses the design requirements for deformable packaging structures by proposing a thin-walled structure based on Origami principles. Using triangles as the fundamental unit, this structure achieves morphological transformation from two-dimensional to three-dimensional through the folding and unfolding of a planar grid, possessing the capability to flexibly wrap irregular objects. The research employs Rhino and Grasshopper for geometric modeling and parametric design, utilizes ABAQUS for nonlinear finite element simulation to analyze the structural deformation behavior under load, and validates the folding performance and wrapping effectiveness through physical paper models. The results indicate that the designed structure can effectively achieve the preset bending and wrapping functions. By adjusting the geometric parameters of the units, it can adapt to objects of different shapes and sizes, providing an innovative design approach for lightweight, customizable packaging structures.

Keywords: Origami structure, Seamless packaging structure, Nonlinear finite element simulation.

1. Introduction:

Packaging engineering is a multidisciplinary field encompassing materials science, mechanical engineering, chemical engineering, logistics management, sustainability, and more [1-2]. Its core objective is to completely envelop a target object, protecting it from external environmental factors and impacts. From consumer electronics and precision instrument transportation to the aerospace sector, the market demand for innovative packaging solutions continues to grow, driving ongoing research and development in adaptive and intelligent packaging design. Common packaging structures include single-layer packaging, multi-layer composite packaging, bubble wrap packaging, foam plastic packaging, vacuum packaging, modified atmosphere packaging, intelligent packaging, paper-based packaging, heat-shrink packaging, and aluminum foil packaging, among others [3-4]. Single-layer packaging is typically used for lightweight, short-term use products, while multi-layer composite packaging provides excellent moisture, oxygen barrier, and impact resistance through the combination of different materials, widely used in food and pharmaceuticals. Bubble wrap and foam plastic packaging offer excellent cushioning protection, suitable for shipping fragile items. Vacuum packaging extends product shelf life by removing internal air, while modified atmosphere packaging maintains food freshness by adjusting the gas composition inside the package. Intelligent packaging integrates technologies like sensors and RFID to monitor product status in real-time. Paper-based packaging is environmentally friendly and offers a degree of protection, suitable for lightweight products. Heat-shrink packaging tightly conforms to the product, providing a neat appearance and dust/ moisture resistance. Aluminum foil packaging boasts excellent light and gas barrier properties, applicable to products with strict requirements regarding the external environment. Each packaging structure provides different solutions based on product characteristics and protection needs.

Thin-walled structures hold a significant position in modern structural engineering due to their excellent strength-to-weight ratio and high material utilization efficiency. Mengesha reviewed recent advances in the design, stability, and sustainability of thin-walled structures, emphasizing how modern engineering practices are reshaping their application and performance [5]. Utilizing cutting-edge tools such as finite element analysis, topological optimization, and emerging artificial intelligence technologies, structural efficiency and stability are enhanced by optimizing load paths and improving geometries [5]. Owing to advantages like lightweight, high strength, and high material utilization, thin-walled structures are widely used in modern engineering and industrial design. For example, they are used in aircraft fuselages and wing surfaces in aerospace to improve aerodynamic efficiency, in chassis and body panels in the automotive industry for lightweighting and enhanced crash performance, and in structural optimization for bridges and buildings [5]. The author posits that thin-walled structures can also be applied in packaging engineering. By optimizing packaging design, material usage can be reduced while ensuring packaging strength and stability, which is significant for reducing environmental burden and improving transportation efficiency [6]. The lightweight and high-strength characteristics of thin-walled structures make them an ideal choice in packaging design, especially in modern logistics and transportation, where the weight and volume of packaging directly impact cost and efficiency [7]. For instance, packaging utilizing thin-walled structures can not only effectively reduce material consumption but also decrease carbon emissions during transportation while providing sufficient protection [7]. Therefore, the application of thin-walled structures not only aligns with the concept of sustainable development but can also effectively improve the overall performance of product packaging, promoting green logistics and environmentally friendly packaging.

As a relatively novel type of thin-walled structure, Origami — the ancient art of paper folding—has transcended its artistic roots to become an important source of inspiration in engineering and structural design. So-called "origami structures" typically refer to engineering structures based on origami patterns, possessing predefinable deployment paths, deformation modes, and mechanical properties. They aim to create deployable, reconfigurable, and functionally versatile mechanical metamaterials through abstracted folding patterns and geometric configurations [8]. These structures can be systematically classified based on their crease patterns—such as Miura-Ori (a rigidly foldable pattern with negative Poisson's ratio properties, proposed by Miura K. in 1985, widely used in aerospace deployable mechanisms), Kresling origami (a bistable origami pattern with a helical deformation mode, often used in reconfigurable structures and robotic joint design [9]), and Square-twist (an origami pattern based on square twisting capable of in-plane to out-of-plane morphological transformation)—and their functional characteristics, which include deployability, energy absorption, tunable stiffness, and morphological programmability [10]. Yang et al. proposed an Origami structure with circular folding functionality and, based oandis, realized the construction of a wheel [11]. The inherent properties of folding allow complex three-dimensional structures to be compactly stored and deployed on demand, making them particularly suitable for applications in packaging, robotics, and aerospace deployable mechanisms [11].

Substantial research has demonstrated practical applications of origami principles. Notable examples include deployable solar panels and flat-panel antenna arrays for spacecraft, which are volume-minimized during launch and deployed into large-area functional structures in orbit. In the packaging field, researchers have also explored specific origami-inspired designs, such as foldable cartons, cushioning structures, and protective casings. For instance, "origami grippers" and some structures based on crumpling utilize folding to conform to and grasp objects of various shapes. However, when the research focus shifts to packaging applications requiring complete, seamless encapsulation, particularly for irregular or non-standard shaped objects, a key limitation emerges. Many existing origami-based packaging solutions lack sufficient deformation adaptability. They may wrap regular, prismatic objects well but often struggle to achieve uniform, gapless, and seamless wrapping for complex geometries. Their exteriors frequently retain obvious, irregular creases or gaps, which not only affects aesthetics but may also compromise the integrity and protective function of the packaging.

To address this issue, this paper proposes and investigates a novel, origami-inspired wrapping structure aimed at achieving seamless encapsulation. The core objective of this research is to design a planar thin-walled structure capable of adaptively conforming to and ultimately forming a foldable, seamless surface structure. The research work will include the conceptual design of the foldable origami structure, kinematic analysis of the folding process, and physical validation through prototyping. This study aims to overcome the limitation of external traces present in traditional wrapping methods by designing an internal folding structure, providing a practical basis for advancing the development of adaptive packaging solutions.

2. Geometric Modeling

2.1. Software Tool Selection

In innovative and performance-driven thin-walled structure design, geometric modeling has transcended traditional morphological expression to become a core means of exploring structural behavior and performance optimization. Among various design tools, the algorithmic design method based on the Rhino platform combined with the Grasshopper visual programming environment demonstrates significant advantages over traditional parametric CAD software (e.g., SolidWorks). This is particularly true for complex surface generation, morphological optimization, and performance-driven packaging structure design. This section argues for the suitability and necessity of Rhino and Grasshopper in this research from the following three aspects:

1. Project Relevance: The core problem of this research is "how to achieve adaptive wrapping of irregular objects." Such problems are difficult to solve effectively in SolidWorks, whereas Grasshopper provides rich algorithmic components and morphological generation tools, offering natural technical support for this research.

2. Innovation Potential: SolidWorks is suitable for known and regular design scenarios, while Grasshopper supports generative design and performance optimization, enabling the exploration of irregular, high-performance structural morphologies and expanding design possibilities.

3. Workflow Integration: From geometry generation and simulation analysis to result feedback and automatic optimization, Grasshopper can construct an integrated "simulation-driven design" workflow, significantly improving design efficiency and system adaptability.

In summary, although SolidWorks still holds value in conventional engineering design, selecting Rhino and Grasshopper as the primary design tools is a key decision to ensure the smooth progress of this exploratory research and achieve innovative breakthroughs, given the morphological complexity and exploratory goals of this study.

2.2. Model Presentation and Discussion

Origami structures are common thin-walled foldable structures. This study selects four connected small triangles to form a basic folding unit (Figure 1a), which combines geometric simplicity with deformation flexibility. A complete foldable planar model is formed by arranging this unit in a two-dimensional array and adding an overall supporting baseplate (Figure 1b). This model controls the bending path through crease design, providing a geometric foundation for subsequent simulations and experiments.

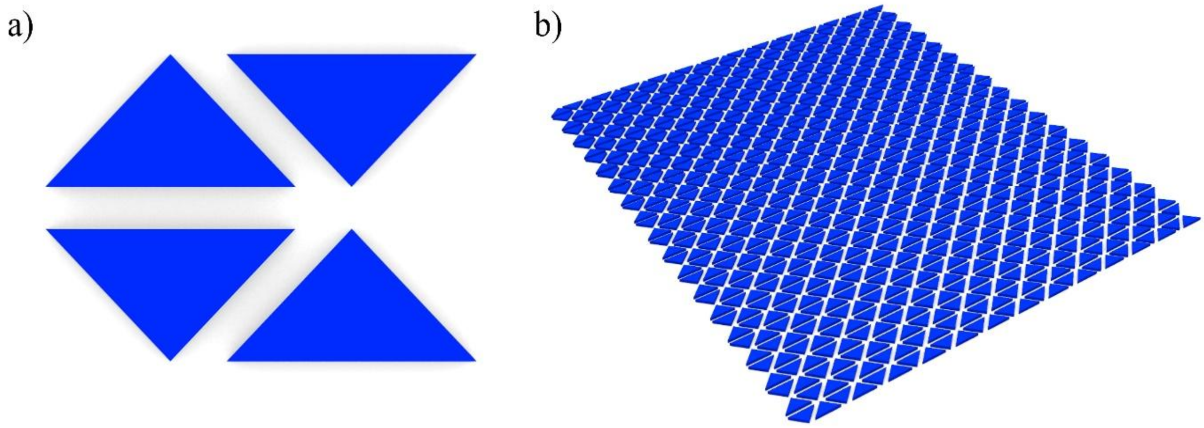

Figure 1. Origami Model Graph:a)Basic unit;b)Array structure.

3. Simulation

3.1. Software Tools and Simulation Setup

To deeply reveal the deformation mechanisms and mechanical response of the structure under load, this study employs ABAQUS/Standard 2022 for nonlinear static finite element simulation. ABAQUS has excellent solving capabilities in geometric nonlinearity, material nonlinearity, and contact nonlinearity, making it particularly suitable for simulating the large deformation behavior of origami structures. The simulation model is strictly constructed based on the geometric parameters established in Section 1, following this systematic procedure:

1. Geometry Import and Topology Repair

The planar origami model generated in Rhino/Grasshopper is imported into ABAQUS/CAE in STEP format. Geometric cleanup is performed in the Part module to repair minor gaps (tolerance ≤ 0.001mm) and duplicate surfaces that may arise from format conversion, ensuring the model is a continuous, complete shell-like entity, laying the foundation for high-quality meshing.

2. Material Property Definition and Constitutive Model

Referencing the mechanical properties of the paper used in experiments, but to facilitate the simulation of the model's bending deformation, a weakened linear elastic material model is defined in the Property module: Elastic Modulus is set to 100 MPa, Poisson's ratio to 0.3, and density to 800 kg/m^3. Three-dimensional solid elements (C3D8R) are used to discretize the model, suitable for large deformation and large strain analysis of solid structures. Section properties are defined as homogeneous.

3. Assembly and Analysis Step Setup

An instance is created in the Assembly module, positioned using the global coordinate system. Subsequently, a "Static, General" analysis step is created in the Step module, with the geometric nonlinearity option activated (Nlgeom: ON). Total time is set to 1, using an automatic increment strategy with an initial increment of 0.01, a minimum increment of 1e-4, and a maximum increment of 0.01 to ensure convergence.

4. Load and Boundary Condition Definition

In the Load module, all degrees of freedom on the bottom edge of the model are constrained (ENCASTRE), simulating actual hand-holding or fixing conditions. The load is applied as a uniform pressure, gradually applied in five analysis steps with different pressure magnitudes to simulate a progressive bending process. Contact behavior is defined as self-contact with a friction coefficient of 0.2, simulating the interaction between facets during folding.

5. Meshing and Convergence Verification

A structured meshing technique is employed, with a global seed size of 1.5 mm and local refinement along crease lines to 0.5 mm. A mesh sensitivity analysis is conducted, comparing the maximum displacement results under three different mesh densities; the difference is less than 3%, indicating that the current mesh setup provides sufficient computational accuracy.

3.2. Simulation Results Presentation and Discussion

Figure 2a shows the final finite element mesh model adopted, with regular element shapes and an aspect ratio controlled within 1.5. Figures 2b and 2c present the deformation displacement contour plots from side and oblique views, respectively, under the phased pressure application.

The simulation results indicate:

The structural deformation exhibits obvious crease-driven characteristics, with displacement increasing from the constrained bottom region towards the free end, and the maximum displacement located in the top central area of the structure.

The deformation process is smooth and controllable, without local buckling or tearing phenomena, verifying the rationality of the crease layout.

The simulation results mechanically confirm that this origami structure possesses the capability for continuous, stable deformation from a planar state to a curved surface, and that the degree of wrapping can be controlled by the load magnitude, providing theoretical prediction and deformation guidance for the physical experiment.

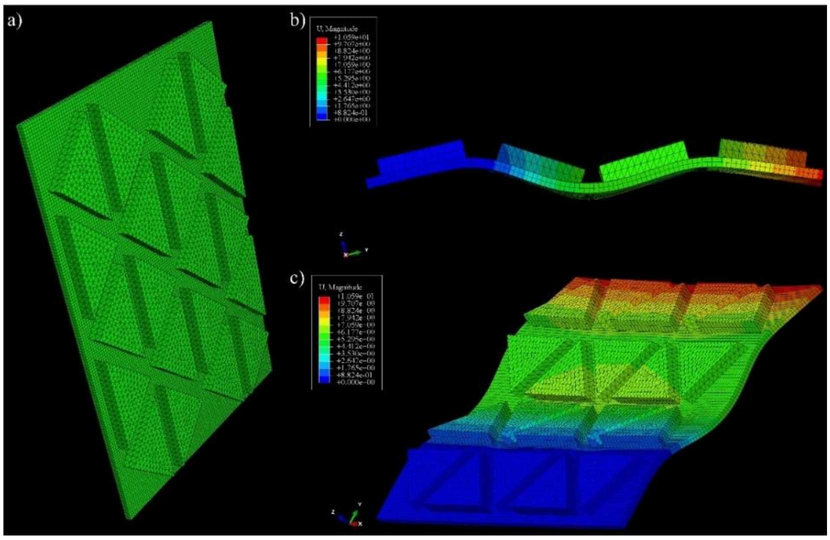

Figure 2. Simulation Model and Results: a) Mesh Model; b) Side View of Deformation Contour; c) Oblique View of Deformation Contour.

4. Experimental Validation

4.1. Materials

To faithfully reflect the material behavior of the simulation model, standard A1 paper (basis weight: 80 g/m², thickness: 0.1 mm) was selected as the folding substrate for the experiments due to its good uniformity, suitable for crease formation. The upper triangular units were made from lightweight EPE foam board (Elastic Modulus ≈ 12 MPa) to provide necessary in-plane stiffness while maintaining overall lightness. PVA white glue was used for bonding, remaining flexible and non-brittle after curing. Auxiliary tools included a precision paper cutter, steel ruler, scoring stylus, and angle positioning template to ensure fabrication accuracy. The physical materials are shown in Figure 3.

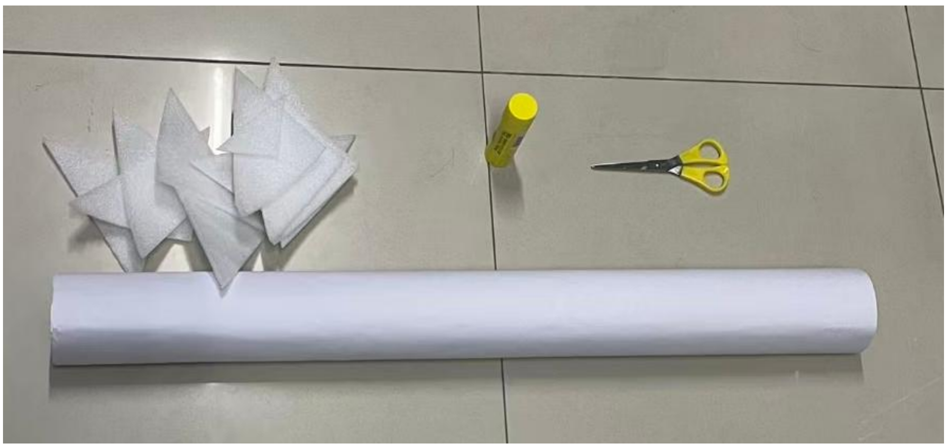

Figure 3. Experimental Materials.

4.2. Fabrication

The fabrication process is as follows (see Figure 4):

a) **Creating Creases on Paper:** First, lightly mark the crease lines on the paper with a pencil, ensuring precise crease positioning. These creases serve as guides for subsequent folding, allowing the paper to fold according to the designed geometry. This step is fundamental to origami structure fabrication; creases must be even and precise to ensure subsequent folding and shape accuracy.

b) **Foam Unit Cutting and Bonding:** Use a paper cutter and an angle template to cut the EPE foam board into equilateral triangles with a side length of 30 mm, controlling the tolerance within ±0.3 mm. After cutting, the edges of all units are sanded to ensure smooth surfaces and avoid stress concentration due to uneven edges. Then, using a positioning jig to fix the foam triangles one by one, apply solid glue evenly to the contact surface of each unit to ensure firm bonding. Apply pressure for 60 seconds to ensure bubble-free adhesion and tight interlayer bonding.

c) **Crease Pre-treatment and 3D Structure Formation:** Use a scoring stylus to score along the designed crease lines; the scoring depth is about one-third of the paper's thickness, creating guiding grooves to reduce folding resistance and ensure shape accuracy. This pre-treatment allows easy control of the paper's bending direction during folding, ensuring more precise formation of the three-dimensional structure.

d) **Squeezing and Final Wrapping Structure Formation:** Based on the pre-formed creases, gradually fold and wrap the paper or foam units through manual squeezing, ultimately completing the designed wrapping structure. During this process, the angle and position of each crease need careful adjustment to ensure structural integrity and stability.

Through these steps, the paper or foam material can be effectively transformed into a three-dimensional structure with high precision and stability.

Figure 4. Fabrication Process of the Paper-based Wrapping Structure Based on the Origami Principle: a) Creating creases on the paper b) Cutting and bonding of foam units c) Crease pre-treatment and three-dimensional structure formation d) Squeezing and final formation of the wrapping structure.

4.3. Experimental Results and Discussion

The completed physical Origami planar structure is shown in Figure 5a, containing a total of 125 = 60 triangular units. Folding tests indicate:

The structure can deform smoothly along the preset creases; applying reasonable manual pressure can guide it to gradually curl into a spherical shape. The entire process occurs without tearing or local failure (Figures 5b, 5c).

The formed structure approximates a sphere, with internal space capable of accommodating small objects.

After repeated folding several times, no significant fatigue damage was observed in the crease areas, and the structure could still return to its complete spherical shape, demonstrating good durability and shape memory characteristics.

The experiments show that this structure exhibits excellent deformation controllability, load adaptability, and geometric adaptability, validating its feasibility as a customizable packaging carrier.

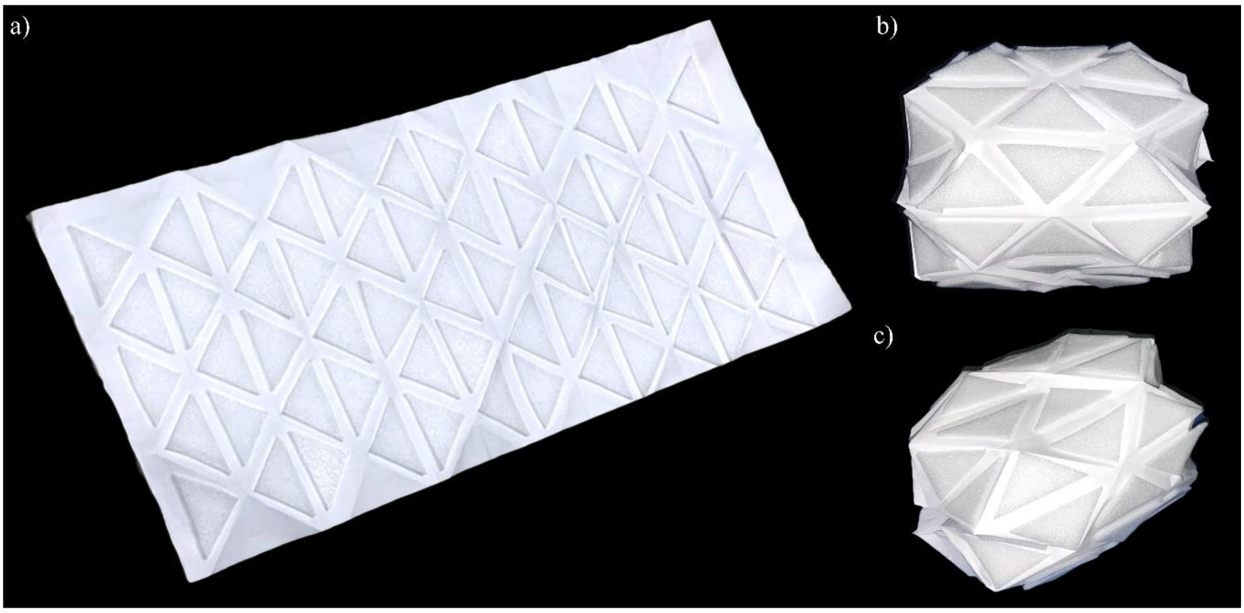

Figure 5. Experimental Results: a) The fabricated Origami structure in its flat state and the structure after folding; b) Front view; c) Oblique view.

5. Conclusion

This paper designed and validated a deformable packaging structure based on Origami principles. Using triangles as the basic unit, this structure achieves efficient transformation from two-dimensional to three-dimensional through planar folding/unfolding, possessing good morphological adaptability and wrapping capability. Combining parametric modeling, finite element simulation, and physical experimentation, the research systematically analyzed the structure's deformation mechanisms and performance. This structure combines lightweight, customizable, and environmentally friendly characteristics, providing a new design approach for future deformable and adaptive packaging structures.

Future research could focus on adjusting the geometric parameters of the triangular units (such as side length ratio, internal angles) to flexibly control the final wrapped morphology's size and curvature, adapting to objects of different volumes and shapes.

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