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Design Scheme and Feasibility Study of Self-locking Inflatable Tent Based on Multistable Inflatable Origami

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Abstract

This study extends the work initiated by Melancon et al., exploring the application of multistable zero-thickness origami schemes. To translate zero-thickness origami design into a functional self-locking inflatable tent, the study proposes a fabrication approach employing thickened origami methods. The tent's multi-stability and comfort are ensured through the design of composite panels. Additionally, PVC membranes are integrated to define the crease structure within the origami, thus enhancing the tent's durability. The assembly of the thick panel origami model is realized through a designated membrane welding procedure. Subsequently, to validate the feasibility of the tent structure design, modal analysis and load-bearing capacity calculations are performed using ABAQUS. The load-bearing capacity calculation can be achieved based on the Riks method through buckling and post-buckling analyses. The critical load for the tent structure in this design scheme is determined to be 0.696 kPa, meeting the load-bearing performance requirements for the tent as a temporary structure. These research findings can provide design solutions and data references for subsequent model fabrication and testing.

Keywords: multistable inflatable origami, composite panels, thick panel origami, modal analysis, Riks method.

1. Introduction

The tent, as a temporary architectural structure, boasts a rich history spanning millennia, distinguished by its portability, lightweight construction, easy setup and dismantling, and versatile applications. It plays a vital role across various domains including emergency relief, commerce, medical services, and tourism, underscoring its significant societal importance (e.g. Shibo. [1]).

Presently, tents can be broadly classified into two main types based on their setup methods: frame tents (e.g. Heping et al. [2], Alekseeva. [3], Yanjun. [4]) and inflatable tents (e.g. De Vries. [5], Findeisen et al. [6], Skouras. [7], Turner et al. [8], Cassapakis et al. [9]). Frame tents comprise a canopy fabric supported by a frame, where the fabric provides protection against sun, wind, and rain, and offers some insulation, while the frame primarily bears the loads, thus dictating the tent's performance. Frame tents are cost-effective, possess reliable load-bearing capabilities, exhibit adaptability, and are available in various mature setups, rendering them the prevailing tent type. However, assembling frame tents can be laborious due to their component-based nature, and they often lack seamless integration. Inflatable tents are predominantly categorized into air-sealed and air-rib types, both employing air ribs as primary load-bearing elements. Air ribs, resembling air bladder structures, endure external loads by forming a unified structure through dual-layer membranes with internal air pressure. Inflatable tents feature high levels of integration and can self-expand through inflation, facilitating a convenient and swift setup. Nevertheless, maintaining optimal internal air pressure within the air rib units post-inflation necessitates ongoing maintenance.

Inspired by the principles of origami, Melancon et al. developed a multistable enclosure structure (e.g. Melancon et al. [10]), laying the theoretical foundation for self-locking inflatable tents. The tent can expand and lock through inflation without the need to maintain internal air pressure. Focusing on geometric principles, Melancon et al. designed a zero-thickness origami model for self-locking inflatable tents and experimentally validated its multistable performance through thin-sheet models. Subsequent research necessitates proposing specific material compositions and fabrication methods from the perspectives of usage performance and thick panel models.

During the engineering application of zero-thickness origami solutions, the thickness of various materials must be considered, as any deviation may result in significant physical interference in the folding direction (e.g. Chen Y et al. [11]). To address this issue, researchers have proposed several methods for handling thick panel origami: wedge surface techniques (e.g. Tachi et al. [12]), offset panel techniques (e.g. Edmondson et al. [13]), offset hinge techniques (e.g. Tolman et al. [14]), auxiliary panel techniques (e.g. Yuanqing et al. [15]), double hinge techniques (e.g. Jason S et al. [16]), and membrane techniques (e.g. Edmondson et al. [17]). These methods enable accommodating the thickness of origami materials while preserving their original folding behaviors, marking significant progress in the practical application of origami in engineering.

Building upon the work of Melancon et al., this study aims to enhance the multistable zero-thickness origami solution by integrating thick panel origami handling methods and tent application requirements, resulting in a self-locking inflatable tent capable of providing certain insulation, waterproofing, airtightness, and load-bearing capabilities. Considering the structural and operational differences between self-locking inflatable tents and traditional tents, further research is necessary to explore the usage performance of this novel tent type.

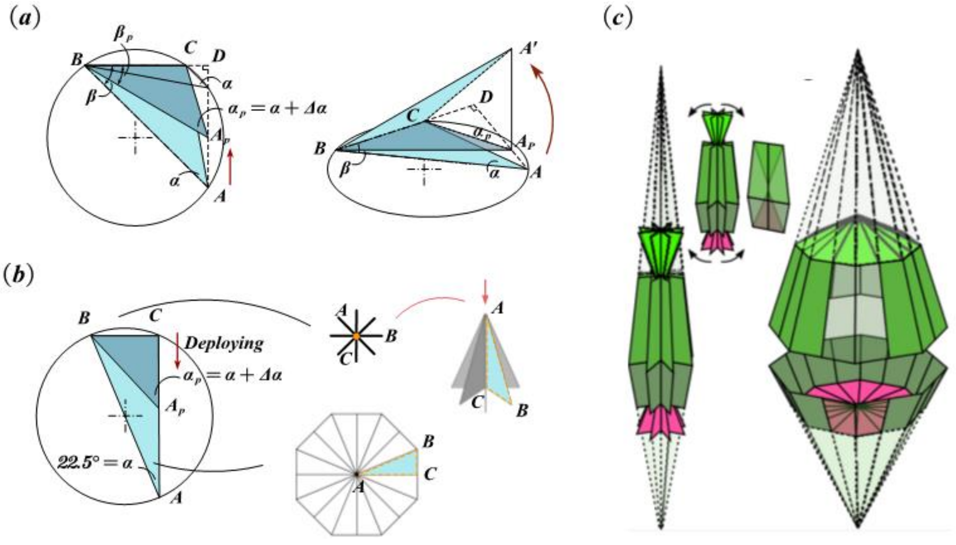

Figure 1: The Unfolding Process and Geometric Conflict Mechanism of Bistable Origami: (a) The schematic diagram of the unfolding process of a triangular prism element is presented, where A_p represents the projection of point A on the initial plane during the unfolding process, α_p and β_p denote the projections of angles A and B on the initial plane, respectively, $\Delta\alpha$ signifies the change in projection angle compared to the initial projection angle.(b) The unfolding diagram of triangular prism elements utilized in the self-locking inflatable tent model is illustrated, with A_p, α_p, β_p, and $\Delta\alpha$ carrying the same symbolic meanings as in Fig (a). (c) Schematic representation of the zero-thickness folding pattern of the self-locking inflatable tent (e.g. Melancon et al. [10])

2. Geometric Dimensions and Fabrication Method of Self-Locking Inflatable Tent Model

This section discusses the geometric design dimensions of the self-locking inflatable tent and the corresponding fabrication method of the physical model. Initially, the bistable mechanism and geometric dimensions of the tent model components are introduced. Subsequently, the design approach for the corresponding thick panel model is presented. Finally, the various components within the composite tent panel are elucidated, alongside the welding assembly strategy for the membranes.

2.1. Design of Bistable Origami Units

The bistable origami structure proposed by Melancon et al. comprises closed structures composed of triangular unit cells. The bistability of this structure arises from the bending deformation of the triangular unit cells during the unfolding process to overcome geometric incompatibilities. The phenomenon of geometric incompatibility can be explained using the theory of inscribed angles in circles: during the unfolding process of the enclosed structure, as depicted in Fig 1(a), the projected angle α of the triangular unit cells satisfying geometric condition (1) increases, leading to a geometric incompatibility Δα.

$$\alpha = \left[0, \frac{\pi}{2}\right] \tag{1}$$

$$\beta = \left[\frac{\pi}{4} - \frac{\alpha}{2}, \frac{\pi}{2} - \alpha\right] \tag{2}$$

In this design, the projection of the inflatable self-locking tent in the unfolded state forms a regular octagon, composed of 16 triangular panels with projected angles of 22.5°, all meeting condition (1). The variation in projected angles of these triangular panels during the unfolding process is illustrated in Fig 1(b), with the panels folded perpendicular to the initial plane. To enhance the volume-to-folded ratio and better suit the tent's usage characteristics, the angle A portion of triangle ABC is removed, leaving a quadrilateral for assembly following the aforementioned method, while still maintaining the structural bistability. Finally, combining the triangles and quadrilaterals as shown in Fig 1(c) yields the basic configuration of the inflatable self-locking tent, also referred to as the zero-thickness origami scheme. The geometric dimensions of the inflatable self-locking tent in this study are depicted in Fig 2, with model dimensions in the folded state measuring 1000×2000×80mm and in the unfolded state measuring 2414×2414×2338 mm.

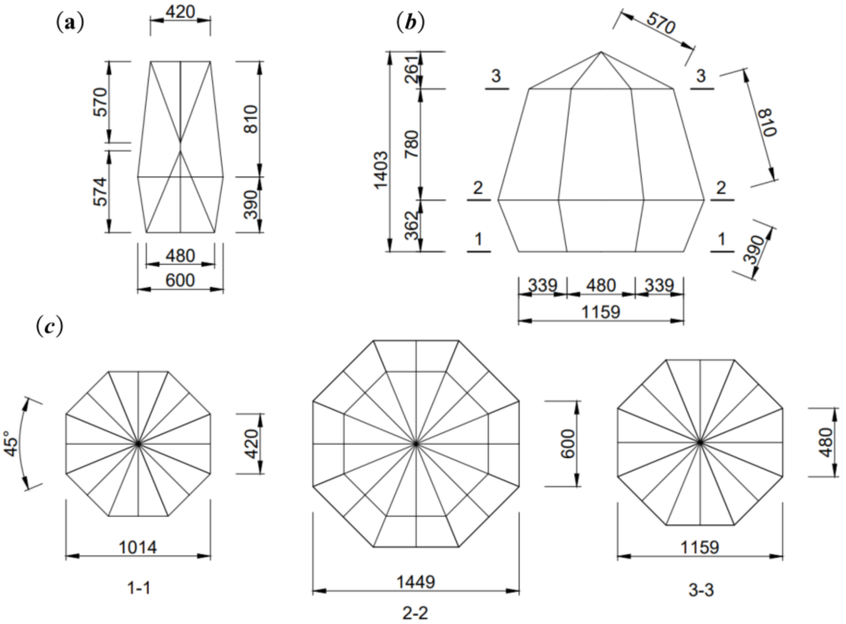

Figure 2: Dimensional Diagram of Zero-Thickness Origami Model:(a) Dimensional diagram of the folded state origami model;(b) Dimensional diagram of the unfolded state origami model;(c) Cross-sectional diagram of the unfolded state origami model, comprising sections 1, 2, and 3

2.2 Thick Panel Origami Model

The objective of the multi-stable origami's thick panel origami model is to achieve rigid rotation between various flexible folding components. In this study, zero-thickness origami is processed into thick panels using auxiliary panel techniques, wedge surface techniques, and thin membrane techniques. The resulting thick panel model should possess foldability and airtightness, while also maintaining geometric continuity between composite panels as much as possible after unfolding, thus reducing gaps between panels. Taking the portion illustrated in Fig. 3 as an example, the thick panel origami model corresponding to the four crease fold vertices cannot be connected through a single hinge after unfolding.

To address this issue and consider the structural load-bearing capabilities of various components of the tent structure, an auxiliary panel (panel 4) is added to facilitate the connection and mutual rotational movement of the left and right panels. Additionally, thin membrane technology is employed using PVC membrane as an intermediary to connect panel 3 and panel 4 within the composite panel. Finally, the thick panel origami model corresponding to each unit can be obtained by eliminating the geometric conflicts between them.

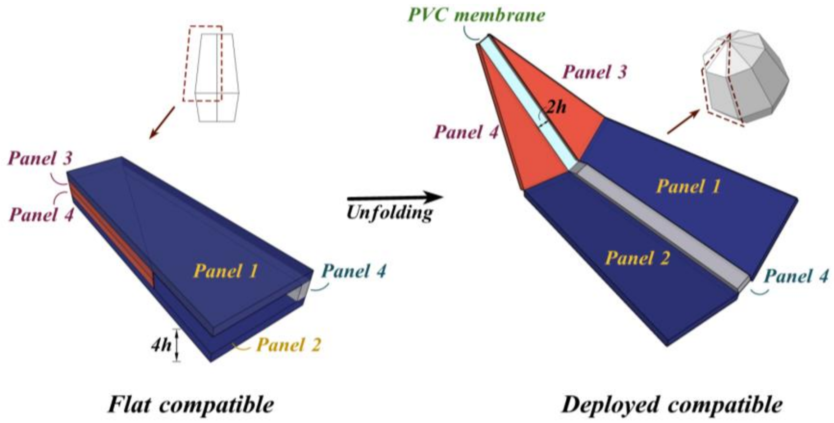

Figure 3: Schematic Diagram of Thickening Treatment Scheme

2.3. Design of Composite Panels and Assembly Scheme

2.3.1 Design of Composite Panels

Unlike traditional tents, the unfolding of the self-locking inflatable tent involves the stable transformation process of its components accomplished through internal air pressure. The energy change during the stable transformation process originates from the deformation potential energy of the panels, implying that the load-bearing components of the self-locking tent can undergo considerable elastic deformation. Considering the tent's usage requirements, polypropylene panels are chosen as the load-bearing components for the self-locking inflatable tent. Polypropylene panels feature lightweight, heat resistant, chemical stability, and non-toxic properties, with their most outstanding performance being resistance to bending fatigue, which aligns perfectly with the needs of the self-locking inflatable tent.

As an emergency temporary structure, and considering comfort, the self-locking inflatable tent needs to have certain insulation capabilities. To achieve this, an insulation layer is adhered outside the structural layer composed of polypropylene panels. The insulation layer primarily consists of aluminum foil, polyethylene, and pearl cotton, providing not only excellent insulation performance but also good fire resistance. The insulation layer can deform along with the structural layer during the tent's unfolding process, and due to its soft texture, its elastic properties can be ignored.

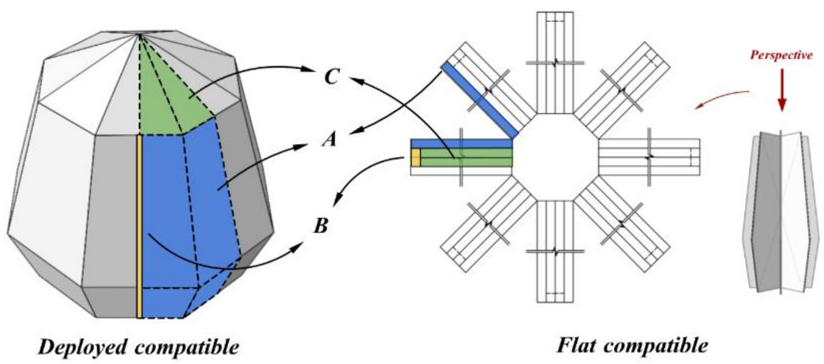

Figure 4: Schematic Diagram of Model Partitioning

Finally, the structural layer and insulation layer are enveloped with PVC membrane to form the basic unit of the self-locking inflatable tent - the composite panel. PVC membrane enables a strong bond between the structural layer and the insulation layer, preventing separation or detachment. Moreover, the PVC membrane itself is corrosion-resistant, fire-retardant, pollution-resistant, and resistant to aging, making it highly suitable for both the inner and outer surfaces of tent panels. Additionally, the welding properties of PVC membrane provide a means for connecting composite panels and can create creases in the origami structure, facilitating the creation of hinges in the thick panel origami design scheme.

2.3.2 Assembly Scheme of Self-locking Inflatable Tent

The connection of composite panels is based on thin membrane technology using PVC membrane, where the membrane is welded in a specific sequence to form corresponding creases of the origami structure. To ensure the feasibility of the structural fabrication scheme, it is essential to start from predetermined rotational axis positions in the thick panel model and strategically arrange the positions of membrane weld seams to meet the constraints of actual welding operations.

As shown in Fig 4, for ease of assembly, the tent structure is divided into three parts: A, B, and C. For component A, the arrangement of the membrane and the position of weld seams are depicted in Fig 5(a). Weld seam a is welded on the workbench after folding component A along the vertical crease, while weld seam e is welded after folding along the horizontal crease. In the thick panel treatment process of component B, auxiliary panels are used to connect various parts of A. The welding of seams b_1 and b_2 occurs in the folded state as illustrated in the diagram.

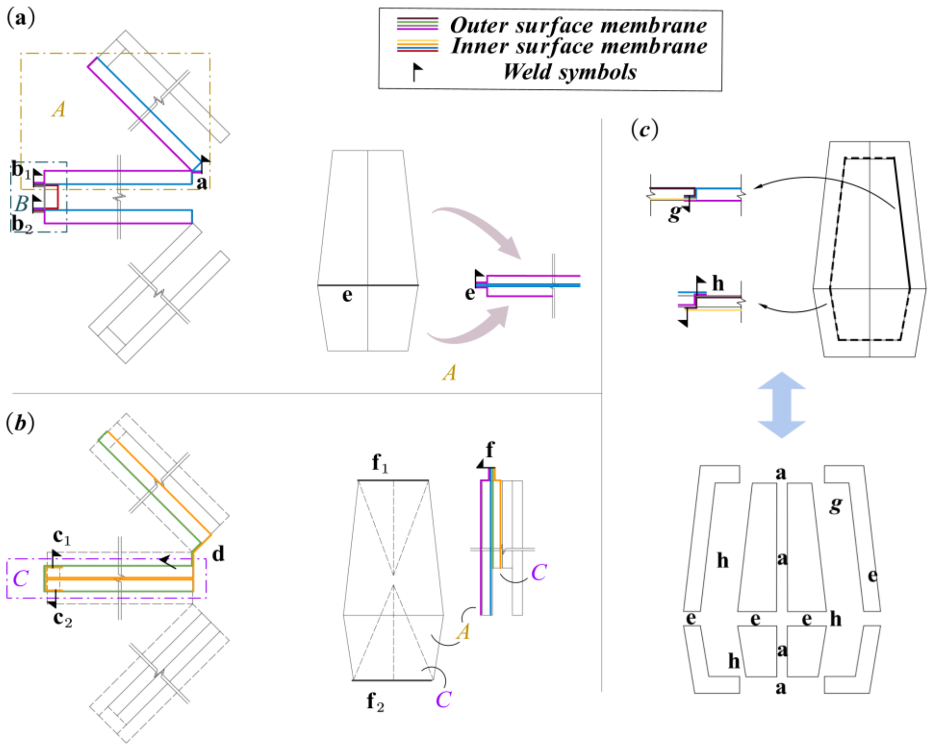

Figure 5: Inflatable Self-Locking Tent Membrane Welding Scheme: (a) Schematic of membrane composition and connection scheme between component A and component B, where a-h represent different cross-sectional welding methods;(b) Membrane welding scheme of component C and its connection scheme with component A;(c) Membrane welding scheme of door component.

The arrangement of the membrane and the position of weld seams for component C are illustrated in Fig 5(b). Unlike components A and B, the welding process for component C involves only the membrane. Specifically, weld seams d, c_1, and c_2 are welded individually for each component C, securing the membrane parts. Subsequently, the membrane parts of each component C are joined together through weld seam d. Then, the structural layer and insulation layer, which were not previously welded, are inserted through openings f_1 or f_2, and component C is connected to component A via weld seams f_1 and f_2 to form the main body of the tent. The welding process occurs in the folded state as shown in the diagram.

The tent model includes a door, designated as component D, which involves creating an opening on component A as shown in Fig 5(c) and assembling it according to the illustrated weld seam arrangement. The connection method between component D and other components is the same as that for component A. In Fig 5(c), the blue dashed lines represent the membrane on both sides that are not welded together but are connected using waterproof zippers installed internally and externally. The red solid lines represent the membrane on both sides welded together, serving as the hinge for the door. The numbering of each weld seam in the diagram represents the scheme for the arrangement of membrane and weld seam positions, consistent with the previously mentioned numbering scheme.

3. FEA model Configuration

Sections three and four will verify the mechanical performance of the inflatable self-locking tent through finite element simulation analysis. This section encompasses the introduction of material properties, constraints, loading scenarios, and analysis methodologies.

3.1. Material properties

First, a geometric model is established based on the dimensions outlined in the above schem. Considering that the insulating layer in the inflatable self-locking tent does not bear any load and that the energy barrier for steady-state transitions comes from the elastic potential energy of the structural layer, polypropylene is chosen as the material property in the finite element model. The relevant mechanical properties are listed in Table 1.

Table 1: Polypropylene material properties

Mass density (g/cm^3)	1.1
Young's modulus (Gpa)	0.89
Poisson's ratio	0.4203

3.2. Loading and Constraint Settings

Due to variations in the assembly scheme of the self-locking inflatable tent, corresponding adjustments are necessary in the finite element model. Specifically, tie constraints are applied between the membrane welding locations to simulate the connection between the panels, as depicted in Fig 6(a). Additionally, to simulate the application of vertical surface loads, the model applies vertical concentrated loads at coupling points, as illustrated in Fig 6(b).

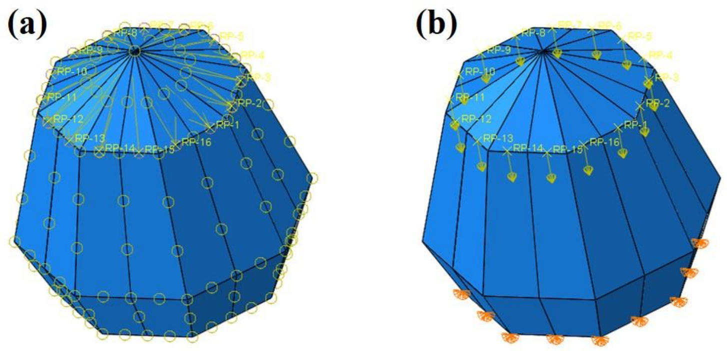

Figure 6: Interaction (a), Constraints, and Loading (b) Settings in Finite Element Model

3.3. Analysis Methods

The analysis focuses on thin-walled structures with significant geometric nonlinearity during loading. Modal analysis is conducted using the built-in Frequency program within the Linear Perturbation module program in ABAQUS. The calculation of load-bearing capacity is based on the Riks method, which incorporates buckling and post-buckling analyses. This involves introducing deformations from the first three buckling modes of the thin-walled structure as initial imperfections to compute the structure's load-bearing capacity.

4. Results Analysis

In this section, modal analysis and load-bearing capacity analysis are conducted based on the simulation settings outlined in Section Three.

4.1. Vibration Modal Analysis

The modal analysis of the structure is conducted according to the constraints shown in Fig 6(b), resulting in the first four vibration modes as depicted in Fig 7. It can be observed from the figure that the vibrations of the inflatable self-locking tent are concentrated on local panels, indicating that overall vibration is not predominant.

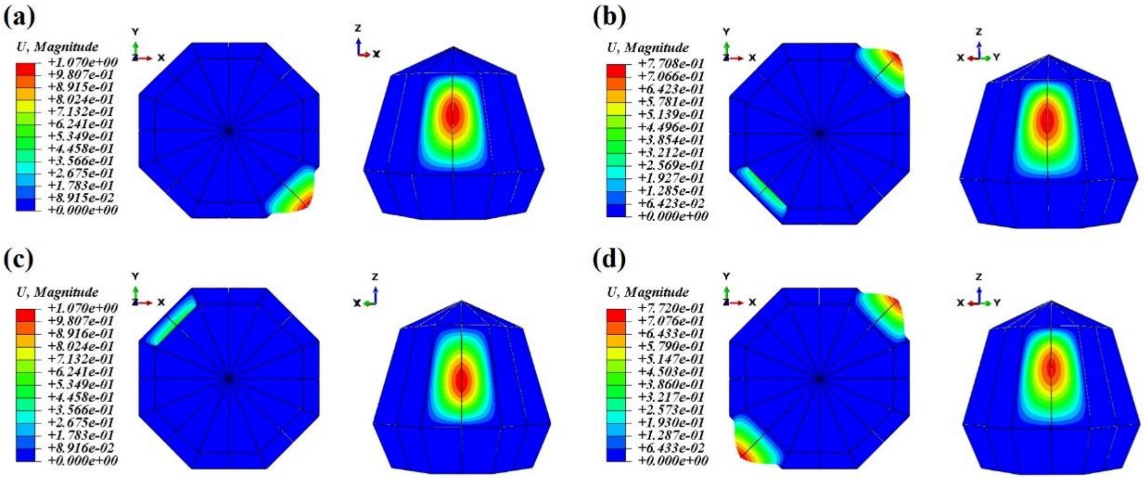

Figure 7: First Four Vibration Modes:(a) First vibration mode (0.10896 cycles/time); (b) Second vibration mode (0.11132 cycles/time); (c) Third vibration mode (0.11144 cycles/time); (d) Fourth vibration mode (0.11159 cycles/time)

4.2. Analysis of Load-bearing Capacity Calculation Results

Initial defects are introduced by reducing the lengthwise dimensions of the deformation plates by 1%. The first three buckling modes of the inflatable self-locking tent structure are illustrated in Fig 8. The computation of the LPF-Arclength curve, depicted in Fig 9, reveals a critical load proportion coefficient of 102.985, corresponding to a critical vertical pressure of 0.696 kPa. Stress and displacement contour plots under critical conditions are presented in Fig 10. These analyses provide crucial insights into the behavior of the tent structure, aiding in the assessment of its stability and load-bearing capacity.

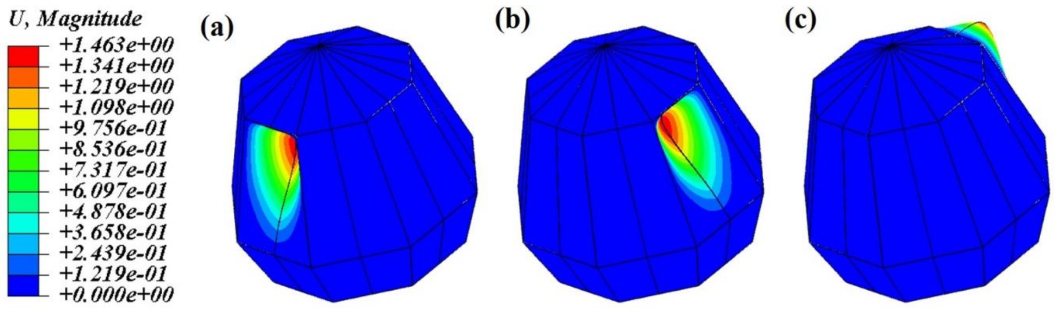

Figure 8: The First Three Buckling Modes of the Self-locking Inflatable Tent: (a) First buckling mode; (b) Second buckling mode; (c) Third buckling mode

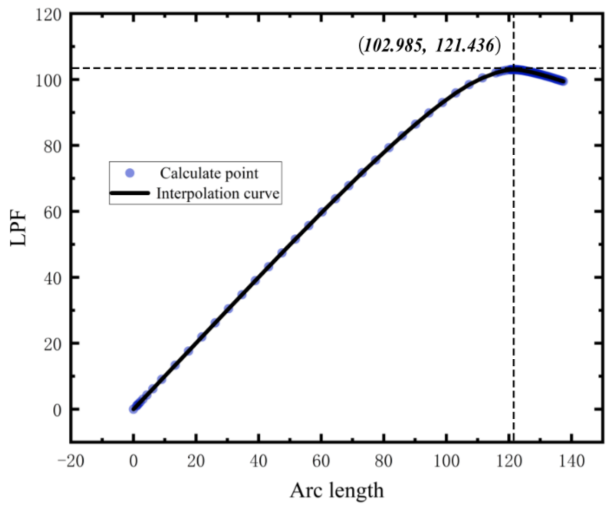

Figure 9: LPF-Arclength curve

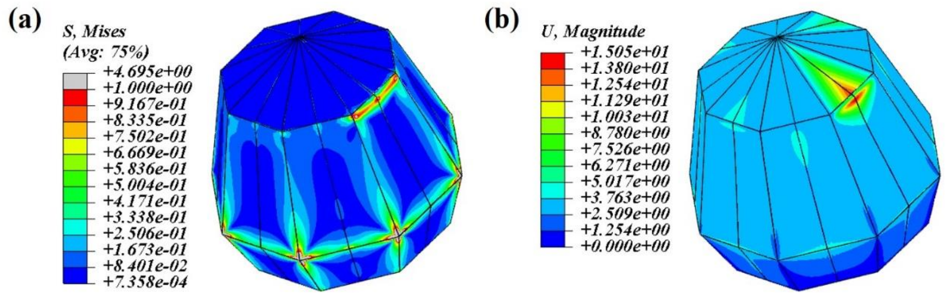

Figure 10: The Stress Contour Plot (a) and Displacement Contour Plot (b) at the Critical State of the Structure

The displacement contour plot at a critical state reveals that localized buckling in the upper portion of the structure leads to loss of load-bearing capacity. At critical state, the material of the structure remains in the elastic phase, and stability issues, as well as geometric nonlinearity, are significant factors determining the load-bearing capacity. The introduction of initial defects enhances the credibility of the simulation results. Furthermore, the critical pressure of 0.696 kPa is sufficient for temporary emergency structures, thereby validating to some extent the feasibility of the proposed inflatable self-locking tent.

5. Conclusion

The introduction of composite panels not only transforms the theoretical multi-stable origami model into a practical self-locking inflatable tent but also enhances its insulation, fire resistance, and durability. These panels facilitate the realization of various structures, akin to the thick plate model, thus laying the foundation for specific manufacturing processes. A practical production plan is proposed to meet the requirements for achieving multi-stable origami and accommodating the usage demands of relevant equipment. The utilization of ABAQUS software, employing the Riks method for buckling and post-buckling analysis, provides insights into the load-bearing capacity of the self-locking inflatable tent. Additionally, employing polypropylene as the structural layer ensures the tent meets the required load-bearing capacity. The critical load in the proposed design, at 0.696 kPa, satisfies the usage demands for temporary structures. These findings offer valuable guidance for subsequent model fabrication and testing.

Acknowledgments

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