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Thin-walled deployable composite structures: A review

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Abstract: The elastic strain energy-driven thin-walled deployable composite structures, characterized by their integration of structure and functionality, have attracted considerable attention in the field of space applications. These structures utilize the stored strain energy accumulated during the folding process to achieve elastic deployment. Significant progress has been made in the understanding of deformation mechanisms, modeling, design, optimization, and applications of such structures based on existing research. This review critically discusses over 300 papers from the past few decades, providing a comprehensive exploration of the development of three representative types of deployable composite structures: deployable composite hinges, booms, and reflectors. Specifically, it starts by reviewing the structural design, functional mechanisms, theories, finite element modeling methods and experimental investigations for these three types of structures. It then introduces optimization design methods and their applications in deployable composite structures. Additionally, specific practical application cases of deployable composite structures are discussed. Finally, future challenges and prospects for deployable composite structures are outlined. This paper serves as a valuable reference and inspiration for the design and application of deployable composite structures. It is expected to promote further advancements in this field.

Keywords: Deployable composite structure; Thin-walled; Boom; Tape-spring; Hinge; Reflector; Optimization

Nomenclature

| | |
|--------------|--|
| A | Stretching stiffness matrix |
| B | Coupling stiffness matrix |
| D | Bending stiffness matrix |
| M | Folding moment of the tape-spring, N·mm |
| M_+^* | Steady-state moment of the tape-spring in the opposite-sense folding process, N·mm |
| M_-^* | Steady-state moment of the tape-spring in the equal-sense folding process, N·mm |
| M_+^{\max} | Peak moment of the tape-spring in the opposite-sense folding process, N·mm |
| M_-^{\max} | Peak moment of the tape-spring in the equal-sense folding process, N·mm |
| R | Cross-sectional radius of the tape-spring, mm |
| u | Total strain energy per unit length of the tape-spring, mJ |
| θ | Cross-sectional angle of the tape-spring, rad |
| κ_x | Curvature in the x -axis of the laminate |
| κ_y | Curvature in the y -axis of the laminate |
| ACO | Ant Colony Optimization |
| AFRL | Air Force Research Laboratory |
| ANN | Artificial Neural Network |
| AST-6 | Application Technology Satellite-6 |
| Bi-DCB | Bistable Deployable Composite Boom |
| BPNN | Back Propagation Neural Network |
| CFRP | Carbon-Fibre-Reinforced-Plastics |
| CLM | Continuous Longeron Mast |
| CLT | Classical Laminate Theory |
| CTM | Collapsible Tubular Mast |
| CSA | Canadian Space Agency |
| DCB | Deployable Composite Boom |
| DCH | Deployable Composite Hinge |
| DLR | German Aerospace Center |
| DOE | Design of Experiment |
| EBF | Elliptical Basis Function |

| | |
|---------|--|
| ESA | European Space Agency |
| FEA | Finite Element Analysis |
| GD | Generational Distance |
| HV | Hyper Volume |
| IGD | Inverted Generational Distance |
| JAXA | Japan Aerospace Exploration Agency |
| JPL | Jet Propulsion Laboratory |
| mIGD | mimicked Inverted Generational Distance |
| MARSIS | Mars Advanced Radar for Subsurface and Ionosphere Sounding |
| MARCO | Multi-Arm Radial Composite |
| MOPSO | Multi-Objective Particle Swarm Optimization |
| MS | Maximum Spread |
| NASA | National Aeronautics and Space Administration |
| NSGA-II | Nondominated Sorting Genetic Algorithm II |
| OSS | Oxford Space Systems |
| PSO | Particle Swarm Optimization |
| RBF | Radial Basis Function |
| RF | Random Forest |
| RSM | Response Surface Method |
| SA | Simulated Annealing |
| SAR | Synthetic Aperture Radar |
| SFU | Space Flight Unit |
| SIASE | Shanghai Institute of Aerospace System Engineering |
| SQP | Sequential Quadratic Programming |
| STEM | Storable Tubular Extendible Member |
| SVR | Support Vector Regression |
| TRAC | Triangular Rollable And Collapsible |
| TRAAC | Technology Research for Autonomous Aircraft Concept |
| VGT | Variable Geometry Truss |

1. Introduction

With the development of aerospace technology, spacecraft are evolving towards increasing size and complexity. There is a growing demand for high-performance and highly stable deployable structures in various applications such as large-scale space antennas, solar sails, flexible robotic arms, solar power stations, and on-orbit assembly structures etc. This presents both significant challenges and extensive opportunities for the development of space deployable structure technology. Space deployable structures are compactly stowed during the launch phase to minimize their volume and facilitate installation. Once in the designated orbit, they are unlocked, deployed, and maintained in a work state according to the design requirements, forming large-scale space structures that meet the specified criteria. The emergence of space deployable structures resolves the contradiction between multifunctionality, large size, and limited storage capacity of launch vehicles.

Currently, space deployable structures mainly include four types: mechanical, inflatable, shape memory alloy-driven, and elastic strain energy-driven [1-4]. Among them, the elastic strain energy-driven deployable composite structures have the characteristics of integrated structure-function, utilizing stored strain energy during the folding process to achieve elastic deployment. Compared to other traditional space deployable structures, the elastic strain energy-driven deployable composite structures have advantages such as simplicity, high level of integration, excellent mechanical properties, high stowage efficiency, high deployment precision, and lightweight, etc [5-11]. In recent years, they have become a research hotspot and frontier in space deployable structures. In the past few decades, elastic strain energy-driven deployable composite structures have been widely applied in the space field, stimulating researchers to conduct more in-depth studies in this area. Fig. 1a visualizes the most frequently associated keywords with deployable composite structures since 1999 using the VOSviewer tool. The size of the circles in Fig. 1a represents the frequency of occurrence of each keyword, the lines indicate the connections between publications, and the colors represent the clusters determined by the algorithm. This visualization tool provides valuable insights into the research focus areas, helping to gain a deeper understanding of the keywords and research trends related to deployable composite structures. An interesting trend has emerged since 1999, with a sharp increase in the number of published papers on deployable structures (shown in Fig. 1b), with over 2300 related papers published in the past five years. This exponential growth demonstrates the increasing interest and recognition among researchers in the immense potential of deployable

structures in advancing space-related technological developments. The expanding body of research signifies an increasing emphasis on harnessing the capabilities of deployable structures to address various challenges. Additionally, Fig. 1c provides a comprehensive overview of the percentage distribution of the four main types of deployable composite structures, based on data from Web of Science, highlighting the diversified structural designs aimed at specific requirements. It is worth noting that the inclusion of the tape-spring is commonly recognized as one of the simplest forms of hinges.

This paper provides an overview of the latest advancements in the design, models, fabrication, experimental verification, optimization, and applications of deployable composite structures in space applications, as shown in Fig. 2. The structure of this paper is as follows: In Section 2, the development process of analytical modeling for the deployable composite tape-spring is outlined, and the characteristics of integral and combined deployable composite hinges are introduced. Section 3 provides a review of the current status of deployable composite booms with different cross-sectional configurations and discusses the functional mechanisms of existing bistable deployable composite booms. Section 4 comprehensively reviews the development status of deployable composite reflector used for antennas. Section 5 reviews classification methods for optimization design, and introduces the coupling surrogate model and evolutionary algorithm technology. In addition, multi-objective optimization design work for deployable composite structures is also reviewed. Section 6 briefly describes the development process of deployable structures and various space application cases. In Section 7, future challenges of deployable composite structures are discussed. Finally, Section 8 provides a summary of the entire paper.

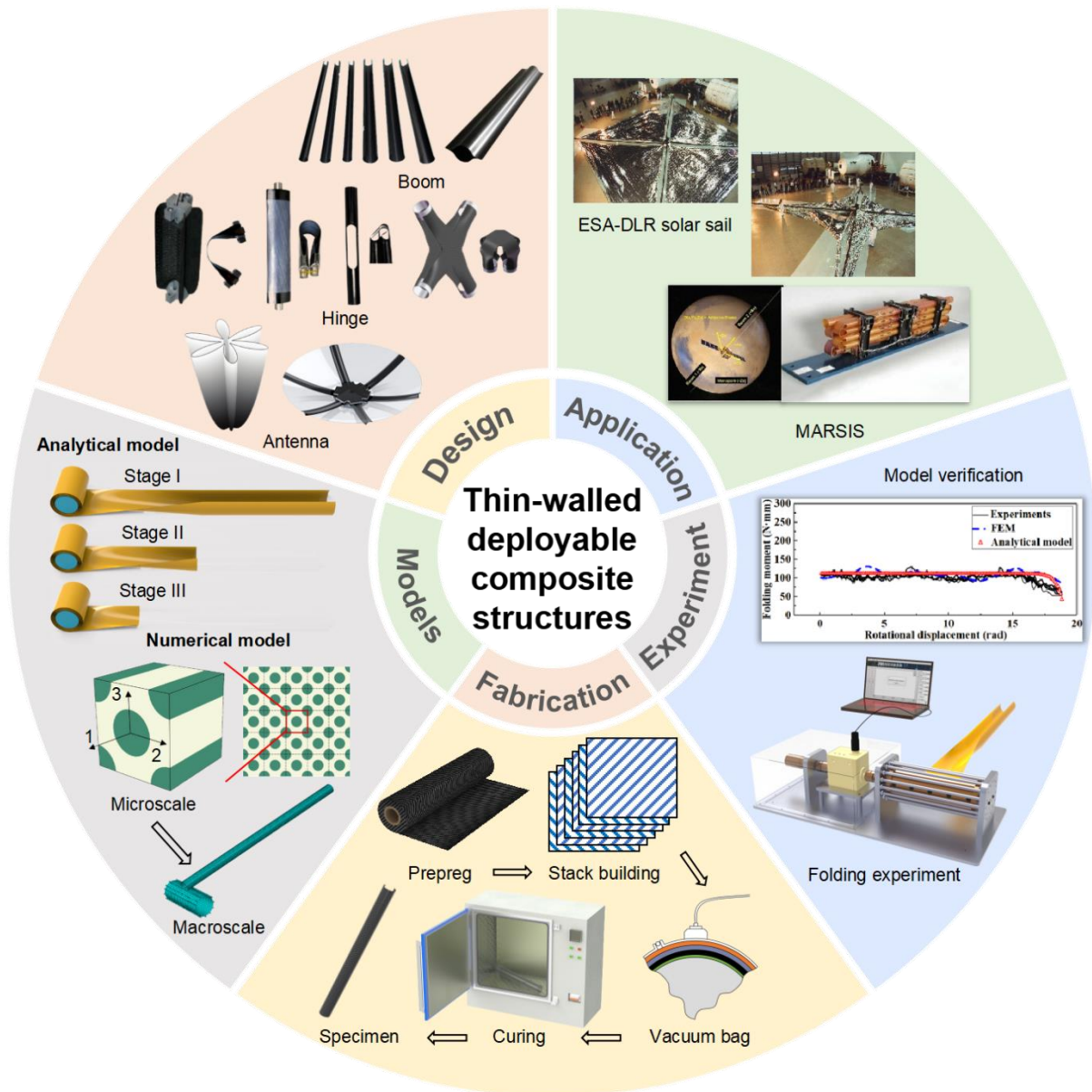


Fig. 2 Overview of design, models, fabrication, experimental verification, and applications of deployable composite structures.

2. Deployable composite hinges

2.1 Deployable composite tape-spring

Inspired by the concept of a tape measure, researchers have developed a structure called a deployable composite tape-spring, which can store and release elastic strain energy [12,13]. The deployable composite tape-spring is a thin shell with a curved cross-section, typically exhibiting uniform curvature and a cross-sectional angle smaller than 180° . Due to its curved cross-section being capable of flattening, the deployable composite tape-spring is well-suited for folding and can achieve self-deployment through the stored strain energy. The folding of the deployable composite tape-spring

can be categorized into two modes: when the longitudinal and transverse curvatures have the same direction, it is referred to as “equal-sense folding”; whereas when they have opposite directions, it is referred to as “opposite-sense folding”, as shown in Fig. 3a. Regardless of the folding mode employed, the deployable composite tape-spring possesses the ability to reversely rotate and lock, enabling important functionalities such as actuation, reverse rotation, and locking. When evaluating the folding behavior of the deployable composite tape-spring, the following parameters are of primary concern: (1) peak moment, which refers to the critical moment the deployable composite tape-spring can withstand when experiencing buckling instability, and serves as a measure of its ability to resist external disturbances. A higher peak moment indicates greater stability of the deployable composite tape-spring; (2) steady-state moment, which represents the moment exerted during the initial deployment stage after folding deformation, reflecting its capability to actuate space deployable structures; (3) stress level, accurately determining the stress level helps determine whether failure occurs and is used for strength design.

Fig. 3b illustrates the relationship between folding moment and bending angle for the deployable composite tape-spring under both equal-sense and opposite-sense folding conditions. In the case of opposite-sense folding, starting from point O, the folding moment M shows a linear variation and gradually increases within a small range of bending angles. The corresponding configuration exhibits a smooth curvature along the longitudinal axis. As the bending angle increases, the cross-section of the deployable composite tape-spring gradually becomes flatter until reaching the peak moment, which represents the maximum value of the folding moment. Subsequently, due to the structural buckling, the folding moment decreases rapidly (AB). In this configuration, only the middle portion of the deployable composite tape-spring undergoes deformation due to folding, while the rest remains straight (shown in Figs. 3a and 3c). Once buckling occurs, theoretically larger bending angles do not alter the folding moment (BC), which is defined as the steady-state moment M_+^* . During the stable phase, only the arc length of the folding region is affected by the variation in bending angle. In the deploying process of the opposite-sense folding configuration, the first part of the curve (CB) coincides with the loading path. However, at point B, the red curve remains unchanged until reaching point D, and then returns to the loading curve at point E. It subsequently linearly recovers back to point O (EO). In the equal-sense folding process, starting from O again, the folding moment shows a linear relationship with the bending angle (OF), exhibiting the same stiffness as the opposite-sense

folding. The folding moment typically reaches its maximum value at relatively small bending angles, known as the peak moment during the equal-sense folding process. Then, similar to the opposite-sense folding, the post-buckling behavior (GH) is defined by the steady-state moment M_-^* . Finally, it is generally assumed that the unloading path of the equal-sense folding theoretically matches the loading path, although it may not be an exact match in practice [14,15].

This section aims to introduce analytical models for predicting the folding behavior of the deployable composite tape-spring. Currently, there are two analytical models (the elastic shell method and the energy method) used to describe the folding behavior of the deployable composite tape-spring, particularly the folding moment versus longitudinal curvature relationship. Based on the small-deflection elastic shell theory, Wuest [16,17] first derived the folding moment versus longitudinal curvature curve for isotropic deployable tape-spring. This model has been widely applied and considered as a significant advancement. However, the model has some limitations, such as underestimating the peak moment and only predicting deployable tape-spring with a cross-sectional angle smaller than 1 radian. Seffen and Pellegrino [18] pointed out that the moment balance equation in the Wuest model is valid only for the flattened state of the tape-spring. To extend the applicability to tape-springs with larger cross-sectional angles, Seffen and Pellegrino numerically solved the modified integral limits of the moment balance equation. Consequently, the Wuest model has been further developed to apply to various materials and structural forms of tape-springs, such as off-axis tape-spring [19], deployable composite tape-spring [20,21], hexagon honeycomb tape-spring [22], star-shape tape-spring [23], auxiliary re-entrant honeycomb tape-spring [22,23], and integrated tape-spring, etc [24]. These analytical models for different structural forms of tape-springs do not significantly differ in modeling approach compared to the Wuest model but consider different material properties.

Shell energy minimization is another widely used method for predicting the folding moment versus curvature relationship of deployable tape-springs. Mansfield [25] proposed an analytical model for predicting the folding behavior of isotropic deployable tape-springs under large deflection conditions. This model considers both stretching and bending strain energy, establishes a total strain energy expression based on the curvature variation of the deployable tape spring during the folding process, and obtains the quantitative relationship between folding moment and longitudinal curvature through variational minimization. In addition, Mansfield derived an analytical model for the torsional

buckling of the tape-spring, i.e., buckling occurs under equal-sense bending load without end effects. Yao et al. [26], combining the Wuest model and the Mansfield model, based on Calladine shell theory and von Karman thin plate large deflection bending theory, derived the expression for the folding moment versus curvature relationship of the deployable composite tape-spring using the energy method. This model considers the influence of transverse bending, longitudinal bending, and longitudinal tension on the elastic strain energy. Recently, Knott [27] and Shore [28] proposed new energy optimization analytical models for analyzing the folding moment versus curvature relationship of the deployable composite tape-spring. One key feature of this model is the use of a single path variable to describe the cross-section of the tape-spring. Comparative analyses have shown that the predictions of this method are in good agreement with the Wuest and Mansfield models [28]. The aforementioned analytical models have made significant progress in predicting the folding behavior of the deployable composite tape-spring, especially in terms of the folding moment versus curvature relationship. However, accurately predicting the folding behavior of these structures relies on determining their geometric configuration during the folding process. Iqbal et al. [29] hypothesized that the cross-section of the deployable composite tape-spring remains circular during the folding deformation. This hypothesis has also been validated by other literature [30-34]. Therefore, based on this assumption, it is possible to establish a new analytical model for predicting the folding behavior of the deployable composite tape-spring. The theoretical modeling approach for the folding behavior of the deployable composite tape-spring is summarized in Fig. 3d, which presents the theoretical framework.

In addition, by changing the boundary conditions and loading methods of the deployable composite tape-spring, axial compression folding deformation can also be achieved. This folding method of the deployable composite tape-spring can be applied to structures such as hinge [35] and cabin [36]. However, there are relatively few theoretical modeling studies on this folding method. Liu and Bai [37] proposed an analytical model based on the Euler-Bernoulli beam theory to predict the load-displacement curve, shape function, and stress level during the axial compression folding of the deployable composite tape-spring. The study showed that the load-displacement curve exhibits a three-stage nonlinear behavior similar to bending folding behavior, and the model was validated through experimental and numerical analysis [36].

Based on the above summary, it can be concluded that the elastic shell method and energy method show a trend of evolution in the space application to the deployable composite tape-spring. The focus of research lies in the folding behavior of the deployable composite tape-spring, particularly the folding moment versus longitudinal curvature relationship. Existing analytical models can predict nonlinear characteristics similar to experiments, but there is a common issue of underestimating the peak moment. Currently, most analytical models mainly predict the opposite-sense folding behavior of the deployable composite tape-spring since both bending and torsion occur during the equal-sense folding deformation [16,18]. Therefore, establishing an analytical model that accurately predicts the equal-sense folding behavior of the deployable composite tape-spring is one of the key areas for future research.

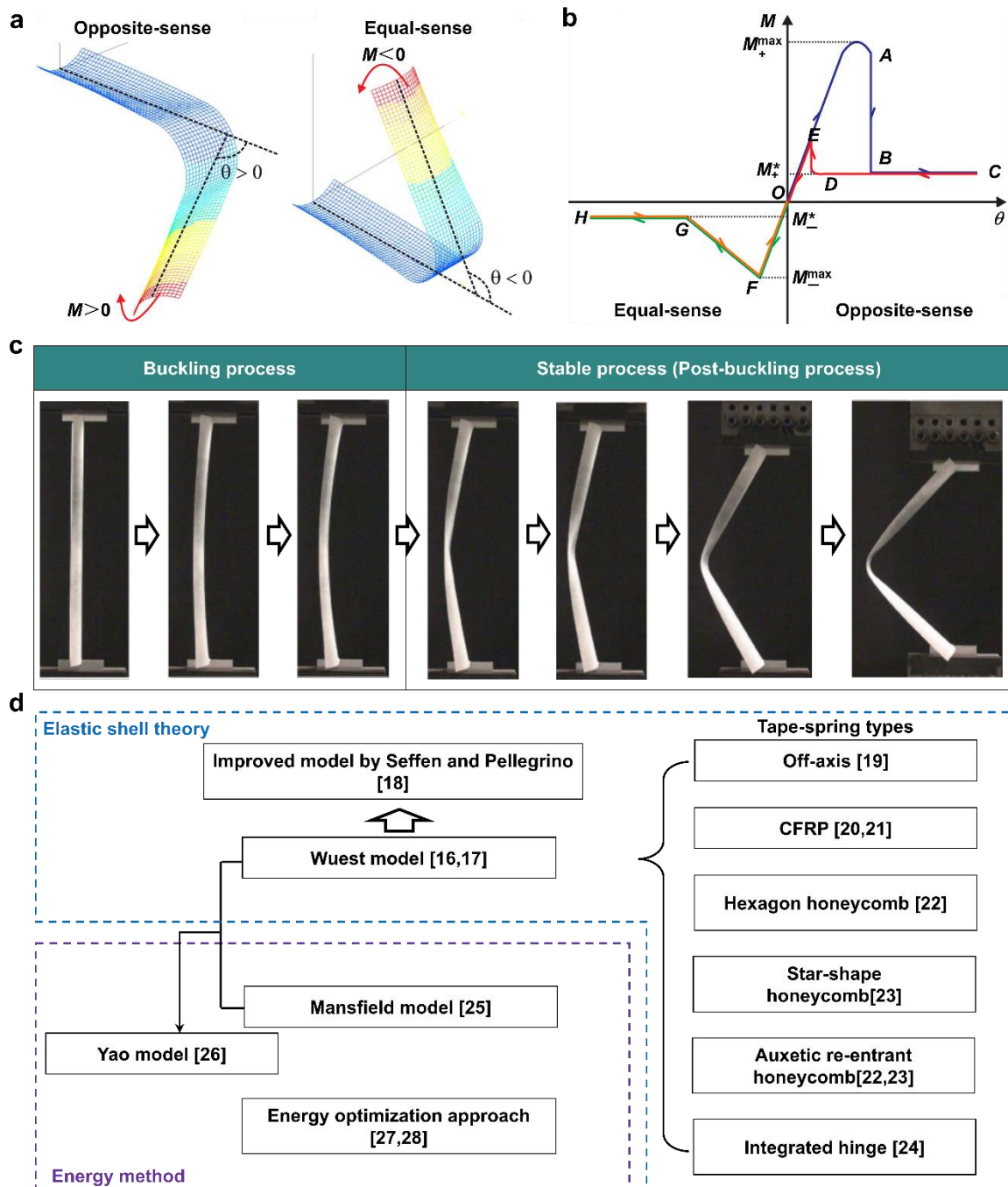


Fig. 3 Folding behavior of the deployable composite tape-spring: (a) Illustration of the senses of folding and sign convention [14] (b) Theoretical evolution of the folding moment with the applied bending angle [14] (c) Opposite-sense folding process [15] (d) Theoretical system of analytical models.

2.2 Integral deployable composite hinges

Due to simplicity and ease of use, the deployable composite tape-spring has been widely employed in the design of space deployable structures. However, they exhibit certain limitations in terms of mechanical properties, such as relatively low bending stiffness and load-bearing capacity.

To overcome these issues, integrated Deployable Composite Hinges (DCHs) have been developed. An integrated DCH is a cylindrical shell structure with symmetric openings and an integral hinge mechanism that enables 180° folding functionality (shown in Fig. 4a) [38,39]. Due to the structural integrity, it possesses features like easy fabrication and fewer connection points. However, this type of hinge experiences stress concentration during folding and repeated folding can lead to damage or failure. In 2003, the European Space Agency (ESA) launched the Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) aboard the Mars Express spacecraft, which was the first radar antenna employing an integrated DCH (shown in Fig. 4b) [40]. This marked the inaugural application of an integrated DCH in space, generating significant interest among researchers and driving further research and broader applications of this hinge. The folding behavior of integrated DCHs that needs to be focused is similar to that of the deployable composite tape-spring, including folding moment-bending angle curve, peak moment, steady-state moment, damage or failure, etc. [41-50]. Folding moment versus bending angle curve of integrated DCHs also exhibit a typical three-stage characteristic [47], as shown in Fig. 4c. It is worth noting that most of the aforementioned studies are based on experimental and numerical methods because the geometric nonlinearity and shell contact during the folding deformation of integrated DCHs make theoretical modeling challenging. In addition to the folding deformation, the dynamic impact response during the rapid deployment process of integrated DCHs is another crucial consideration. Some literature has numerically modeled the deployment process of integrated DCHs and used high-speed cameras to measure the varying angle versus time (shown in Fig. 4d) [47,49-52].

Integrated DCHs typically experience maximum stress (i.e., the critical location) near the end of the slot [47,49,50], as shown in Fig. 5a, which is a stress concentration area. To address this issue, Mallikarachchi and Pellegrino [53-55], as well as Mobrem et al. [40], introduced circular cutouts at both ends of the slot in the integrated DCH (shown in Fig. 5b). The folding and deployment process of this new design was investigated through experiment and numerical simulation. The research revealed that the circular cutouts effectively reduce the stress level. However, in certain design configurations, the failure may occur at the location of the circular cutout, as shown in Fig. 5c. To further reduce the folding radius and stored strain energy in the integrated DCH, Sakovsky et al. [38,56] proposed a dual-matrix integrated DCH (illustrated in Fig. 5d). The folding and deployment process of this hinge was studied using experiment and numerical simulation, as shown in Fig. 5e.

The predicted geometric configurations matched well with the actual configurations. It is worth noting that the aforementioned integrated DCHs are all based on a straight tube configuration. Ferraro and Pellegrino [57,58] introduced a novel integrated DCH with an angled shape, where two thin-walled cylinders intersect at a 90-degree angle (shown in Fig. 5f).

The mentioned researchers primarily conducted comprehensive studies on the folding and deployment behavior of symmetrically open integrated DCHs using experimental and numerical methods. However, they also identified stress concentration issues in these hinges during the folding process, which could lead to damage or failure upon repeated folding. By optimizing the shape and parameters of the cutout, the reliability of integrated DCHs can be improved. Future research can further explore the application of integrated DCHs in complex space environments and enhance their bending stiffness and load-carrying capacity through optimized designs. Additionally, attention should be given to hinge durability and damage prediction, along with exploring their potential application in complex folding mechanisms.

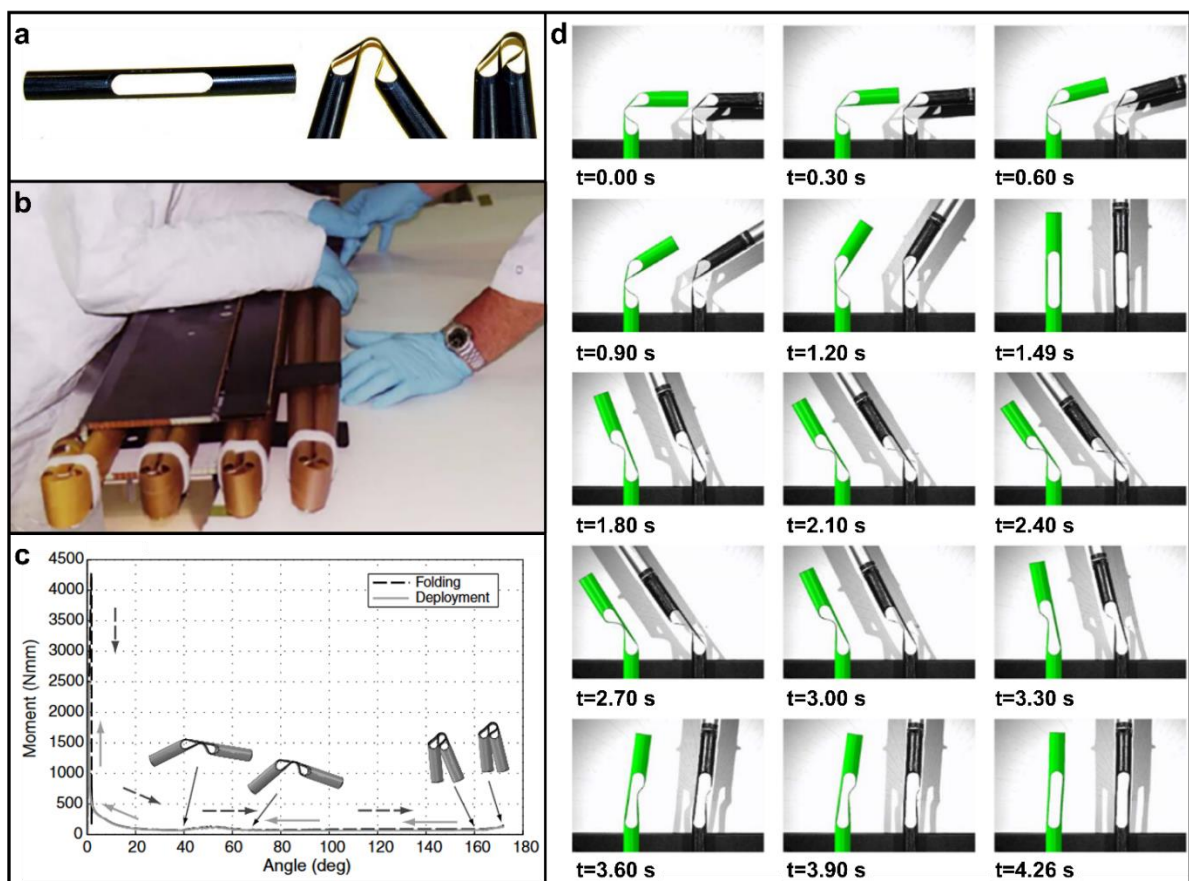


Fig. 4 Folding behavior of integrated DCHs: (a) Deployed, partially folded and fully folded configuration [39] (b) MARSIS [41] (c) Folding moment-bending angle profile for folding and deployment simulation [47] (d) Comparison of snapshots from experiment and simulation [52].

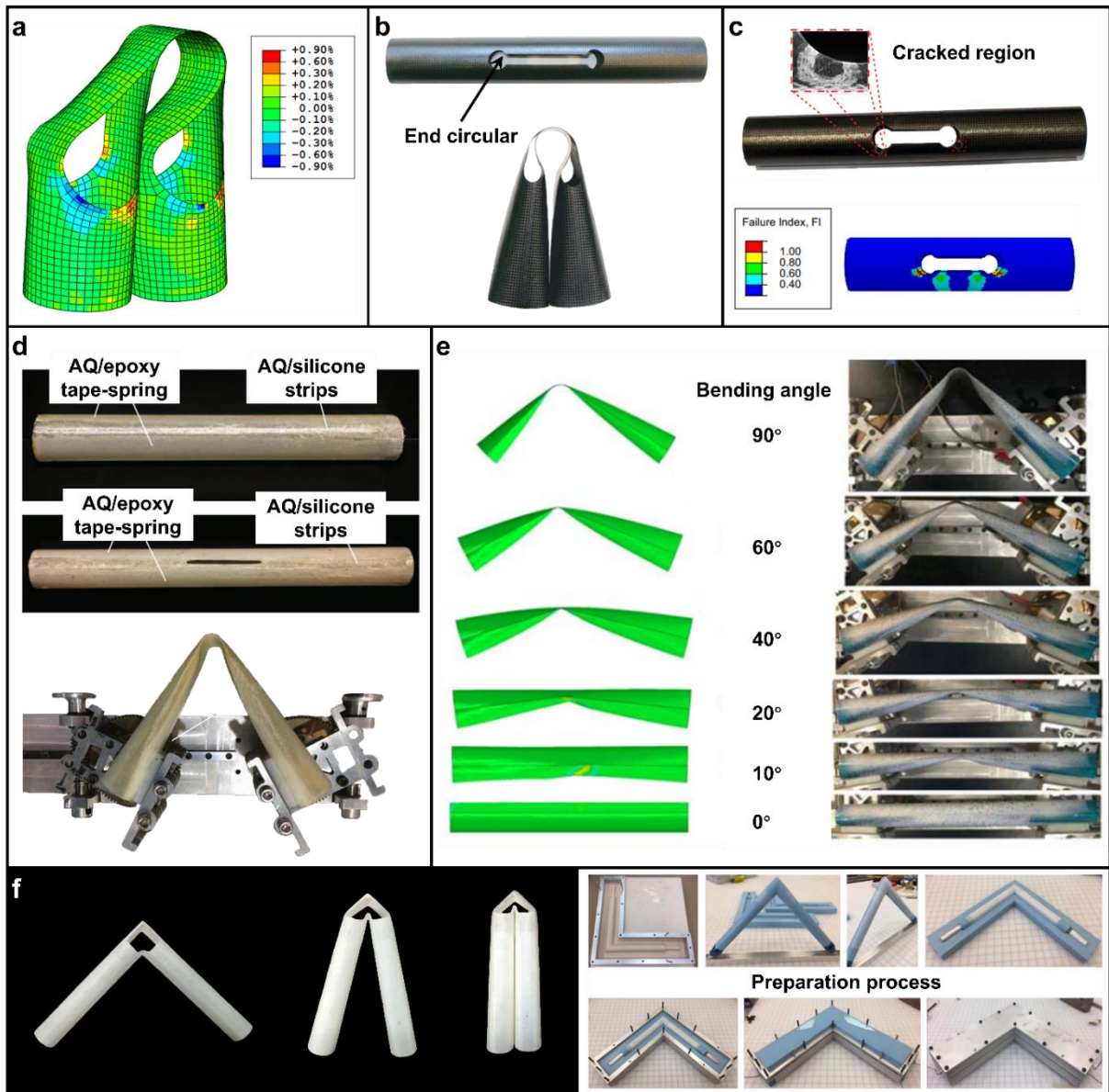


Fig. 5 Folding behavior of other types of integral DCHs: (a) Strain contour plot in the folding state [50] (b) Integral DCH with end circular [53] (c) Failure at the end circular position after folding [55] (d) Dual-matrix integral DCH and folding apparatus [56] (e) Comparison of experimentally observed and simulated deployments of dual-matrix integral DCH [56] (f) Folding process of DCH with diagonal geometry and its manufacturing process with silicone molding [57].

2.3 Combined deployable composite hinges

Combined DCHs have also gained increasing attention. They are typically composed of multiple deployable composite tape-springs arranged in opposite or back-to-back configurations. These hinges offer higher bending stiffness and load-carrying capacity compared to deployable composite tape-spring alone. Furthermore, they can be structurally and material optimized to meet specific application requirements. Echter et al. [59] and Pellegrino et al. [60,61] proposed an opposite

configuration for combined DCHs. In this design, two opposing deployable composite tape-springs are secured together using end components, as shown in Figs. 6a and 6b. Francis et al. [62,63] and Fosness [64] developed a back-to-back DCH (also known as an X-hinge), as depicted in Fig. 6c. When deployed, this hinge aims to have equal bending stiffness in two directions perpendicular to the longitudinal axis of the hinge. Other combined spring-based deployable hinges have also received attention [65-73]. Figs. 6d to 6g show several representative examples of such hinges. In 2009, the United States Air Force Research Laboratory [74,75] proposed a cross-shaped DCH for use in mesh reflector antennas (shown in Fig. 6h). When combined with support rods, this hinge can be utilized in the design of various one-dimensional and two-dimensional structures.

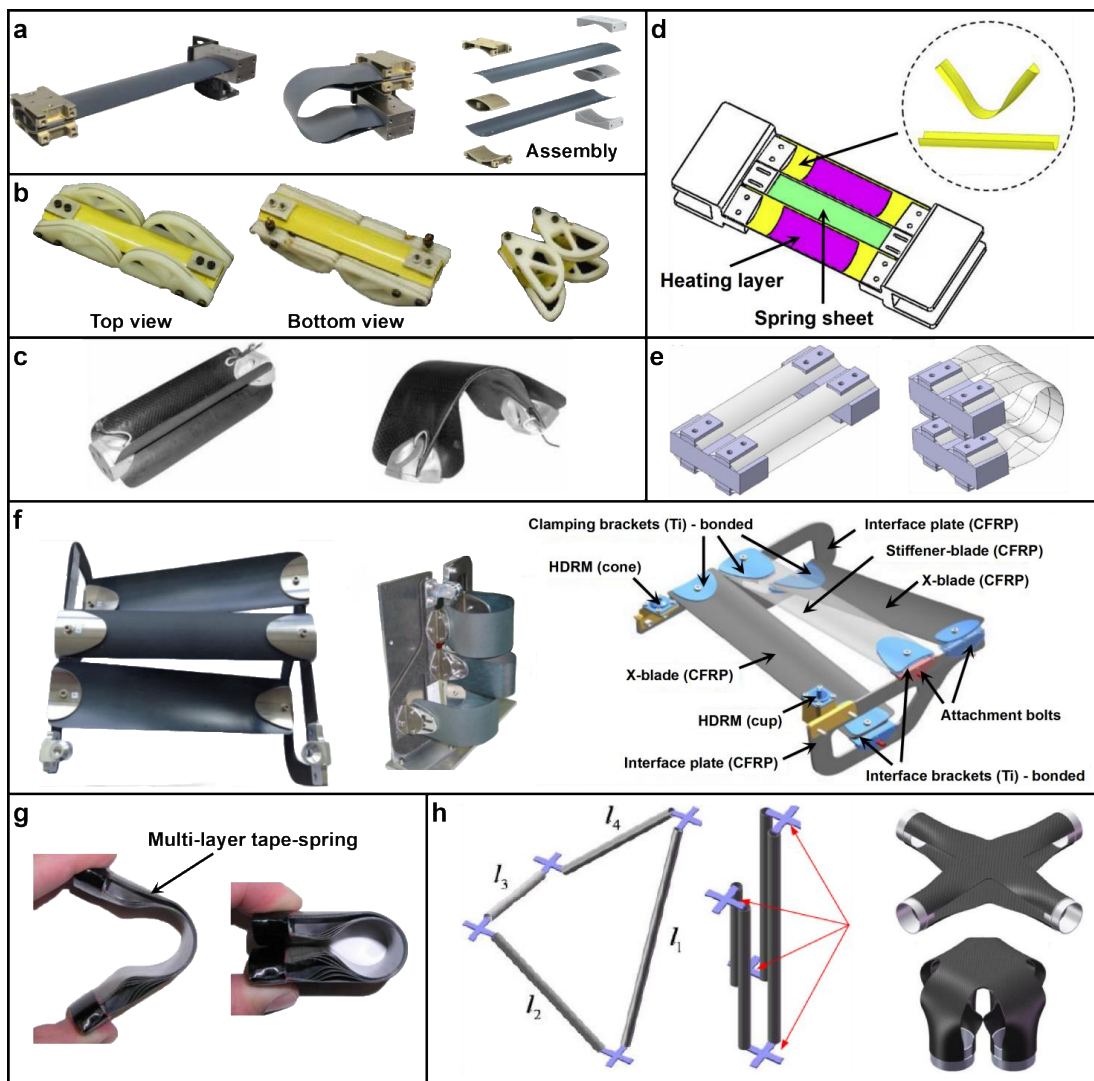


Fig. 6 Folding behavior of combined DCHs: (a) CAD model of equal-type hinge [60] (b) Tape-spring rolamite hinge [61] (c) X-shape hinge [64] (d) Hybrid intelligent hinge [66] (e) Combined hinge with four tape-springs [68] (f) Ultra-light deployment mechanism [72] (g) Multi-layer tape-spring hinge [73] (h) Four-cornered hinge [74].

3. Deployable composite booms

3.1 Tubular deployable composite boom

Similar to the deployable composite tape-spring, tubular Deployable Composite Boom (DCB) is thin-shell structures with uniform transverse curvature. However, the cross-sectional angle is usually larger than 180° , enabling it to undergo coiling and folding deformation. The tubular DCB can be folded in two ways: equal-sense folding and opposite-sense folding, as shown in Figs. 7a and 7b. The tubular DCB can not only be compactly packaged through folding but also restore to its initial configuration by releasing the stored strain energy during the folding process. It serves as fundamental components for constructing space deployable structures, offering advantages such as lightweight, high stiffness, and repeatability of deployment [76]. Additionally, it is crucial structures for space applications such as deployable mesh reflector antennas, deployable solar sails, thin film antennas, and space probes [77,78]. Regarding the folding behavior of the tubular DCB, the following parameters are of primary concern: (1) folding moment: This refers to the moment required to coil the tubular DCB from its deployed state using an auxiliary mechanism. Accurate prediction of the folding moment is crucial for the design of the auxiliary mechanism; (2) stored strain energy: This refers to the strain energy stored in the structure due to its deformation during the folding process. The stored strain energy significantly affects the deployment behavior of the tubular DCB; (3) stress level: This refers to the magnitude of stress experienced by the tubular DCB during the folding process. It is used for strength design considerations.

In 1961, Klein designed the thin-walled Storable Tubular Extendible Member (STEM) for the communication antenna of Canada's first satellite, the Alouette. This deployable boom is folded and stored in corresponding constraints before launch, while being fixed to the satellite. After launch, it gradually extends outward until fully deployed through motor control. The successful application of the Alouette satellite laid the foundation for the development of tubular deployable booms. Subsequently, many scholars established various analytical models to describe the folding behavior of tubular deployable booms. Early studies focused on using isotropic materials to fabricate deployable booms. Based on the plate shell theory, Rimrott et al. [79-82] conducted extensive analysis on various mechanical behavior of deployable booms, including bending stiffness, torsional stiffness, ploy zone length, stress distribution, and stored strain energy. Iqbal et al. [29] proposed an analytical model to predict the stored strain energy of the tubular Bistable Deployable Composite Boom (Bi-

DCB) during the folding deformation process, considering the influence of stretching strain energy and bending strain energy. This model has been widely used and developed into various versions to analyze the stored strain energy, folding moment, and stress level of the tubular DCB. For example, Wang et al. [83] developed the Iqbal model and used the energy method to model the folding and deployment process of the tubular DCB. The model was used to predict the end force that the boom can withstand before relaxation occurs, as shown in Fig. 7c. In addition, experimental setup was developed to realize the folding and deployment process of the tubular DCB. The experimental results were compared with the predictions of the analytical model, and they showed good agreement. Liu and Bai et al. [84] considered the boundary conditions and geometric configurations of the tubular DCB under realistic working conditions, and developed a folding machine to achieve equal-sense and opposite-sense folding and deployment of the tubular DCB. This folding machine can measure the drive moment during the deformation process of the tubular DCB, including folding system, driving system, and data acquisition system, as shown in Fig. 7d. The folding behavior of the tubular DCB was analyzed through experiments and numerical simulations, and the predicted folding moment-rotational displacement curve showed good agreement with the experiments, as shown in Fig. 7e. In subsequent work, based on the energy principle and two classical failure criteria, an analytical model was established to predict the folding moment and stress level of the tubular DCB throughout the entire folding process. The predictions using the analytical model were in good agreement with the numerical and experimental results [85], as shown in Fig. 7f.

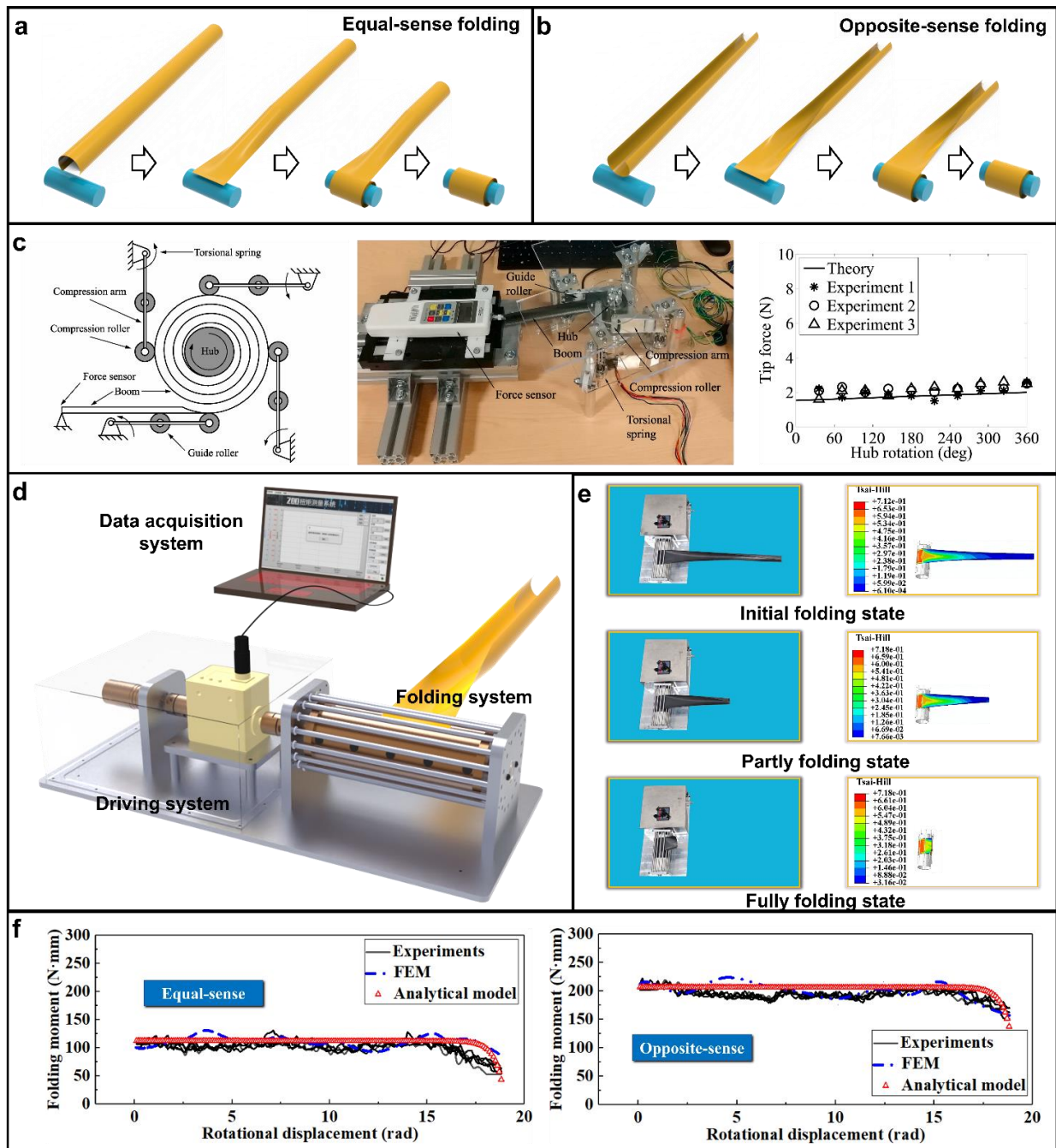


Fig. 7 Folding behavior of the tubular DCB: (a) Equal-sense folding (b) Opposite-sense folding (c) Folding and deploying experimental setup and tip force during blossoming [83] (d) Folding machine [84] (e) Folding deformation processes of the tubular DCB through experiment and numerical simulation [84] (f) Folding moment versus rotational displacement curves of the DCB in the folding processes [85].

3.2 No-circular cross-section deployable composite booms

In recent years, deployable booms have undergone continuous innovation in terms of their cross-sectional forms, attracting widespread attention. The United States Air Force Research Laboratory

has developed a Triangular Rollable And Collapsible (TRAC) boom [86,87]. The cross-section of the TRAC boom consists of two arcs connected on one side, forming two curved edges and a flat belly plate, as shown in Fig. 8a. This boom has been used in three different solar sail missions, namely NanoSail-D [88], The Planetary Society's LightSail-1 [89], and LightSail-2 [90]. In all three cases, the TRAC boom was made of metal. Recent studies have shown that the metal TRAC boom is sensitive to temperature gradients. In space, when one edge faces the sun while the other remains in shadow, significant end deflections can occur [91]. Therefore, in recent years, extensive research has been conducted on TRAC boom made of carbon fiber-reinforced composites. The preparation of composite TRAC boom involves a secondary bonding process. First, two half-sections are cured, and then they are bonded together. Fig. 8b shows the fabrication process of the TRAC boom. Lecler [92] proposed an analytical model to predict the buckling load of the TRAC boom under pure bending and designed a buckling test setup (shown in Fig. 8c). Buckling modes and locations have been investigated through experiments, numerical simulations, and analytical models [93] (shown in Fig. 8d). Lecler et al. [94-96] and Luo [97] analyzed stress concentration and material failure in the ploy zone of the TRAC boom using theoretical and numerical methods. Inspired by the design of the TRAC boom, Yang et al. [98,99] proposed the concepts of N-shaped and M-shaped DCBs (shown in Figs. 8e and 8f) and studied the strain energy stored during the folding process, as well as the peak bending moment.

It is worth noting that a key characteristic of the aforementioned booms is their open cross-section, which typically exhibits lower torsional stiffness. In 1999, the German Aerospace Center (DLR) first used carbon fiber-reinforced composites to fabricate a lenticular DCB, also called Collapsible Tubular Mast (CTM) [100]. The lenticular DCB consists of two axially symmetric Ω -shaped carbon fiber composite shells, as shown in Figs. 9a and 9b. Due to its closed cross-section, the lenticular DCB has higher torsional stiffness. There are numerous space applications for the lenticular DCB, including rollable rib antennas developed by Oxford Space Systems Limited (OSS), solar sail spacecraft by the ESA and DLR, and solar sail spacecraft used by National Aeronautics and Space Administration (NASA) in deep space science and exploration missions, etc [101]. Bai et al. conducted theoretical analyses on various key performance aspects of the lenticular DCB, including nonlinear mechanical response during tensile and compressive flattening processes [102-104], neutral cross-section position in the flattened state [105], in-plane strain and interlaminar shear stress during

folding [106], folding moment and stored strain energy [107,108]. Figs 9c to 9e respectively depict the tensile, compressive, and folding deformations of the lenticular DCB determined by experiment and numerical simulation. The deployment behavior of the lenticular DCB mainly focuses on buckling, stiffness and thermal effect in space environment, such as local buckling under axial compressive loading [109] (shown in Fig. 10a), global Euler buckling [110], nonlinear buckling and post-buckling under pure bending conditions [111,112], temperature field and thermal deformation in extreme environment [113] (as shown in Figs 10b and 10c), as well as natural frequency [114].

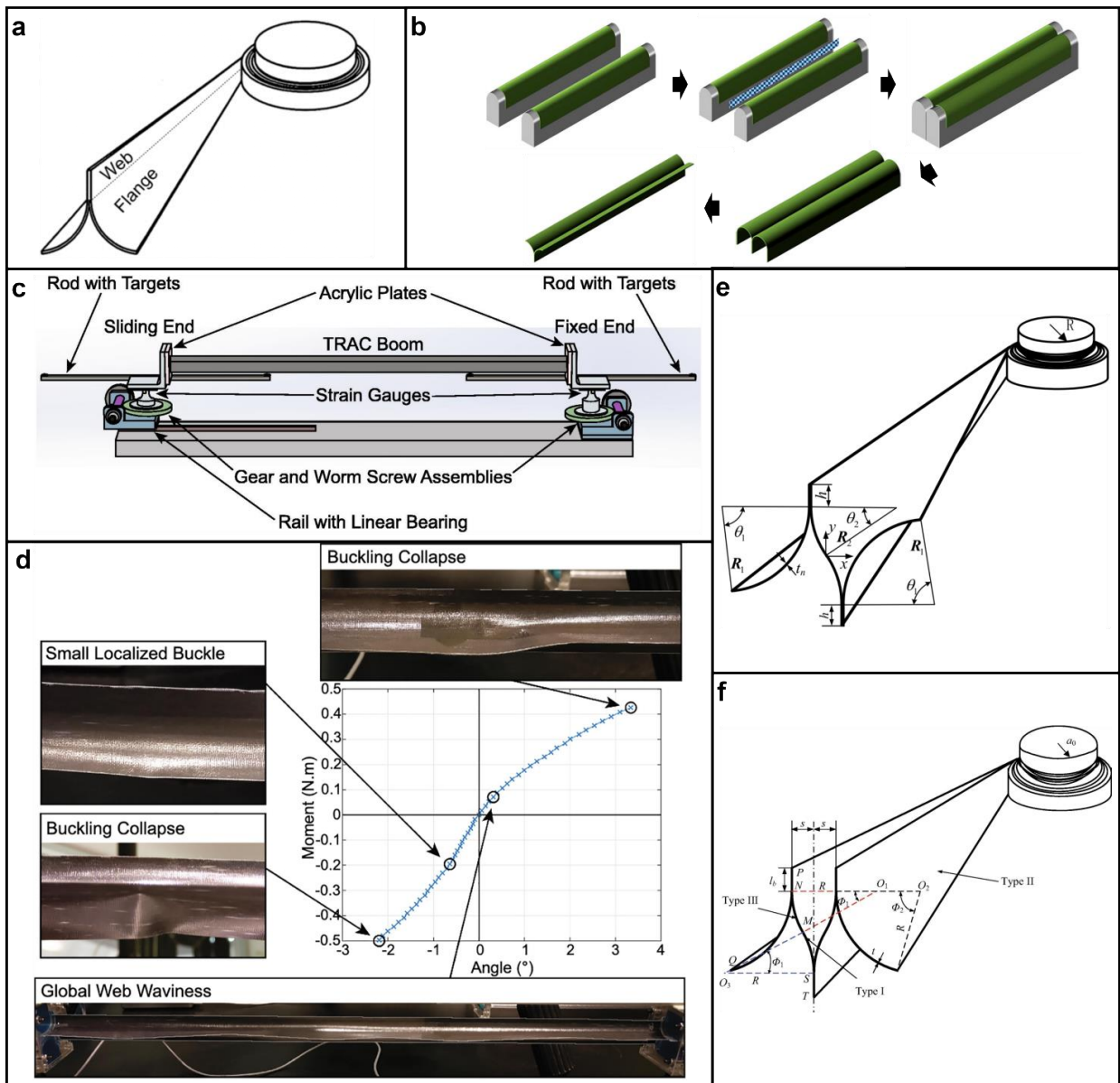


Fig. 8 No-circular deployable composite booms: (a) TRAC boom [86] (b) Manufacturing process of TRAC boom [92] (c) Bending experimental setup (The sliding end is mounted on a rail to allow longitudinal translation) [92] (d) Buckling modes under equal-sense and opposite-sense moments [93] (e) N-shaped DCB [98] (f) M-shaped DCB [99].

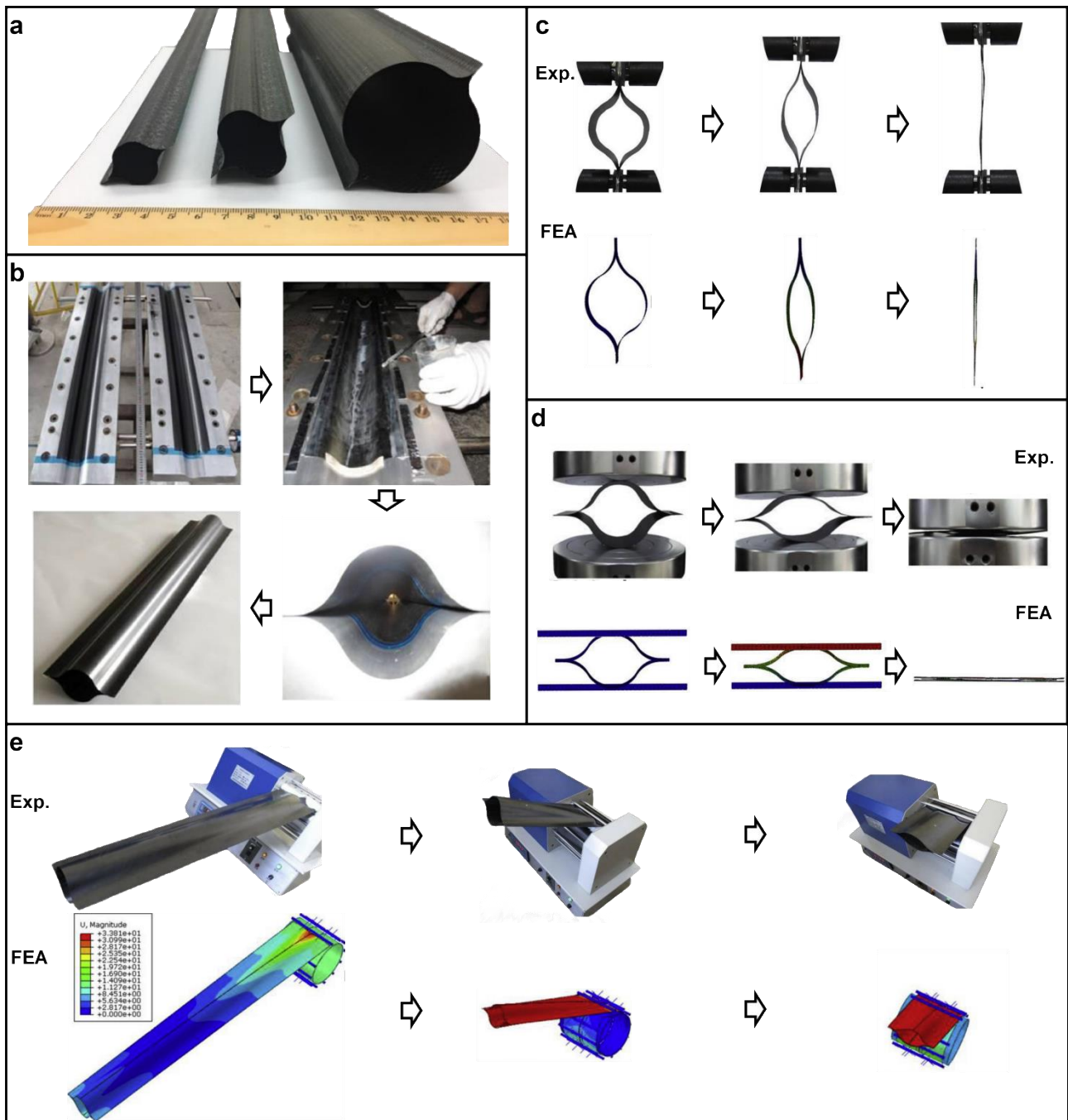


Fig. 9 Lenticular deployable composite boom [108]: (a) LDCB specimens (b) Manufacturing process of the lenticular DCB (c) Tensile deformation process determined by the Exp. and FEA (d) Compressive deformation process determined by the Exp. and FEA (e) Coiling deformation process determined by the Exp. and FEA.

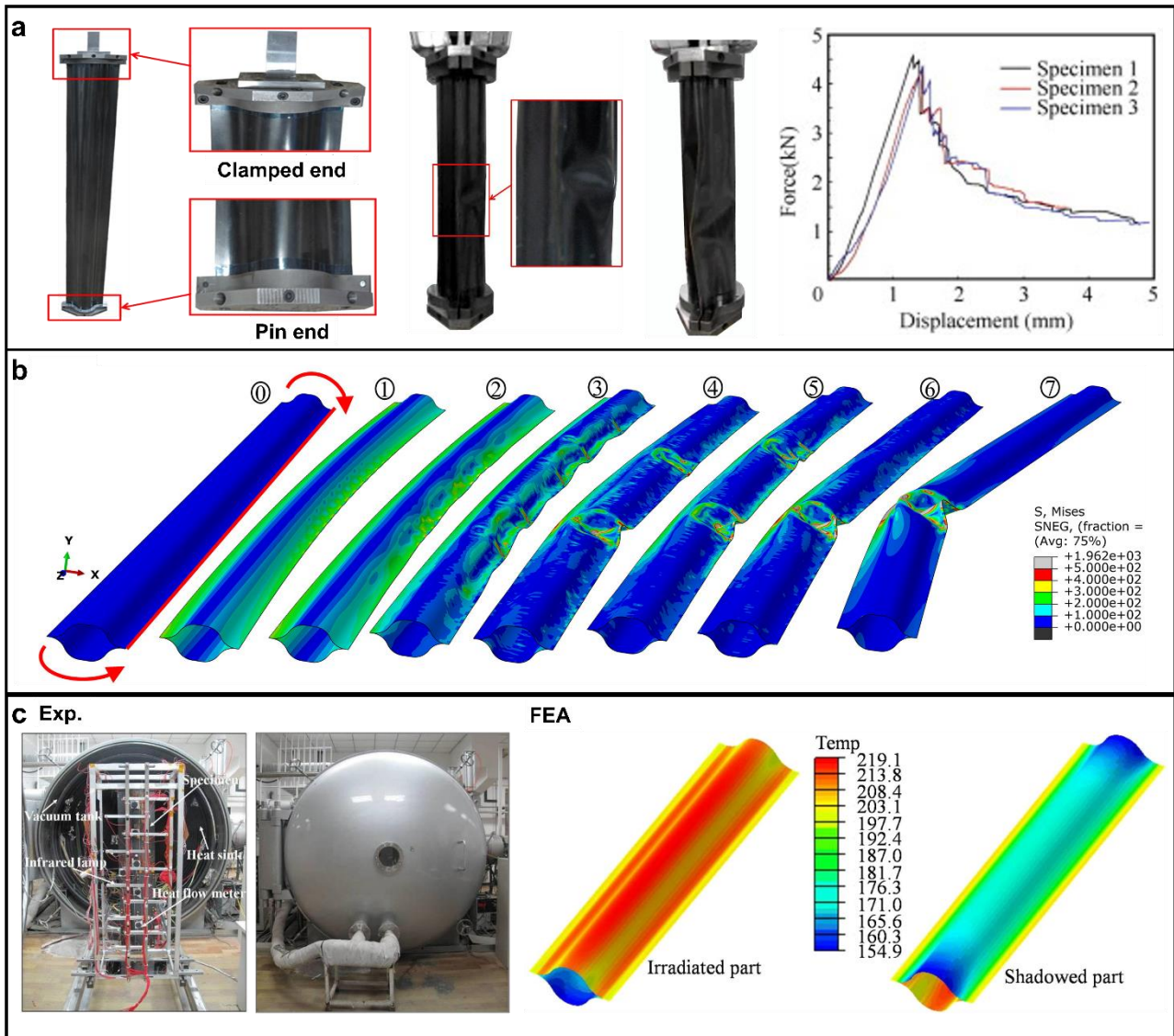


Fig. 10 Buckling and thermal behavior of lenticular DCB: (a) Subjected to axial compression [109] (b) Subjected to a pure bending load about y -axis [112] (c) Temperature field and thermal deformation in extreme environment [114].

3.3 Bistable deployable composite booms

The aforementioned DCBs typically have only one deployed stable state, while the folded state usually possesses high strain energy and cannot stay stable without external constraints (i.e., having self-deployability). Therefore, mechanisms are required to control the deployment process, which increases system mass and the risk of deployment failure. By employing suitable material and mechanical designs, DCBs can be designed with bistable functionality, meaning they possess two stable equilibrium states in both the deployed and folded configurations (shown in Fig. 11a). Bi-DCBs can maintain a folded stable state without any restraining devices and exhibit lower strain energy in

the folded stable state, demonstrating more controllable self-deployment characteristics [115-117]. As a result, Bi-DCBs hold significant potential for a wide range of applications.

Since the initial proposal of the tubular Bi-DCB by British scholar Daton Lovett in 1996, Cambridge University has been at the forefront of related research in this field. Various theoretical models have been developed to predict the geometrical configuration, stored strain energy, and stress levels of the tubular Bi-DCB in the folded stable state. Fig. 11b provides an overview of the evolution and development of the most representative analytical models. Based on the CLT and the principle of minimum potential energy, Iqbal et al. [29] successfully established a simple linear elastic analytical model and derived expressions for the strain energy as a function of longitudinal and transverse curvatures, as well as the cross-sectional angle. This model can be used to predict the cross-sectional radius of the tubular Bi-DCB in the folded stable state. However, the bistable behavior exhibited by symmetric and antisymmetric laminates cannot be distinguished in this model. Galletly and Guest [30] further developed a “beam model” based on the Iqbal model, considering all possible deformation modes, including torsion, shear, and stretch-bend coupling effects. The theoretical predictions are consistent with numerical simulations but show significant discrepancies with experimental results. In subsequent studies, Galletly and Guest [31] proposed a “shell model” that abandoned assumptions about cross-sectional shapes. Compared to the “beam model”, the predictive performance of the “shell model” is essentially the same, but still presents noticeable deviations from experimental results. This difference may be attributed to plastic deformation of the matrix at high strains, while the material is assumed to be linear elastic throughout in the analytical models. Additionally, Guest and Pellegrino [32] introduced a two-parameter analytical model assuming a uniformly distributed deformation of the shell, with zero Gaussian curvature at all times. This model can determine the cross-sectional radius of the tubular Bi-DCB in the folded stable state, and its predictions align with those of the aforementioned three analytical models. However, these four analytical models still cannot accurately predict the true geometrical configuration of longer tubular Bi-DCB in the folded stable state, as their cross-sectional geometry more closely resembles an Archimedes’ helix rather than a circle. Therefore, based on the works of Iqbal et al. [29] and Guest et al. [32], Liu and Bai et al. [118] introduced more precise geometric models to describe the folded stable state (arbitrary length and number of coils) of tubular Bi-DCBs. An analytical model was established to predict the folding behavior, including stored strain energy, geometric configuration,

and stress levels of the tubular Bi-DCB. Based on this, Liu and Bai further analyzed the effect of temperature on the folded stable state through theoretical modelling and numerical simulation [119]. Figs 11c to 11e illustrate the modelling process of the representative Iqbal model, two-parameter model, and improved model proposed by Liu and Bai.

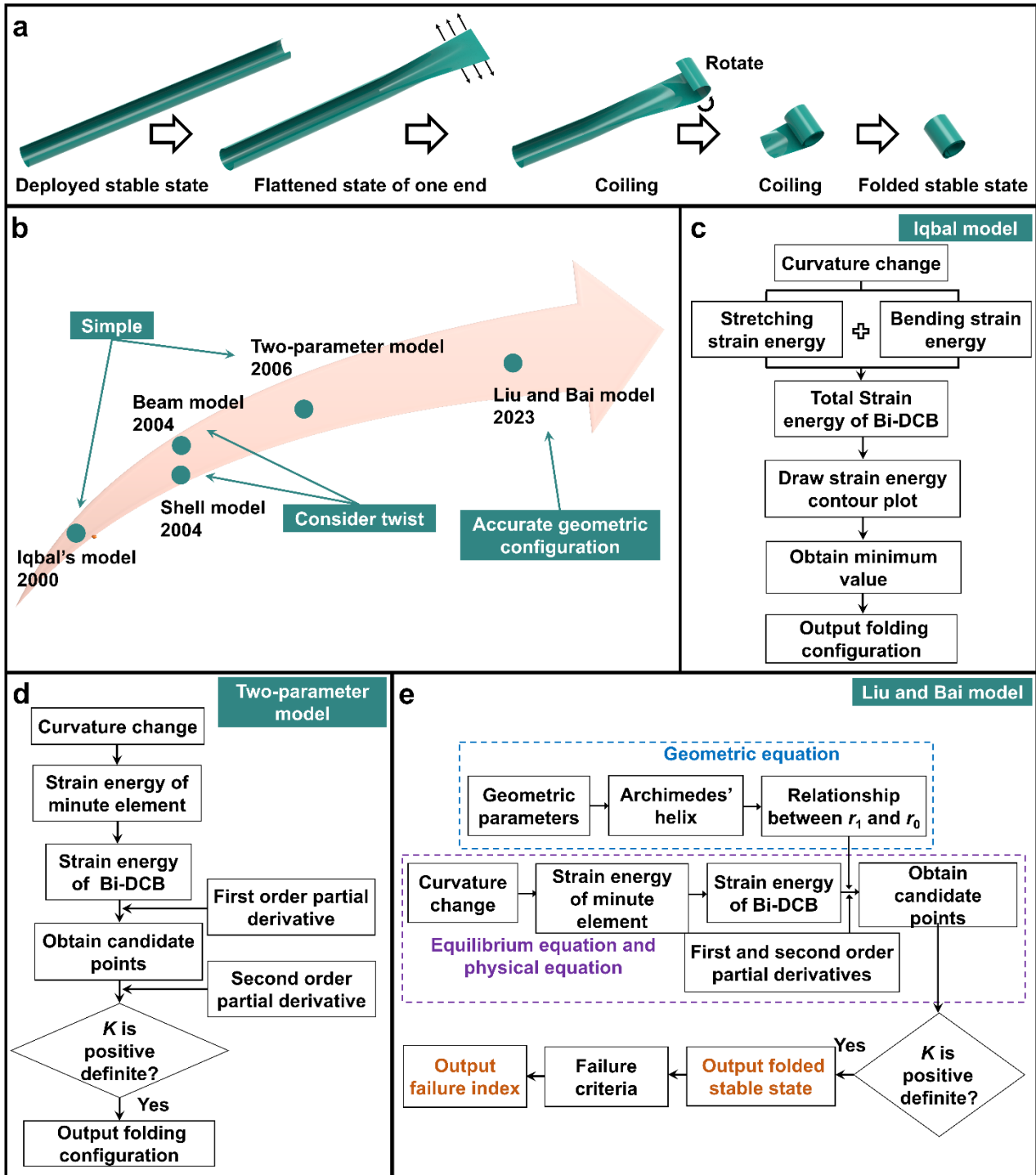


Fig. 11 Tubular bistable deployable composite boom: (a) Bistable deformation process (b) Evolution and development process of analytical models (c) Modelling process of Iqbal model (d) Modelling process of two-parameter model (e) Modelling process of Liu and Bai model.

The deployment behavior of Bi-DCBs, which are of particular interest for space applications, needs to be carefully examined. This includes stability [120-122], driving force [123], deployment speed [124], deployment deformation process [125], and viscoelastic behavior, etc [126-142]. Additionally, the ploy region length of Bi-DCBs should be considered, which refers to the length of the region between the folded state and the deployed state. The length of the ploy region can range from a few inches to several feet and has a significant impact on the efficiency of folding. Furthermore, the ploy region can potentially weaken the final structure, necessitating additional support structures for reinforcement. Yang et al. [143] hypothesized that longitudinal and transverse curvatures are the primary factors influencing the ploy region and derived a function describing the variation of energy with curvature along its length. They found that as the curvature approaches the final deployed curvature, and the total energy gradually increases. This model provides a convenient way to predict the ploy region length and curvature distribution. Based on the analytical model proposed by Rimrott et al. for isotropic tubular deployable boom, Wang and colleagues [144-146] theoretically predicted the ploy region length of Bi-DCBs. Rakow and Reedy [147] compared these two analytical models through experiments and numerical simulations and discussed the parameters influencing the ploy region length. These studies highlight the importance of understanding and predicting the behavior of the ploy region in order to optimize the design and performance of Bi-DCBs.

Apart from the tubular Bi-DCB, several researchers have utilized the analytical model established by Guest and Pellegrino [32] along with numerical simulation to design various other configurations of Bi-DCBs. For instance, the parabolic Bi-DCB [148-150], the Bi-DCB with initial longitudinal curvature [151,152], the Bi-DCB with flat region [153], the lenticular Bi-DCB [149,154-156], bistable TRAC boom [150,154], and SHEARLESS Bi-DCB [149,156].

4. Deployable composite reflectors

Deployable composite reflector antennas are a common type of antenna in the space field. It is made of composite materials and possesses high flexibility and toughness. Deployable composite reflector antennas find wide applications in spacecraft. For instance, they can be used as a high-gain antenna in communication satellites, as a radar antenna in earth observation, as a microwave radiometer in remote sensing, and as a radio telescope in scientific exploration. Additionally, deployable composite reflector antennas can also be utilized for adaptive deformation and vibration control of spacecraft. Based on the folding and deployment methods, deployable composite reflector

antennas can be classified into taco-shaped type, petal-shaped type, umbrella-shaped type, and warp-rid type.

4.1 Taco-shaped deployable composite reflectors

The taco-shaped deployable composite reflector antenna, also known as the spring-back reflector antenna, is a common type of antenna in the space field. The reflector of this antenna is made of composite materials and features a secondary backplane and support structure to provide deployment stiffness and accuracy. During launch, a restraint device is used to maintain the folded configuration. Once in orbit, the restraints are released, and the antenna automatically deploys. The taco-shaped deployable composite reflector has been successfully applied to communication antennas on the satellite by the Canadian Space Agency (CSA) [157], as shown in Fig. 12a. However, the deployment stiffness of the taco-shaped deployable composite reflector is relatively low. To address this issue, Tan et al. proposed a method of locally reinforcing the reflector [158,159], as shown in Fig. 12b. Research has shown that local reinforcement significantly increases the stiffness and accuracy of the reflector without adding mechanical complexity to the system. This type of reflector meets the stringent requirements of high-precision communication while offering advantages such as low cost, high dimensional accuracy, and ease of folding. For Ku-band missions, Türkmen et al. designed a full-sized off-axis reflector and considered different reinforcement schemes (shown in Fig. 12c) [160]. The study reveals that this design has advantages in terms of mass, natural frequency, number of components, production, and assembly. Subsequent work involved the validation of its performance through testing the modal behavior, folding, dynamic deployment, and surface accuracy of prototype samples [161]. Soykasap et al. developed a taco-shaped deployable composite reflector based on composite tape-springs as the supporting structure [162]. The study demonstrates that design variables such as initial curvature of the tape-springs, projected length, and three-dimensional folding angle have significant influences on its bending behavior. However, further research is needed to investigate the effects of the connection between the tape-springs and the reflector on the entire folding and deployment process. Fig. 12d illustrates the folding and deployment process of this reflector. Tan et al. analyzed a taco-shaped deployable composite reflector with curved reinforcing ribs [163]. It is found that by utilizing curved reinforcing ribs, local instability can be prevented, the maximum packing force required for the reflector can be increased, and its bending stiffness can be improved. Soykasap et al. presented a design scheme for an X-band satellite taco-shaped deployable composite

reflector, which was experimentally validated for folding and deployment functionality (shown in Fig. 12e) [164].

It should be noted that this type of deployable composite reflector also has some limitations, such as difficulties in controlling dimensional accuracy, lower folding efficiency, and the potential for sudden release of stored strain energy causing deployment shocks. These limitations restrict its applications.

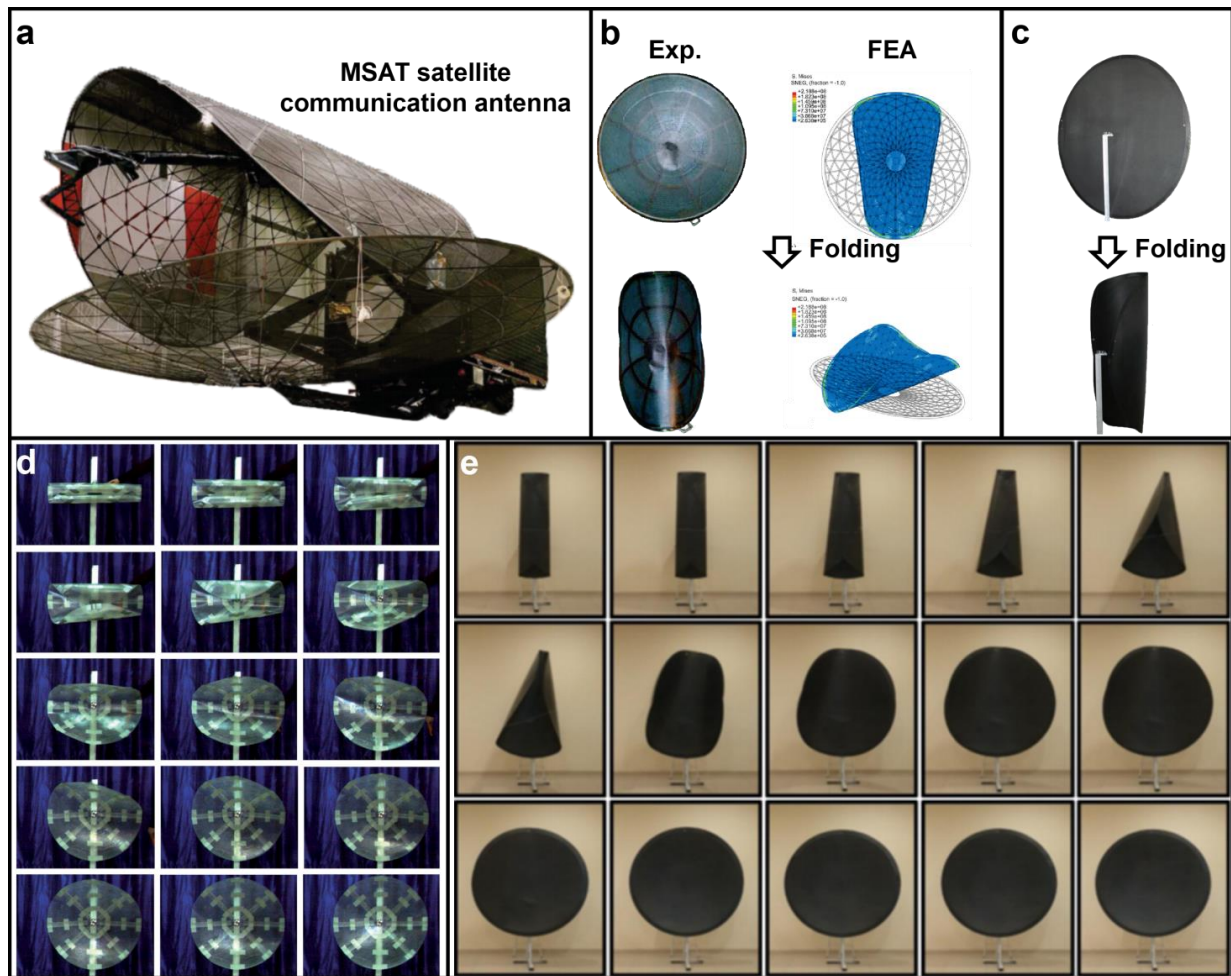


Fig. 12 Taco-shaped deployable composite reflectors: (a) Spring-back reflector in deployed and packaged configurations (Courtesy of the Canadian Space Agency [http://www.space.gc.ca.](http://www.space.gc.ca)) [157] (b) Stiffened spring-back reflector [159] (c) Predesign reflector made of three-ply (0/45/0) plain weave carbon/epoxy [160] (d) Ultra-thin shell deployable reflector based on curved large tape springs [162] (e) Dynamic deployment of self-deployable CFRP flexible shell reflector [164].

4.2 Petal-shaped deployable composite reflectors

The petal-shaped deployable composite reflector antenna is typically composed of a reflector and a feed source at the focal point. The reflector features a petal-like shape, hence it is referred to as

a petal-shaped reflector [165] (shown in Fig. 13a). This type of reflector exhibits high mechanical complexity to achieve the required accuracy during the folding and deployment process. To meet the requirements of deployable antennas with aperture sizes ranging from 0.3m to 1m, Stiles and Garrett [166] proposed a radial segmented winding scheme, which divides the flexible shell surface into multiple segments along a spiral path. Through the design of the spiral shell surface, each segment remains purely curved in the folded configuration, avoiding the shape accuracy variation caused by shear loads. To achieve synchronization during the deployment process, a scissor-hinge-like connection scheme is employed along the circumferential edge of each segment. However, due to the weak stiffness of a single shell segment, significant deformations can occur under the influence of gravity, thus the prototype was only subjected to deployment verification tests on a forming mold. Enhancing the stiffness of the individual shell segments and controlling the deployment behavior are important issues to be addressed for petal-shaped deployable composite reflectors. Reynolds et al. [167] designed a highly compact petal-shaped deployable composite reflector that can be stored within a 1U CubeSat. They developed a radial segmented winding method and utilized constraints to limit the reflector, resulting in the desired load characteristics of the planar structure. Footdale et al. [168] developed a Multi-Arm Radial Composite (MARCO) reflector to reduce costs (shown in Fig. 13b). This multi-arm radial segmented coiling reflector employs segmented composite shell bodies as the reflector, and a simplified assembly technique to lower the costs. The deployed diameter of this reflector is 4m and it can be stowed within a cylindrical container with a diameter of 0.66m and a height of 1.1m (shown in Fig. 13c). Experimental validation was conducted to demonstrate that the shape and gravity-induced deformations of the reflector meet the accuracy requirements for surface profiles.

Petal-shaped reflector antennas offer high gain, high directivity, wideband characteristics, excellent interference resistance, and a high signal-to-noise ratio. However, such reflectors require highly complex mechanical structures for folding and deployment to achieve the desired accuracy. The use of mechanical components introduces thermal deformations, which further complicate system design. To effectively address the limitations of petal-shaped reflector antennas, Harris Corporation has developed a novel type of petal-shaped deployable composite reflector antenna, also known as a flexible precision reflector antenna [169] (shown in Fig. 13d). This flexible precision reflector is composed of composite material thin shells and can be folded in an umbrella-like folded

manner. By dividing the reflector into multiple panels, a larger diameter can be achieved while ensuring high precision and flatness. Harris Corporation also developed a lightweight and structurally simple flexible precision reflector antenna with a diameter of 0.9 meters (shown in Fig. 13e), which operates in frequencies above 40GHz [170]. The feasibility of this design approach has been validated through the fabrication and testing of a petal-shaped reflector antenna model. Dufour et al. [171] reported a new concept for a flexible precision reflector antenna, as shown in Fig. 13f. Compared to traditional fixed reflector antennas, this deployable design offers smaller folding dimensions and lighter weight. Additionally, the use of origami-inspired techniques enables higher surface accuracy, thereby improving RF performance. The reflector is suitable for antennas ranging from 0.5 meters to 2 meters in diameter and can operate at high frequencies in the Ka-band, providing more options for communication and scientific missions.

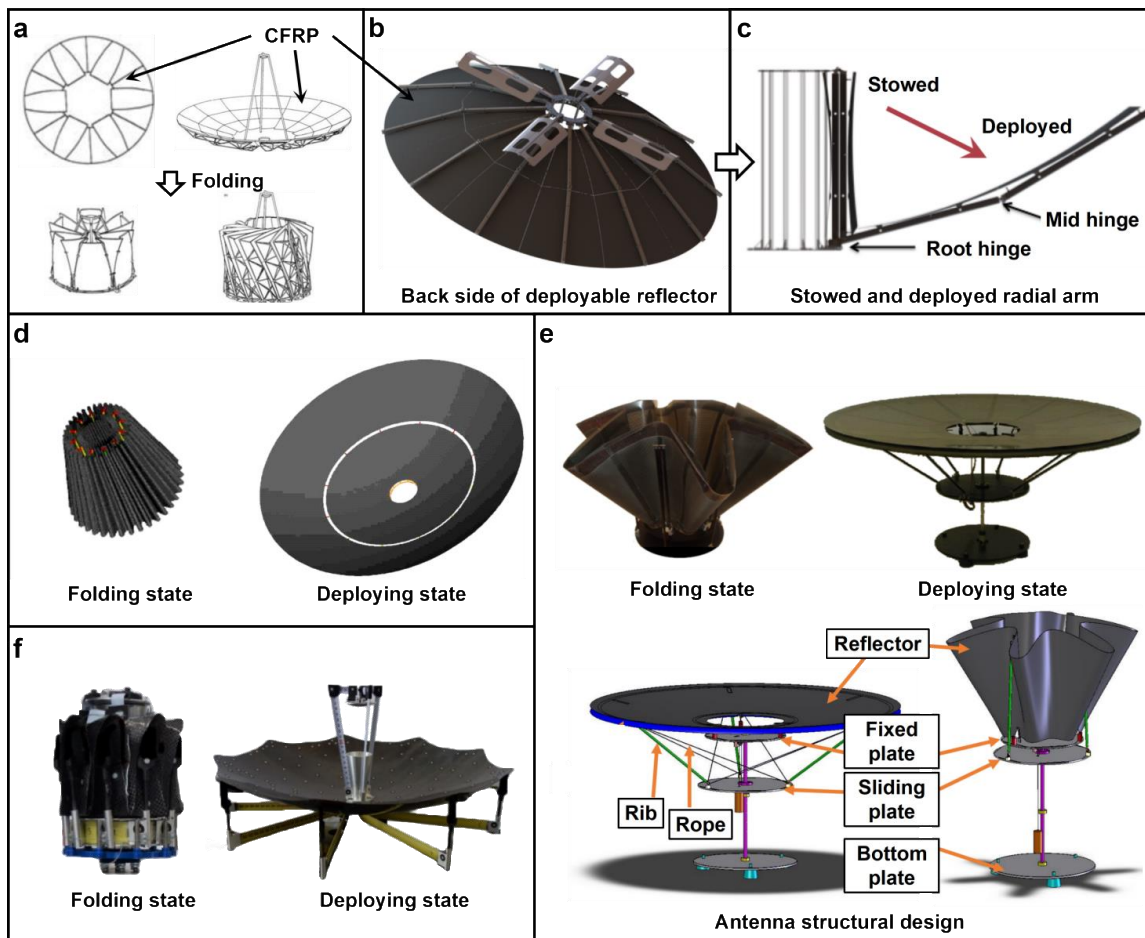


Fig. 13 Petal-shaped deployable composite reflectors: (a) Early reflector schematic diagram [165] (b) Back side of multi-arm radial composite reflector [168] (c) Folded and deployed multi-arm radial composite reflector [168] (d) Flexible precision reflector [169] (e) Breadboard reflector [170] (f) Origami deployable reflector [171].

4.3 Umbrella-shaped deployable composite reflectors

Umbrella-shaped deployable composite reflector antennas are characterized by low areal density and compact stowage volume. They can operate in a high-frequency range and achieve a large deployment diameter. Compared to traditional flexible reflectors, umbrella-shaped deployable composite reflectors can withstand larger stowage strains without creep and maintain high accuracy with fewer ribs (shown in Fig. 14a) [172].

To meet the requirements of spaceborne Synthetic Aperture Radar (SAR) antennas, Schmid and Barho [173] proposed an umbrella-shaped deployable composite reflector scheme with a 3-meter aperture. The reflector is assembled from 30 thin shell panels, each with a thickness of approximately 0.4mm and a surface accuracy of around 0.5mm. The weight of each panel is approximately 200 grams. Folding and deployment of the panels are achieved by arranging radial support ribs on the backside. When folded, the back support ribs rotate around the axis, causing the shells to tilt and undergo pure bending, allowing for overlapping of adjacent panels and improving stowage efficiency. For example, the stowage diameter of a 3-meter aperture reflector is less than 1 meter, with a weight of approximately 10 kilograms. After deployment, the panels are individually formed and combined to form the reflector, with a gap of about 0.5mm between panels, avoiding the problem of reduced surface accuracy due to mismatched dimensions (shown in Fig. 14b). This scheme is suitable for X-band frequencies and above, with an aperture range between 3 meters and 6 meters. Yoon et al. [174] investigated an umbrella-shaped deployable composite reflector (shown in Fig. 14c), which offers advantages such as lightweight, low loss, high precision, and stability. They also studied the radiation pattern, gain, and polarization variation effects of the antenna in the X-band by considering the changes in effective electrical properties affected by fiber direction. Datashvili et al. [175] designed a mechanically reconfigurable umbrella-shaped deployable composite reflector (shown in Fig. 14d) by simplifying support ribs. This reflector can achieve larger diameters and operating frequencies with high surface accuracy. Klimm and Kwok [176] proposed a concept for an umbrella-shaped deployable reflector based on composite tape-springs. The composite tape springs store strain energy during deployment and guide the development direction while simplifying the structure. The composite tape-springs in this approach closely follow the shape of the reflector and can independently recover their original shape (shown in Fig. 14e). Pellegrino [177] presented a design for a novel multifunctional deployable reflector. The reflector consists of a central deployable hub,

several composite tape-springs connected to the hub, ribs for support, and tensioned precision membrane, as shown in Fig. 14f. For a deployable reflector with a 10-meter diameter and a focal length of 7.8 meters, a surface accuracy of approximately 2 millimeters can be achieved. Additionally, they introduced a proof-of-concept design with a 1.5-meter diameter and experimentally validated the accuracy and deployment behavior of the theoretical model. [Morozov and his colleagues \[178\]](#) introduced a novel umbrella-shaped deployable composite reflector based on anisogrid composite lattice spoke. This spoke takes the form of a long lattice shell, with its cross-section shaped as a rounded rectangle. The loads acting on the spoke are produced by the radio-reflective stretched mesh of the reflector when it is deployed. In the follow-up work, they proposed another umbrella-shaped deployable composite reflector that achieves deployment through integral deployable composite hinges [179].

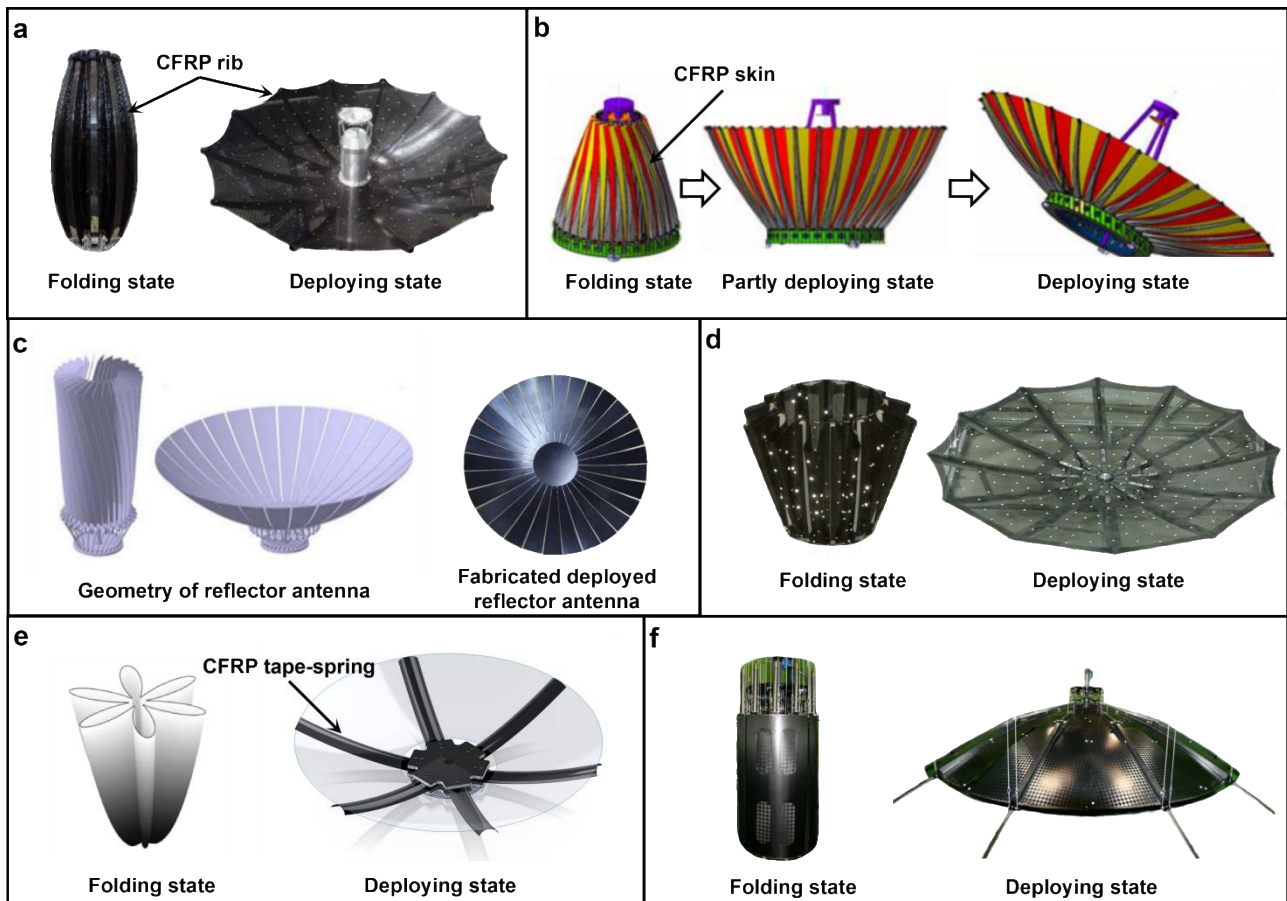


Fig. 14 Umbrella-shaped deployable composite reflectors: (a) 1 m diameter FlexRS®-I SUTRA antenna in deployed and folded states [172] (b) 3 meter unfurlable CFRP skin reflector [173] (c) Deployable CFRP reflector for SAR [174] (d) Flexible shell-membrane reflector [175] (e) Deployable reflector with a continuous composite thin-shell and six tape-springs [176] (f) Collapsible rib-tensioned surface reflector [177].

4.4 Warp-rib deployable composite reflectors

In the 1970s, the concept of a wrap-rib deployable reflector was first proposed by the Jet Propulsion Laboratory (JPL) of NASA and Lockheed Missiles & Space Company. It mainly consists of a central axis, wrap-ribs, and a mesh reflector. The wrap-ribs are hinged to the central axis and extend radially along the axis to support and maintain the parabolic shape of the mesh reflector. In the folded state, the wrap-ribs are tightly wound around the central axis in one direction. During deployment in orbit, the wrap-ribs rely on their own elastic potential energy to rebound and deploy. Therefore, the wrap-rib deployable reflector has advantages such as high stowage efficiency, simple folding and deployment control mechanisms, and high reliability.

The wrap-rib deployable reflector was first installed on the ATS-6 satellite launched in 1974 (shown in Fig. 15a). The reflector consisted of 48 wrap-ribs, with a central axis diameter of 2.0m and a height of 0.45m. When deployed, the effective aperture of the reflector was 9.1m. The complete structure weighed approximately 60kg [180]. Following this, the U.S. Department of Defense successfully developed a series of wrap-rib deployable reflectors. For example, a partially folded sector of a 55-meter reflector structure was successfully deployed on the ground in 1984 (shown in Fig. 15b) [181]. Urata et al. [182,183] developed a 3.6-meter diameter wrap-rib deployable reflector for earth observation, as depicted in Fig. 15c. OSS designed a wrap-rib deployable reflector antenna for X-band SAR in low earth orbit, as shown in Fig. 15d [184-186]. This antenna has a diameter range from 2.7 meters to 5 meters and utilizes a mesh reflector surface. It includes a central axis, multiple lenticular DCBs to support the reflector, and a deployable secondary composite reflector and supporting pole. Urata et al. [187] designed a novel wrap-rib deployable reflector, and Figs. 15e and 15f illustrate the schematic and experimental process of the reflector deployment, respectively.

However, wrap-rib deployable reflectors suffer from poor stiffness, vibration resistance, and accuracy. To improve the surface accuracy, a large number of wrap-ribs and a central axis with a corresponding volume are required. This significantly increases the weight of the reflector and makes it difficult to fold, making it unable to meet the requirements for larger apertures.

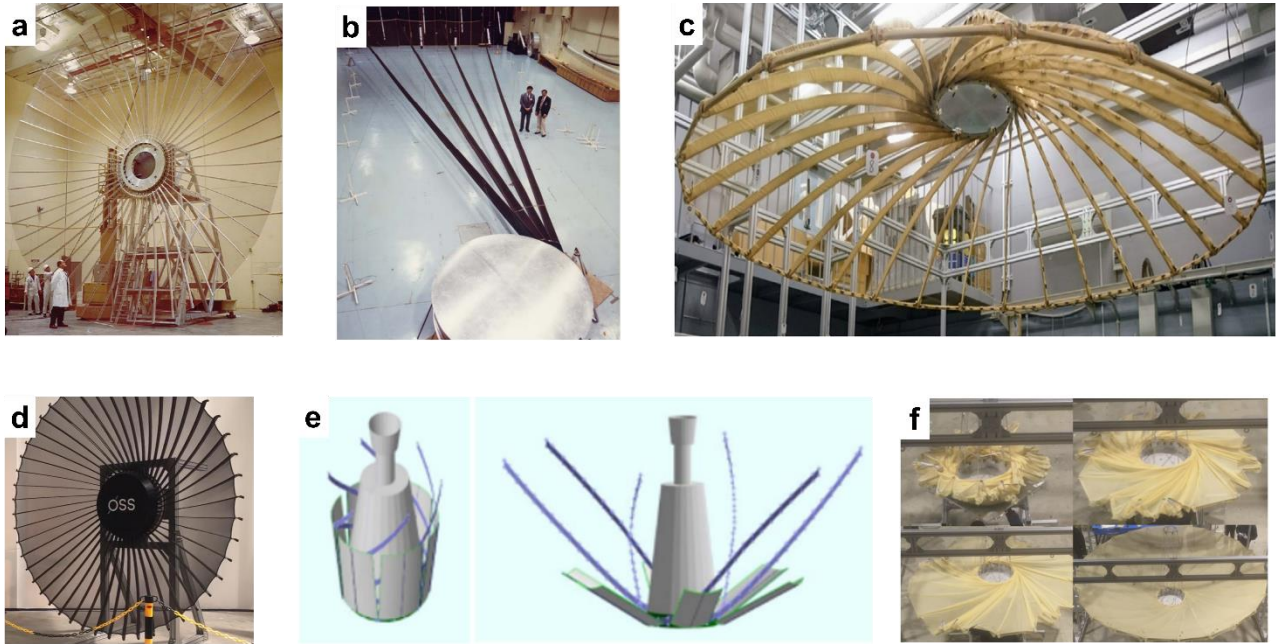


Fig. 15 Warp-rid deployable composite reflectors: (a) $D=9.5$ m deployable composite reflector fabricated in the 1970's [180] (b) $D=55$ m deployable composite reflector fabricated in the 1980's [181] (c) Prototype of warp-rid deployable composite reflector [182] (d) Deployed 2.7m OSS warp-rid deployable composite reflector [184] (e) Conceptual mechanism [187] (f) Deployment test [187].

5. Optimization design

5.1 Classification and optimization process

Not only are engineers interested in designing different structural forms, but they also seek the optimal solution. The process of finding the best design is known as optimization and is widely applied in various engineering fields. The optimization design of deployable composite structures has been extensively reported. Design variables such as material type, geometric dimensions, number of layers, ply angles, and individual layer thickness can be considered as optimization parameters to achieve different objectives. These objectives may include maximizing natural frequency, maximizing stiffness, minimizing folding moment, minimizing steady-state configuration, maximizing buckling load, minimizing total weight, and maximizing critical buckling temperature. The optimization problem of deployable composite structures can be categorized based on the quantitative relationship between design variables and optimization objectives, objective functions, and attributes of design variables and constraints. The following are common classification approaches:

- Univariate and multivariate optimization problems: This category is based on the number of design variables involved. For a single design variable, it is referred to as a univariate optimization problem, while multivariate problems involve multiple design variables.

- Discrete and continuous optimization problems: Based on the type of value range for design variables, problems can be classified as discrete or continuous optimization problems. Discrete optimization problems refer to cases where design variables take on discrete values, such as material type, number of layers in laminate, and ply angles. On the other hand, continuous optimization problems refer to cases where design variables take on continuous values.

- Constrained and unconstrained optimization problems: Some optimization methods require satisfying certain constraints, such as dimensions and mass of deployable composite structures during folding configuration and prevention of failure during large deformation processes. These problems are known as constrained optimization problems, while unconstrained optimization refers to cases where design variables can freely vary without any constraints.

- Single-objective and multi-objective optimization problems: The classification of problems depends on the number of objective functions involved. Single-objective optimization problems evaluate the optimal solution based on a single objective function. Multi-objective optimization problems, based on the Pareto front, are often considered more interesting as engineers can better understand the design space and choose designs that match other considerations not included in the optimization.

- Static and dynamic optimization problems: If the optimization process depends on time and the performance changes after a certain period, it is referred to as a dynamic optimization problem, which is different from static optimization problems. In static optimization, the optimal design does not depend on time.

The coupling surrogate model and evolutionary algorithm has been widely applied in the design of deployable composite structures. Fig. 16 presents the specific optimization process using this technology, as follows:

- 1) A set of initial samples are collected, which can be obtained through Design of Experiment (DOE) or random sampling methods. These samples serve as the basis for constructing the surrogate model.

2) The surrogate model is trained using the collected samples. The most common surrogate models include Response Surface Method (RSM), Kriging model, Elliptical Basis Function (EBF), Radial Basis Function (RBF), Artificial Neural Network (ANN), Support Vector Regression (SVR), and Random Forest (RF) [188].

3) The predictive capability of the surrogate model is validated using statistical error functions. Table 1 summarizes nine high-performance statistical error functions, and specific evaluation methods can be found in the original references [189-197].

4) The surrogate model is embedded into the evolutionary algorithm. Each individual in the evolutionary algorithm consists of a set of decision variables, which are inputted into the surrogate model to obtain the corresponding objective function value, serving as the fitness score of the individual. The most popular evolutionary algorithms include Genetic Algorithm (GA), Simulated Annealing (SA), Particle Swarm Optimization (PSO), and Ant Colony Optimization (ACO) [198,199].

5) In evolutionary algorithms, mechanisms such as selection, crossover, and mutation are used to generate new individuals, which are then evaluated for their fitness using surrogate models. These mechanisms are based on the principles of natural selection and evolutionary theory, mimicking the process of biological evolution. The new individuals replace the old ones gradually in the search process, aiming to optimize the value of the objective function.

6) Repeat step 5 until a predefined termination condition is met. The termination condition can be reaching the maximum number of iterations or satisfying the convergence requirements of the objective function. In each iteration, the surrogate model is used to evaluate the fitness of each individual, enabling the evolutionary algorithm to further explore the solution space. Performance evaluation of different evolutionary algorithms and hyperparameters can be quantitatively assessed based on key indicators such as convergence, distribution diversity, and distribution range. Common quantitative evaluation methods for optimizers include Hyper Volume (HV) [200], Maximum Spread (MS) [201], Generational Distance (GD) [202], Inverted Generational Distance (IGD) [203], and mimicked Inverted Generational Distance (mIGD) [204].

It should be noted that although the computational process of coupling surrogate model and evolutionary algorithm is relatively complex, there are currently many integrated software options available, such as Insight, modeFRONTIER, OptiStruct, MATLAB Optimization Toolbox, ANSYS DesignXplorer, and OpenMDAO. These software platforms integrate different models and algorithms

into a unified platform for design and optimization workflows. By integrating different computational models and tools, engineers can find optimal structural design solutions faster and more accurately.

Table1 Statistical error functions.

| Error function | Equation |
|--|--|
| Root mean square error [189] | $RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (Y_i - Y_{i,pre})^2}$ |
| Mean square error [190] | $MSE = \frac{1}{N} \sum_{i=1}^N (Y_i - Y_{i,pre})^2$ |
| Mean absolute error [191] | $MAE = \frac{1}{N} \sum_{i=1}^N Y_i - Y_{i,pre} $ |
| Mean predictive error (%) [192] | $MPE(\%) = \frac{100}{N} \sum_{i=1}^N \left \frac{Y_i - Y_{i,pre}}{Y_i} \right $ |
| Chi square statistics (χ^2) [193] | $\chi^2 = \sum_{i=1}^N \frac{(Y_{i,pre} - Y_i)^2}{Y_{i,pre}}$ |
| Correlation coefficient (R^2) [194] | $R^2 = 1 - \frac{\sum_{i=1}^N (Y_{i,pre} - Y_i)^2}{\sum_{i=1}^N (Y_i - Y)^2}$ |
| Adjusted correlation coefficient (R_{adj}^2) [195] | $R_{adj}^2 = 1 - \left[\frac{(1 - R^2)(N - 1)}{N - P - 2} \right]$ |
| Willmott's index of agreement (d1) [196] | $d1 = 1 - \frac{\sum_{i=1}^N Y_{i,pre} - Y_i }{\sum_{i=1}^N Y_i - Y_e + Y_{i,pre} - Y_e }$ |
| Hybrid fractional error function [197] | $HYBRID = \frac{100}{N - P} \sum_{i=1}^N \frac{(Y_i - Y_{i,pre})^2}{Y_i}$ |

Note: The meaning of the formula symbols in Table 1 can be found in the corresponding literatures.

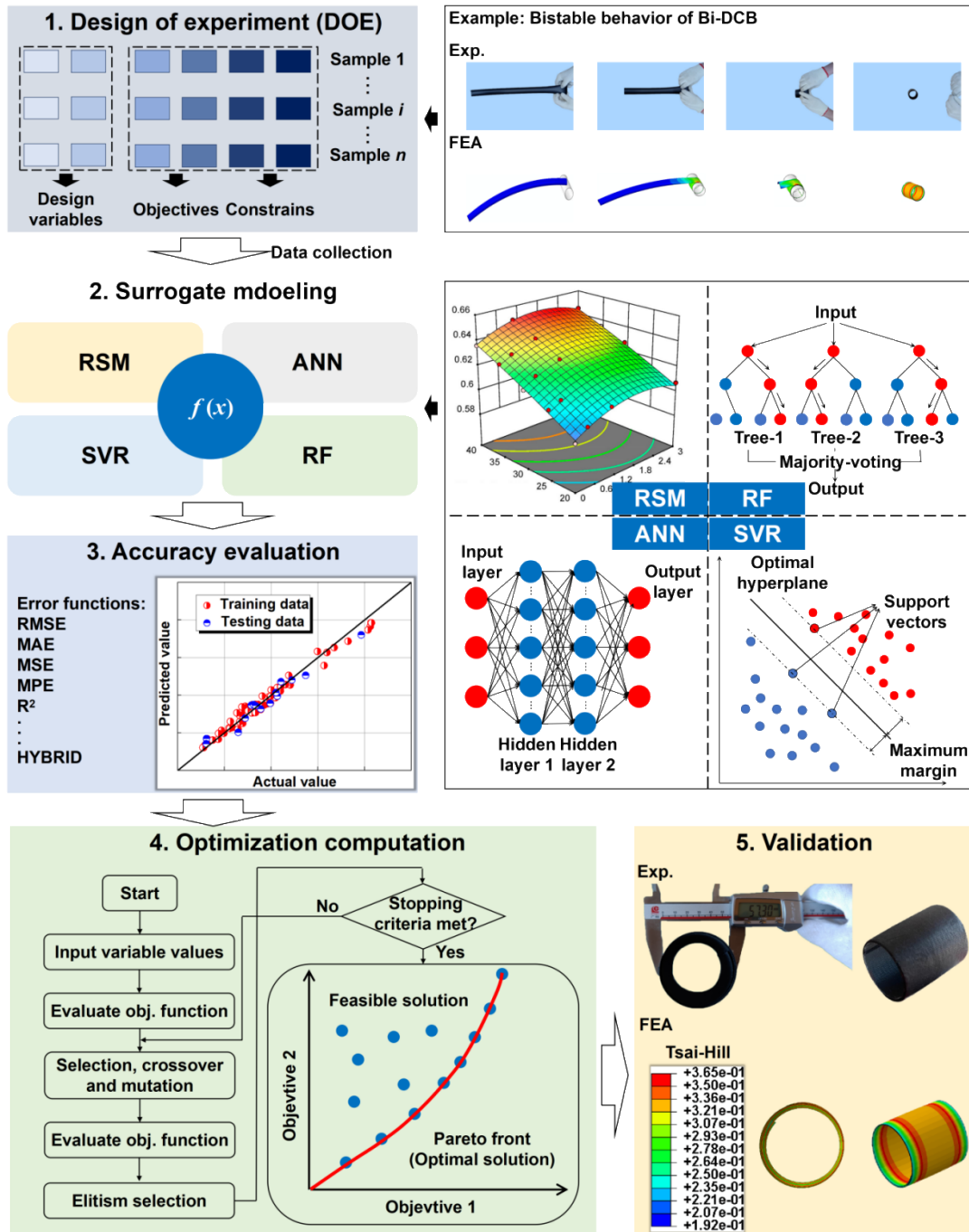


Fig. 16 Flowchart of coupling surrogate model and evolutionary algorithm technology for optimizing deployable composite structures.

5.2 Optimization for deployable composite structures

A brief review of existing optimization designs for deployable composite structures. Klimm et al. [205] investigated the influence of geometric parameters on the deployment behavior of viscoelastic deployable composite tape-spring using Gaussian process regression. They applied Nondominated Sorting Genetic Algorithm II (NSGA-II) for multi-objective optimization of residual deformation, strain, and mass. Su et al. [206] employed optimal Latin hypercube sampling method

for DOE, established a surrogate model based on EBF, and then conducted sensitivity analysis. They achieved the optimal design of the integral DCH in terms of lightweight, peak folding moment, and peak torsional moment using Multi-Objective Particle Swarm Optimization algorithm (MOPSO). Building upon the previous works, Liu et al. [207] utilized four surrogate models and four GAs to optimize the integral DCH. The study reveals that the coupling RSM-NSGAIII approach is the most effective optimization method. Jin et al. [208] focused on the slot shape optimization problem for the integral DCH. They used four surrogate models and shape optimization methods to maximize the stored maximum strain energy during folding and the maximum bending moment during deployment. Li et al. [209] established an optimal model based on RSM to obtain the maximum strain energy and minimum peak moment for the integral DCH, ensuring stable deployment. Additionally, the Hashin failure criterion was adopted to examine material damage during the folding process to prevent failures. Inspired by the work of Mallikarachchi et al. [210] and considering the requirements defined in ESA's 2016 work statement [211], Fernandes et al. [212] discussed the design concept incorporating damage tolerance, allowing for damage initiation during the folding process for the integral DCH to meet stricter requirements. GAs were used to maximize the natural frequencies of two types of integral DCH: one operating within the elastic range with restricted design, and another allowing for limited damage initiation during folding.

Yang et al. [98,213-215] performed the multi-objective optimization design of DCBs, including tubular DCB, TRAC boom, N-shaped DCB, and lenticular DCB. Firstly, a full factorial design method was employed to create sampling designs for the four types of DCBs mentioned above. Subsequently, efficient computational analyses were conducted on each design sample using the nonlinear finite element solver ABAQUS/Explicit, focusing on the deployment stiffness, folding behavior, and mass of the four types of DCBs. RSM and Back Propagation Neural Network (BPNN) were utilized to establish surrogate models for the deployment stiffness and folding behavior. Lastly, NSGA-II and the Sequential Quadratic Programming algorithm (SQP) were employed for multi-objective optimization design. Similar to the optimization approach used by Yang et al., Shi et al. [216] optimized the M-shaped DCB using a coupling RSM and NSGA-II technique. Bessa and Pellegrino [217] proposed a data-driven computational framework combining Bayesian regression, uncertainty quantification, and multi-objective optimization for the design of the TRAC boom. The results show a significant increase in the ultimate buckling load and potential benefits of up to 100%

compared to previously proposed design schemes. In addition to the single-stable DCBs mentioned above, recent attention has been given to the multi-objective optimization design of Bi-DCBs. Zhang et al. [218,219] proposed a combination of Finite Element Analysis (FEA), multi-objective optimization techniques, and experimental methods to determine the optimal geometric parameters (including cross-sectional angle, thickness, cross-sectional radius, and length) of the tubular Bi-DCB. An optimal Latin hypercube sampling algorithm was employed to obtain sample points for DOE. RSM and NSGA-II were used to obtain the Pareto front of the tubular Bi-DCB. Wu and Vinquerat [220] conducted natural frequency optimization design of the tubular Bi-DCB using MATLAB Optimization Toolbox. To achieve this, they optimized the braid angles and stacking sequences with the constraint of folded stable radius, while considering the maximum and minimum physically achievable braid angles as bounds.

At present, there is a lack of research on multi-objective optimization design of deployable composite reflector antennas using the coupling surrogate model and evolutionary algorithm. Given the wide applications of deployable composite reflector antennas in fields such as communication, radar, and satellites, future research can explore the application of multi-objective optimization design methods to the design of deployable composite reflector antennas. This would enable a balance and optimization between different performance indicators. It will be a key research direction in the design of deployable composite reflector antennas.

A brief review of literature on multi-objective optimization design of deployable composite structures reveals that most existing works utilize RSM to establish surrogate models between design variables and objective functions. There are several reasons for this trend. Firstly, RSM is a simple and widely used mathematical regression model that establishes predictive equations by statistically fitting the relationship between design variables and objectives [221]. Secondly, RSM exhibits high prediction accuracy for fitting problems with small datasets [206,207]. It is noted that most studies employ NSGA-II for multi-objective optimization design, which is likely due to its good performance as a general solver for many problems. However, it is important to consider that improving algorithm performance for a specific problem may inevitably lead to a decrease in performance for other types of problems, as stated by the “No Free Lunch” theorem. Hence, in specific cases, benchmarking multiple evolutionary algorithms is necessary to select the optimal algorithm and achieve the best

optimization results [207]. Lastly, other surrogate models such as ANN and RF possess certain limitations, such as the requirement for large datasets and susceptibility to parameter influence.

In addition, another optimization method, namely coupling analytical model and evolutionary algorithm, has also received some attention. For example, Liu and Bai et al. used this technique to solve the multi-objective optimization problems of deployable composite structures such as lenticular DCB [107], tubular DCB [222], and deployable composite helical antennas [223]. Analytical models typically have clear expressions, simple forms, and high computational efficiency. However, compared to surrogate models, they have a limited range of applicability. It is difficult to establish analytical models for some key objectives of deployable composite structures, such as natural frequencies, buckling, and folding behavior in the presence of contacts.

6. Application

In the early days, most of the deployable structures for space applications were made of metal materials such as titanium alloy, high-performance steel, and aluminum alloy. In the 1960s and 1970s, deployable booms were engineered and utilized in flight missions such as Technology Research for Autonomous Aircraft Concepts (TRAAC), Alouette I, and Application Technology Satellite-6 (AST-6). With technological advancements, the use of space deployable structures has shifted from initially relying on metal materials to lighter-weight composite materials. The technology of Continuous Longeron Mast (CLM), which employs glass fiber composite materials, has been successfully applied in various spacecraft, including Voyager (1977), Galileo (1989), Mars Observer (1992), and the GOES constellation (since 1994 to now). Towards the late 1970s, Lockheed Corporation replaced the aluminum ribs with carbon fiber composite ribs in the design of wrap-ribs for antennas [224]. This section provides a review of the application of deployable composite hinges, booms, and reflectors in the field of space exploration.

Deployable Composite Hinges: The concept of using deployable tape-springs as deployable structures can be traced back to 1968 [225], serving as an effective alternative to traditional hinge mechanisms. Since 1998, a series of deployable hinges have been developed, with their repeatability initially demonstrated in the integrated hinged optical support structure fabricated at the U.S. Air Force Research Laboratory. Integral DCHs have found wide-ranging applications in space missions. Examples include the antenna on the Mars Express spacecraft, launched by the ESA in June 2003 [226] (shown in Fig. 17a), and the successfully tested deployable optical telescope [227]. Furthermore,

DCHs have also led to various other design concepts and space applications, including astronomical telescopes depicted in Figs. 17b to 17d [72,228,229], deployable booms depicted in Fig. 17e [230], prism masts shown in Fig. 17f [231], and antennas illustrated in Fig. 17g [232,233]. Table 2 summarizes the various space applications of DCHs.

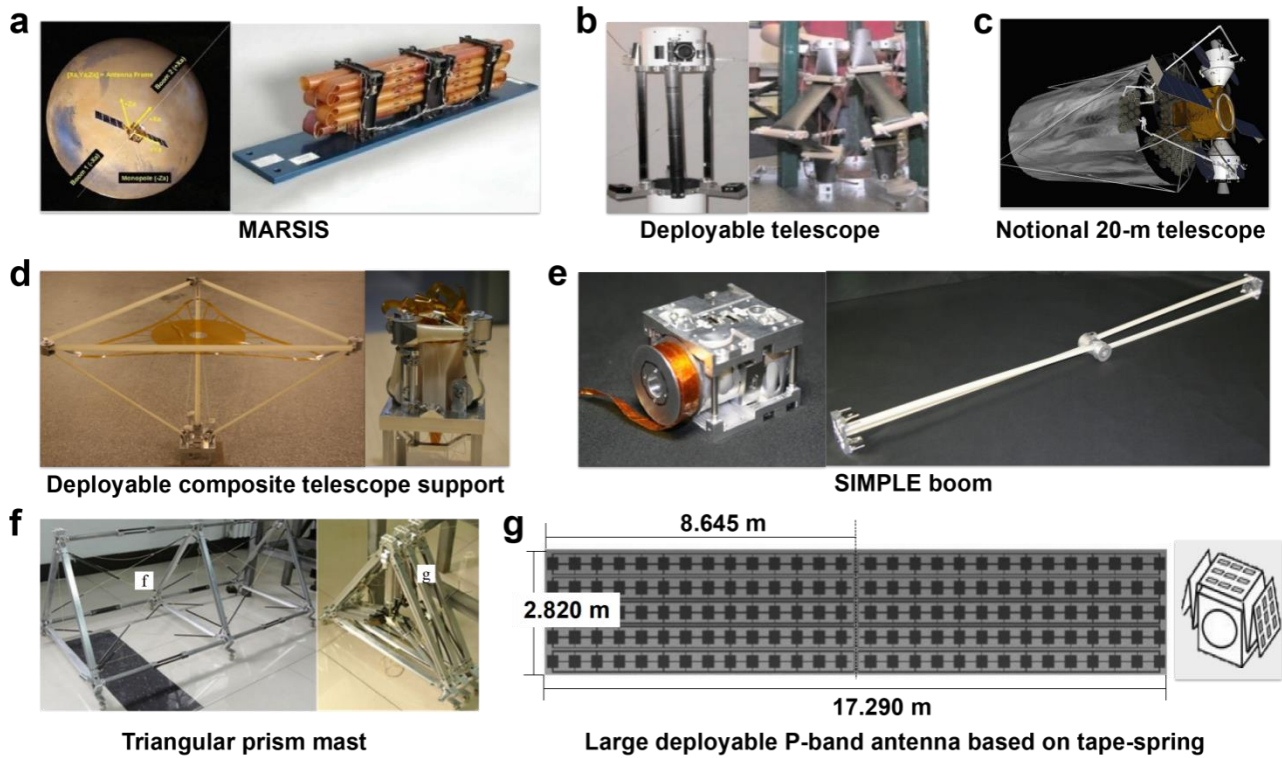


Fig. 17 Space applications of deployable composite hinges [226,228-232].

Table 2 A summary of space applications of deployable composite hinges.

| Type | Application | Operator | Material | Status |
|----------------|---|-------------------------------|----------|----------------|
| Integral [226] | Mars advanced radar | ESA | CFRP | In-orbit |
| Integral [227] | Precision optical telescope mirror | Foster Miller, Inc. | CFRP | In-orbit |
| Combined [228] | Deployable astronomical telescope | Air force research laboratory | CFRP | Porotype |
| Combined [72] | 20 meter aperture UV-visible-IR telescope | Warren et al. | CFRP | Porotype |
| Combined [229] | Deployable composite telescope | Footdale and Murphey | CFRP | Concept design |
| Combined [230] | Self-contained linear meter-class boom | Jeon and Murphey | CFRP | Concept design |
| Integral [231] | Roll-out solar array | Inc. (DSS). | CFRP | Porotype |
| Integral [232] | P-band dual polarization antenna | Soykasap et al. | CFRP | Concept design |

Deployable composite booms: In early space missions, most deployable booms were made of metal materials [224,234]. For example, the metal tubular boom used on the Hubble Space Telescope [234], as well as the metal TRAC booms used on NanoSail D2 [235], Lightsail 1 [236], Lightsail 2 [237], CubeSail [238], and NEA Scout [239], as shown in Figs. 18a to 18f. However, the use of metal materials posed certain challenges due to their heavy weight and high thermal expansion coefficient.

In response to these challenges, many research institutions have begun to focus on developing DCBs with superior performance. Since 1990, the German Aerospace Center (DLR) has been conducting research and development on the lenticular DCB with funding from the ESA. One successful application of the lenticular DCB in a flight mission is the jointly developed thin-film solar sail demonstrator by DLR and ESA, which underwent ground deployment tests [240], as shown in Fig. 18g. Additionally, the lenticular DCB was used for the support structure of a solar sail in the GOSSAMER-1 mission [241], as shown in Fig. 18h. Furthermore, various deployable structures have been developed based on the lenticular DCB, including radial ribs, filament-wound ribs, and Astro-tube masts [242,243], as shown in Fig. 18i. These structures have been widely applied in practical space missions, such as the Space Flight Unit (SFU) developed by the Japan Aerospace Exploration Agency (JAXA), Muses-V, Variable Geometry Truss (VGT), solar sails, and pact-truss deployable antennas [244-246]. Some applications are still in the conceptual design [247] and testing stages [248].

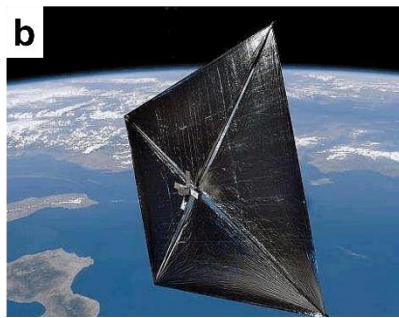
Based on the successful development of TRAC booms, the NASA further developed TRAC booms made of composite materials. This concept was proposed by Murphey and Banik and further developed and applied by the Air Force Research Laboratory (AFRL). Building upon AFRL's solar sail research, NASA developed the flexible unfurlable lightweight reflector, which utilizes four TRAC booms for the folding and deployment of the solar sail [249,250], as shown in Fig. 18j. In addition, the SIASAIL-I solar sail, launched with the Xiaoxiang-1 07 satellite, utilizes tubular DCBs for the sail deployment [251], as shown in Fig. 18k. Other forms of DCBs have also been applied, such as foldable masts [252] and trusses [253], as shown in Fig. 18l.

In China, over the past decade, a research group led by Bai from Beihang University has been devoted to the fundamental research and engineering applications of deployable composite structures. They have successfully addressed key technical issues in materials, mechanics, fabrication processes, and experimental validation. The team has developed a series of deployable composite structures with excellent properties, including one of the earliest domestically developed lenticular DCB. The

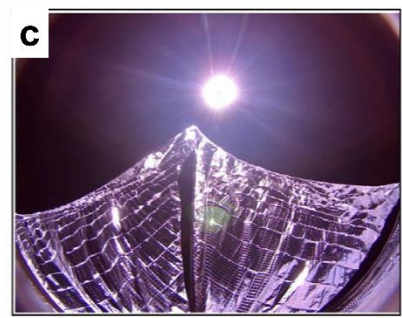
technological achievements made by Bai's team have been gradually applied in engineering models by institutions such as China Academy of Space Technology (CAST) and Shanghai Academy of Spaceflight Technology. For example, in 2019, Shanghai Institute of Aerospace Systems Engineering (SIASE) conducted the first technology demonstration of deployable deorbit sail on the Chinese micro-nano satellite "Taurus", achieving significant sail deployment results [254]. Subsequently, deployable deorbit sails were also equipped on commercial satellites such as "Qilu-4", "Foshan-1", "Tianshu-1", and "Jinzijiang-2" [255]. In 2022, a 25-square-meter deorbit sail was installed in the payload section of the Long March 2D Y64 launch vehicle [256]. Additionally, the AIS/VDE thin-film antenna was used on the "Pujiang-2" satellite in 2022 [257], along with other upcoming applications in orbit, such as sun shields and thin-film antennas. Table 3 summarizes various space applications of deployable booms.



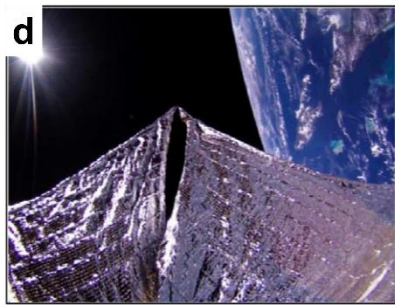
a Hubble space telescope



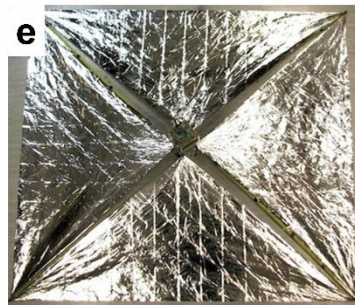
b NanoSail D2



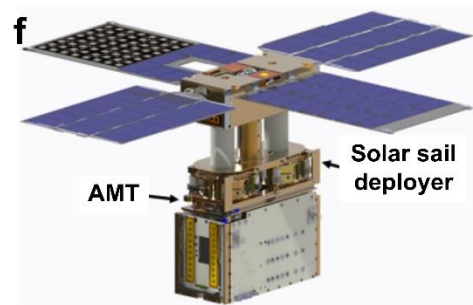
c Lightsail 1



d Lightsail 2



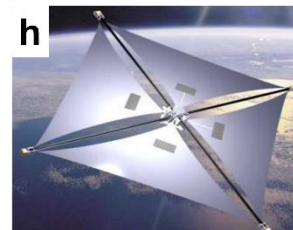
e CubeSail



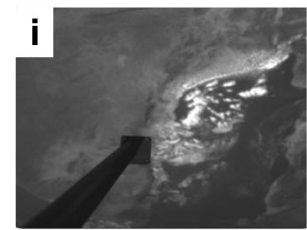
f NEA Scout spacecraft



g ESA-DLR solar sail



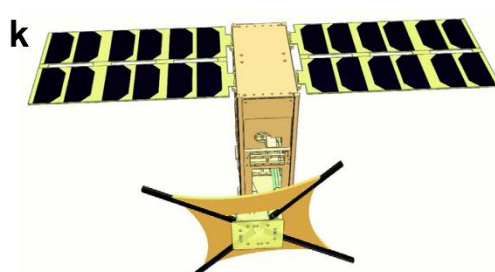
h Gossamer-1 demonstrator



i Astro tube



j FURL



k SIASAIL-I



l ROSA

Fig. 18 Space applications of deployable booms [234-242,249,251,252].

Table 3 A summary of space applications of deployable booms.

| Type | Mission | Application | Operator | Material | Status |
|------------------|------------------------------------|------------------------|--------------------------------------|----------|----------------|
| Tubular [234] | N/A | Hubble space telescope | NASA and ESA | Metal | In-orbit |
| TRAC [235] | Low earth orbit | Nanosail-D2 | NASA | Metal | In-orbit |
| TRAC [236] | Nano-solar sail mission | CubeSail | Surrey space centre | Metal | Prototype |
| TRAC [237] | Low earth orbit | Lightsail-1 | Planetary society | Metal | In-orbit |
| TRAC [238] | Low earth orbit | Lightsail-2 | Planetary society | Metal | In-orbit |
| TRAC [239] | Near earth asteroid scout | NEA solar sail | NASA | Metal | Prototype |
| Lenticular [240] | N/A | ESA-DLR solar sail | DLR and ESA | CFRP | Prototype |
| Lenticular [241] | Low earth orbit | GOSSAME R-1 | DLR and ESA | CFRP | Prototype |
| Tubular [242] | CubeSat mission | ALSat-1N | Space agencies of the UK and Argeria | CFRP | In-orbit |
| Lenticular [243] | Risk reduction | ACS3 | LaRC | CFRP | Concept design |
| Lenticular [244] | Near earth asteroid scout | CS3 | LaRC | CFRP | Testing |
| TRAC [245,246] | N/A | FURL solar sail | NASA | CFRP | Prototype |
| Tubular [247] | Xiaoxiang-1 07 satellite | SIASAIL-I solar sail | Spacety Co., Ltd. | CFRP | In-orbit |
| Tubular [248] | SpaceX commercial resupply mission | Roll-out solar array | NASA | CFRP | In-orbit |
| TRAC [256] | Space debris removal | Deorbit sail | SIASE | CFRP | In-orbit |
| Lenticular [257] | Communication applications | Membrane array antenna | SIASE | CFRP | In-orbit |

Deployable composite reflectors: Hughes Corporation (now Boeing) utilized carbon fiber composite materials in the design of the taco-shaped deployable reflector antenna and successfully achieved a flight mission on Mobile Sat-1 in 1996 [258]. Subsequently, this concept was expanded to the Tracking and Data Relay Satellite System (TDRSS) in the United States. The second generation of TDRS (TDRS I and TDRS J) was successfully used for missions in the S, Ku, and Ka bands between 2000 and 2002. The same concept was also applied in the third generation of relay satellites, which were launched successfully in 2013 and 2014 [224]. Additionally, CAST conducted ground tests of taco-shaped deployable reflectors [259].

Currently, the application of petal-shaped deployable reflector antennas is limited [260]. Umbrella-shaped deployable reflector antennas are more commonly used, such as the 3-meter

diameter umbrella-shaped deployable antenna carried by technology experiment carrier SAR developed in Israel [261], the 0.5-meter diameter Ka-band umbrella-shaped deployable antenna developed by the Jet Propulsion Laboratory (JPL) in the United States [262,263], and the 4.2-meter diameter umbrella-shaped deployable antenna carried by Chinese relay satellites [264]. However, most reflector antennas currently use metallic materials. With the development of carbon fiber composite material technology, researchers have gradually begun to pay attention to deployable composite reflector antennas. However, there are still few cases of deployable composite reflector antenna applications, and most of them are still in the testing phase [174,175,265]. Table 4 summarizes various space applications of deployable reflectors.

Table 4 A summary of space applications of deployable reflectors.

| Type | Mission | Application | Operator | Material | Status |
|--------------------------------------|------------------|--|---------------------|---------------|----------------|
| Taco-shaped [224,258] | MSAT | Mobile Sat-1 | Stephen A. Robinson | CFRP | In-orbit |
| | TDRS mission | TDRS-H TDRS-I TDRS-J TDRS-K | NASA | CFRP | In-orbit |
| | N/A | 4200mm flexible spring-back reflector antennae | CAST Xi'an | Polyimide | Testing |
| Petal-shaped [259] | X-band | Deployable radio frequency reflector antenna | Footdale et al. | CFRP | Concept design |
| Umbrella-shaped [260-264,174,175] | LEO | TECSAR | Israel | CFRP | Prototype |
| | RainCube mission | Ka-band parabolic deployable antenna | JPL | Metal | Prototype |
| | Chang'e-4 (CE-4) | Queqiao | China | N/A | In-orbit |
| | X-band | An unfurlable skin antenna reflector | Astrium GmbH | CFRP | Testing |
| | N/A | Dual polarization of deployable reflector antennas for SAR | Yoon et al. | CFRP | Testing |
| | Ku-band | SMART deployable telescope | Murphey et al. | CFRS and CFRP | Testing |

7. Outlook

The current research progress and successful engineering application cases have greatly enhanced the understanding of deployable composite structure technology for space applications. However, there are still many urgent challenges that need to be addressed. Through in-depth investigation and analysis of a large number of references, some issues and prospects were discussed.

We hope that these prospects will stimulate more research interest to address the current challenges of deployable composite structure technology. Currently, deployable composite structures face the following six challenges:

7.1 Modelling of folding behavior

Theoretical modeling and finite element modeling are the two most commonly used methods for analyzing deployable composite structures. There are currently multiple theoretical models available for predicting the folding behavior of deployable composite structures (including tape-springs, hinges, and various types of booms) [16-18,25,26,29,30-32,83], but there are still some issues. For example, the ability to describe geometric configurations in highly nonlinear or large deformation situations is limited [26], and the influence of boundary conditions is ignored [16,17], which significantly reduces the prediction accuracy of theoretical models. Liu and Bai et al. demonstrated through comparison with various classical theoretical models that accurately predicting the folding behavior of DCBs [85] and Bi-DCB [118,119] is crucial in determining their geometric configurations during the folding process. Further improving the model, enhancing its accuracy and applicability, will be an important direction for the future. In addition, the failure analysis of deployable composite structures during the folding process is often overlooked, and failure analysis involves the strength properties of materials under different environments and usage conditions, which is a key indicator in the design process of deployable composite structures [6,37].

Compared with theoretical modeling, finite element modeling is a more practical method that discretizes the structure into a finite number of elements and uses numerical calculation methods to simulate the folding process of the structure. Finite element modeling relies on input parameters such as material properties, geometric dimensions, and boundary conditions, and predicts structural deformation, stress, and energy changes by solving the equations of the discretized model. This modeling method can provide more detailed and accurate information, which helps evaluate the performance and stability of the structure under different folding states. Due to the nonlinear and deformation characteristics of deployable composite structures, traditional finite element modeling methods may not be able to effectively handle their complex behaviors. Therefore, to improve computational efficiency, it is necessary to explore modeling algorithms with stronger applicability for this special structure. These algorithms can include simplification methods based on physical models, model dimensionality reduction techniques, and efficient numerical solution methods. By

selecting and optimizing these algorithms reasonably, computation time and resource consumption can be significantly reduced, while maintaining the accuracy of simulation results.

7.2 Stowage and deployment behavior

Deployable composite structures typically go through three different stages: (1) Folding stage: Before entering space, deployable composite structures are folded into a compact form. This process is a relatively slow and quasi-static process [34,85,118,119]. (2) Storage stage: During launch and transportation to orbit, deployable composite structures are firmly held in a folded state through a locking mechanism. The storage phase can last for a long time, ranging from several months to several years depending on the task requirements. (3) Deployment stage: Once in orbit, deployable composite structures can be deployed by releasing the previous locking mechanism. During the deployment process, the stored strain energy will be rapidly released. The deployment process is a dynamic process that typically completes quickly within a few seconds. The current research mainly focuses on the behavior of deployable composite structures during the folding stage, and the storage and deployment stages are equally crucial for the successful in orbit operation of the structure. Therefore, in future research, it is necessary to understand and address the challenges faced by deployable composite structures during long-term storage and deployment processes. During the storage stage, prolonged storage may cause changes in the aging properties of materials, such as the evolution of viscoelastic and plastic properties [266-271]. This may lead to changes in material properties, reduce the stored strain energy, and may affect the deployment ability and shape recovery accuracy of the structure. Therefore, in the design phase, it is necessary to consider and address the aging performance of materials, and take corresponding measures to avoid irreversible failure. During the deployment stage, plastic deformation and stress accumulation may lead to a decrease in structural performance, especially at the boundaries or connection points of deployable composite structures. Therefore, in the design phase, it is necessary to fully consider the viscoelasticity of the material and reduce the accumulation of plastic strain through appropriate structural design and connection methods, in order to ensure the reliability and accuracy of the structure during the deployment process [272-275].

Moreover, the utilization of advanced materials and manufacturing processes can effectively enhance the storage and deployment behavior. Firstly, advanced materials exhibit superior physical and chemical properties, such as higher strength, enhanced corrosion resistance, and reduced thermal expansion coefficients. These improvements in performance contribute to reinforcing the stability of

deployable composite structures during the storage phase, mitigating material performance degradation triggered by environmental variations. Secondly, cutting-edge manufacturing techniques can optimize the microstructure of composites, minimizing internal defects and stress concentrations. This optimization enhances the overall performance of the materials, imparting superior durability and reliability throughout the storage and deployment cycles.

7.3 Impact of extreme space environments

In extreme space environments, deployable composite structures face various challenges, such as special conditions such as high/low temperatures, radiation, atom oxygen, high vacuum, and microgravity etc. These environmental factors may have a significant impact on the physical and chemical properties of materials, thereby affecting the mechanical properties, stability, and reliability of structures [276,277]. In response to the impact of extreme space environments, future research directions can focus on the following aspects: (1) Material properties in high/low temperature environments: In high/low temperature environments, the mechanical properties of materials such as strength, toughness, and stiffness may change. Therefore, it is necessary to study the stress-strain relationship, fracture behavior, and fatigue life of materials under high/low temperature conditions to ensure that deployable composite structures can maintain their design target property [278]. (2) The impact of radiation environment on materials: In space environment, radiation can cause damage to materials and may lead to material degradation and property degradation. Therefore, it is necessary to study the radiation failure mechanism, radiation tolerance, and mechanical property changes caused by radiation of materials in radiation environments to ensure the reliability and durability of deployable composite structures [279]. (3) Material properties and stability in vacuum environment: Under vacuum conditions, materials may be affected by factors such as gas escape, volatilization, and adsorption. Therefore, studying the gas escape characteristics, mass loss, and deformation behavior of materials in vacuum environments can help ensure the property stability of deployable composite structures after long-term vacuum condition. (4) Material properties and deployment control in microgravity environments: Under microgravity conditions, the deformation, deployment behavior, and control methods of materials may differ from those on Earth. Therefore, studying the mechanical response, deformation control, and structural dynamics behavior of materials in microgravity environments can help design and optimize the deployment process and behavior of deployable composite structures in space [280-283]. In summary, considering the impact of extreme

environments on deployable composite structures is one of the important directions for future research. By thoroughly studying these influencing factors and optimizing the composition, structural design, and preparation process of materials, the performance, stability, and reliability of deployable composite structures in extreme space environments can be improved, thereby achieving more sustainable and reliable space applications.

7.4 Structural design and space application

One of the future works is to propose diverse types of deployable composite material structures to meet different space applications. Firstly, deployable composite structures with different shapes and sizes can be designed and developed for different task requirements and space environmental conditions. Through flexible and customizable design, efficient deployment and operation can be achieved in different task scenarios. Secondly, it is necessary to research and develop multifunctional deployable composite structures. For example, by combining technologies such as sensors and actuators, the structure can perceive the external environment and internal state, and make corresponding responses or adjustments. This structure can complete specific tasks after deployment, such as shape adjustment, deformation control, and adaptive adjustment [284-287]. New deployment mechanisms can also be explored, such as using shape memory composites to achieve simpler deployment and shape control [288-294]. In addition, new material combinations and processing methods can be explored to improve the behavior and reliability of deployable composite structures. For example, introducing nanomaterials, fiber reinforced materials, and new resin systems to improve the strength, stiffness, and durability of structures. In summary, future work should focus on proposing new deployable composite structures to meet the needs of different space applications, and continuously innovate and optimize in materials, structural design, and manufacturing methods. This will provide more possibilities and opportunities for future space exploration and applications.

7.5 Optimization design

There are three urgent challenges to be addressed in the multi-objective optimization design of deployable composite structures. (1) Choosing appropriate surrogate models and evolutionary algorithms: Different surrogate models (such as RSM, Kriging model, EBF, RBF, ANN, SVR, and RF) and evolutionary algorithms (such as GA, SA, PSO, and ACO) have been widely used, but there is still a lack of theoretical basis for selecting appropriate surrogate models and evolutionary algorithms for specific optimization problems [107]. In most cases, surrogate models and

evolutionary algorithms are usually selected based on experience. Therefore, establishing a guide with theoretical basis for selecting appropriate surrogate models and evolutionary algorithms can greatly improve the efficiency of deployable composite structure optimization. It is necessary to develop new surrogate models and evolutionary algorithms suitable for specific deployable composite structure optimization problems, or further improve existing surrogate models and evolutionary algorithms to adapt to the current challenges. (2) Optimization of hyperparameters for surrogate models and evolutionary algorithms: The prediction accuracy and robustness of surrogate models are closely related to their hyperparameters. Evolutionary algorithms implement random global search in a defined optimization space, so the definition of hyperparameters in evolutionary algorithms directly affects the efficiency and convergence of optimal search in optimization problems. However, the selection of hyperparameters for surrogate models and evolutionary algorithms is often based on previous research or experience. This may result in the inability to identify the optimal hyperparameter settings for surrogate models and evolutionary algorithms [198,222,223]. Therefore, there is a great demand in the future to develop hyperparameter optimization methods suitable for deployable composite structures. (3) The number of design variables, objectives, and constraints: Deployable composite structure optimization is a complex engineering problem. Therefore, the number of design variables and objectives also plays a crucial role in determining the final optimization scheme. In most published literature, geometric parameters and layering schemes are the most commonly considered design variables [295,296]; Folding and deployment behavior (such as the required load for folding, stiffness and frequency of deployment state) are the most commonly considered objective functions; Non failure, geometric dimensions, and weight are the most commonly considered constraints. Generally speaking, the more design variables, objectives, and constraints considered, the closer the optimization solution is to the practical application scenarios of deployable composite structures. Therefore, considering more design variables, objectives, and constraints in future optimization models, and designing suitable surrogate models and evolutionary algorithms, can significantly improve the quality of optimization solutions.

Furthermore, the emergence of advanced design methodologies, such as generative artificial intelligence, will provide robust support for the optimization of deployable composite structures. By integrating artificial intelligence algorithms with numerical simulation techniques, the design space

can be efficiently explored, revealing novel structural forms and connection methods. This integration is expected to enhance the performance of structures while simultaneously reducing design costs.

7.6 Auxiliary devices for folding and deployment

For practical engineering applications, auxiliary devices used in deployable composite structures can achieve specific task objectives. A large amount of engineering practice has shown that the smooth deployment based on deployable composite structures is the key to the success of the entire system. In other words, faults are often prone to occur during the deployment process, leading to the inability to achieve complete tasks or even complete failures. Auxiliary devices aim to support, drive, and control the movement process of deployable composite structures, enabling them to smoothly achieve folding and deployment functions [297-299]. These auxiliary devices include mechanical structures, mechanisms, drivers, controllers, etc. The most representative ones include folding mechanisms, release devices, etc. When designing auxiliary devices, engineers not only focus on the behavior of the deployable composite structure, but also pay special attention to the reliability and deployability of the auxiliary device from the perspective of the success of the entire task. The ideal solution is to maximize the efficiency of deployable composite structures while minimizing the impact on the entire system's tasks and ensuring the achievement of critical capabilities, even in extreme cases where partial deployment or failure to deploy is possible. In addition, specific requirements and working environment conditions for deployable composite structures need to be considered, such as overload and vibration during launch, extreme high/low temperatures during orbit, vacuum, weight loss, radiation, etc. These devices must have sufficient rigidity and stability to support and control the movement process of deployable composite structures [300]. Meanwhile, precise position control capability is also essential to ensure that the structure can be accurately deployed to the predetermined position and retracted back into a compact form when needed [301,302]. In addition, auxiliary devices also need to meet the requirements of lightweight and compactness to adapt to the mass and volume limitations of deployable composite structures. With the continuous development of technology, future research can focus on the following aspects to further improve auxiliary devices. Firstly, according to the needs of different application scenarios, more advanced materials and manufacturing technologies can be explored to improve the property and reliability of auxiliary devices. Secondly, intelligent materials and intelligent structures can be used to achieve adaptive deformation and functional adjustment, enabling auxiliary devices to autonomously adjust

according to environmental changes and operational requirements. In addition, for long-term space missions, the durability and maintainability of auxiliary devices are also fields that need attention. In summary, auxiliary devices play an important role in the research of deployable composite structures for space applications. Future research should focus on technological improvement, material innovation, new concept design, optimization, and other aspects to further enhance the functionality and reliability of auxiliary devices.

8. Conclusions

In summary, thin-walled deployable composite structures with integrated structure function characteristics have become an interesting and popular research topic, with more and more research works published and increasingly cited. In this review, a detailed exploration of different types of thin-walled deployable composite structures (such as hinges, booms, and reflectors) was conducted to gain a deeper understanding of their deformation mechanisms, theoretical modeling, design methods, etc. This paper provides a detailed analysis of existing multi-objective optimization design methods and their applications in thin-walled deployable composite structures. In addition, specific practical application cases and corresponding space tasks of thin-walled deployable composite structures were reviewed. So far, although thin-wall deployable composite structures have been extensively discussed and a lot of progress has been made, there are still some challenges that need to be overcome. This research looks forward to potential research directions for thin-walled deployable composite structures in the future, and looks forward to addressing these challenges. We believe that thin-walled deployable composite structures with better functionality and behavior will emerge in the future. Overall, the research findings of this paper may provide important guidance and inspiration for the design and application of thin-walled deployable composite structures. We firmly believe that with the joint efforts of our peers, we will further promote the development of this field.

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