Advances in the Application of Deployable Structures in Bridge Engineering

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Abstract. With the fast urbanization and the increasing requests of various infrastructures, traditional bridge technologies are more and more constrained in terms of construction speed, logistical effectiveness and versatility to diverse environments. The fold-to-deploy functionality of deployable bridge systems offers promising benefits from transportation and site installation. They are also found to have better performance under emergency conditions and extreme geology, making them a new hot spot of innovation in the bridge engineering. The review article summarizes some recent research advances of deployable structures for use in bridge engineering. This article systematizes the classification of dominant design techniques, namely, origami-based structures, linked-member trusses and scissors-based mechanisms. At the same time, critical mechanical properties related to the design including deformation compatibility of the folding and load carrying functionality of the folded state, dynamic stability during the morphing, as well as the utilization of lightweight high-strength materials and the development of related manufacturing processes are also reviewed. By exemplary summary from temporary emergency, long span adaptive structures, and the special geological fields, the present domestic and foreign research findings are analyzed, while the technical bottlenecks in current research are summarized, and some orientations for future research are proposed, which serves as a preliminary basis for continuous development. We conclude that deployable structures can be seen as revolutionary methodology with a great potential in developing bridge engineering technology.

Keywords: Deployable architecture; Bridges; Foldable systems; Mechanical behaviors; Lightweight and high-strength materials.

1. Introduction

Due to fast-paced urbanization and multi-function infrastructure demands, large-scale bridge construction encounters greater and greater urgent demands such as rapid assembling, emergency rescue and standardized module structure. Conventional bridge construction methods, which typically involve extended transportation and on-site assembly periods, often fail to meet these urgent timelines. Zhao et al. [1] pointed out that collapsible and highly mobile deployable structures have great potential for enhancing spatial utilization and construction efficiency and thus may be an effective technical path to break through these constraints. While considerable advances have been made in both theoretical and experimental aspects of such structures, a cohesive theoretical system has yet to be fully established, and documented engineering applications remain relatively scarce, underscoring the need for further systematic investigation.

Substantial contributions have been offered by domestic researchers. Zhao et al. [2] conducted a systematic analysis of fundamental deployment mechanisms in deployable systems, establishing that carefully engineered folding units can achieve highly efficient folding and unfolding sequences. This efficiency directly enhances transport ability and accelerates construction. Other researchers have developed origami-inspired foldable bridge designs, concentrating particularly on mechanical performance and stability throughout the folding process. These contributions not only strengthen the theoretical foundations of structural design but also supply practical guidance for bridge engineering applications.

Globally, important advances have been achieved, especially in structural dynamics and kinematic analysis. Han et al. [3] investigated a large multi-loop deployable truss antenna mechanism featuring synchronized motion. Their study examined the system's kinematic and dynamic behavior in detail and introduced a comprehensive dynamic modeling approach. It allows the prediction of structural mechanical response and stability during folding and deployment, providing valuable insights for the design of analogous bridge structures. Furthermore, the modeling framework supports optimization of deployment trajectories and control laws, enhancing operational reliability. International research in this field increasingly incorporates lightweight high-strength materials and advanced fabrication techniques, substantially improving the practicality of deployable systems for real-world engineering applications.

This article presents a systematic review of recent advances in deployable structures for bridge engineering, with emphasis on structural design, mechanical performance, material selection, and representative project implementations. By synthesizing a broad range of domestic and international literature and case studies, we identify key technical characteristics and trace the evolving development trends within this field. The review additionally examines theoretical progress, manufacturing refinements, and practical implementation outcomes, offering a consolidated knowledge base for both researchers and practitioners. It is hoped that this comprehensive analysis will promote further adoption of deployable structural solutions, thereby supporting the transition from conventional bridge construction toward more efficient and intelligent development paradigms.

2. Fundamental Theory and Key Technologies of Deployable Bridges

2.1. Structural Design Classifications

2.1.1. Origami-Inspired Foldable Structure

Operating on origami principles, these structures utilize engineered crease patterns and nodal systems to control their spatial deployment and retraction. They still give high levels of deformable mobility and guarantee robust bearing integrity once completely expanded. According to Cai et al. [4], the essential design problem is the co-optimization of the folding unit's geometry and its deployment path, which determines the folding efficiency and mechanical performance. They show via mathematical modeling and mechanics analysis that, given the folding angle (deformation compatibility requirement in the folded condition) and the structure stiffness requirement (mechanical compatibility requirement when deployed), the optimal folding angle and connection mechanism can be identified.

2.1.2. Linkage-Truss Foldable Structures

Due to their simple geometry and robustness, linkage-trusses have become a prime design choice for deployable bridges. Chen et al. [5] used six-crease thick-panel origami strategy to realize a new deployable parabolic bridge. By designating multiple linkage-truss units they successfully create a compact deployable form when the structure is folded and create strong structural support when deployed. The link joints act as pivot points where DOF motion conversion will be achieved and they contribute to structural stiffness. Mechanical analysis confirms that this structure has geometric compatibility in both folding and unfolding processes. After being unfolded, it can bear large static and dynamic loads, which effectively ensures the safety and stability of the bridge. This research not only provides theoretical support for the design of linkage-truss foldable structures but also offers a reference for practical engineering.

2.1.3. Scissor-Type Supplementary Structures

The scissor unit is a typical deployable structural unit. Because of its simple geometric form and excellent mechanical properties, it is widely used in the design of deployable bridges. Wang et al. [6] designed an emergency rescue bridge with a multi-stable Miura-ori structure. Through the reasonable combination of scissor units, this structure can achieve a stable translation during folding and unfolding process. The research indicates that the key points of the scissor unit lie in two aspects: one is the coordinated movement of the hinged joints, and the other is the mechanical coupling between the units. They use kinematic models and energy analysis methods to describe mechanical behavior, meet the load-bearing requirements in the unfolded state and also ensure compactness in the folded state.

2.2. Fundamental Mechanical Characteristics

2.2.1. Deformation Compatibility in Folding Phase

The deformation compatibility in folding phase is a key mechanical property in the design of deployable structures. It directly affects the folding efficiency and stability. For example, Liu et al. [7] pointed out that in the folding process, they have done a lot to meet the continuity of geometric deformation and the coordination of node movement, successfully avoiding concentration of local stress and structural damage. Inspired by origami structures, they also proposed the deformation compatibility condition, which is constrained by kinematic pair. These conditions ensure synchronized movement of all components, enabling a smooth and continuous transition between the folded and deployed states.

2.2.2. Load-Bearing Capacity in Deployed State

The static load-bearing capacity in deployed state is also a critical performance indicator for deployable bridges. Liu et al. [8] demonstrated that carefully engineered folding units can achieve optimized load transfer efficiency, which forms rigid interconnections upon deployment. Their analysis further revealed that material selection, joint detailing, and construction methods also significantly influence the ultimate structural capacity. With the adoption of strong and lightweight building materials and optimal connections, the structural strength and life span have better application prospects.

2.2.3. Dynamic Transition Stability

The dynamic deployment process may drastically affect structural safety and service. Zhou et al. [9] proposed an asymmetric deployable mechanism which is composed of the Wohlhart 6R linkage and the kinematic passage of the mechanism is smoothly transferred under a dynamic excitation by the optimized profile design. The mechanism has higher stiffness and better damping nature during dynamical excitation and can efficiently reduce instability and fatigue damage. Their results show the importance of geometry and the mechanisms of joint construction for designs of functional engineering-scale, deployable structures.

2.3. Material Selection and Fabrication Technologies

2.3.1. Lightweight High-Strength Materials

Comprehensive analysis by Xu et al. [10] on modular lightweight steel systems identified elastic modulus and yield strength as dominant parameters controlling folding stability. The exceptional strength-to-weight ratio of advanced steel alloys fulfills the dual requirements of high load capacity and deformation adaptability in bridge applications. Material selection criteria must simultaneously address deformation compatibility during folding and structural integrity in service conditions.

2.3.2. Integrated Design and Fabrication Optimization

Akgün et al. [11] demonstrated through architectural umbrella structures that the combination of scissor mechanisms and foldable panels enables hybrid structures and mechanisms to have superior performance compared to systems relying on foldable panels only. Their work identifies modular design and efficient assembly as essential for feasibility. The system uses precision-engineered joints and folding mechanisms to ensure robustness while eliminating many challenges in manufacturing and on-site assembly.

3. Typical Applications of Deployable Structures in Bridge Engineering

3.1. Temporary Emergency Bridges

Emergency rescue bridges in a short time are key to connecting the transportation during the rescue at disaster sites or emergencies in which high deployment speed and stable load-carrying capacity are needed. Wang et al. [12] designed a Kirigami-based bidirectional expandable planar structure with a novel actuation mechanism so that it has high deployment efficiency and can adapt to the environment more effectively during emergency rescue.

3.2. Long-Span Adjustable Bridges

The advantages of existing long span collapsible bridges are targeted at solving the bottleneck of span length and adjustability. Liang et al. [13] designed a deployment-based emergency bridge in a modular concept, which can be flexibly deployed with rapid adjustment, effectively shortening the construction time and providing a high load capacity and adjustability. Saito et al. [14] developed novel deployable systems based on elastic origami models, providing theoretical foundations for large-span adjustable designs. The two studies converge on a key principle: the design of long-span deployable structures must be intrinsically guided by their mechanical behavior during folding and deployment. As a central methodology, they propose leveraging mathematical analysis to optimize designs by linking the stiffness matrix of folding units with their deformation vectors. This performance-driven strategy guarantees precise adjustability and safe operation of the bridge.

3.3. Bridges in Challenging Geological Conditions

Bridges in special geological conditions have high requirements for adaptability and safety. Because of great deformation compatibility, deployable structures can reduce stress concentrations caused by geological movements. Meanwhile, by optimizing the truss structure, the deployable structure can be rapidly deployed in almost any complex terrain conditions [15, 16].

4. Conclusion

The deployable structure has great potential for development in the future. This structure features extremely high construction efficiency and convenient transportation, making it highly suitable for emergency operations and temporary passage. At present, theoretical research on deployable structures has made considerable progress. However, there are still many material and technical bottlenecks, which limit its application in super projects. Therefore, it is particularly important to build a "theory-technology-engineering" trinity development model: theory provides support for technological innovation and technology promotes the application of engineering. Only by relying on this model can the deployable structure achieve comprehensive development in application and contribute to the quality improvement and upgrading of modern bridge construction.

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